The Urban Geology of Hong Kong

A. Page
S.J. Reels (Eds.)

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The Urban Geology of Hong Kong

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With 122 Figures including three in colour

Front Cover
GIS ArcView 3-D image of a buried karstic surface that forms the upper contact of a marble formation beneath the Tin Shui Wai area in the northwestern New Territories of Hong Kong. This image was generated using data from 144 boreholes within an area of approximately 1.2 square kilometres, and has been merged with Lands Department data on roads and buildings.

The Urban Geology of Hong Kong

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Preface

An understanding of ground conditions and geological problems is at the forefront of issues in urban construction. The Hong Kong Special Administrative Region (SAR), characterised by a high density of urban development and diverse and challenging ground conditions, provides fascinating case study material for the geologist and geotechnical engineer. The objective of this volume is to document the range of subjects addressed in 15 papers delivered at a conference hosted jointly by the University of Hong Kong's Department of Earth Sciences and the Geological Society of Hong Kong. The contributors comprise a mixture of professional engineers in industry and government and applied researchers from academia. Together their papers present a broad snapshot of geological issues in the urban environment. The book will be of interest to geologists, engineering geologists and geotechnical engineers in industry and academia, especially those working in Hong Kong or concerned with urban geological problems.

The volume begins with a thematic paper. In the vanguard **Fletcher et al.** stress the importance of a sound geological model in development and infrastructure projects, underpinned by good geological databases. Cases are presented where the value of regional geological surveys, site surveys, hydrogeology, mineralogy and geophysics and geochemistry are used in understanding ground conditions. The importance of geologists, engineering geologists and geotechnical engineers working together in multidisciplinary teams is emphasised.

The geological modelling in the construction of HKIA is discussed by **Pinches, Tosen and Thompson**. The airport was built on a platform created by marine reclamation and the levelling of the islands Chep Lap Kok and Lam Chau. Formation of the platform and subsequent large structures were influenced by the solid and superficial geology of the area, including rock type, jointing, weathering and faulting. The authors emphasise the importance of the early development of a comprehensive geological model, to allow the optimisation of engineering design. Examples of how geology influenced the design of HKIA are cited, including : (a) how the compressibility of marine muds influenced the overall strategy of reclamation; (b) how the thickness and variability of the weathering profile governed the type of foundations; and (c) how the presence of drainage layers affected the overall settlement of the platform.

Hencher and **Daughton** discuss what constitutes difficult ground conditions" and "how they might be foreseen". A systematic approach is proposed to consider these questions, which may assist in avoiding delays, increased costs or project abandonment during construction. The paper covers the definition of difficult ground, geotechical hazards, material and mass scale factors, a project's environmental setting and the impact of engineering works themselves. It is argued that a careful, systematic appraisal of possible engineering geological conditions, based on a general knowledge of particular lithologies, can go a long way to preventing difficulties during construction.

Tse addresses the issue of managing ground uncertainty by identifying risks and using "observational methods" or "quantitative risk assessment" to manage those risks. The author describes two extremes of ground risk, those associated with gradual deterioration of ground to its limits, and those leading to sudden failure. The observational method is proposed as appropriate for managing risks where hazards can be monitored and where sufficient time is available to respond to developing problems. For the risk of failure suddenly, without warning, quantitative risk assessment and mitigation measures provide alternative methodologies.

Continuing the theme of difficult ground conditions, **Kirk** reviews the adverse ground conditions encountered at the Tung Chung new town, a satellite project to the new Hong Kong International Airport (HKIA). Tung Chung is developed on buried marble proposed to occur as lenses in a northeast-trending fault zone. Kirk draws attention to buried karst terrain, cavities and the development of localised sediment-filled collapse basins. In igneous rocks adjacent to the marbles, weathering fronts are abrupt and have unusually steep gradients. Drilling and seismic profiling are shown to have limitations in providing an understanding of this environment, but the effectiveness of gravity surveys is demonstrated.

Koor et al. provide a case history of a large, retrogressive, deep seated landslide affecting a cut slope at Lai Ping Road, Shatin, Hong Kong in July 1997. Five discrete slide zones totalling 4000 m^3 are identified as part of a much larger failure estimated at 100 000 m^3. Surface mapping revealed numerous scarps of differing ages and morphotypes, the development of which was influenced by joint structure, weathering depth and hydrogeology. The authors establish that the cut slope had a history of deep seated, spasmodic failure dating back to its initial formation in 1978.

Taylor discusses ground instability in decomposed volcanic rocks in the western foothills of the Tuen Mun area, Hong Kong, close to the alignment of a proposed major bypass highway. Geology, geomorphology and hydrogeology are discussed as components in developing a geological model and ultimately an engineering solution for the bypass alignment.

On a quite different theme, **Whiteside** discusses the contamination of marine mud, which was dredged and disposed of during major infrastructure developments in Hong Kong. Of 200 M tonnes of mud moved between 1992 and 1997, some 10 M tonnes was classified as contaminated. A data set of some 3000 mud analyses for seven heavy metals (Cr, Zn, Cu, Hg, Pb, Cd, and Ni) is compared to the results on 1300 analyses from stream courses throughout Hong

Kong. Zinc and nickel have higher values in seabed mud, whilst for other analysed metals, the model values in marine mud are similar to those for uncontaminated stream sediments and average levels in Hong Kong bedrock. Mud disposal in Hong Kong typically cost US\$7/m^3 in the 1992-97 period. The author stresses that over-conservative screening criteria for definition of contaminated mud which set screening levels below natural heavy metals levels will result in rapidly increasing costs of mud disposal. Given the natural levels of heavy metals in Hong Kong, the current regulatory screening levels are proposed to be close to optimum.

Following the marine sediment theme, **Parry** describes the origin and variability of suspended sediments in Hong Kong marine waters. The importance of understanding these issues is stressed as a component of environmental impact assessments (EIA) for offshore infrastructure developments. Suspended sediment levels in marine waters are influenced by a number of natural and anthropogenic factors. Natural factors include Hong Kong's location at the estuary of China's third largest river, changing ocean currents, tidal effects and storms. Amongst the anthropogenic effects are shipping movements, sewage disposal, reclamation, dredging for sand, mud disposal and fishing. It is argued that current monthly and bimonthly monitoring of suspended sediment levels is not sufficiently frequent to determine the natural variation in suspended sediments in marine waters.

The quarrying industry in Hong Kong, its current and future situation, is addressed in a paper by **Lam** and **Siu**. The Hong Kong construction industry has consumed some 229 M tonnes of aggregates in the last 15 years, 50% of which is sourced locally from four quarries. By 2003, Anderson Road will be the only quarry operating in the SAR, producing about one quarter of anticipated aggregate supply. As a consequence of this proposed scale down in the industry, the authors discuss the rehabilitation of three quarries scheduled to close and arguments for and against the development of new local quarries.

Owen and **Shaw** present the first large-scale study of the development of the weathering profile of mainly volcanic rocks in the Tuen Mun corridor. With a database of over 4000 boreholes, the authors modelled variations in the thickness of weathering, contoured the rockhead, examined the influence of major structures and identified the distribution of corestones. Their main findings include the recognition of up to 492 m of altitudinal range in the weathering front, and of significant topography of the weathering front of the valley floor. Four weathering lows are identified in the weathering profile. Deep weathering is also preferentially developed along a major, buried fault. Corestones are fairly evenly distributed across the area, but tend to occur where the weathering profile is at least 20 m thick.

Archeological studies have become an integral part of EIAs in Hong Kong. **Rumball Rogers** discusses the increasing interaction between archaeology and geology in a field now termed "geoarcheology". The paper discusses examples including the importance of interpreting Quaternary and more recent sedimentary environments, e.g. sandbars and tombolos, which may have been sites of prehistoric habitation; understanding soil stratigraphy from both geological and archeological perspectives and the use of geophysical tools in identifying buried structures. The absolute dating of archeological remains is a main task of geoarcheology, using methods familiar to the geologist, e.g. radio carbon and archaeomagnetic tools. Additionally, geology can assist archeology by identifying the sources and material properties of stone used in tools in antiquity, with possible implications for historical and prehistorical migration and trade.

Geophysical topics are discussed in two papers. **Fletcher, Collar** and **Lai** report the findings of marine magnetic surveys around Hong Kong and their contribution to subsurface geological mapping. A preliminary residual magnetic anomaly map reveals a large number of magnetic anomalies and lineaments in offshore areas. These are interpreted to arise from granite plutons, dyke systems, volcanic plugs and faults. The value of marine magnetic surveys has already been demonstrated in a number of infrastructure projects including the strategic sewage disposal scheme, development of Hong Kong International Airport at Chek Lap Kok and reclamation at Tolo Harbour.

On a different geophysical theme, **Chan** and **Chen** examine the geophysical and radiometric properties of weathered saprolites in Hong Kong. They show that saprolitisation in studied rock is associated with a decrease in resistivity and increase in permittivity and that both total gamma ray intensity and gamma emission by potassium bearing minerals decrease with an increase in weathering grade. It is proposed that these geophysical properties can be used as supplementary techniques for engineering geology ground investigations.

Returning to the development theme, **Yim** proposes a policy for the development of coastal areas in Hong Kong. In this policy, the coastal waters of the Hong Kong SAR are divided into : (a) a central zone where land demand is greatest and regulated effluents might be constrained; (b) a naturally high turbidity western zone, where offshore waste disposal and sand exploitation can be permitted; and (c) an eastern zone which should be reserved for marine mariculture, coastal fisheries and recreation. Yim emphasises the importance of co-operation between the SAR Government and Guangdong authorities for the effective implementation of a coastal waters policy.

The organisers are grateful to local government and industry for their support of the conference. In particular they would like to acknowledge contributions from :

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The Role of the Geological Model in the Urban Development of Hong Kong

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Abstract

The role of the geological model in the urban development of Hong Kong is discussed with reference to recent development and infrastructure projects, landslide investigations and geological surveys. The current status, importance and future of geological databases held by the Geotechnical Engineering Office are described, and examples of how visualisation techniques can assist the understanding of complex datasets are presented. It is emphasised that it is only through the formation of multidisciplinary teams, which include geologists, engineering geologists and geotechnical engineers, that the safe, cost-effective and environmentally aware development of Hong Kong can be realised.

Introduction

The Urban Geology Conference, organised by the Department of Earth Sciences of Hong Kong University (September 1998), brought together geologists, engineering geologists and geotechnical engineers from government departments, universities, consultants and contractors to present recent case studies of urban development projects in which geology was an essential component. The wide spectrum of papers that were given at the conference highlighted the importance of geology in development and infrastructure projects, landslide investigations and geological surveys. In particular, where urban developments increase in size and impinge on areas underlain by complex ground conditions or steep mountainous slopes, the establishment of a comprehensive and reliable geological model is essential.

This paper explores the role of geology in relation to the formulation of the geological model in a variety of engineering environments in Hong Kong. It emphasises the widening recognition of the potential value of geologists as integral members of multidisciplinary teams involved with the planning, creation and maintenance of this rapidly expanding community.

Key words: geological model, regional geological survey, site geological survey, hydrogeology, mineralogy, geophysics, geochemistry, multi-disciplinary teams.

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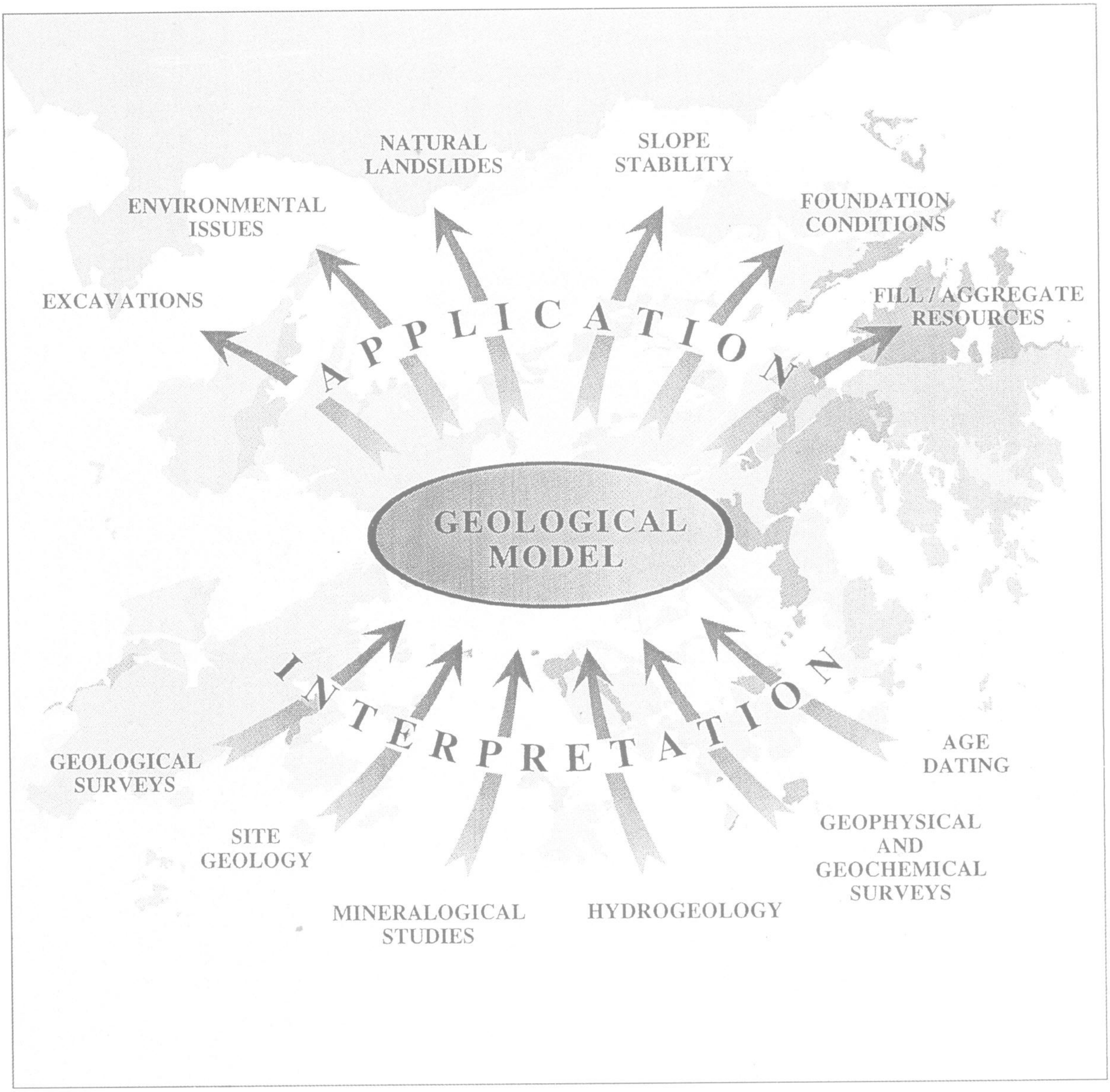
The Geological Model

At the core of any geotechnical assignment is the establishment of the best possible geological model for the ground conditions in any project area. Figure 1 illustrates the central position and importance that the geological model has in many development projects, particularly those in a region such as Hong Kong with its complex geology and rugged terrain. Without such a model, or with a poorly constrained model, all subsequent calculations, designs or conclusions are at best suspect, or at worst misleading, potentially costly and even hazardous. Geologists, in close working relationship with other professionals, have a crucial role in the formulation of such geological models. They rely on a variety of geological techniques to establish the geological model. Figure 1 sets out some of the techniques commonly used in Hong Kong and lists examples where such

Fig. 1. The geological model in relation to the use of geological techniques in urban development projects



techniques have been applied successfully. Only when the geological model has been established, to the best level possible with the available information, should it be confidently used in engineering projects.

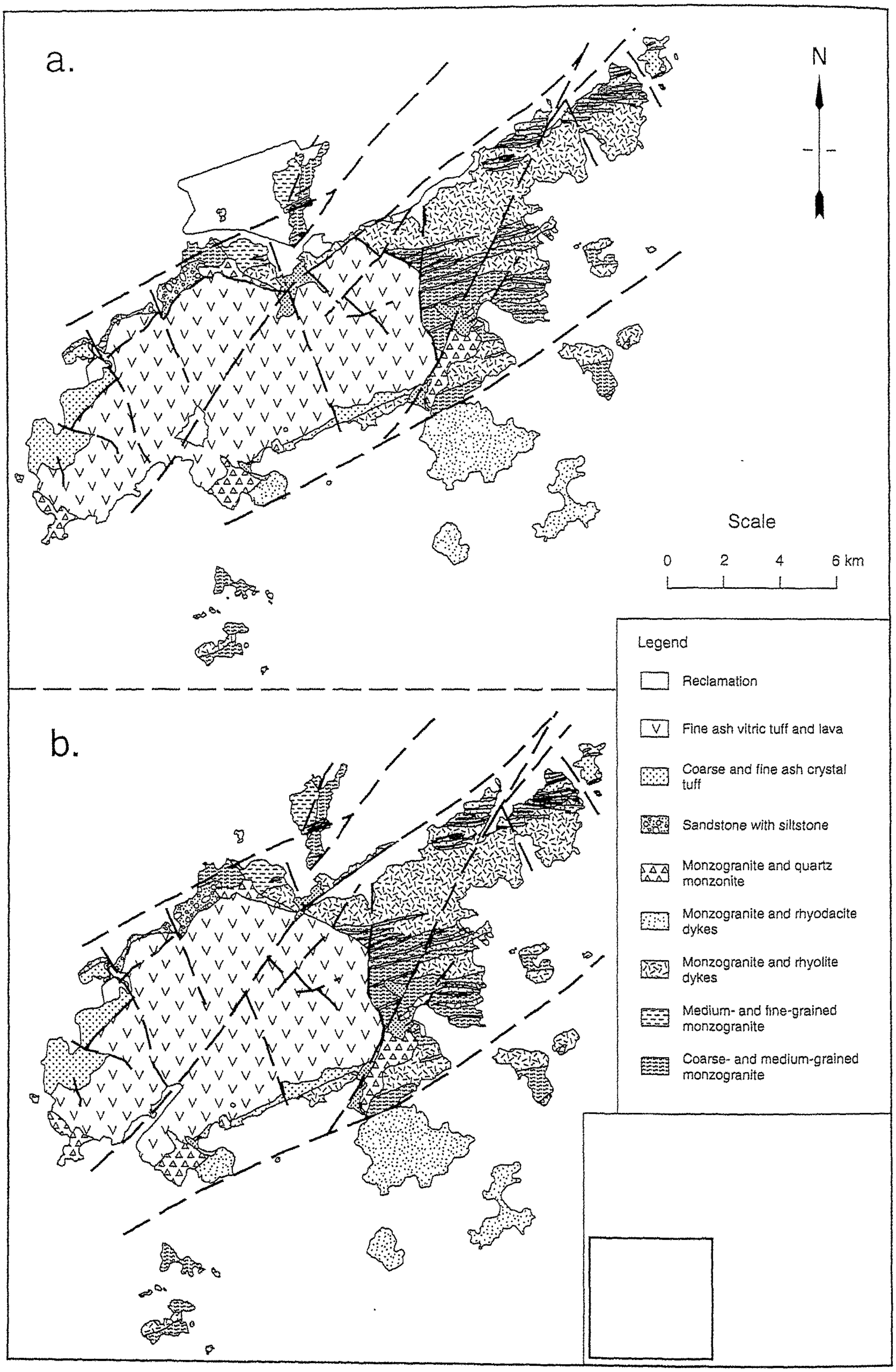
Some of the main geological techniques used for the development of the geological model are described below with reference to selected studies recently undertaken by the Geotechnical Engineering Office (GEO) and examples from the Urban Geology Conference. However, these component techniques must be underpinned by accurate, comprehensive and reliable geological databases that are used to store, access, model and display the increasingly complex and numerous data. The current status, importance and future of geological databases are described later, and examples of how visualisation techniques have been used in Hong Kong to display complex datasets are presented.

Geological Surveying

A set of fifteen 1:20 000-scale geological maps, produced by the Hong Kong Geological Survey (HKGS) of the GEO, provides the geological framework of the Territory and these are supplemented in development areas by 1:5000-scale geological maps. Six regional memoirs and five sheet reports describe the geology depicted on these maps, and in the near future two further publications, synthesising the 'Quaternary' and the 'Palaeozoic, Mesozoic and Tertiary' geology of Hong Kong, will be published by the HKGS. Increasingly, however, more detailed geological assessments of the subsurface geology are required, particularly offshore or in those areas with poor rock exposure. It has become essential, therefore, that the understanding of the geology is continually re-assessed, geological maps updated and databases maintained.

Where the geology is poorly constrained, the geologist has to rely on geological extrapolations, geophysical surveys and an intimate knowledge of the geological processes that have actively controlled the distribution and structure of the rock and soil. It is therefore essential that the geologist is fully aware of the local and regional geological framework in order to propose and substantiate any geological model. For example, the pattern and timing of faulting in Hong Kong is complex and it is only by reference to the regional tectonic setting that a thorough understanding can be attained. The recent recognition of the volcanic groups in Hong Kong (Campbell and Sewell, 1997, 1998) and the new compilation of the geology at 1:100 000 scale (GEO, in press) have provided the essential evidence for large-scale sinistral, ductile strike-slip faulting during the Early Cretaceous, with displacements on individual faults of up to 3.5 km. This knowledge of the regional fault dynamics has allowed a reconstruction of the geology of Hong Kong to be generated prior to this significant episode of strike-slip faulting. An example of a restoration for Lantau Island is shown in Fig. 2. Using such restorations it is possible to determine the distribution of geological features that existed prior to the strike-slip faulting, such as belts of marble-bearing strata, syn-volcanic faults and hydrothermal zones. Identification and mapping of these and other features can have significant ramifications for future development, as they are commonly associated with poor foundation conditions related to anomalous deep weathering profiles and solution cavities (Kirk, this volume).

The understanding of the regional fault distribution and kinematics is also essential for interpreting the data from the Seismic Monitoring Network


a.
N
Scale
0
2
4
6 km
b.
Legend
Reclamation
Fine ash vitric tuff and lava
Coarse and fine ash crystal tuff
Sandstone with siltstone
Monzogranite and quartz monzonite
Monzogranite and rhyodacite dykes
Monzogranite and rhyolite dykes
Medium- and fine-grained monzogranite
Coarse- and medium-grained monzogranite

that has recently been commissioned by the Hong Kong Observatory (Tam et al., 1997). The data from this network, combined with up-to-date knowledge of the faults, will allow knowledge of the seismic hazard of Hong Kong to be continually improved.

Site Geology

Detailed geological mapping of any development site, infrastructure project area or landslide is of paramount importance to any investigation. However, all too commonly, too much attention is placed on the actual area under investigation, without taking into account the broader geological setting. Understanding the detailed geology does not necessarily mean just mapping the geology in extreme detail, but rather making sure that certain key geological features are fully documented and their significance understood. This invariably requires studying not only the site itself but also the surrounding areas, and is especially important in areas of complex ground conditions, or where particular adverse geological features may have more than local significance. Equally, this may help to identify specific geological features that could be local hazards.

Regional geological features had a profound influence on the fatal landslides at Shum Wan Road and Fei Tsui Road in 1995. In both cases the attitude of the eutaxitic foliation in the volcanic tuffs was of critical importance in formulating the geological model of the two landslide sites. At Fei Tsui Road (GEO, 1996a; Kirk et al. 1997) a weak clay-rich zone dipped at a shallow angle out of the cut slope and was subparallel to the eutaxitic foliation in the nearby rocks; this indicated that the seam could have been a bedding feature,

Fig. 2 (facing). (a) Geological map of Lantau Island. (b) Restoration of the geology of Lantau Island prior to the Late Jurassic to Early Cretaceous strike-slip displacements on faults

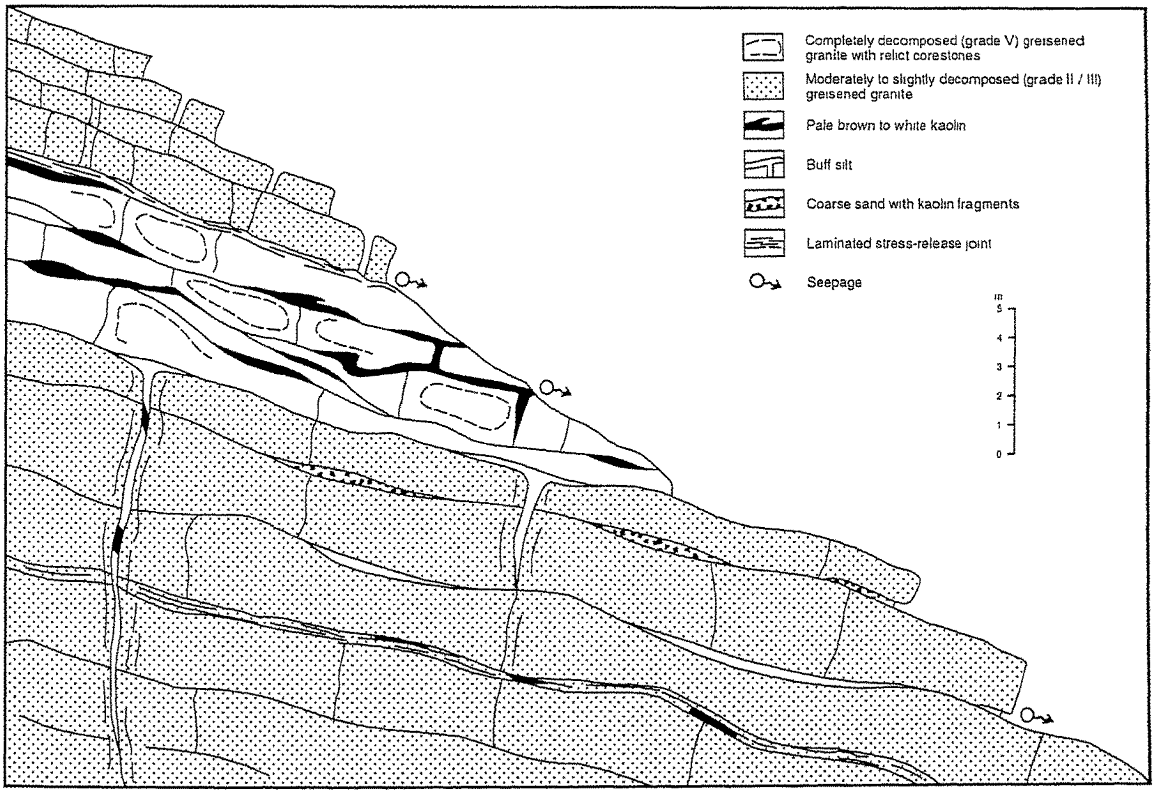


Fig. 3. Schematic section through a cut-slope in the eastern New territories showing the development of kaolin lenses and stringers

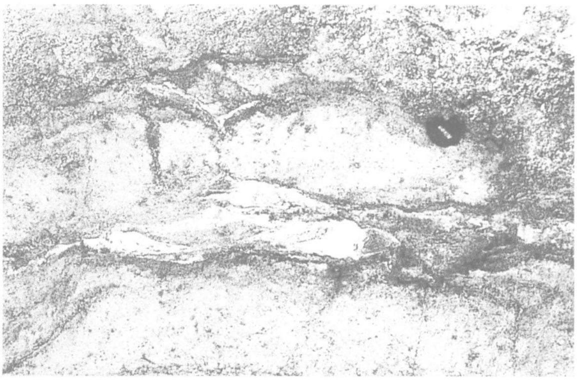


Fig. 4. Kaolin lenses and stringers in completely decomposed greisenised granite

and therefore be laterally extensive. At Shum Wan Road (GEO, 1996b) the eutaxitic foliation was subvertical and trending down the slope of the landslide. A shallowly inclined, weak clay seam had developed in an orientation adverse to the stability of the slope, and in addition many subvertical discontinuities were infilled with clay also. There, it was considered that the steep eutaxitic foliation had facilitated ingress of surface and ground water and as a consequence a localised deep weathering profile, with a concentration of clay near the soil/rock interface, had developed.

Subsequent area studies by teams of geologists and engineering geologists in the vicinity of both landslides included detailed geological mapping that was specifically targeted to identify similar adverse conditions (Campbell and Koor, 1996, Franks et al., 1997, Campbell et al., 1998). Small-scale geological maps were produced that highlighted, among other features, the orientation of the eutaxitic foliation, and as a result assisted in identifying sites of potential instability within the study area, eventually leading to some selective re-engineering of cut slopes in the two areas.

Subsequent investigations at landslide and development sites have emphasised the common occurrence of kaolin concentrations close to the interface between rock and soil, and provide additional evidence for the nature of their formation. For example, significant kaolin concentrations have been found within a completely decomposed layer of greisened granite exposed in an 80 m-high cut slope in the eastern New Territories (Parry et al., in press) (Fig. 3). The kaolin is generally concentrated in thin stringers and lenses (up to 50 mm thick) which may be traced for over 10 m along the cut slope (Fig. 4). These laterally persistent discontinuities dip at shallow angles (20°-35°) out of the slope and are associated with significant seepage. They are subparallel to stress relief joints within the rock mass and are considered to have been formed by a process of weathering that involved dissolution of the kaolin, its migration, either as a colloid or in solution, and its re-precipitation. Such concentrations of low-strength kaolin have significant implications for slope design in Hong Kong. Further studies are underway to investigate the controls of the distribution of these kaolin-rich discontinuities.

Detailed geological studies at several landslide sites in weathered granites and volcanic rocks have described a variety of deformation structures associated with the development of kaolin. Kaolin lenses are commonly folded and sheared, and the discontinuities associated with slickensided surfaces. At the Shum Wan Road Landslide site (GEO, 1996b), slickenside lineations and S-C fabrics defined the sense of movement along the surface of rupture (Fig. 5),

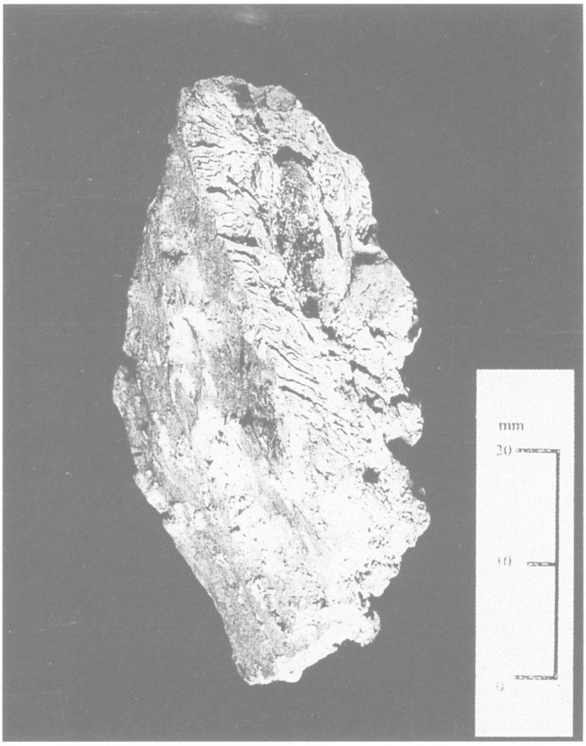


Fig. 5. Kaolinitic clay layer sampled above the basal surface of rupture of the Shum Wan Road landslide. The planar rupture surface (left side of specimen and seen from below) shows faint slickenside lineations (plunge top left to bottom right); above this, sigmoidal S-C fabrics (seen in cross-section and accentuated by drying out) are consistent with the landslide displacement (right-side down); a further shear plane separates the S-C fabric zone from the landslide debris to the right

and at landslides at Sai Sha Road, (GEO, 1999), kaolin-infilled, slickensided relict joints, S-C fabrics and disharmonic folding were commonly developed within a corestone-bearing, completely decomposed tuff (Fig. 6). The slickenside plunges were not constant for any given joint set and this may reflect 'jostling', i.e. differential movement of individual joint-bounded blocks of material during weathering.

Detailed geological mapping at Tung Chung New Town (Kirk, this volume) illustrates the need to extend the geological investigation beyond the bounds of a particular site. There, during the early 1990s, the complex ground conditions had been interpreted in many ways between development sites on the reclamation. As a result there was no consensus on the geological model. Only by the re-examination of selected boreholes and the amalgamation of all available borehole data (over 2000 logs were compiled in a database) was a reliable geological model firmly established, thereby allowing areas with potential future foundation problems to be identified. The knowledge gained by this detailed investigation has been used to plan site investigations at other reclamations along the north Lantau Island shoreline, and to re-examine other geologically similar areas within the territory (e.g. Yuen Long and Ma On Shan).

Mineralogical Studies

Detailed mineralogy, combined with field observations, can often provide essential evidence as to the origin and conditions of formation of rocks and soils, thereby significantly affecting the geological model. This is well illustrated by recent studies on the distribution and mineralogy of kaolin in saprolites in relation to the stability of soil slopes.

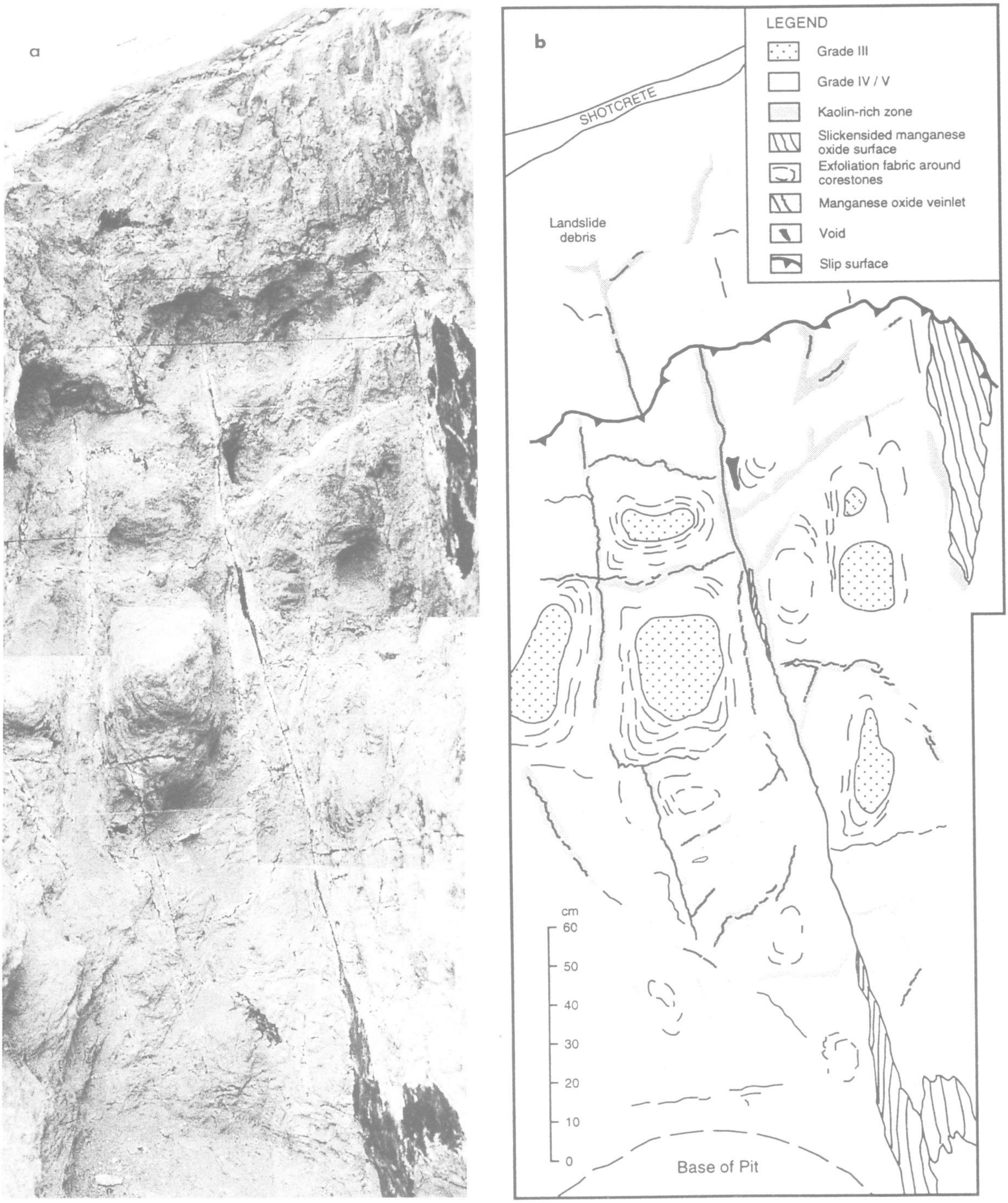


Fig. 6. (a) Photograph of a trial pit face at the site of landslides at Sai Sha Road, northeast New Territories. (b) Sketch of relict features observed in Figure 6(a)

Until recently, most kaolin found in Hong Kong was commonly regarded as the product of hydrothermal alteration related to the intrusion of the granite plutons (see review by Parry, 1999). However, following the two fatal landslides at Fei Tsui Road (GEO, 1996a) and Shum Wan Road (GEO, 1996b) the kaolin occurrences are now considered to be mainly associated with weathering (see above). The Geotechnical Engineering Office is currently undertaking further

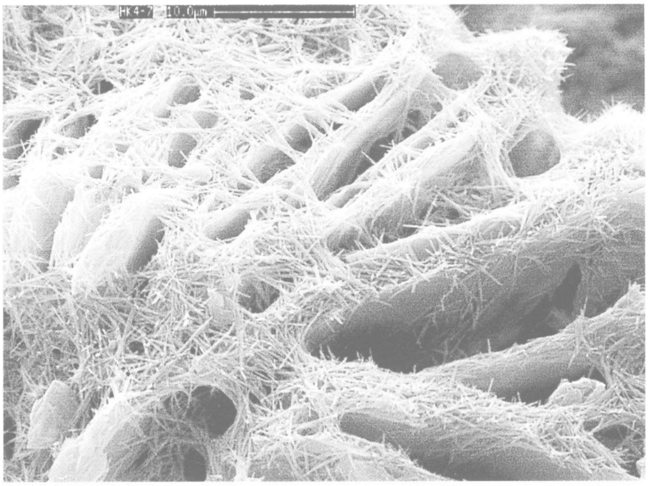


Fig. 7. Scanning electron microscope image of halloysite fibres growing on a dissolved book of kaolinite

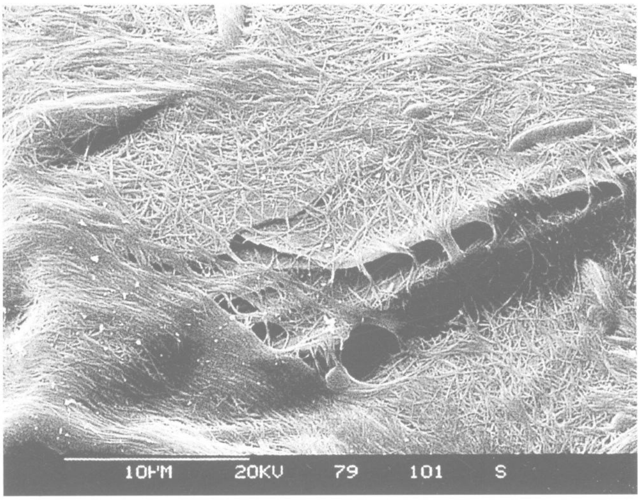


Fig. 8. Scanning electron microscope image showing bundles of halloysite fibres over mica

mineralogical investigations at several sites in Hong Kong (e.g. Parry et al., in press) to determine the origin of the kaolin. Initial results have shown that the clay minerals in all samples are predominantly kaolinite and halloysite. The kaolinite formed first from the alteration of both feldspar and mica, and was subsequently altered to halloysite (Fig. 7). At one site, halloysite forms long bundles of fibres within clay infills (Fig. 8), and it is suggested that this type of halloysite crystallised directly from solution in an open system. Some samples show microscopic evidence for movement and re-deposition of the clay minerals (Parry and Franks, in press). These studies have shown that groundwater movement during weathering plays a significant role in the preferential deposition of halloysite in the more permeable locations, particularly joints. However, the presence of dehydrated halloysite in association with iron and manganese oxide minerals in some samples suggests that later periods of drying have occurred locally.

These mineralogical observations have considerable implications for assessing slope stability in Hong Kong and elsewhere, and have greatly increased our understanding of the processes involved with the accumulation of low strength, low permeability clay infills within the weathering profile.

Hydrogeology

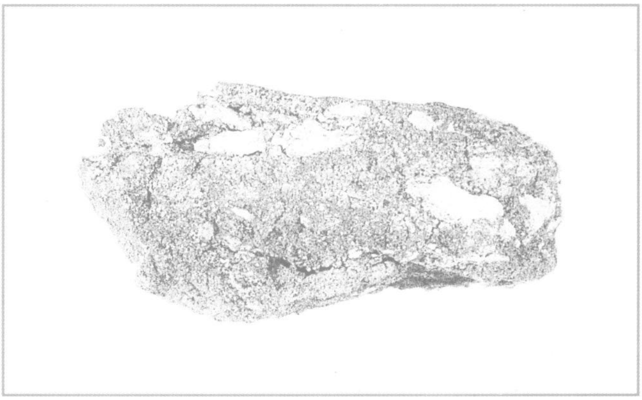
The importance of hydrogeology in slope stability of soils and weathering studies is paramount. However, monitoring present day hydrogeological regimes is only undertaken in restricted areas, and extrapolation of these data to establish regional ground water flow patterns is generally highly subjective. The modelling of ancient hydrogeological regimes is even more difficult and relies on the recognition of geological phenomena related to changing flow patterns and water table levels. One control of water flow patterns is associated with the development of soil pipes (e.g. Nash and Dale, 1984). Their importance was again highlighted in the recent reports on the Ching Cheung Road Landslide (GEO, 1999) and the Lai Ping Road Landslide (Koor et al., this volume). The former study concluded that the hydrogeology of the area was controlled primarily by soil pipe systems, many of which had become infilled by sand. These pipes enabled rapid transfer of water from the catchment area to the landslide zone and have probably played a significant role in the long-term instability of the area.

Kaolin-infilled discontinuities can also act as present-day aquicludes. However, evidence for ancient water flow patterns are provided by coarse sand-infills along stress relief joints in the underlying rock mass. Some of these sands contain angular fragments of kaolin (Fig. 9), derived possibly from lenses of kaolin in the saprolite.

The cliff section on the northern shores of Kau Shat Wan, on the northeastern coast of Lantau Island, also provides evidence of past hydrogeological regimes. The section exposes a porphyritic microgranite that is sharply overlain by a 5m-thick zone of saprolite. A thin zone of highly mottled, light grey to reddish brown, silty clay forms an irregular layer above the soil/rock interface. This is in turn overlain by a coreslab of Grade IV material with relict joints which contain Grade V material. The Grade I/II granite contains closely-spaced, shallowly-inclined stress-relief joints and sets of moderately- to steeply-dipping joints. White kaolin veins have formed along several of these joints and these are cut by small, sediment-infilled pipes. In detail, it is possible to distinguish between the early formed pure kaolin veins and the later disseminated kaolin and iron staining that is associated with *in situ* alteration of the host granite around the pipes (Figs. 10a and b).

These phenomena illustrate the effect of changing hydrogeological regimes with time. Although it is recognised that the weathering is an ongoing

Fig. 9. Coarse sand void-infill containing angular kaolin fragments along stress-release joint. Width of specimen 10 cm



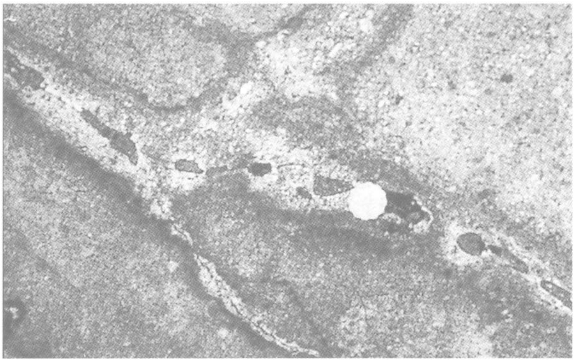


Fig. 10(a). Kaolin veins, filled pipes and kaolin-rich alteration haloes in porphyritic microgranite at Kau Shat Wan, Lantau Island

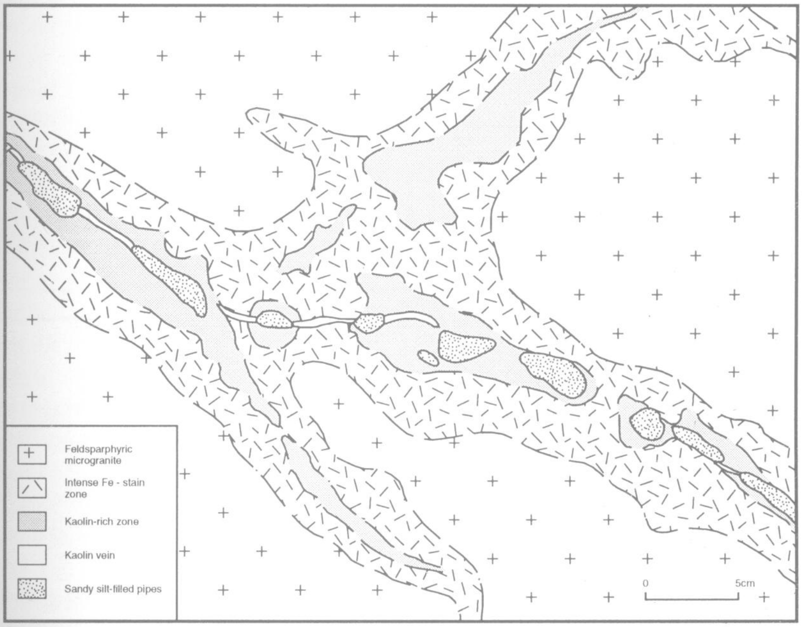


Fig. 10(b). Sketch of the features shown in Fig. 10(a)

process, it is considered that most of the geological structures exposed in these soil and rock profiles were the result of ancient weathering processes that occurred tens of thousands, or possibly up to millions of years ago.

Geophysical and Geochemical Surveys

The use of geophysical surveys has for many years greatly assisted in the understanding of ground conditions in development and infrastructure project areas. One of the most frequently used techniques has been offshore seismic profiling of the Quaternary sediments and the underlying weathered rock. Extensive seismic surveys in the late 1980s and early 1990s over a large part of Hong Kong waters defined significant sand resources in the alluvial sequences beneath the Holocene marine mud (Cheung and Shaw, 1993). These sands and gravels were extensively used, for example, as the major source of fill for the airport platform at Chek Lap Kok. Detailed seismic surveys over the airport project area itself provided vital information on the variability of the alluvial channel sequences, thickness of marine mud and extent of the weathering of the underlying granite. Seismic surveys combined with borehole information continue to be the main investigative method for major reclamation sites.

Fig. 11 (facing). Residual marine magnetic anomaly map between Tsing Yi and northwestern Hong Kong Island. The northeast-trending magnetic low extending from Stonecutters Island is a continuation of the Tolo Channel Fault Zone and is flanked to the southeast by a magnetically high syenite/ monzonite dyke; the east-trending magnetically neutral and high bands to the west and southwest of Tsing Yi reflect interdigitated feldsparphyric rhyolite dykes and granite; south-southeast- to southeast-trending magnetic lineaments define faults that have displaced northwest-trending structures

However, interpretation of the seismic data requires an in depth knowledge of the geological processes active during the deposition of the Quaternary sediments. This becomes particularly important where only part of the seismic record is available due to acoustic blanking, as is the case in the Penny's Bay area of northeastern Lantau Island.

More recently, microgravity surveys over the reclamation at Tung Chung New Town (Kirk, this volume) have been very successful in identifying zones of exceptionally deep weathering (over 170 m deep in places) related to the presence of marble xenoliths in granite and fault zones. Boreholes have been used to confirm and constrain the geophysical models.

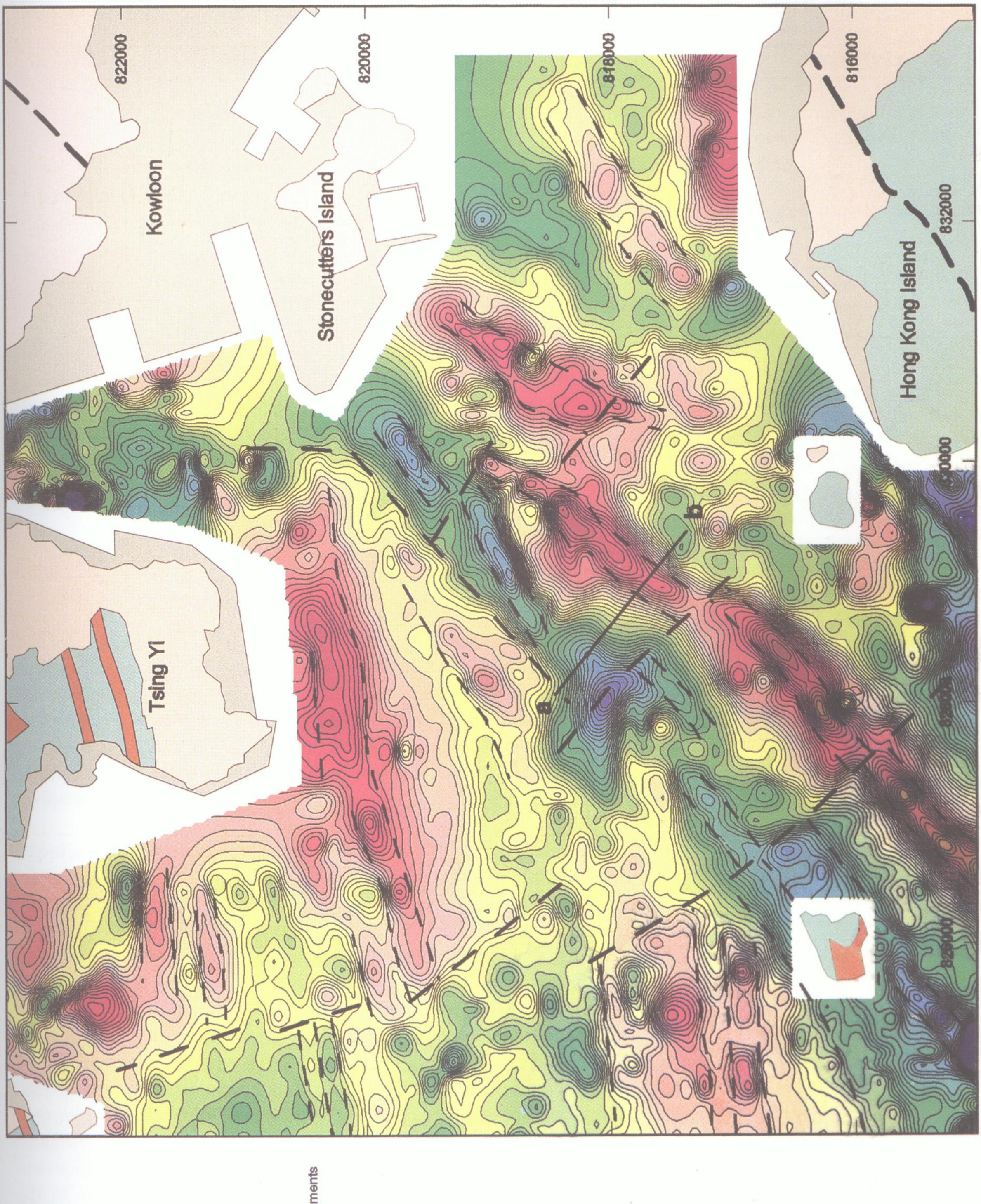
Marine magnetic surveys over the Western Harbour area (Fletcher et al., this volume) have allowed offshore solid geological maps to be reliably constructed for the first time. Major faults and lithological boundaries are well displayed in the filtered residual magnetic maps. For example, in the Western Harbour area the extension of the northeast-trending Tolo Channel Fault (magnetic low), a monzonite dyke (magnetic high), the east-trending Lantau Dyke Complex (magnetic lineaments) and northwest-trending cross-cutting faults (magnetic lineaments) can be readily recognised (Fig. 11). Computer modelling of the magnetic data, comparing observed and calculated magnetic profiles (Fig. 12), can generate possible geological cross-sections (EGS (Asia) Ltd., 1999).

All the above examples of recent geophysical surveys have been analysed in co-operation with geologists who have an intimate knowledge of the regional geology; without such input the geophysical interpretation could be highly misleading. Geophysics provides a cost-effective method to obtain extensive information on the ground conditions, both on a site-specific and regional basis, and allows subsequent ground investigations to more focussed. Research continues into other geophysical techniques (Chan and Chen, this volume), including ground penetrating radar and resistivity imaging that could assist in interpreting the ground conditions in selected engineering projects.

Geochemical surveys, including rock, mineral and stream sediment analyses, have been used extensively in Hong Kong to elucidate problems related to rock genesis, weathering processes and environmental issues. For example, the Hong Kong Geological Survey has recently published a *Geochemical Atlas of Hong Kong* (Sewell, 1999). This publication describes the results of a territory-wide stream sediment survey, and includes intensity maps for 36 elements that will provide the essential base-line data for future studies on natural elemental levels, distribution patterns and anthropogenic contamination. The study has highlighted the presence of widespread contamination in certain elements, such as lead, in areas not coincident with high concentrations of naturally occurring related minerals. The results from this survey have also been used to assess the levels of contamination in offshore marine mud deposits (Yim, this volume, Whiteside, this volume), and it is expected that the atlas will be used for other environmental investigations.

Age Dating

Accurate dating of the volcanic rocks and granites, combined with whole rock geochemistry and detailed petrography, has enabled, for the first time rational and process-oriented correlations of disparate volcanic sequences across the territory to be made. Age dating techniques have improved greatly over the


Kowloon
Stonecutters Island
Tsing Yi
Hong Kong Island
822000
820000
818000
816000
832000
830000
828000
826000
a
b
Reclamation
Granite
Volcanic rock
Rhyolite dyke
Fault
Magnetic lineaments
130
120
110
100
90
80
70
60
50
40
30
20
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0
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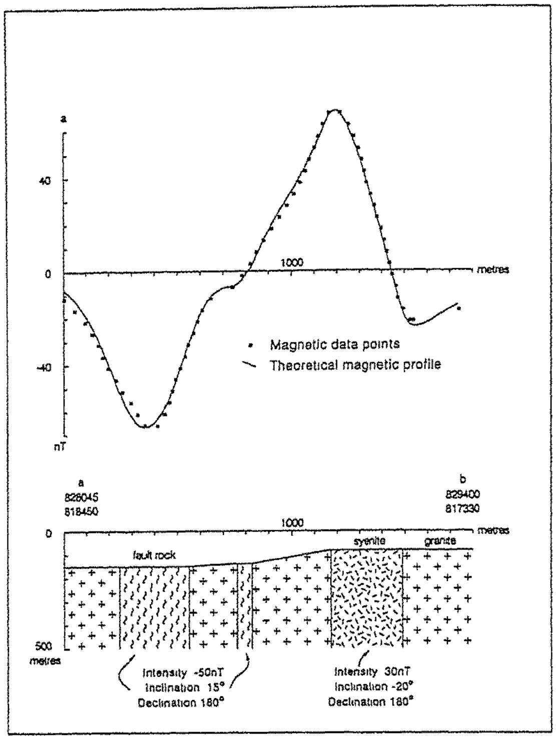


Fig. 12. Magnetic profile and theoretical 2-D geological model for contrasting sources with remanent magnetism. The line of section (a-b) is shown on Figure 11

last decade and it is now possible to date single zircon crystals in Jurassic and Cretaceous granites and volcanic rocks using U and Pb isotopes, to within about 200 000 years. This compares with about 2 to 4 million years for the previously used Sr and Rb isochron method as applied to a variety of minerals and whole rocks. Thus, it has been possible to identify four distinct episodes of volcanism and related plutonism in Hong Kong, each only lasting a few millions of years, but separated by up to 18 million years (Davis et al., 1997; Campbell and Sewell, 1998).

The confident identification of the four magmatic episodes has allowed the distinctive characters of the different volcanic groups and granite phases, including mineral composition, structure, alteration and weathering potential and homogeneity to be firmly established. These characteristics may significantly influence the susceptibility of natural terrain to landsliding and the stability of soil cut slopes, and therefore the groupings will allow confident comparisons to be made between sites.

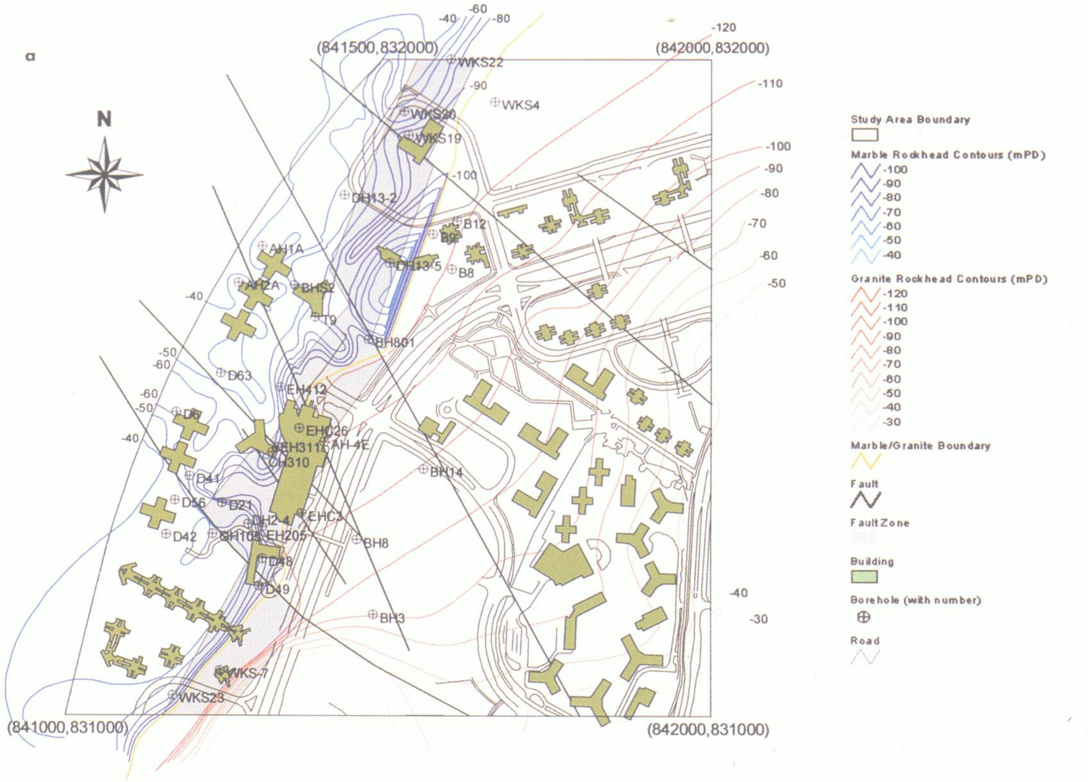
The timing of fault movement and regional deformation in Hong Kong has recently been investigated using the Ar-Ar method on minerals such as feldspar and pyrite within fault zones. Multiple phases of movement have been recognised by this method and one sample suggests that the last displacement occurred only about 2 million years ago. Recent movement on faults has also been investigated using the thermoluminescence technique (Ding and Lai, 1997). The displacement dates derived by these methods will be of paramount importance in the determination of the reliable return periods for seismic risk analysis.

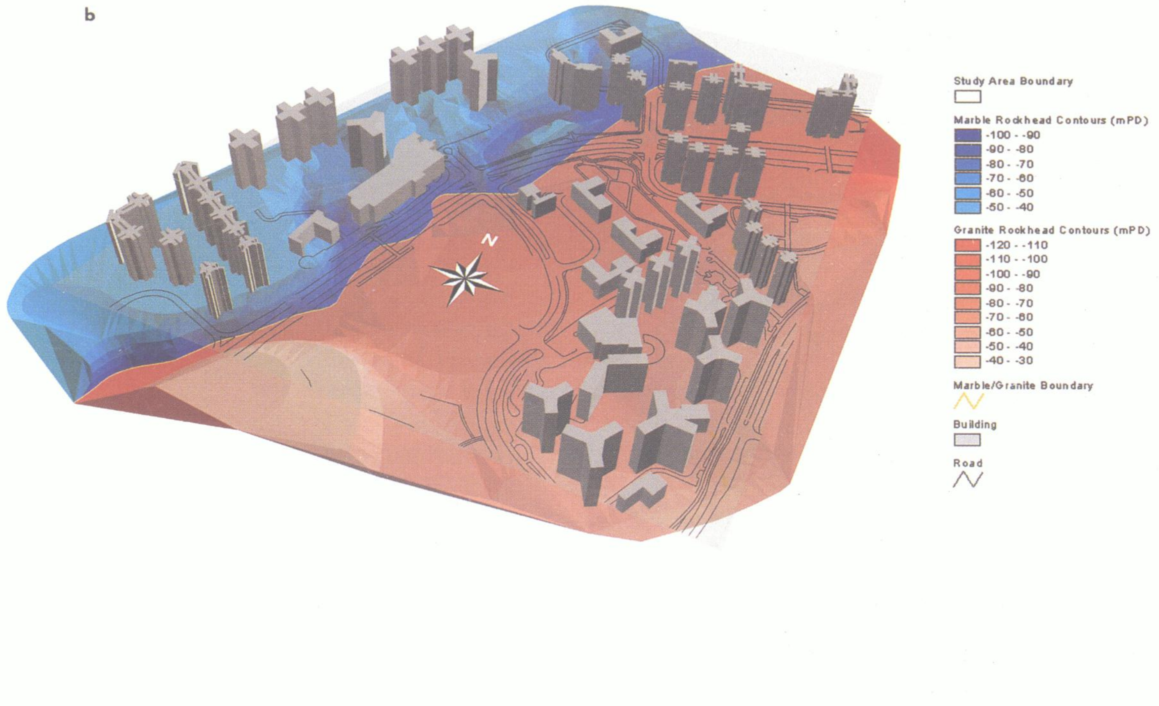
The ^{14}C method has been used to determine the age of plant debris in soil pipes related to recent landslides. In a study of the Ching Cheung Road landslide (GEO, 1998) leaf debris in soil pipes suggested that the pipe systems have been active for at least the last 40 years. Thermoluminescence dating of

Table 1. Geological datasets currently held in the Geoscience Database, GEO

Topic	Themes	Scale/Resolution	Extent	Comments
Geology	Man-made gelogy	1:20 000	SAR wide	systematic coverage at 1:20 000
	Superficial geolog	1:20 000		(continuous update by HKGS)
	Solid geology	1:20 000		
	Man-made geology	1:5000	Project areas	(partial coverage at 1:5000 scale)
	Superficial geology	1:5000	project areas	
	Solid geology	1:5000	Project areas	
	Site geology	<1 5000	project areas	site specific mapping
	Regional geology	1:100 000	SAR wide	various small scale coverage
Geotechnical Area Studies	Terrain classification	1:20 000	SAR wide	
	Derived maps			
	Terrain classification	1:5000	Lantau Island	
	Geotecs	Low resolution	SAR wide	c 150 m grid land use
Natural Terrain Landslide Study	Natual terrain Landslide Inverntory (NTLI)	High level API	SAR wide	updated in 1999
	NTLI-Large landslides	Low leve API	SAR wide	
	Gulley, development etc.	High level API	SAR wide	
	Derived maps			
	Landslide susceptibility		SAR wide	
Digital Terrain Model	1:20,000 TIN	1:20 000	SAR wide	based on LIC data (1996)
	Derived models:			
	Slope angle polygon map		SAR wide	
	1:5,000 DEM	1:5000 & 1:1000	SAR wide	based on LIC data (1999)
	Elevation GRID	(10m)	SAR wide	
	Gradient GRID	(10m)	SAR wide	
	Aspect GRID	(10m)	SAR wide	
	Slope angle polygon map			
Site Investigation	Drillhole	n/a	SAR wide	index, detail (AGS) and summary
	Seismic profile	n/a	SAR wide(offshore)	
	Gravity	n/a	SAR wide	
	Magnetic	n/a	SAR wide(offshore)	
Miscellaneous	Stream sediment geochemistry	n/a	SAR wide	
	Minerals & mining	n/a	SAR wide	
	Weathering	1:20 000	Kowloon Peninsula	
	Cavern area study	1:20 000	Kowloon Peninsula	
Collections	Samples, fossils, photographs	n/a	SAR wide	

colluvial deposits have been used with some success at the Shum Wan Road Landslide site (GEO, 1996b) and on the debris lobe at Sham Wat (King, 1998). Ages of between a few thousand to hundreds of thousands of years since the last exposure to light have been obtained; however the reproducibility and reliability of te technique is still being investigated.


a
N
(841500,832000)
(842000,832000)
(841000,831000)
(842000,831000)
-40
-60
-80
-90
-100
-110
-120
-70
-50
-30
WKS22
WKS4
WKS20
WKS19
DH13-2
B12
B9
DH13-5
B8
AH1A
AH2A
BHS2
T9
BH801
D63
EH412
D6
EH026
BEH311
AH-4E
CH310
BH14
D41
D56
D21
DH2-4
EHC3
D42
GH105
EH205
BH8
D48
D49
BH3
WKS-7
WKS23
Study Area Boundary
Marble Rockhead Contours (mPD)
-100
-90
-80
-70
-60
-50
-40
Granite Rockhead Contours (mPD)
-120
-110
-100
-90
-80
-70
-60
-50
-40
-30
Marble/Granite Boundary
Fault
Fault Zone
Building
Borehole (with number)
Road


b
N
Study Area Boundary
Marble Rockhead Contours (mPD)
-100 - -90
-90 - -80
-80 - -70
-70 - -60
-60 - -50
-50 - -40
Granite Rockhead Contours (mPD)
-120 - -110
-110 - -100
-100 - -90
-90 - -80
-80 - -70
-70 - -60
-60 - -50
-50 - -40
-40 - -30
Marble/Granite Boundary
Building
Road

Geological Databases

Fig. 13 (facing). (a) Geological map of the Ma On Shan area showing marble and granite rockhead contours for the top of Grade III. (b) 3-D visualisation of the top of Grade III beneath the Ma On Shan area with buildings projected, viewed from the south

The ability to develop and then communicate appropriate geological models is dependent on good data resources. Like most geological surveys the Kong Geological Survey increasingly relies on information technology, and in particular Geographic Information Systems (GIS), to support its work and manage and integrate increasingly large volumes of data.

GIS are computerised databases that are used to store, manage, analyse and present spatial data. In Hong Kong, development of GIS for geological data has been underway for about five years, and all of the SAR's key geological datasets are now available in digital form (Table 1). The Hong Kong Lands Department and other Government departments also have GIS programmes; thus, base topographic maps and other information can be used in the system.

The simplest application of GIS technology is for presentation of data. It is straightforward to customise the content and scale of a map on screen (e.g. production of a thematic map) by exploring different combinations of datasets (or selected parts of datasets) and then printing the result. More advanced applications of GIS involve integration and spatial analysis of different geological datasets (e.g. natural hazard analysis) or modelling of geological surfaces (e.g. production of cross-sections or a map of contoured rockhead levels from borehole data). These types of applications enable geologists to improve their use of the data, by undertaking a much wider range of analyses or processing large volumes of data.

Perhaps the greatest benefit of adoption of GIS is the capability for presentation of geological data in new ways, appropriate to end-users who may not be trained in geosciences. For example, traditional geological maps may not be fully appreciated by planners, but information in them may be used if the relevant data are suitably highlighted and presented in conjunction with the planners' own data. Other approaches emphasise the visualisation of geological information, for example as 3D simulations (Front Cover, Figure 13).

Relatively simple tools on low-cost desktop-GIS enable this type of treatment, though such approaches are limited by lack of awareness of available data, and restrictions in sharing of data, and lack of standardisation between data from different systems.

Conclusions

The objective of this paper, and indeed the Urban Geology Conference as a whole, was to focus on the important role that geology has, and will increasingly have, in many development and infrastructure projects in Hong Kong. The expertise of the geologist, engineering geologist and geotechnical engineer, working as coherent multidisciplinary teams, will be of paramount importance if the urban development, that will inevitably increase over the next few decades, is to be undertaken in the safest and most cost-effective manner, taking full account of environmental issues. Sound geological knowledge and reasoning is critical for the collection and interpretation of the field data so that the very best 'geological model' may be established. The continued implementation and maintenance of geological databases is paramount to the urban development of Hong Kong, as they allow efficient storage, analysis, integration and presentation of the datasets.

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References

Campbell, SDG & Koor, NP (1996) *Assessment of Geological Features Related to Recent Landslides in Volcanic Rocks of Hong Kong Phase 2A- Chai Wan Study Area*. Geotechnical Engineering Office, Special Projects Report SPR 9/96, Hong Kong, 75 p

Campbell, SDG, Franks, CAM. Koor, NP & Shum, WWL (1998) Geological assessment of slopes in areas close to major landslides on Hong Kong Island. In: KS Li, JN Kay & KKS Ho (eds) *Slope Engineering in Hong Kong*. Proceedings of the annual seminar on slope engineering in Hong Kong, 2 May 1997, Balkema, Rotterdam, pp 121-128

Campbell, SDG & Sewell, RJ (1997). Structural control and tectonic setting of Mesozoic volcanism in Hong Kong. *Journal of the Geological Society, London*, 154, pp 1039-1052

Campbell, SDG & Sewell, RJ (1998) A proposed revision of the volcanic stratigraphy and related plutonic classification of Hong Kong. *Hong Kong Geologist*, Vol 4, pp 1-11

Chan, LS (2000) Geophysical and radiometric properties of weathered saprolites in Hong Kong. In: A Page & SJ Reels (eds) *The Urban Geology of Hong Kong*, Geological Society of Hong Kong, Bulletin No 6, pp 189-202

Cheung, PCT & Shaw, R (1993) *Seamat Study: Final Report*. Geotechnical Engineering Office, Hong Kong Government, 163 p

Davis, DW, Sewell, RJ & Campbell, SDG (1997) U-Pb dating of Mesozoic igneous rocks from Hong Kong. *Journal of the Geological Society, London*, Vol. 154, pp 1067-1076

Ding, YZ & Lai, KW (1997) Neotectonic fault activity in Hong Kong: evidence from seismic events and thermoluminescence dating of fault gouge. *Journal of the Geological Society, London,* Vol. 154, pp 1001-1007

EGS (Asia) Ltd (1999) Green Island, Tsing Yi and Peng Chau, marine magnetic survey – data interpretation. Report for Geotechnical Engineering Office, Job No HK137399, Contract No GE/97/12, Works Order No GE/97/12.53

Fletcher, CJN, Collar FA & Lai, MWC (2000) Marine magnetic survey of Hong Kong: results, interpretation and significance. In: A Page & SJ Reels (eds) *The Urban Geology of Hong Kong*, Geological Society of Hong Kong, Bulletin No 6, pp 179-188

Franks, CAM, Campbell, SDG & Shum, WWL (1997) *Assessment of Geological Features Related to Recent Landslides in Volcanic Rocks of Hong Kong Phase 2B - Aberdeen Study Area*. Geotechnical Engineering Office, Hong Kong, SPR 9/97, 93 p

Geotechnical Engineering Office (1996a) *Report on the Fei Tsui Road Landslide of 13 August - Volume 2, Findings of the Landslide Investigation*. Geotechnical Engineering Office, Hong Kong, 68 p

Geotechnical Engineering Office (1996b) *Report on the Shum Wan Road Landslide of 13 August 1995 - Volume 2, Findings of the Landslide Investigation*. Geotechnical Engineering Office, Hong Kong, 51 p

Geotechnical Engineering Office (1998) *Report on the Ching Cheung Road Landslide of 3 August 1997.* GEO Report No 78, Geotechnical Engineering Office, Hong Kong SAR, 142 p

Geotechnical Engineering Office (1999) *Detailed Study of the Landslides at the Junction of Sai Sha Road and Tai Mong Tsai Road in June 1998.* LSR 13/99, Geotechnical Engineering Office, Hong Kong SAR

Geotechnical Engineering Office *Geological Map of The Hong Kong SAR, 1:100 000-scale.* Geotechnical Engineering Office, Hong Kong SAR

King, J.P. (1998) *Natural Terrain Landslide Study, The Sham Wat Debris Lobe, Interim Report.* Technical Note TN 6/98, Geotechnical Engineering Office, Hong Kong SAR, 37 p

Kirk, PA (2000) Adverse ground conditions at Tung Chung New Town. In: A Page & SJ Reels (eds) *The Urban Geology of Hong Kong*, Geological Society of Hong Kong, Bulletin No 6, pp 89-98

Kirk, PA, Campbell, SDG, Fletcher, CJN & Merriman, RJ (1997) The significance of primary volcanic fabrics and clay distribution in landslides in Hong Kong. *Journal of the Geological Society, London*, Vol 154, pp 1009-1019

Koor, NP, Campbell, SDG, Sun, HW & Ho, KKS (2000) Scarp morphology and development associated with a large retrogressive compound landslide at Lai Ping Road — Hong Kong. In: A Page & SJ Reels (eds) *The Urban Geology of Hong Kong*, Geological Society of Hong Kong, Bulletin No 6, pp 77-88

Nash, JM & Dale, MJ (1984) Geology and hydrogeology of natural tunnel erosion in superficial deposits in Hong Kong. In: WW-S Yim (ed) *Geology of Surficial Deposits in Hong Kong.* Geological Society of Hong Kong Bulletin No 1, pp 61-72

Parry, S (1999) *Literature review of kaolin occurrences in Hong Kong saprolite.* Geological Report GR 1/99, Geotechnical Engineering Office, Hong Kong SAR, 21 p

Parry, S & Franks, CAM The mineralogy of clay-rich zones within some weathered volcanic and granitic rocks in Hong Kong. *Proceedings of the 8th International Symposium on Landslides, Cardiff, UK, June 2000*

Parry, S, Campbell, SDG & Fletcher, CJN (in press) Typical kaolin occurrences in Hong Kong – a model for their origin and implications for landslide development. *Proceedings of the 8th International Symposium on Landslides, Cardiff, UK, June 2000*

Sewell, RJ (1999) *Geochemical Atlas of Hong Kong*. Geotechnical Engineering Office, Civil Engineering Department, Hong Kong SAR, 110 p

Tam, CM, Leung, YK, Pun ,WK, & Fletcher, CJN (1997) The new Hong Kong digital seismic monitoring network. *Hong Kong Geologist*, 3, pp 1-7

Whiteside, PGD (2000) Natural geochemistry and contamination of marine sediments in Hong Kong. In: A Page & SJ Reels (eds) *The Urban Geology of Hong Kong*, Geological Society of Hong Kong, Bulletin No 6, pp 109-122

Yim, WW-S (this volume) Towards sustainable development in Hong Kong. In: A Page & SJ Reels (eds) *The Urban Geology of Hong Kong*, Geological Society of Hong Kong, Bulletin No 6, pp 203-219

The Contribution of Geology to the Engineering of Hong Kong International Airport

G. Pinches[1], R. Tosen[2] and J. Thompson[3]

Abstract

The new Hong Kong International Airport was constructed on a platform created by levelling the original islands of Chek Lap Kok and Lam Chau combined with a marine reclamation. The development of this major project required a comprehensive understanding of the underlying geology, which affected many aspects of the design and construction of the airport. Formation of the platform and the follow-on construction of the airport large structures and infrastructure have been strongly influenced by both the solid and superficial geology of the area, in particular the rock type, jointing, faulting and the weathering profile. The reclamation area was underlain by a very soft marine clay, the properties of which dictated the reclamation strategy. The marine clay overlies the heterogeneous, generally alluvial, Chek Lap Kok Formation. Individual units within this Formation are often lenticular and of limited extent. The majority of the settlement of the airport reclamation derives from the consolidation of compressible layers within these highly variable deposits. Beneath the superficial deposits lies an irregular buried topography of rock whose upper weathered layer varies substantially in thickness. Due to the complexity of the local geology it was realised that a comprehensive geotechnical model would be needed to optimise the design for levelling of the islands, allow reliable estimates of settlement and understand the founding conditions. This paper sets out the compilation of the geological information used, the site geology and the basis for interpretation in geotechnical terms, and provides examples of how the geology controlled elements of the engineering.

Key words: Hong Kong International Airport, geological modelling, onshore geology, offshore geology, reclamation, quarrying, fill material, foundations, settlement, hydrogeology.

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Table 1 (facing). The main phases of site investigation and the development of the geological model. ***AA***, Airport Authority (prior to December 1995: Provisional Airport Authority); ***APCJV***, Airport Platform Contractors Joint Venture; ***BGS***, British Geological Survey; ***CKL***, Chek Lap Kok; ***EGS***, Electronic and Geophysical Services Ltd; ***GCO***, Geotechnical Control Office (now Geotechnical Engineering Office); ***HKGS***, Hong Kong Geological Survey; ***IGS***, Institute of Geological Sciences (now BGS); ***SPC***, Site preparation contract

Site Description

Prior to construction, the site of the new Hong Kong airport consisted of two islands off the north shore of Lantau island: Chek Lap Kok (302 ha) and Lam Chau (8 ha), separated and surrounded by shallow seas in an overall site area of 1248 ha. The seabed was typically between –3 mPD and –6 mPD, although lying deeper to the west of Lam Chau. Chek Lap Kok and Lam Chau were rocky mountainous islands, attaining maximum elevations of +122 mPD and +30 mPD respectively. To the east of the airport site lie the two Brothers islands which formerly reached up to a maximum elevation of +64 mPD. Since both island were on the flight path, and as a source of extra fill, they were leveled to about 6 mPD.

Investigations

The geological model for the new airport site evolved during the conceptual, design and construction phases of the project. The model was advanced by contributions from the various organisations involved, the Hong Kong Geological Survey, the Geotechnical Engineering Office, the British Geological Survey and the Airport Authority Hong Kong, (Table 1). The techniques used in developing the model included geological field mapping, onshore and offshore ground investigation, cone penetration testing (CPT), air photo interpretation and geophysical surveys supplemented by construction site records, observations and photographs. The framework for the final comprehensive model was determined by the British Geological Survey (BGS, 1994) which devised a three-dimensional model of the marine geology by interpretation of the high resolution reflection seismic records (100 m grid) correlated against existing boreholes and CPTs. A full treatment of the investigations and geological model development are provided in Chapters 3 and 4 of Plant et al. (1998).

Geology

Onshore Geology

The original island of Chek Lap Kok was almost entirely granite, being mapped as fine grained on the western side and fine to medium grained and generally megacrystic to the east (Fig. 1). In two areas the granite had been altered by kaolinisation, in one place substantially enough for it to be economic to operate a commercial kaolin mine. The centre and south of the island were characterised by numerous lesser intrusions of feldsparphyric and quartzphyric rhyolite in the form of ENE-trending dykes commonly more than 20 m, and in places up to 100 m thick.

The geological structure is dominated by the NNE-trending Chek Lap Kok fault (Fig. 1), which had a marked physiographic effect on the original island, forming the NNE- and SSW-trending stream valleys that traversed the island and coincided with Sham Wan bay. Except for the NE-trending Sha Lo Wan Fault, the other major faults in the area were all offshore. Occasional minor faulting was identified by the mapping.

Aerial photographs revealed an ENE-trending set of photolineaments, which were found to coincide with the dominant joint set within the granite. It is considered likely that the major joints influenced the emplacement of the dykes. In addition, there were numerous quartz veins, also with a similar trend.

Date	Title	Organisation	Description or Scope	Findings
1963	aerial photography	for Hong Kong Government	orthophotography	high quality aerial photographs of terrain prior to major revegetation
1967-1969	geological surveying of Hong Kong	IGS	first geological mapping of CLK in territory-wide 1: 50 000 scale maps	1:50 000 maps of whole territory
1977 & 1981	land geophysical survey	EGS	seismic refraction surveys	information on weathering profile
1982	civil engineering design studies	RMP-Encon	development of site-specific geological model onshore and offshore interpretation with long sections	divided offshore geology into upper marine clay, alluvial crust, lower marine clay and lower alluvial deposit overlying decomposed granite
1984		for GCO		type borehole of Chek Lap Kok Formation drilled at GCO test embankment
1989		HKGS	geological mapping of CLK at 1:50 000 scale, 13 thin sections	detailed map of the granite, fine-grained granite and minor intrusive dyke rocks
1990	Geotechnical Investigations Vol 2 Marine Geology	GCO	integration of 1990 data with 1982 study, reinterpretation of offshore geology	basic model of Hang Hau Formation overlying Chek Lap Kok Formation superceded old terms
1990	Geotechnical Investigations Vol 3 Geology of Chek Lap Kok	GCO	46 boreholes on CLK. desk study	characterised solid geology of island which was subsequently to be quarried
1991	geotechnical report for design of site preparation	Greiner-Maunsell	development of GCO interpretation into design for SPC	subdivided QCK Formation into 4 units and characterised them
1992	geophysical surveys	EGS	335km seismic traces on 100m grid, 236 marine DH, 404 "deep" CPTs	originally designed to derive the thickness of marine muds (Hang Hau Formation) for determining dredge volumes
1993	interpretation of marine geology	BGS	correlation of CPTs, boreholes and geophysical data	formal subdivision of QCK Formation, definition of QSw, distribution of palaeosols
1994	sheet report for CLK	HKGS	publication of findings of mapping, desk study, inter-pretation of aerial photographs	detailed picture of the geology of Chek Lap Kok island prior to quarrying
1995	geological memoir of Lantau district	HKGS	publication of findings of mapping, desk study, inter-pretation of aerial photographs	brought all geological findings onshore and offshore into a complete model
1993-199	SPC instrumentation	APCJV for AA	extensometers, inclinometers and piezometers inserted in drillholes	monitored behaviour directly related to geology
1993-1997	AA term site investigation contracts	Intrusion Prepakt and Lam Geotech	land and marine investigations: drillholes (some instrumented), CPTs, vibrocores	detailed geological findings for design of particular follow-on construction contracts on site
1994-1998	AA construction contracts	various consortia and contractors	excavation logging: pre-bores for foundations additional instrumentation	description of actual conditions encountered
1996	Phase 2 study	BGS	correlation of geological model with GI in computer database. interpretation of environments of depsition and origins of offshore strata	coded majority of excavation holes on platform. suggested revision of sub-division of Sham Wat Formation

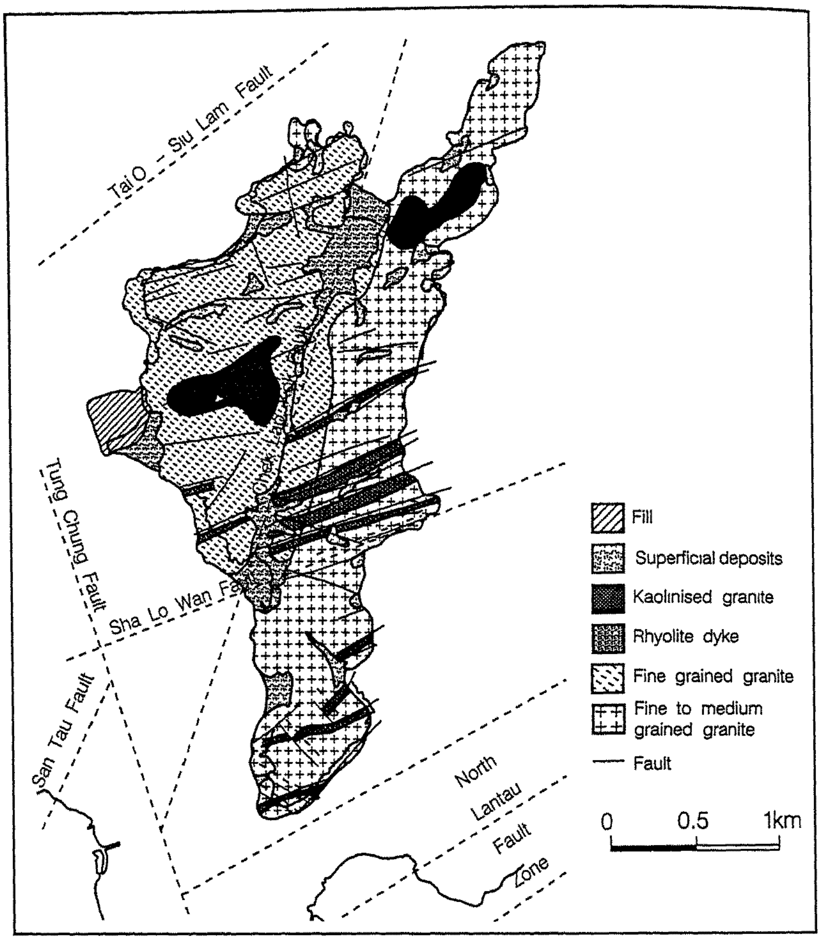


Figure 1. Geology of Chek Lap Kok island (from Hong Kong Geological Survey Map at 1:5000)

The original mapping and site investigations (Langford, 1994) showed the depth of weathering of the granites to be highly variable. Extensive zones of weathering coincided with the Chek Lap Kok Fault and the areas of kaolinisation; elsewhere the weathering was generally shallow. While solid bedrock is exposed along much of the coastline and some hilltops, the surface geology is typically characterised by large corestone derived surface boulders underlain by a mantle of weathered rock. As a result of differential weathering, quartz veins often appeared as upstanding ribs.

Onshore, the development of superficial deposits was limited to occasional bodies of thin colluvium on the hillsides, some alluvium in the stream valleys and beach deposits at the back of the main bays.

Offshore Geology

The reclamation area is underlain by Quaternary deposits comprising a laterally extensive very soft marine clay that unconformably overlies a mixed succession of materials, the stratigraphy of which is summarised in Fig. 2 and detailed more fully below. By use of a standard system of geological coding, the Airport Authority organised all the information into a geotechnical database. An example of the geological interpretation as output using the system is the geological long section along the Northern Runway reproduced in Fig. 3.

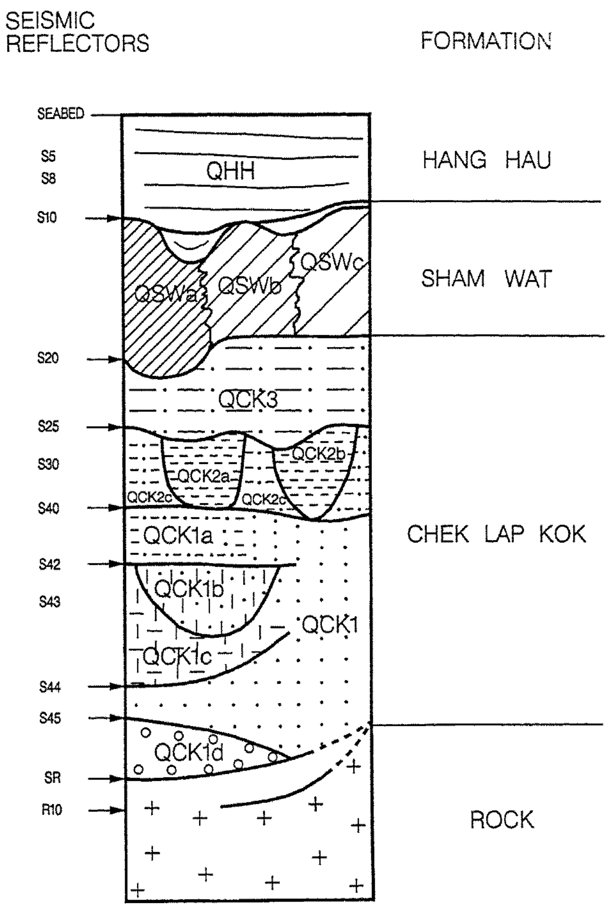
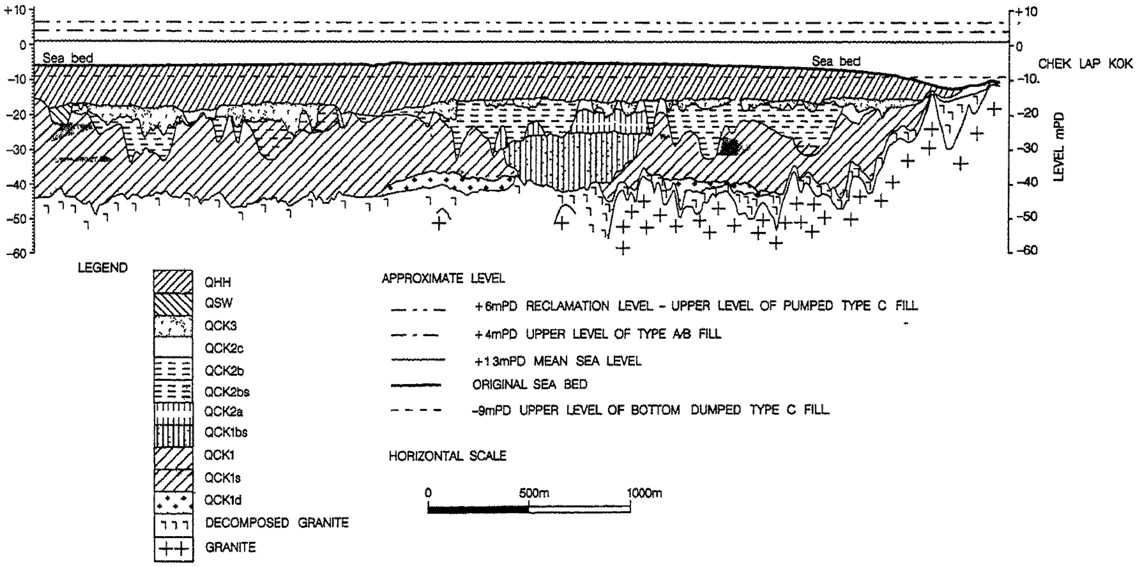


Fig. 2. Summary stratigraphy of offshore superficial deposits in North Lantau – Chek Lap Kok area (from BGS, 1994)

Fig. 3. Geological section along Northern Runway



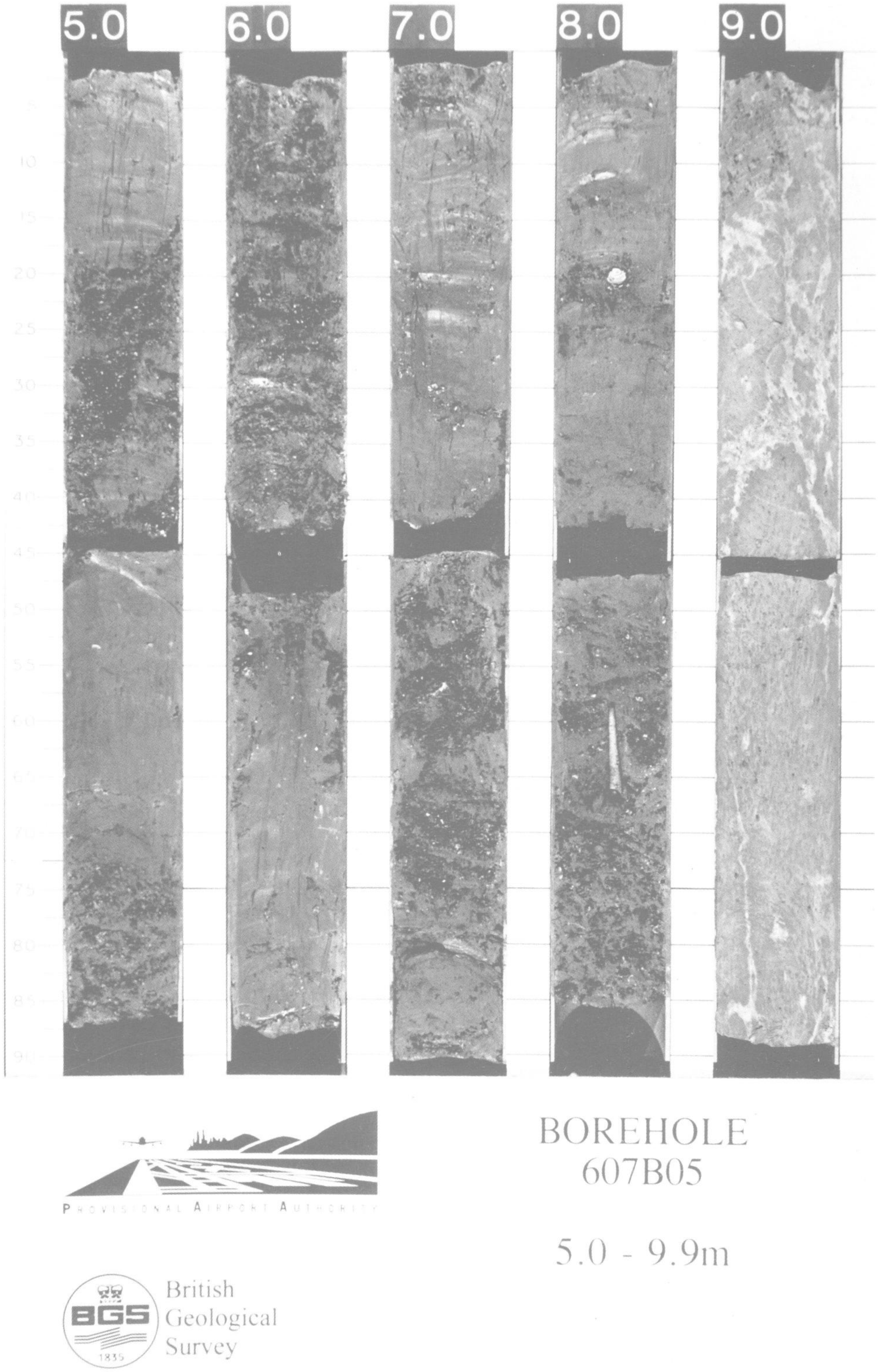


Plate 1. Marine Hang Hau Formation (QHH) overlying desiccated crust of Sham Wat Formation. The very soft grey silty clay with shell debris of the QHH was dredged off site at the commencement of reclamation. The stiff oxidised red clay with yellow veining of the Sham Wat Formation represents a palaesol crust

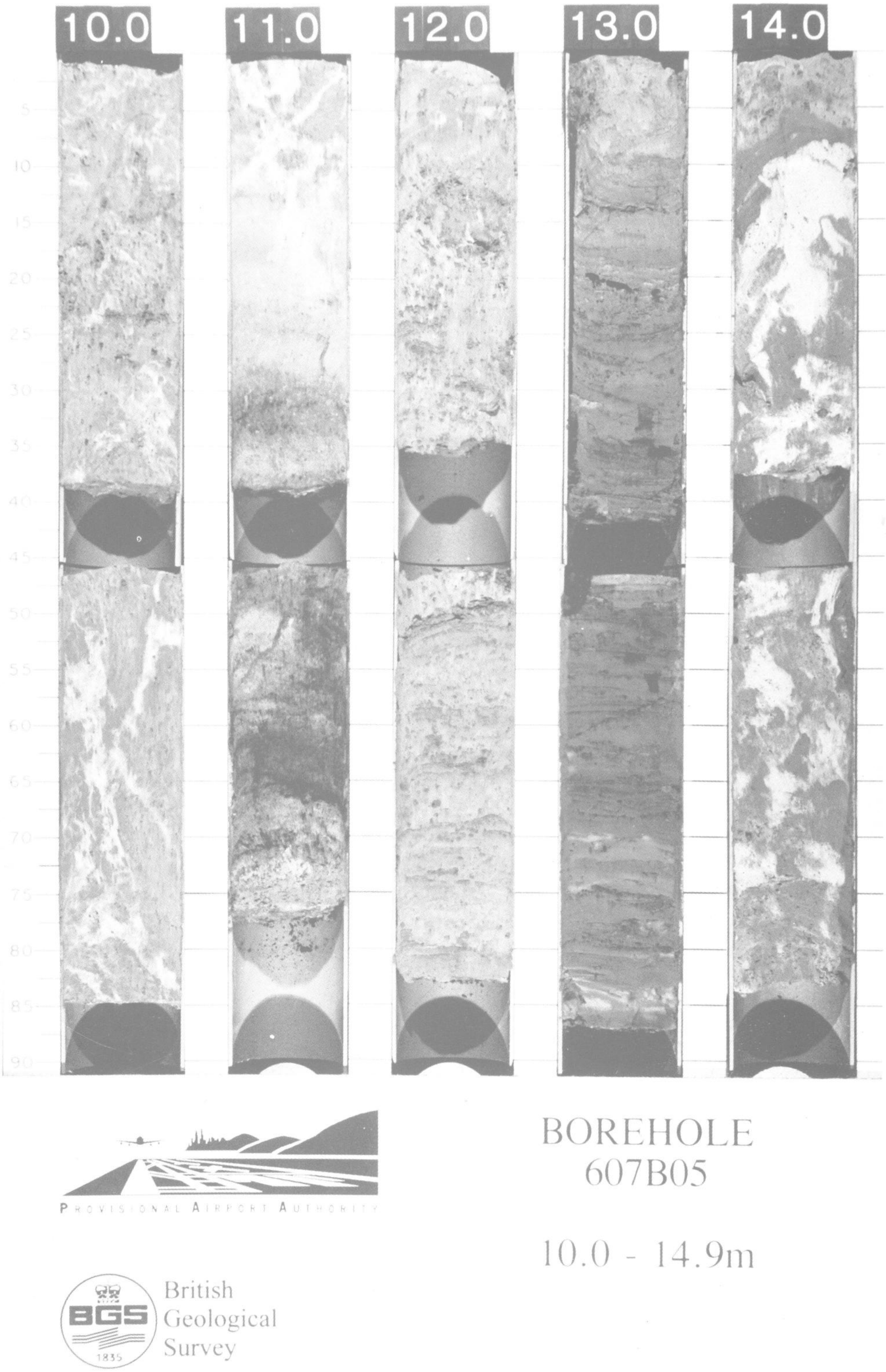


Plate 2. Sham Wat Formation (QSw) overlying the typical mottled oxidised silty clay of the Chek Lap Kok Formation (QCK) at 14.1 m. Below the palaeosol (cont. from Plate 1) the QSw is a grey silty clay with organic smear spots. From 12.05-13.1 m the QSw is firm oxidised and mottled yellow brown silty clay with silt/sand lenses. Above the QCK is firm grey silty clay with sand lenses

Hang Hau Formation

The uppermost layer of superficial deposits, which was traditionally named the "marine" layer, was reclassified by Strange and Shaw (1986) as the Hang Hau Formation. The formation is a fairly uniform deposit of very soft to soft greenish grey silty clays with well preserved shell fragments_(Plate 1). It was ubiquitous across the platform, forming a layer 5-10 m thick which completely and unconformably caps the Chek Lap Kok Formation. The formation has formed from suspended fine particles settling in low energy water conditions and is therefore normally consolidated.

Sham Wat Formation

The Sham Wat Formation (James, 1993) is developed as an intervening unit distinct from the overlying Hang Hau Formation and underlying the Chek Lap Kok Formation formally defined by Fyfe and James (1995, Plates 1 and 2). This formation comprises generally firm grey silty clay. The Sham Wat Formation is distinguished from the Hang Hau Formation by a higher shear strength and lower moisture content. Where shells occur, they are well preserved in the Hang Hau Formation but in the Sham Wat Formation they are smaller, poorly preserved and appear as comminuted debris. The top and bottom of the formation are marked by major unconformities which are particularly distinct on seismic reflection traces characterised by a channelled morphology (Langford et al., 1995) and best developed in the south-west of the platform. This formation is absent from the centre and north of the reclamation.

Chek Lap Kok Formation

The bulk of the offshore sediments, which were previously described by geologists in Hong Kong as "alluvium", were formally classified as the Pleistocene Chek Lap Kok Formation by Strange and Shaw (1986) using a borehole drilled on the GCO test embankment at Chek Lap Kok to define the type section. This formation is complex and heterogeneous, comprising assorted materials ranging from clays to cobbles and varying between uniform and poorly sorted (Plate 2). Individual soil layers may be both laterally extensive or of only limited extent. The Chek Lap Kok Formation is characterised by some intensely oxidised horizons (due to subaerial exposure) and the presence of organic material. Organic remains may occur as disseminated comminuted plant debris, wood fragments and root channels or as partings of compressed material often still with visible leaf structure. The clays tend to be firmer than in the overlying formations. The depositional environment of the Chek Lap Kok Formation varies from low energy to turbulent channel under fluvial, estuarine or marine conditions and deposits may have fining upward sequences, coarsening upward sequences, massive units or be interbedded. The Chek Lap Kok Formation has been subdivided into three major units (QCK 1, 2 & 3) and seven sub-units (Table 2). The best developed features within the Chek Lap Kok Formation are :

- A major buried channel aligned north-south between the original islands of Chek Lap Kok and Lam Chau linked to Tung Chung (Fig. 4). Deposits within this channel tend to be of mixed material type (QCK2a & 2b) whereas in the banks lies the more cohesive (QCK2c) sub-unit which forms the thick soft to firm clay layer which is most susceptible to consolidation settlement.

- Lying at the base of the Chek Lap Kok Formation and also within this central zone are the widespread basal sands and gravels (unit QCK1d).
- A palaeosol crust (3-5 m) which extends over much of the site and immediately underlying the marine deposits. This oxidised and desiccated layer was formed during subaerial exposure of the surface soils prior to the marine transgression which resulted in the formation of the Hang Hau Formation. Other crusts exist at depth but these are intermittent in their extent and not as important as the uppermost one.

Reclamation Design

Since the Hang Hau marine muds were known to be a soft compressible deposit, construction over this formation would have resulted in large settlements needing to be accommodated. A solution for this was considered to be the installation of a system of vertical drains which would increase the rate of consolidation. To investigate the feasibility of this approach and compare it with the alternative of dredging, a full scale instrumented test embankment was constructed between 1981 and 1982 (Foott et al., 1987).

Table 2. Summary of superficial deposits at Chek Lap Kok (derived from BGS, 1994)

Geological Formation	Geological (Sub) Units	General Layer Code	Seismic Reflector	Typical Lithologies	Extent	Typical Thickness (m) Range
Hang Hau Formation		QHH	S10	Soft greenish grey silty CLAY	Platform-wide; dredged	5-10 (3-15)
Sham Wat Formation	a	QSWa	S20	Firm grey silty CLAY	West of Lam Chau & western edge.	4-12
	b	QSWb	S20	Firm mottled silty CLAY	Between Lam Chau and Chek Lap Kok.	2-4
	c	QSWc	S20	Firm (brown) grey (sandy) silty CLAY	Northeastern corner.	2-6
Chek Lap Kok Formation	Unit 3	QCK3	S25	Firm to stiff silty CLAY (often with palaesol crust)	Widespread, missing in parts of west.	2-10 (0-14)
	Unit 2a	QCK2a	S30	Firm grey slightly silty CLAY, thin sand and silt layers	NW-trending central channel from Tung Chung.	6-16 (0-20)
	Unit 2b	QCK2b	S30	Firm-stiff silty or sandy CLAY with silt and sand layer.	SW-NE channel across centre and north.	6-16 (0-20)
	Unit 2c	QCK2c	S40	Soft-firm grey silty CLAY	To sides of NW-trending central channel	4-10 (0-18)
	Unit 1 (undifferentiated)	QCK1		Heterogeneous	Platform wide	5-15 (0-20)
	Unit 1a	QCK1a	S42	Firm-stiff brown to grey silty CLAY, some thin sand partings.	North-central	(0-10)
	Unit 1b	QCK1b	S43	Dense light grey SAND.	North-central	10 (0-17)
	Unit 1c	QCK1c	S44	Soft and firm-stiff silty CLAY, some organics.	West of Lam Chau	8 (0-16)
	Unit 1d	QCK1d	S45	SANDS and GRAVELS.	Central channel	0-10 (15)
Base of superficials / top of rock in any grade of decomposition			SR			

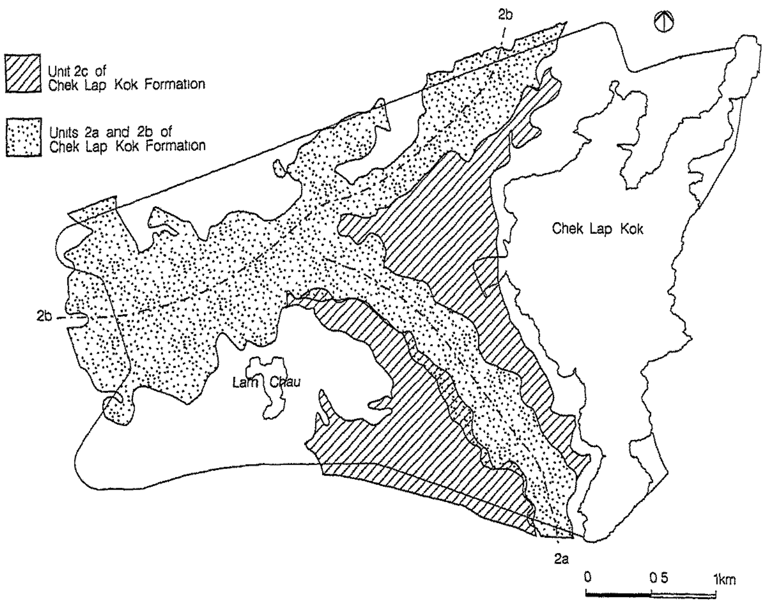


Fig. 4. Distribution of units 2a, 2b and 2c of the Chek Lap Kok Formation

Monitoring over 12 years showed that the marine mud reduced in thickness by 35-40%. This deformation combined with the period of consolidation, even with vertical drains, led to the decision to dredge the marine muds. The reclamation therefore consisted first of dredging up to 10 m of marine muds to form a new seabed at about −15 mPD. Subsequently, fill materials were placed to bring the platform up to about +6 mPD.

A summary of the geotechnical aspects of the project is provided by Anon (1996).

Quarrying

To form the airport platform in the area of the original islands of Chek Lap Kok and Lam Chau involved excavating the surface level to about +6 mPD. This generated about 82 Mbcm of material which could then be used as fill for the reclamation part of the platform. The method of removal of this material and the type of material generated was controlled by the engineering geology. The thick weathered zones and superficial deposits were suitable for bulk excavation. Approximately 25% of the material from Chek Lap Kok island was freely dug and generally conformed with the specification for Type B material.

Ripping as a means of quarrying was discounted for the vast majority of the rock material present, which was excavated using bulk blasting methods. Prior to production blasting, a series of trial blasts were carried out. These trial blasts identified three orthogonal joint sets which resulted in a blocky fracture style suitable for quarrying.

The presence of sub-horizontal stress release joints, more pronounced nearer ground surface, was detrimental to the blast efficiency due to explosive product leakage. These exfoliation, sheeting joints are continuous and dilated and often infilled with highly weathered rock or soil.

The sub-vertical joints generally displayed a 1-3 m spacing, which strongly controlled the face geometry. Where the joint orientation and face geometry were similar it was proposed that blasting be carried out to change the face strike to more than 30° from that of the dominant subvertical joint set, thereby preventing "slabby" rock fragments in the blast product.

The rock structure and alteration is more complex near the surface with the change from fresh rock to residual soil generally being gradational. In areas where the weathering pattern was irregular the blast effect was not uniform. The highly weathered material tended to absorb much of the blast energy resulting in a local reduction in the efficiency of the blast.

In the later stages of the blasting, it was evident that insufficient quantities of armour rock for seawall protection (5-tonne boulders) would be produced. The quantity of suitable armour rock produced in any one blast depends both on blasting method and the local joint spacing and orientation. Attempts were made by altering the spacing, size and orientation of the blast face with reference to the prominent joint orientation to maximise the numbers of large boulders produced. While this resulted in an increase in armour rock production, it was not sufficient for the final requirements.

The northern half of the Chep Lap Kok island was marked by a more variable geology, heavier weathering and more irregular transition from weathered rock to fresh underlying granite. The weathering style in this area is typically of corestones (up to house size) set in a matrix of completely decomposed granite. Blasting was often unsuccessful in these mixed deposits as the explosive energy tended to vent towards the CDG, which impeded the subsequent clearing work. The relatively fresh corestones usually had to be broken up by secondary blasting.

Fragmentation blasting was used to break up the rock below the final formation level in key locations to assist later excavations for trenches or cuttings. The resulting depth of fragmentation varied due to different susceptibilities of the underlying rock. Some trenches were found to have large masses of unbroken rock projecting in from their bases and sides (Plate 3). The result of this was a time-consuming methodical pecking away by hydraulic breakers or expansive agents.

After the main quarrying programme had ceased, it was decided that a

Plate 3. Trench excavation on original Chek Lap Kok island. Note rock exposure unbroken by fragmentation blasting, requiring subsequent break-up

headland that had previously been left outside the development area would also be levelled for follow-on construction. The headland was characterised by extensive weathering, associated with two faults. For these reasons and due to its limited size and the numerous follow-on contracts then ongoing it was assessed for ripping excavation rather than blasting. Rippability was assessed by three alternative methods as below:

- Seismic velocity - The seismic velocity of the area (determined from seismic surveys carried out ahead of the island levelling works) ranged between 2440 and 3350 m/s which is categorised as marginally rippable to unrippable.
- Rock mass rating (RMR) - The RMR for the area was generally greater than 60. This indicated that the area would require blasting as opposed to areas with RMR values less than 30 which can be dug or ripped where RMR values range from 30 to 60.
- Excavatability graph - This method relies on the point load index and joint spacing of the rock for rippabillity assessment. For the Chek Lap Kok site the joint spacing ranged from 0.3-1 m and the estimated point load index generally fell within the range 5-10 MPa. Exposures with criteria in this range fall within the area set out for blasting or hard ripping.

The result of these assessments was that it was not practical to excavate the headland by ripping so blasting was subsequently used.

Fills

The quarrying of Chek Lap Kok, Lam Chau and The Brothers islands generated about 120 Mcm (assuming a rock bulking factor of 1.3) of fill for the reclamation. In addition there was a requirement for imported fill. Some came from other projects but the majority was 76 Mcm of marine sand obtained by dredging. These different sources of fill led to three main types of fill material:

Rock fill. As-blasted rock formed a hard durable rock fill named as Type A Fill, which was specified as well graded with a maximum size of 2.0 m and fines content limited to 5%.

Other excavated soil or rock. Materials generated from excavation that had a maximum size of 300 mm and could include up to 50% of fines were specified as Type B. Typical Type B material is the completely decomposed granite (CDG) generated from the weathered zones on Chek Lap Kok island. In parts of the platform the contractor was permitted to reclaim using a mixed material of both Type A (rock fill) and Type B (CDG) so that a variable and broadly graded Type A/B resulted; typically this was rock fill with a small but variable content of CDG.

Marine sand fill. Offshore sand deposits were dredged to obtain sand fill, known as the Type C fill. This was specified as having less than 20% fines and a maximum size of 100 mm. In practice Type C had a mean grain size of 0.8 mm (Newman et al., 1995). The marine sand fill mainly originated from four different borrow areas; viz western Po Toi, southern Tsing Yi, The Brothers and eastern Sha Chau.

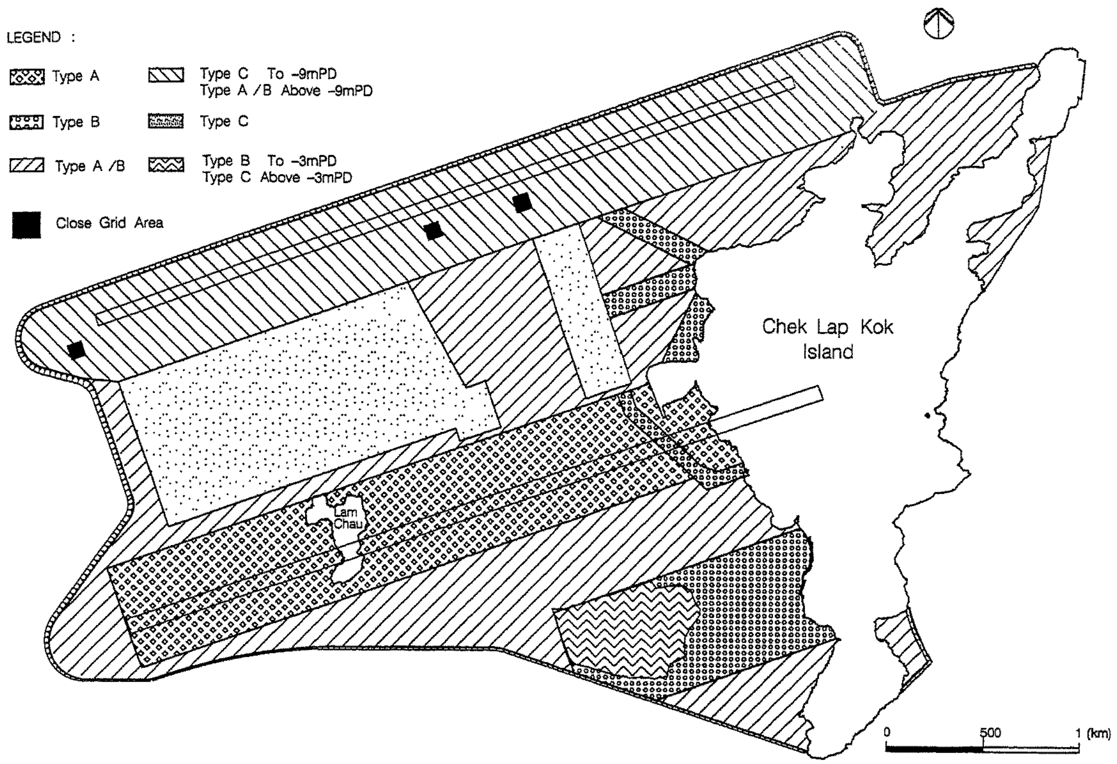


Fig. 5. Fill allocation plan

Filling

Each of the fill materials had its own characteristics and was particularly suitable for certain parts of the reclamation. A fill allocation plan was developed (Fig. 5) which optimised the use of available fill materials in the reclamation either on account of their as-built or their handling characteristics.

Due to its hardness, durability and lower settlement characteristics, Type A rock fill was used to form the first (southern) runway. Rock fill with a similar specification was used to form the armourstone of the seawalls (Plate 4).

The key feature of Type B fill is that it could be subsequently re-excavated or piled through with relative ease. This fill was therefore used along the alignment of the concourses, the APM Tunnel, the Eastern Vehicle Tunnel and the Southern Commercial Area.

Type A/B fill was a relaxation of the specification used along the Northern Runway, aprons and the remainder of the southern part of the site.

Type C was versatile in its means of handling. Not only could it be bottom dumped, it could be pumped as a hydraulic suspension and rainbowed ashore. A large island of sand fill was thus created in the middle of the reclamation. Sand fill was also used as the lowermost part of the Northern Runway reclamation and in the upper part of the Southern Commercial Area (Plate 5).

The reclamation was initially built up to an intermediate level of about +4 mPD. A capping layer was formed above this to bring the level to the final elevation. Since numerous trenches, services, excavations and shallow foundations would take place subsequently, it was important that the capping layer should

Plate 4. Hard durable Type A rock fill used as armourstone for the seawalls

Plate 5. Sand fill, Type C, with steel driven H Piles for Cargo Terminal II. Type C was extensively used as a capping layer above –2 mPD in the reclamation of this part of the Southern Facilities Area

ing ashore of marine sand (Type C), although some was rehandled CDG fill (Type B).

Because of the large contrast in grain size between sand fill used in capping and the underlying rock fill, it was necessary to separate the layers using a geotextile as a filter material. The importance of this layer is demonstrated by the development of a number of sinkholes within the capping layer of the platform; later investigation generally found that these sinkholes were associated with areas of damage to the geotextile.

Foundations

The type of foundations used in the various structures at Chek Lap Kok were controlled by the depth to a satisfactory founding stratum and the nature of the overlying materials.

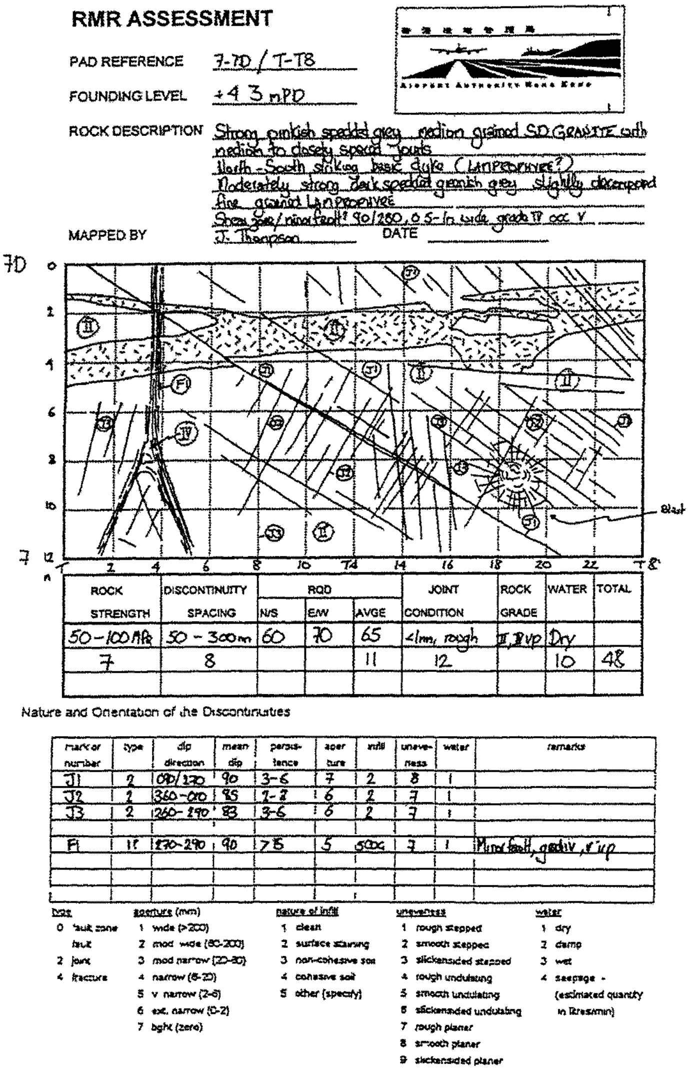
For the major structures, where solid rock lay close to the surface, pad foundations were used. Some minor structures were built on raft foundations. Over much of the site, however, grade III rock lay at significant depths and piled foundations were needed. In most cases these were cast in-situ concrete bored piles although, on those parts of the platform where foundations had to be taken through sand fill, driven steel H piles were used.

Most of the medium and small size structures were constructed using a single type of foundation. For instance the HACTL air cargo facility, located in the southern part of the platform on a large expanse of sand fill, was founded on steel H piles (Plate 5). The Government Flying Services on the other hand used large diameter bored piles. The largest structure on Chek Lap Kok, the passenger terminal building, was constructed using a variety of foundation types, the choice of which was controlled by the local geological conditions.

The terminal building is partially located on the original island and partially on new reclamation. Consequently the formation below the footprint of the building ranged from 200 MPa granite to soft clays associated with the former agricultural paddy fields. In general, piles were used through the reclamation and pads on the original island but, due to geological variations, it was not always so simple. The building straddles the original shoreline where the rock surface falls away offshore leading to a transition between foundation types. In some places there was a dramatic fall in founding level across the width of a pad.

Excavations for pad foundations were thoroughly cleaned and inspected prior to casting the foundation (Plate 6). The bearing capacity of each foundation, and hence the size that needed to be installed, was verified by carrying

Plate 6. Cleaning of excavation for a pad foundation. Note variation in weathering and discontinuity pattern to be taken into account in RMR rating



RMR ASSESSMENT

PAD REFERENCE 7-7D / T-T8

FOUNDING LEVEL +4 3 mPD

ROCK DESCRIPTION Strong pinkish speckled grey medium grained SD GRANITE with
medium to closely spaced joints
North-South striking basic dyke (LAMPROPHYRE?)
Moderately strong dark speckled greenish grey slightly decomposed
fine grained LAMPROPHYRE
Shear zone/minor fault? 90/280, 0 5-1m wide, grade III occ V

MAPPED BY J. Thompson DATE

ROCK STRENGTH	DISCONTINUITY SPACING	RQD			JOINT CONDITION	ROCK GRADE	WATER	TOTAL
		N/S	E/W	AVGE				
50-100 MPa	50 - 300mm	60	70	65	<1mm, rough	II, III vp	Dry	
7	8			11	12		10	48

Nature and Orientation of the Discontinuities

marker number	type	dip direction	mean dip	persistence	aperture	infill	unevenness	water	remarks
J1	2	090/270	90	3-6	7	2	8	1	
J2	2	360-010	85	1-2	6	2	7	1	
J3	2	260-290	83	3-6	6	2	7	1	
F1	1	270-290	90	7.5	5	500G	7	1	Minor fault, grade V, [illegible]

type
0 fault zone
fault
2 joint
4 fracture

aperture (mm)
1 wide (>200)
2 mod wide (80-200)
3 mod narrow (20-80)
4 narrow (6-20)
5 v narrow (2-6)
6 ext. narrow (0-2)
7 tight (zero)

nature of infill
1 clean
2 surface staining
3 non-cohesive soil
4 cohesive soil
5 other (specify)

unevenness
1 rough stepped
2 smooth stepped
3 slickensided stepped
4 rough undulating
5 smooth undulating
6 slickensided undulating
7 rough planar
8 smooth planar
9 slickensided planar

water
1 dry
2 damp
3 wet
4 seepage - (estimated quantity in litres/min)

Plate 7. Example of RMR field inspection sheet

out a rock mass rating (RMR) assessment (Bienawski, 1973, Plate 7). The RMR value obtained from the field inspection was used within the semi-empirical Hoek-Brown criterion (Hoek and Brown, 1992) to determine the strength parameters and deformation properties of the rock mass. Rock strength parameters were then substituted into bearing capacity equations to obtain an allowable bearing capacity (Goodman, 1989). The key factors in the field assessment of RMR were the assessment of the rock's weathering grade and the frequency, persistence and characteristics of the joints.

The high variability of the ground conditions beneath the terminal building required a flexible approach to foundation construction. This was achieved by providing within the design a number of foundation options, with the particular option used depending on the ground condition exposed during construction. The variability of the ground was due to a number of geological factors including:

- Extensive weathering, generally associated with faults, shear zones, dykes and veining;
- presence of sub-vertical stress relief sheeting joints with 100-200 mm clay infills;
- the high variability in the level to rock head over the original coastline; and
- fragmentation of the in-situ rock during the blasting.

As an example of the geological variation, there was a substantial zone of weathering running completely across the terminal building. Due to the depth to rock in this zone, it was necessary to install piled foundations. The orientation of this weathered zone coincided with the geological structure noted on the original geological map (Fig. 1) and it was concluded that the deep weathering here was controlled by a fault striking ENE.

Offshore, the layer of completely decomposed granite was usually about 10 m thick. In the north-west corner of the platform however, the weathering was substantially more advanced so that the layer of CDG off the western end of the Northern Runway was up to about 60-70 m. Fortunately no major structures were located here. There is however an array of approach lighting on small offshore structures. If the BD requirements were to be followed strictly the Airport Authority would have had to install piles for these light structures of about 120 m length. Luckily an exemption was approved and the piles were allowed to have all their load taken in a combination of friction and end bearing.

Settlement

The majority of the QCK and QSW deposits underlying the palaeosol crust are silty and sandy clays and clayey silts, laid down over a variable topography with a combined thickness ranging from 10 to 30 m. The major proportion of the settlement of the airport reclamation derives from the consolidation of these deposits. In general relatively higher settlements are expected from areas where the more cohesive units of the Chek Lap Kok Formation are thicker.

The settlement is however not easily modelled strictly according to the stratigraphy. For example the delineation of areas of the QCK1 unit with similar properties is made difficult by their high lateral and vertical variability, in particular due to:

- The limited extent of the deposits as a result of their lenticular nature;
- the clay and sand/gravel layers being interbedded and gradational transitions between these layers;
- the large variability in the degree of over-consolidation of the deposits as a result of the many cycles of erosion and deposition associated with sea level fluctuations; and
- the formation of discontinuous, relatively incompressible palaeosol crusts, also as a result of the erosion and deposition cycles.

The QCK1d, QCK1s, QCK2 and QCK3 units and the Sham Wat Formation are however more well defined, which has enabled the extent of drainage boundaries and limits of major compressible units to be well appreciated. The extents of these deposits has been used in zoning the platform for residual settlement assessments. The major components are:

- A stiff to very stiff, highly over-consolidated, palaeosol crust (QCK3) extending over much of the site and which in some areas provides an upper drainage boundary as a result of fissures developed by desiccation of the clays;
- a continuous basal sand and gravel layer (QCK1s and QCK1d) encountered over much of the central portion of the site thereby serving as a lower drainage boundary to the overlying consolidating clay units;
- a north-south-trending band of clays between Lam Chau and Chek Lap Kok (QCK2) and an east-west-trending band of clays (QCK2) oriented parallel to the northern flank of the platform (Fig. 4); and
- a band of compressible material extending west of Lam Chau to the northern limit of the platform.

In view of this information, settlement of the reclamation has been reviewed in terms of platform-wide settlement based upon the extent of massive, continuous units and differential settlement which considers the more variable constituents of the QCK1 unit.

In terms of the underlying geology, there is a good correlation with the settlement measured on site and the resultant forecast of residual settlement (Fig. 6). Higher settlement is expected for areas underlain by the QCK2a and QCK2b units (Fig. 4) in addition to areas where a thicker combined succession of compressible units (including the Sham Wat Formation) is located west of Lam Chau and extends to the northern limit of the platform. An early appreciation of the control of the underlying geology on settlement of the platform resulted in the marine stratigraphic model providing the framework for planning site investigation, geotechnical instrumentation, ground improvement works and installation levels drawings.

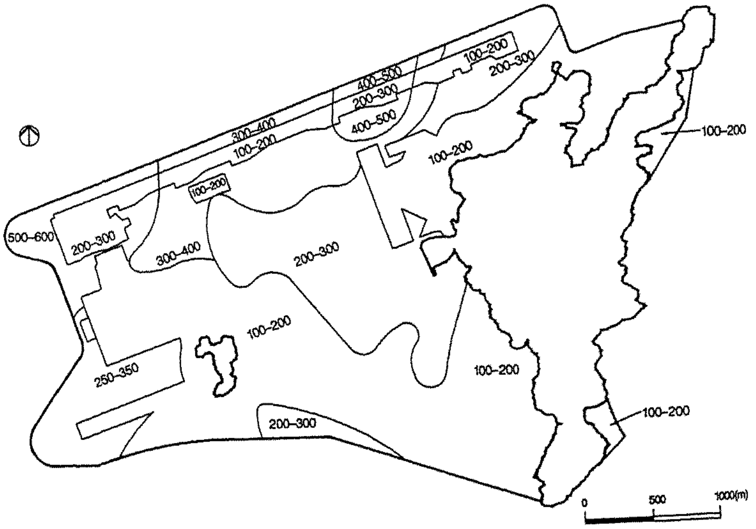


Fig. 6. Platform-wide prediction of residual settlement (mm)

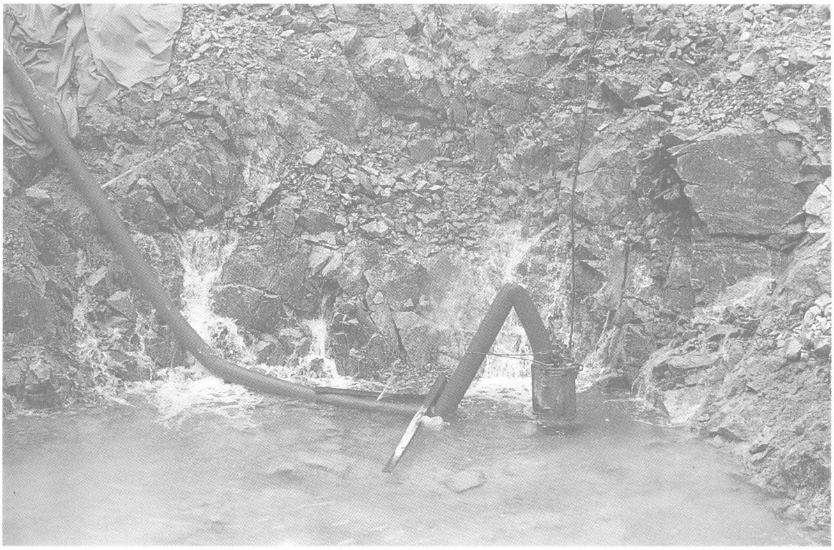


Plate 8. Excavation for road cutting through original Chek Lap Kok island. Note high groundwater inflow from high permeability zone created by fragmentation blasting

Differential settlement originating in the alluvium is less significant than that due to creep in the fill materials. This is because differential settlement originating in the alluvium occurs over longer baselengths (>45 m) due to:

- The lenticular form of the units;
- the gradational transition between units; and
- the variable compression being dispersed as it is expressed up through the overlying fill (20-30 m thick).

Hydrogeology

The blasting and subsequent excavation of the original island resulted in a dramatic change in the hydrogeology of the area. The fragmentation blasting generated a highly permeable zone 2-5 m thick across the former island (Plate_8). Since fragmentation blasting was not carried out along the original coastline, this highly permeable rock was surrounded by a lower permeability material effectively forming a semi-confined aquifer. It was found that rainwater infiltrating into the highly permeable but relatively low porosity rock of this aquifer caused a rapid and substantial rise in groundwater level. One result of this is that it was necessary to construct a cut-off around the road cutting at the interchange to the east of the Southern Runway. Within the moderately blast-shattered rock the cut-off was formed by grouting while in the highly blast-shattered zone close to the surface a mass concrete wall was constructed.

The reclamation fills are generally permeable but the granular Type C and coarsely granular Type A in particular are highly permeable. As a consequence and because the reclamation forms an island totally surrounded by the sea, the groundwater is in hydraulic connection with the sea. This means that the groundwater response is strongly tidally influenced.

At depth the Chek Lap Kok Formation is predominantly of low permeability silts and clays. These are the most significant strata for the elevation of pore pressures in response to loading from the reclamation fill.

Dissipation of these pore pressures towards hydrostatic levels was expected to be slow. However the presence of more permeable layers, either the intermittent sandy lenses or the persistent and extensive QCK1d basal sands and gravels unit, has considerably aided the drainage so that the excess pore pressures have generally dissipated more quickly (Pickles and Tosen, 1998).

Conclusions

This paper has attempted to demonstrate how the local geology has had a critical influence in the design and construction of the new airport. This underlines the importance of an early development of a comprehensive geological model to allow the optimisation of the design of major projects. Examples of this influence include:

- The high compressibility of the Hang Hau Formation marine muds dictated the overall strategy of the reclamation.
- The onshore geology controlled both the methods of excavation and types and properties of the final fill material obtained.
- The types and quantities of fill material available defined the plan of the reclamation.
- The variability in compressibility of the in-situ superficial deposits controlled the total and differential settlement of the platform.
- The presence of drainage layers affected the rate of settlement of the platform.
- The thickness and variability of the weathering profile governed the types of foundations.
- The jointing affected the batter of all temporary work excavations within the rock and governed the size of pad foundations.
- The joint pattern affected the rate of water ingress into excavations and the methods of treatment.

References

Anon (1996) Geotechnical Aspects of Hong Kong's New Airport. *Ground Engineering*, special supplement, December 1996

Bienawski ZT (1973) Engineering Classification of Jointed Rock Masses. *Trans S Afr Inst Civ Eng*, 15, pp 335-344

British Geological Survey (1994) *An Interpretation of the Marine Geology for the Replacement Airport at Chek Lap Kok, Hong Kong*. Report prepared for the Provisional Airport Authority, January 1994

Foott R, Koutsoftas DC & Handfelt LD (1987) Test fill at Chek Lap Kok, Hong Kong. *J Geotech Di. ASCE*, 1987, 113, No 2, 106-126

Fyfe A & James JWC (1995) The offshore Quaternary Sham Wat Formation of Hong Kong. *Hong Kong Geologist*, Vol 1 (spring), pp 30-33

Goodman RE (1989) *Introduction to Rock Mechanics* (2nd Edn). John Wiley and Sons.

Hoek E & Brown ET (1992) *A Modified Hoek-Brown Failure Criterion for Jointed Rock Masses*. Eurock '92. Thomas Telford, London, pp 209-214

James JWC (1993) *The Offshore Geology of the Area Around Lantau Island, Hong Kong*. British Geological Survey Technical report WB/931/13R

Langford RL (1994) *Geology of Chek Lap Kok*. HKGS Sheet Report No 2, 1:50 000 sheet 9-NE-D/D, Geotechnical Engineering Office, CED, August 1994

Langford RL, James JWC, Shaw R, Campbell SDG, Kirk PA & Sewell RJ (1995) *Geology of Lantau District*. HKGS Memoir No 6, 1:20 000 sheets 9, 10, 13 & 14, Geotechnical Engineering Office, CED, December 1995

Newman RL, Covil CS, Ng NWH & Pickles AR (1995) Characteristics of the sand fill used in the reclamation for Hong Kong's new airport at Chek Lap Kok. Proceedings of the 48th Canadian Geotechnical Coference on Themes in Geotechnique, Vancouver, Canadian Geotechnical Society, pp 461-469

Pickles AR & Tosen R (1998) Settlement of reclaimed land for the new Hong Kong International Airport. *Proc Instn Civ Engrs Geotec Engng*, Vol 131, October 1998, pp 191-209

Plant GW, Covil CS & Hughes RA (1998) (eds) *Site Preparation for the new Hong Kong International Airport*. Thomas Telford, 576 p

Strange PJ & Shaw R (1986) *Geology of Hong Kong Island and Kowloon*. 1:20 000 sheets 11 & 15, Hong Kong Geological Survey Memoir No 2, Geotechnical Control Office, Hong Kong

Anticipating Geotechnical Problems

S Hencher and G Daughton

Abstract

Engineering projects often run into “difficult” ground conditions which cause delays, failures, hugely increased costs or even abandonment with consequent disputes and claims. Pertinent questions are “what constitute difficult conditions?” and “how might they be foreseen?” These questions provide the focus for this paper. Geological, geotechnical and hydrogeological models for engineering projects need to be developed in a systematic manner. The potential risks associated with engineering properties and characteristics of the geological materials, the mass fabric, the environmental setting and the influence of the engineering works themselves need to be considered individually and in a progressive, integrated manner. This paper illustrates such a systematic approach with reference to examples from various engineering works.

Key words: difficult ground conditions, prediction, geotechnical hazards, material factors, mass scale factors, environmental setting, engineering works.

Introduction

Disputes relating to ground conditions are often based on the premise that the conditions were unforeseen or unforeseeable. The questions of “what constitute difficult conditions?” and “how might they be foreseen?” are the focus for this paper. A systematic approach is introduced whereby the various geological and environmental factors that might conceivably affect the success of the project are considered.

What Are Difficult Ground Conditions?

Often in engineering projects, the extent of difficulties associated with ground conditions are not foreseen prior to something going seriously wrong. The difference between *unforeseen* (not predicted) and *unforeseeable* (outside common experience, not to be expected and without indications) is important. Quite often, in hindsight the factors resulting in the problem are simple, even trivial, and it is apparent that the “unforeseen” condition might at least have

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been anticipated to some degree had a more thorough approach been taken to weighing up the geology and environmental setting.

What is important is that ground conditions which have the potential for causing problems are recognised at the correct time and dealt with adequately by the designer. Following failures of designed works, it is often found that the model of ground conditions was inadequate, either because some geological feature or property had been missed or overlooked during investigation, or because its significance had not been recognised. It is the authors' opinion that, even where nothing major goes wrong in many projects, it is often a matter of good fortune (absence of difficult conditions) rather than the result of a proper appreciation of the ground.

In practice, it is dangerous to disregard any property (e.g. chemistry, fabric, structure) of material or mass without careful consideration of its potential effect on the proposed works, both during and post- construction, and examples of the severe influence of apparently minor factors will be given later.

Geotechnical Hazard Review

A broad overview of the geological and environmental setting can provide many insights into the likely difficulties to be faced throughout an engineering project. DeFreitas (1993) suggests that, when dealing with works of any significant size, careful consideration should be given to three questions :

- what do we know?
- what do we need to know?, and
- what do we not know?

Each question should be considered at an early stage with reference to possible design solutions and methods of working. The site investigation should be specified accordingly. This might seem obvious but, for many reasons, it is rarely done systematically or comprehensively.

It is suggested that potential hazards be considered in a formal way through which potential problems are identified so that they can be categorised and mitigated against as far as possible. Such a systematic way of approaching hazard and risk is becoming common throughout civil engineering (Godfrey, 1996; Brown, 1999).

An approach for carrying out a *geotechnical hazard review* is described

Table 1. Engineering geology expressed as simple equations (after Knill, 1976)

Equation 1
material properties + mass fabric ⇒ mass properties

Equation 2
mass properties + environment ⇒ engineering geological situation

Equation 3
engineering geological situation + influence of engineering works
⇒ engineering behaviour of ground

Table 2. Commentary on Knills Equation

Equation 1 GEOLOGY	The first quation includes the geology of the site and concerns the physical, chemical and engineering properties at small and large scales It essentialy constitutes the soil and rock ground conditions
Equation 2 ENVIRONMENT	The second equation describes the geological setting within the environment Environment includes factors such as climate, stress, time and natural hazards
Equation 3 WORK	The third equation relates to changes caused by the engineering works. It is the job of the engineer to ensure that the changes are within acceptable limits

An approach for carrying out a *geotechnical hazard review* is described here with reference to three equations (Tables 1 and 2). The equations were originally conceived by Knill and Price (Knill, 1976) and subsequently used by Price and Lumsden as the framework for teaching advanced courses in engineering geology at Delft University (Holland) and Leeds University (UK) respectively (Hencher, 1994; 1996). The equations provide a useful way of and, essentially a checklist for, approaching geotechnical aspects of many engineering works. The equations focus attention progressively on *geological materials* (mineralogy, fabric, texture and hence intrinsic engineering properties), then more broadly to include *mass features* (discontinuities and overall geological structure), *environmental setting* and, finally, the influence of the *engineering work* themselves.

Examples of factors that should be considered systematically during such a review for a project are listed in Tables 3 to 6 at the end of this paper. The relevance of particular factors will depend upon the specific nature of each project.

Material Scale Factors

If not recognised at the appropriate time, intrinsic properties of the rock or soil can lead to difficulties.

One common problem is wear or damage to equipment such as drills or tunnelling machine teeth due to abrasiveness of the ground. Rocks to be wary of include those with high silicate contents such as rhyolites, quartzites, sandstones and cherts. Even quartz-rich soils can lead to unacceptable wear for tunnelling machines.

Minerals such as gypsum can be dissolved leading to damage to properties (e.g. Cooper & Waltham, 1999) . Conversely swelling due to the growth of gypsum, partly as a result of oxidation of pyrite can lead to heave and building damage (e.g. Hawkins & Pinches, 1987). Similarly swelling pressures in some mudrocks can seriously delay tunnel projects (Steiner, 1994).

Chemical reactions between different minerals can cause problems. For example at Carsington Dam in the UK, the original dam was constructed largely from Carboniferous mudrock with a limestone riprap cover. Iron pyrites within the mudrock oxidised on exposure producing a weak sulphuric acid (with water) which polluted water courses. The acid also reacted with the limestone riprap producing carbon dioxide which, because it is heavier than air, accumulated in tunnels beneath the dam and led to fatalities.

Silica reactivity in concrete can cause severe deterioration and yet is readily avoided if the mineralogy of the aggregate is considered properly (Smith & Collis, 1993). Figure 1 shows the crazing of the Pracana dam in Portugal caused by silicate reactivity which necessitated major repair works.

An experienced engineering geologist should be able to predict many of the potential problems simply through general knowledge of the geology. For example, coal bearing strata close to the surface might be expected to be mined in a populated area even if there are no records that the area was mined.

Figure 2 shows deep storage caverns being excavated in chalk. The original design was to use the illustrated road header to cut the caverns but the method had to be changed to drill and blast. The change was necessitated because of unacceptable wear to teeth in the road header from flints within the chalk. The flints were under-sampled in the ground investigation but might have been anticipated through general geological knowledge.

A site underlain by karstic limestone, bought by a building contractor for house development, is shown in Fig. 3. The irregular bed rock profile caused significant problems for constructing shallow foundations, yet might have been anticipated through general review of the local geology and proved inexpensively by a few shallow trial pits.

In Hong Kong, textures of the weathered rocks are important. Disintegrated (highly microfractured) but otherwise not severely chemically decomposed rock can be apparently just as weak as completely decomposed rock (grade V) in hand sample (unconfined), but in-situ and undisturbed, is probably far stronger. The distinctive property of completely decomposed rock (grade V), by most definitions (see Anon, 1995), is that it slakes (disintegrates) in water. This material property is reflected in distinctive slope failures and gulleying (see Figures 4 and 5). The differences in mineralogy and texture of variously weathered rock are reflected in variations in shear behaviour which are quite subtle and difficult to measure (Ebuk et al., 1993).

Weathering along joints contributes to a significant reduction in shear strength down to a typical basic value of 28 to 40 degrees, (Hencher & Richards, 1989; Hencher, 1995; Papaliangas et al., 1996). However, where joints are coated with minerals or infilled with clays, the influence of the mineralogy can result in shear strength being much lower (Papaliangas et al., 1993).

Figure 6 shows a failed rock slope where sliding occurred on dry joints coated with very-thin chlorite. The daylighting joints were dipping at only 21 degrees. Subsequent shear testing confirmed that such joints could have friction angles less than 20 degrees at low stresses (Brand et al. 1983). Apart from reduction in strength, an important influence of thick clay infills like kaolin can be their control of groundwater permeation. Figure 7 shows a detail from a failure at Junk Bay Road where a perched water table developed above a kaolin-infilled joint (Hencher et al., 1985).

Mass Scale Factors

The most important mass scale features in geotechnical engineering are discontinuities – bedding planes, fissures, joints and faults. These typically reduce strength and stiffness and increase the permeability of the rock or soil mass. Discontinuities are generally approximately planar and there is often a regular pattern, which means that engineering properties of the mass are anisotropic. Therefore structural orientation relative to the geometry of the project is often extremely important. Cutting a slope into jointed rock with a

Fig. 1. Crazing of the Pracana dam in Portugal caused by silicate reactivity in concrete

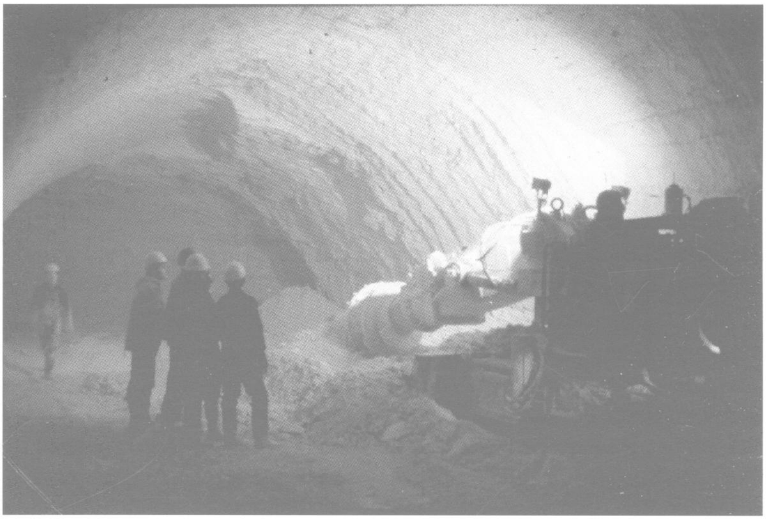


Fig. 2. Deep storage caverns being excavated in chalk. Flints in the chalk caused unacceptable wear to road header teeth, prompting a change to drill and blast methods

Fig. 3. A site underlain by karstic limestone. The irregular bed rock profile caused significant problems for constructing shallow foundations,

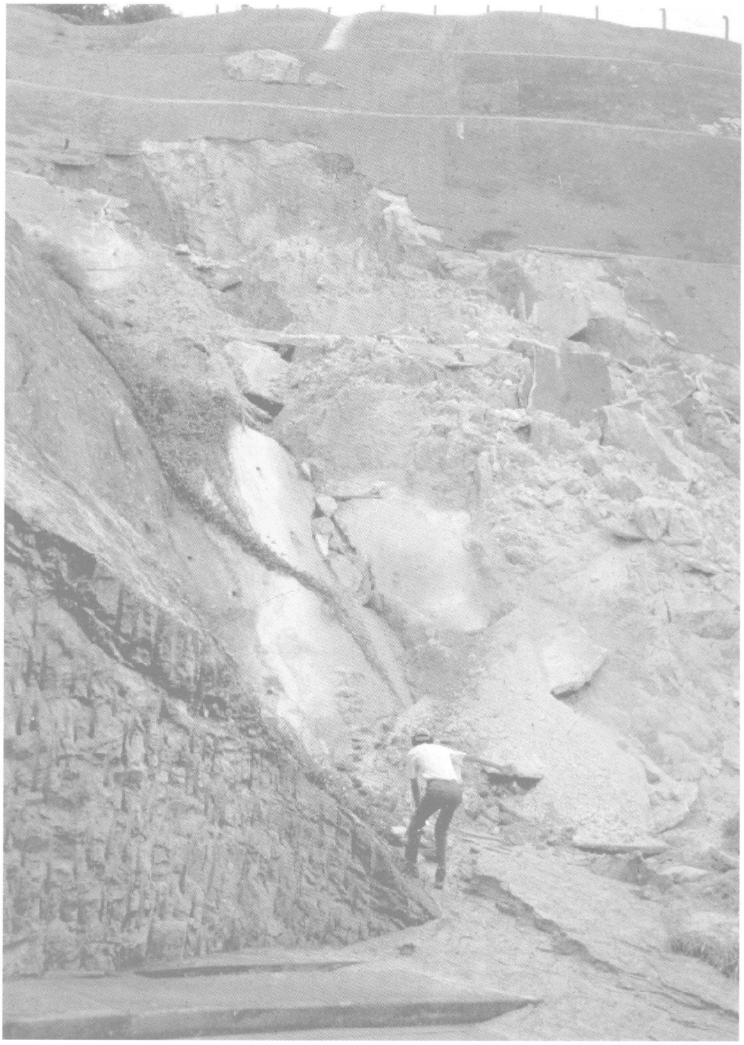


Fig. 4. Slope failure caused by slaking of completely decomposed rock (grade V)

Fig. 5. Gulleying caused by slaking of completely decomposed rock (grade V)

Fig. 6. Failed rock slope where sliding occurred on dry joints coated with very-thin chlorite. The daylighting joints were dipping at only 21 degrees

Fig. 7. Detail from a failure at Junk Bay Road where a perched water table developed above a kaolin-infilled joint

Fig. 8. Geological structural control by discontinuities on quarry faces

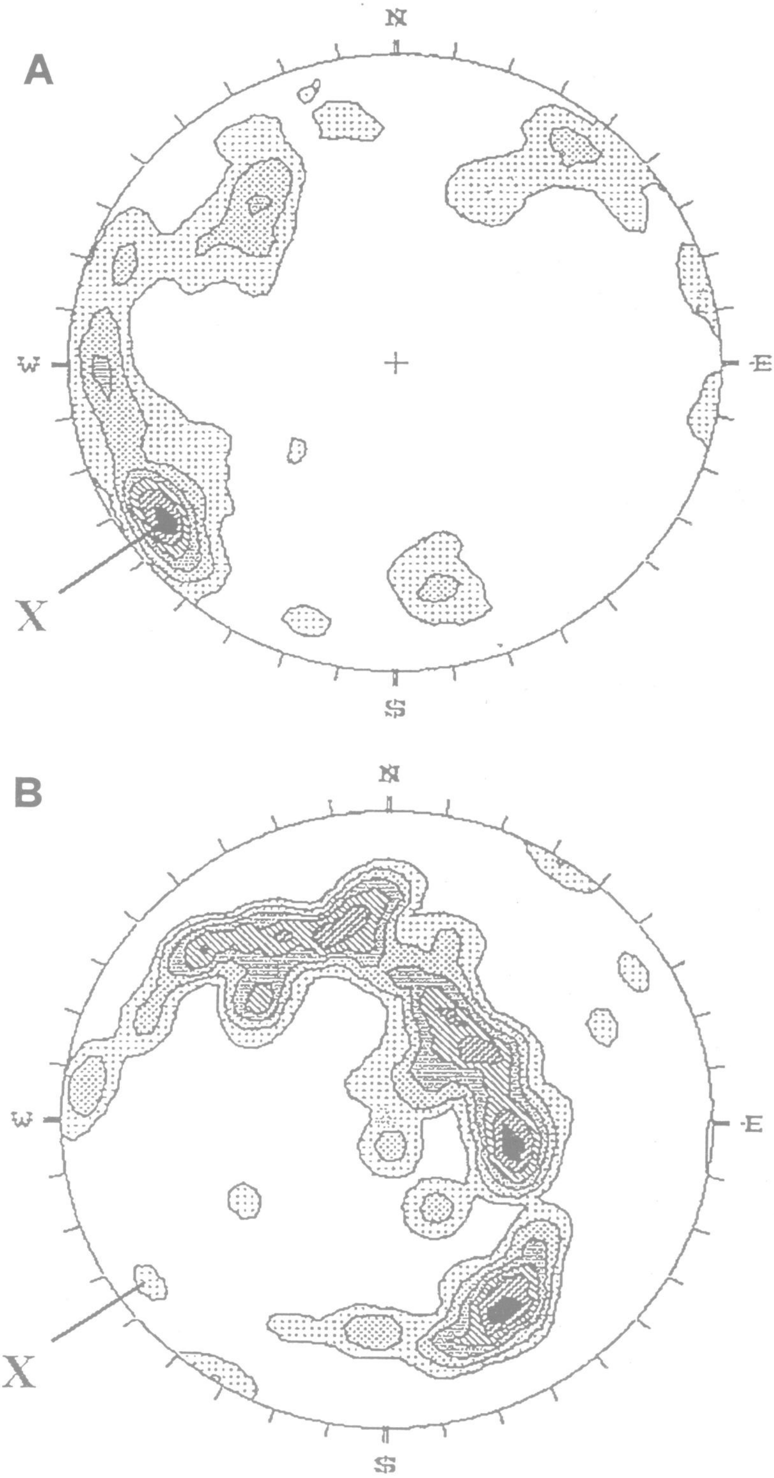


Fig. 9. Stereoplots for the same weathered rock mass. ***A***, discontinuities measured during face mapping; ***B***, discontinuities measured in vertical boreholes. Note girdle of points, about 90 degrees around main concentration measured in exposures

particular aspect may be perfectly safe whilst cutting at some other orientation may result in failure. In Figure 8, the geological structural control of the discontinuities on the quarry faces is obvious.

Joints and other fracture systems are often consistent with the tectonic history of the site and it is useful to try to interpret the origin of the fractures rather than just measure them and treat them in a statistical sense (Hencher, 1987; Rawnsley et al., 1990; Pollard & Aydin, 1988; Hancock, 1991). That said, in the predominantly granitic and volcanic rocks of Hong Kong, whilst fracture patterns are often locally consistent, they are difficult to predict on structural grounds (Nau, 1984).

In characterising the rock mass, care must be taken to sample carefully and to account for bias. For example in Figure 9 (Halcrow Asia Partnership, 1998), two stereoplots are presented for the same weathered rock mass. Figure 9a contains data measured during field mapping, mostly on steep exposed faces. Joints measured are predominately steeply dipping. Figure 9b shows data measured using a BIPS system (Kamewada et al., 1990) in vertical drillholes. In these drillholes, the steep fractures were under-sampled and most of the discontinuities recorded were shallowly dipping.

If vertical holes are used predominantly to investigate a site (as is common practice) then steeply dipping structural features may be overlooked. Figure 10 shows the site of the Pen-Y-Clip headland (Al-Harthi and Hencher, 1993). A tunnel through the headland encountered vertical fractures infilled with soil. The soil collapsed into the tunnel and a chimney extended up to the surface of the hillside above. The vertical boreholes had missed the fissures during investigation which therefore came as a surprise during the tunnel excavation. The vertical joints were probably unloading fractures which run roughly parallel to the coastline and as such, might have been anticipated and investigated using inclined boreholes.

A photograph of typical core from an investigation for a very wide span underground station, planned to be excavated in mudrock at a depth of about 50 m, is presented as Fig. 11. The vertical, calcite infilled fracture is obvious. Faced with such evidence the designer has to consider the possibility of extensive roof failure (as in Fig. 12), the difficulties in preventing such failure and the long term implications for rock load. This requires that the fractures be properly characterised in terms of their planarity, frequency and persistence. If joints are impersistent, and infrequent, the problem may be only minor. Similarly if the joints are wavy at the field scale, then the rock mass will dilate and may lock up as movement occurs towards the tunnel so that the volume of failure will be restricted. These are, however, serious questions which demand careful consideration of the geological mass features.

Faults often cause problems for engineering works. Faults are rarely simple breaks through the rock but are often associated with other shear zones and poor quality rock. The collapse of a tunnel, which buried a TBM, is illustrated in Fig. 13. The tunnel had encountered a fault zone, the extent and weaknesses of which had not been anticipated even though it was known from ground investigation that a fault occurred at that location.

Figure 14 shows a major rock slope failure in Repulse Bay, Hong Kong that occurred due to sliding within a zone of fractured rock and pink clay (probably a fault). The zone was about 700 mm thick and persistent throughout the hillside. Because of the thickness of the zone, the rock did not contribute to shear strength.

Fig. 10. The Pen-Y-Clip headland tunnel collapse. Soil-infilled vertical fractures led to the soil collapsing into the tunnel and a chimney extending up to the surface of the hillside above

Fig. 11. Typical core from site investigation borehole. Note the vertical, calcite-infilled fracture

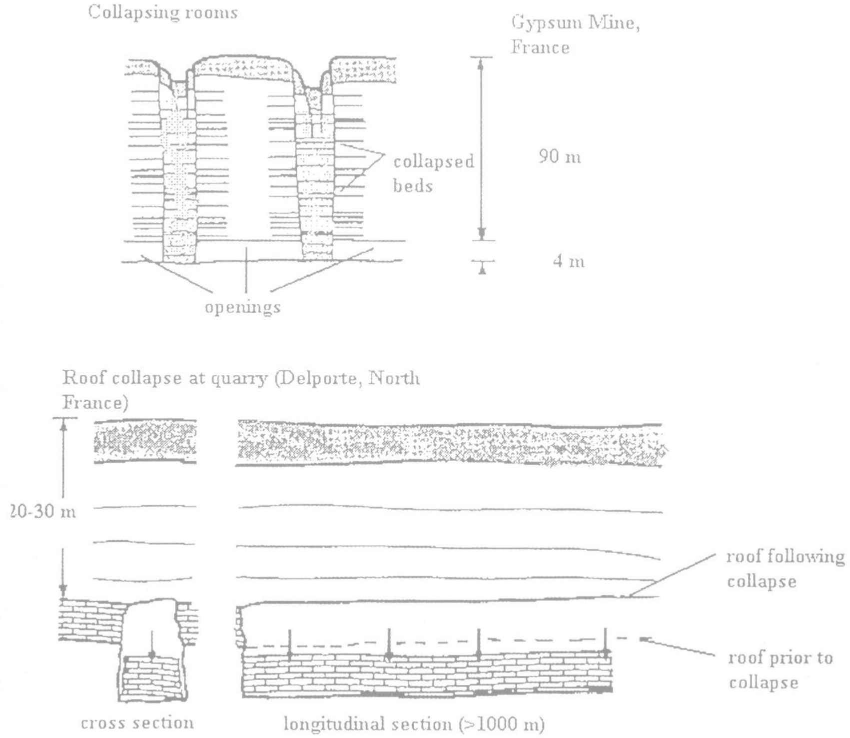


Fig.12. Examples of extensive roof failure

Fig. 13 (below). Tunnel collapse after encountering a fault zone. The extent and weaknesses of the fault zone had not been anticipated even though it was known from ground investigation that a fault occurred at that location.

Fig. 14. Major rock slope failure at Repulse Bay, Hong Kong that occurred due to sliding within a zone of fractured rock and pink clay

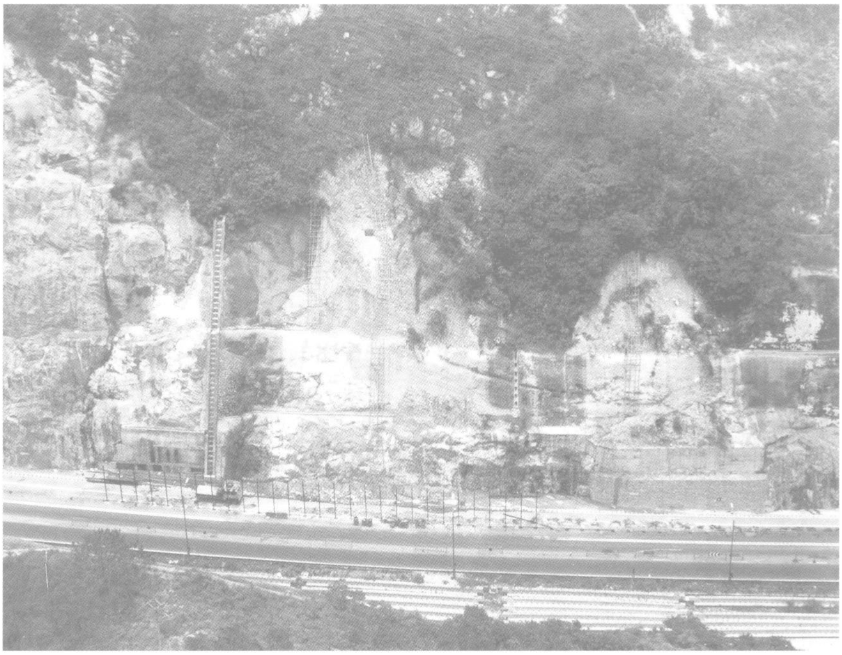
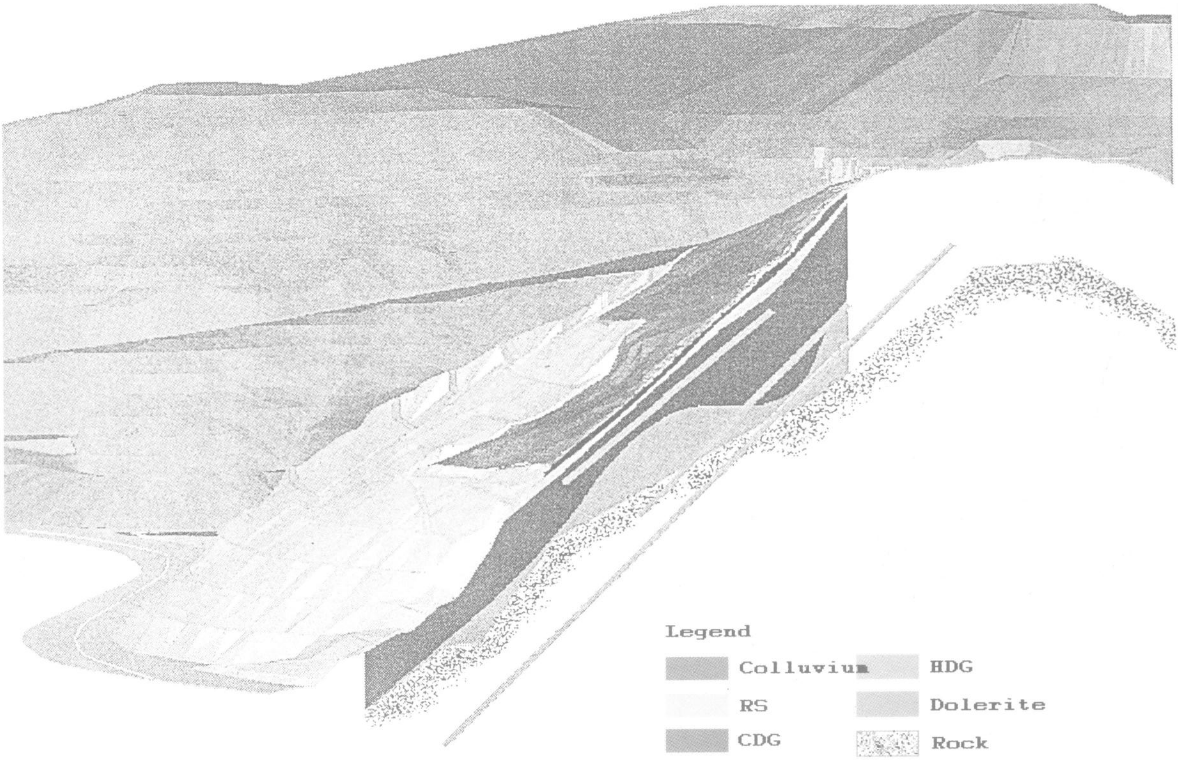


Fig. 15. Landslide on Tuen Mun Highway, Hong Kong where failure was interpreted as having been caused by perching of water above a gently dipping dolerite dyke

The importance of lithology contrasts in controlling hydrogeological patterns is well established but sometimes not looked for or the significance is not appreciated in design. Figure 15 shows a landslide on Tuen Mun Highway, Hong Kong where failure was interpreted as having been caused by perching of water above a gently dipping dolerite dyke (Hencher & Martin, 1984). Similarly, dolerite dykes within the weathered granite contributed to the complex hydrogeology and system of pipes which were an integral part of the failure mechanism of the major landslide affecting Ching Cheung Road, Hong Kong in 1997 (Halcrow Asia Partnership, 1998). A cross-section across the failure



showing the interpreted dyke structure is shown in Fig. 16. Other examples of geological control of landslides are given in Hencher et al., (1985).

Fig. 16. Cross-section across the failure associated with the 1997 Ching Cheung Road landslide, Hong Kong, showing interpreted dyke structure

Environmental Setting Factors

Environmental factors include natural factors such as seismicity, rainfall, flood and in-situ stresses together with man-induced problems such as contaminated groundwater, blast vibrations and gases and disturbed ground due to mining activities.

The natural factors to be considered will depend upon geographical setting and the nature of the project. Quite often the factor will have to be considered on a risk basis. For example, in Hong Kong there is a high probability that structures will be affected by ground vibration induced by nearby earthquakes of magnitude up to say 5.0 over a 100-year period, but a very low probability that they will be affected by an earthquake of, say, 7.5 magnitude (Chandler, 2000). Similarly wind loading of 100 km/hour might be expected annually but wind speeds of 200 km/hour are a low probability, though not impossible in the lifetime of a structure.

An important environment factor is the change in groundwater levels, temporary due to rain storms or drought and possibly longer term due to the construction of a reservoir, or drainage induced by the excavation of a drained tunnel underneath a site. The latter two are actually the result of engineering works and will be discussed later in this paper.

Groundwater infiltration and flow is extremely important to Hong Kong slopes but very poorly understood. The forensic level investigation of Ching Cheung Road landslide, 1997 (Halcrow Asia Partnership, 1998) revealed a series of natural pipes, partly infilled with sediments ranging from well sorted sands to gap graded clays and gravels. This complex pipe system played a major role in the nature of the subsequent failure but ways to incorporate such features in standard analysis (especially limit equilibrium) are essentially unknown. Some of the pipe structures are discussed in Halcrow Asia Partnership (1999).

Natural in-situ stresses can cause major problems, especially to underground structures. Where stresses are high, the structure may deform and support systems may be insufficient. If stresses are low (area of extension), joints may be open and high groundwater inflows can occur.

Harmful gases can occur naturally in rocks. The major explosion of methane in finished tunnels and associated underground structures at Abbeystead, UK in the early 1980s provided a warning to the industry (Health & Safety Executive, 1985; Orr et al., 1991). Radon gas can be found not only in materials normally thought of as radioactive but in sediments such as mudstones and shales and should be investigated (e.g. Talbot et al., 1997).

Tunnelling through or close to contaminated land has its own special problems, as reported by Barla & Jarre (1993)

Engineering Works

The final part of the equation is to consider the effects of the works themselves. Obvious aspects include permanent changes in stress – unloading by excavation or loading due to the construction of a building.

More subtle changes include the effect on groundwater regime. For example, in cutting a slope the well-established groundwater flow paths and patterns will often be disturbed. New and very active flow paths may be developed as the groundwater system reacts to the changed geometry and stresses and may result in piping and movement of materials (e.g. leaching and redistribution of clays). This will be exacerbated by stress relief and opening of discontinuities in the mass.

The effects of the works during construction should be considered as carefully as the integrity and performance of the final structure. It is often during construction that things go seriously wrong. For example, Fig. 17 shows some of the 20 000 piles driven to support the second phase of Drax Power Station in Yorkshire, UK. The piles shown were driven to various depths (the holes in the front are where piles disappeared below carpet level). This was not through design or choice. The variable penetration achieved was totally unexpected and due to varied grading in the essentially sand horizon where the piles were founded. Where the clay/silt content was relatively high, high temporary pore pressures were generated during driving of the piles, resulting in low shear resistance and deep penetration. This caused major difficulties in predicting pile length and added perhaps 10% to the cost of pile production (Hencher & Mallard, 1989).

Tunnelling is often associated with ground deformation and the potential for damage needs to be accounted for in selecting the route. Figure 18 illustrates the undesirable effects of tunnelling for the Singapore Subway.

Discussion

It is clear that site investigation will rarely provide a comprehensive picture of ground conditions to be faced. This is particularly true for tunnelling because of

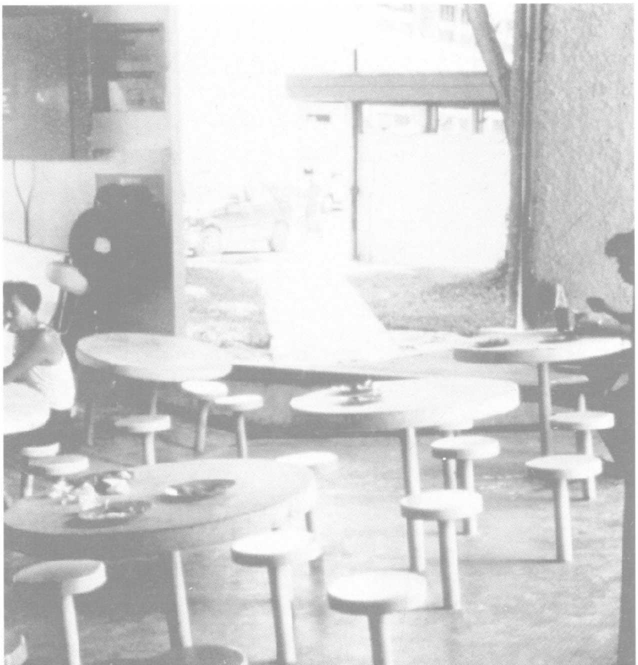


Fig.17. Some of the 20 000 piles driven to support the second phase of Drax Power Station in Yorkshire, UK

Fig. 18. Effect of ground deformation caused by tunelling in Singapore

the length of ground to be traversed, the volume of rock to be excavated and often the nature of the terrain. Instead reliance must be placed on engineering geological interpretation of available information, prediction on the basis of known geological relationships and careful interpolation and extrapolation of data. Factors crucial to the success of the operation need to be judged and consideration given to the question *what if*? It is generally too late to introduce major changes to the methods of working, support measures etc. at the construction stage without serious cost implications.

Site investigation must be targeted at establishing those factors most likely to be important to the project. This requires the careful *ground hazard review* process advocated in this paper. Even then, one must remain wary of the unknowns. In tunnelling, which is often one of the riskiest processes, probing ahead to establish the position of structures likely to cause difficulties may delay operations but that is better than simply driving on in the hope that everything will be all right. Instrumentation can be of great benefit in identifying problems before they become too severe (the 'observational process'), but the use of advanced electronic devices may prove inefficient because of a lag time between measurement and interpretation back in the site office. This was highlighted as a possible contributing factor in the severity of the collapse of tunnels at Heathrow (NCE, 1994).

Conclusions

For any project, the ground conditions must be carefully assessed for economy and safety. Sometimes the complexity of the situation is so great that it is difficult to focus on everything that can go wrong. Alternatively, in many situations a single, simple aspect of the site may control the success or otherwise of the whole project.

All rock and soil masses are complex to some degree or other at some scale. Gross geological complexity is readily recognised from mapping but the importance of apparently minor features may be overlooked. It is argued that a careful appraisal of the possible engineering geological conditions based on general knowledge of the typical features of particular lithologies can go a long way to preventing difficulties during construction. This is best done systematically as advocated in this paper.

Table 3. Examples of material scale factors that should be considered for a project

Factor	**Considerations**	Examples of rock types.situations
mineral hardness	abrasivity, damage to drilling equipment	silica-rich rocks and soils (e.g. quartzites, flints in chalk)
mineral chemistry	reaction in concrete oxidation - acids swelling, squeeazing dissolution low friction	olivine, high-temperature qyartz, etc. pyrites mudrocks, salts, limestone clay-infilled discontinuities, chlorite coating
loose, open texture	collapse on disturbance or overloading, liquefaction, piping, low shear strenth	poorly cemented sandstone, completely weathered rocks (V); loess; quickclays

Table 4. Examples of mass scale factors that should be considered for a project

Factor	Considerations	Examples of rock types/situations
lithological hetero geneity	dissiculty in establishing engineering properties; construction problems (plant and metho do logy)	colluvium, unengineered fill, interbedded strong and weak strata, soft ground with hard corestones
joints/natural fractures	sliding or toppling of blocks deformation water inflows / collapse leakage migration	slopes foundations tunnels reservoirs muclear repository
faults	radiomucleide as joints; sudden changes in conditions; displacement	tunnels, foundations, seismically active areas
structural boundaries, folds, intrusions	heterogeneity; local stress concentrations; changes in permeability - water inflows	all rocks/soils
weathering (mass scale)	mass weasening; heterogeneity 9hard in solt martrix); local water inflow, unloading fractures	all rocks and soils close to earth's surface especially in tropical zones; ravelling in disintegrated rock massed
hydrothermal alteration	as for weathering, minerals low strength	generally igneous rocks

Table 5. Examples of environmental factors that should be considered for a project

Factory	Considerations	Examples of rock types/situations
in sity stresses	squeezing, overstressing, rockbursts	mountan slopes and, at depth, shield areas, seismically active areas
natural gases	methane, radon	coal measures, grantiuc, black shales
seismicity	design loading, liquefaction, landslides	seismically active zones; high consequence situation in low seismic zones
influenced by man	unexpectedly weak rocks, collapse structures	undermined areas
	gases and leachate	landfills, industrial areas
ground water	chemical attack on anchors/nails	acidic ground water, salt water
biogenic factors	physical weathering by vegetation; rotted roots leading to piping	near surface slopes weathered rocks
	insect attack	causing tree collopse

Table 6. Examples of the influence of engineering works

Factory	Considerations
loading/unloading static/dynamic	settlement, failure, opening of joints, increased permeability in cut slopes, blast vibrations
change in water table	increased or decreased pressure head, change in effective stress, drawdown leading to settlement, induced seismicity from reservoir loading
denudation or land clearance	increased infiltration, erosion, landsliding

References

Al-Harthi AA & Hencher SR (1993) Modelling stability of the Pen-Y-Clip tunnel, UK. *Safety and Environmental Issues in Rock Engineering, Eurock '93*, Lisbon. Balkema, pp 451-459

Anon (1995) The description and classification of weathered rocks for engineering purposes. Geological Society Engineering Group Working Party Report (Cripps, Hencher, Norbury). *Quarterly Jounal of Engineering Geology*, 28, pp 207-242

Barla G & Jarre P (1993) Tunnelling under an industrial waste landfill in Italy: Environmental controls and excavation procedures. *Safety and Environmental Issues in Rock Engineering, Eurock '93*, Lisbon. Balkema, pp 259-266

Brand EW, Hencher SR & Youdan JD (1983) Rock slope engineering in Hong Kong. *Proceedings of the 5th International Rock Mechanics Congress*, Melbourne, C, pp 17-24

Brown RHA (1999) *The Management of Risk in the Design and Construction of Tunnels*. Korean Geotechnical Society, Tunnel Committee Seminar, 21st Seminar, 21st September, 22 p

Chandler AM (2000) Review of Hong Kong Seismic Parameters and determination of design level earthquake events. Hong Kong Institution of Engineers, *Transactions*, Vol. 7, 1, pp 1-12

Cooper AH & Waltham AC (1999) Photographic feature: Subsidence caused by gypsum dissolution at Ripon, North Yorkshire. *Quarterly Journal of Engineering Geology*, Vol. 32, 4, pp. 305-310

deFreitas MH (1993) Discussion. *Proc. 26th Annual Conf. Engineering Group Geological Society, The Engineering Geology of Weak Rock*, Leeds. Balkema, p 493

Ebuk EJ, Hencher SR & Lumsden AC (1993) The influence of structure on the shearing mechanism of weakly bonded soils. *Proceedings 26th Annual Conference of the Engineering Group of the Geological Society, The Engineering Geology of Weak Rock*, Leeds, pp 207-215

Godfrey PS (1996) *Control of Risk. A Guide to the Systematic Management of Risk from Construction*. CIRIA Special Publication 125, London, 66 p

Halcrow Asia Partnership (1998) *Report on the Ching Cheung Road Landslide. Findings of the Landslide Investigation*. Geotechnical Engineering Office, Hong Kong, 47 p

Halcrow Asia Partnership (1999) Addendum Report on the Geology and Hydrogeology of Slope No. 11NW-A/C55 Ching Cheung Road, unpublished report

Hancock PL (1991) Determining contemporary stress directions from neotectonic joint systems. *Phil. Trans. R. Soc. Land. A*, 337, pp 29-40

Hawkins AB & Pinches GM (1987) Cause and significance of heave at Llandough Hospital, Cardiff – a case history of ground floor heave due to gypsum growth. *Quarterly Journal of Engineering Geology*, Vol 20, 1, pp 41-47

Health And Safety Executive (1985) *The Abbeystead explosion.* London: Her Majesty's Stationery Office

Hencher SR (1994) *Recognising the significance of complex geological conditions.* Tunnelling in Difficult Conditions. *Proceedings, Quinto Ciclo Di Conference di Meccanica E Ingegneria Delle Rocce.* Torino, pp 1-1 to 1-8

Hencher SR (1995) Interpretation of direct shear tests on rock joints. In: Deaman & Schultz (eds) *Proceedings 35th U S Symposim on Rock Mechanics,* Lake Tahoe, pp 99-106

Hencher SR (1996) Geological causes of geotechnical difficulty, reported by A Collins. *Ground Engineering*, 29, no. 3, pp 38-39

Hencher SR (1987) The implications of joints and structures for slope stability. In: (Anderson MG & Richards KS, eds) *Slope Stability - Geotechnical Engineering and Geomorphology.* John Wiley & Sons Ltd, UK, pp 145-186

Hencher SR & Mallard DJ (1989) On the effects of sand grading on driven pile performance. *Proceedings of the International Conference on Piling and Deep Foundations*, London, pp 255-264

Hencher SR & Martin RP (1984) The failure of a cut slope on the Tuen Mun road in Hong Kong. *Proceedings of the International Conference on Case Histories in Geotechnical Engineering*, St Louis, Missouri, 2, pp 683-688

Hencher SR, Massey JB & Brand EW (1985) Application of back analysis to some Hong Kong landslides. *Proceedings of the 4th International Symposium on Landslides*, Toronto 1, pp 631-638

Hencher SR & Richards LR (1989) Laboratory direct shear testing of rock discontinuities. *Ground Engineering*, 22, 2, pp 24-31

Kamewada S, Gi HS, Taniguchi S & Yoneda H (1990) Application of borehole image processing system to survey of tunnel. *Proceedings of the International Symposium on Rock Joints*, Leon, Norway, pp 51-58

Knill JL (1976) *Cow Green revisited.* Inaugural Lecture, Imperial College of Science and Technology, University of London

Maury V (1993) An overview of tunnel, underground excavation and boreholes collapse mechanisms. *Comprehensive Rock Engineering*, Vol 4, (ed. in chief JHudson), Pergamon Press, pp 369-412

Nau PS (1984) Joint system of Hong Kong granite. *Proc Conf Geological Aspects of Site Investigation*, Hong Kong, pp 89-98

New Civil Engineer (1994) *"Heathrow movements went unnoticed"*, 3rd November, p 3

Orr WE, Muir-Wood A, Beaver JL, Ireland RJ & Beagley D (1991) Abbeystead Outfall Works: background to repairs and modifications - and the lessons learned. *Journal of the Institution of Water and Environmental Management*, Vol 5, 7-20

Papaliangas T, Hencher SR, Lumsden AC & Manolopoulou S (1993) The effect of frictional fill thickness on the shear strength of rock discontinuties. *International Journal of Rock Mechanics & Mining Sciences*, Vol 30, No. 2, pp 81-91

Papaliangas T, Hencher SR & Lumsden AC (1996) A comprehensive peak shear strength criterion of rock joints. *Proceedings 8th International Congress ISRM*, Tokyo, 1, pp 356-366

Pollard DD & Aydin A (1988) Progress in understanding jointing over the past century. *Geol Soc America Bulletin*, 100, pp 1181-1204

Rawnsley KD, Hencher R & Lumsden AC (1990) Joint origin as a predictive tool for the estimation of geotechnical properties. *Proceedings of the International Symposium on Rock Joints*, Loen, Norway, pp 91-96

Smith MR & Collis L (eds) 1993 *Aggregates.* Geological Society Engineering Geology Special Publication No. 9, 339 p

Steiner W (1994) Tunnelling in squeezing rocks: case histories. Tunnelling in difficult conditions. *Proceedings, Quinto Ciclo Di Conference di Meccanica E Ingegneria Delle Rocce*, Torino, pp 14-1 to14-8

Talbot DK, Hodkin DL & Ball TK (1997) Radon investigations for tunnelling projects: a case study from St Helier, Jersey. *Quarterly Journal of Engineering Geology*, vol. 30, 2, pp 115-122

Managing Ground Risks

C.M. Tse

Abstract

For many civil engineering projects, the ground is a major source of uncertainty because of geological variability, difficulty in selecting design parameter values or in modelling the problem realistically. These uncertainties pose high risks to project safety and finance. In this paper, the author describes the two extremes of ground risks commonly experienced by geotechnical specialists: Risks associated with ground conditions which deteriorate gradually to their limit states, e.g. ductile soil; and risks associated with ground conditions which could deteriorate rapidly, e.g. brittle soil or the event of landslide debris avalanche. Suitable strategies for managing these two types of risks are discussed in this paper. These strategies involve the use of the observational method (OM) and quantitative risk assessment (QRA) respectively. The merits and limitations of these two techniques are also discussed.

Key Words: ground risks, managing uncertainty, observational method, quantitative risk assessment, gradual failure, rapid failure

Introduction

Fookes (1997) considers that some degrees of uncertainty exist in the geological (and geotechnical) knowledge for any site, because of insufficient data, natural spatial variability, and even changes within engineering time. For simplicity, the author classifies the ground uncertainties commonly experienced by geotechnical specialists (including geologists and geotechnical engineers) into the following categories:

- Geological uncertainty – where there are complex geological and hydrological conditions, the ground may vary unexpectedly between boreholes.

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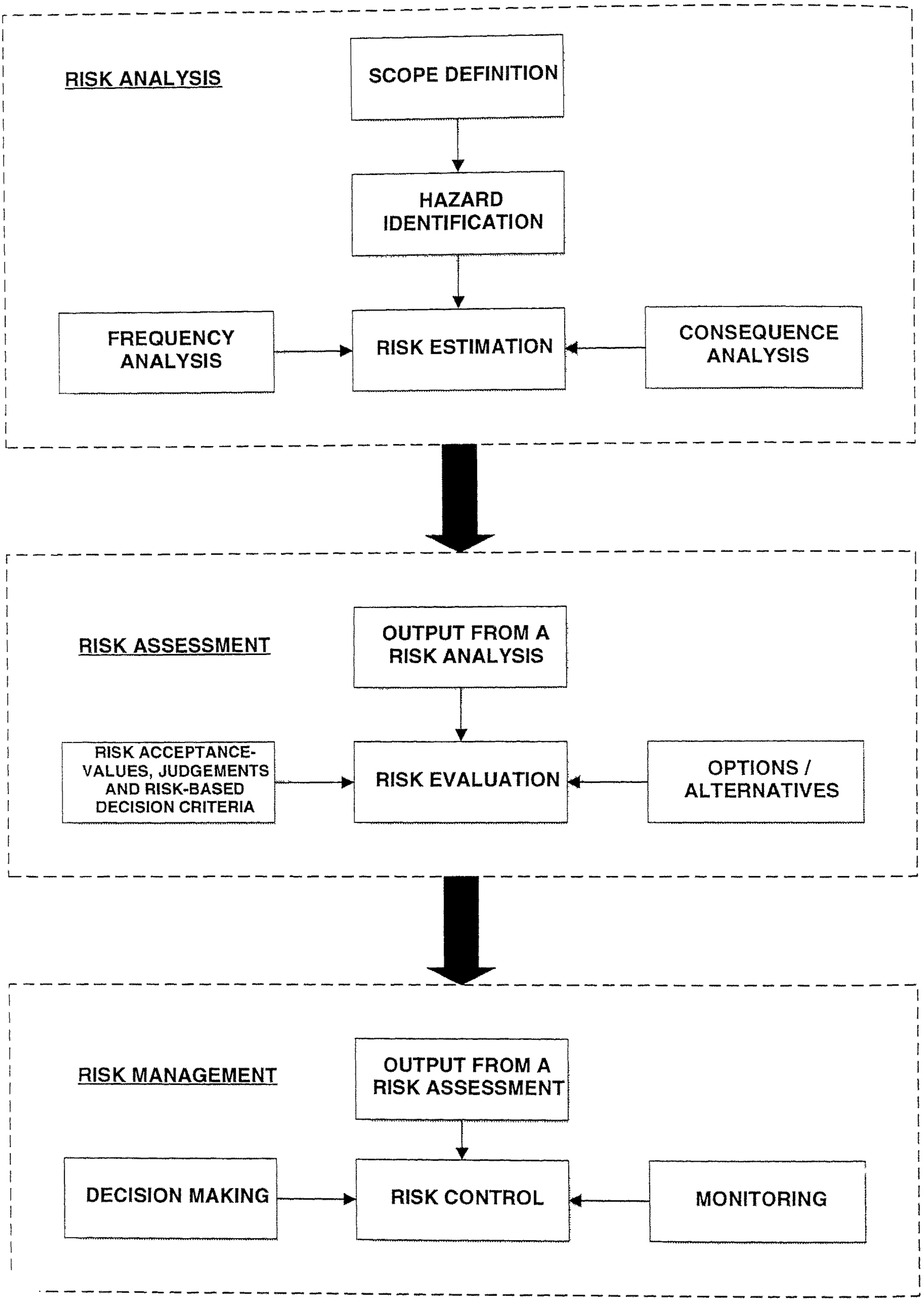

RISK ANALYSIS
SCOPE DEFINITION
HAZARD IDENTIFICATION
FREQUENCY ANALYSIS
RISK ESTIMATION
CONSEQUENCE ANALYSIS
RISK ASSESSMENT
OUTPUT FROM A RISK ANALYSIS
RISK ACCEPTANCE-VALUES, JUDGEMENTS AND RISK-BASED DECISION CRITERIA
RISK EVALUATION
OPTIONS / ALTERNATIVES
RISK MANAGEMENT
OUTPUT FROM A RISK ASSESSMENT
DECISION MAKING
RISK CONTROL
MONITORING

Fig. 1 (facing). Landslide risk management (Fell and Hartford, 1997)

- Parameter uncertainty – uncertainties in knowledge of the ground and modelling its behaviours mean that it may not be possible to assess ground parameters accurately.

- Ground treatment uncertainty – a range of ground treatment techniques has been developed to improve different properties of the ground. However, the effectiveness of a technique needs to be monitored and reviewed during the treatment process and modifications implemented where necessary to meet the specified performance.

These uncertainties can pose high risks to project safety and finance. Peck (1969) refers to a quotation from Terzaghi : 'In facing uncertainties in the ground, two methods have been postulated: either the use of an excessive factor of safety, or else to make assumptions about the ground in accordance with general, average knowledge. The first approach may be wasteful and the second could be dangerous.'

Risk is defined as the combination of the probability of occurrence of an undesired event and the possible extent of that event's consequence. Mathematically, it is expressed as:

$$Risk = Likelihood \leftrightarrow Consequence.$$

It is generally accepted that zero risk scenarios do not exist. Risks, therefore, cannot be 'eliminated' but can be 'managed'. Risk management is the process whereby decisions are made to accept a known or assessed risk and also the implementation of actions to reduce the consequences or probability of risk occurrence. Potential hazards are identified during the planning and design stage of a project, measures are then taken to eliminate the risks if at all practical and the residual risks managed and controlled throughout the project lifetime. Fell and Hartford (1997) present a framework for landslide risk management, shown in Fig. 1.

The Observational Method

The appropriateness of a strategy for managing ground risks largely depends on its ability to 'discover' the onset of the adverse behaviour of the ground, to respond to the hazard in time (by implementing contingency and emergency plans) and consequently to enable the 'recovery' of a normal situation. This concept has been illustrated by the 'discovery-recovery' model shown in Fig. 2 (Health and Safety Executive, 1996).

For ductile soils, the strength deteriorates gradually to the design limit states. A design can then be carried out initially using the 'most probable' ground conditions (ground conditions most likely to occur). In parallel, a contingency plan is prepared for the 'most unfavourable' conditions (worst design conditions which might occur). The performance of the design can then be monitored during construction by instrumentation and the monitoring records are reviewed. As the rate of deformation is relatively slow, there is time after discovery of an adverse situation for the contingency or emergency plan to be implemented. This is in fact the basis of the observational method (OM) described by Peck (1969), who considers that the complete application of the OM embodies the following eight ingredients:

Fig. 2. The discovery-recovery model (HSE, 1996).

Legend

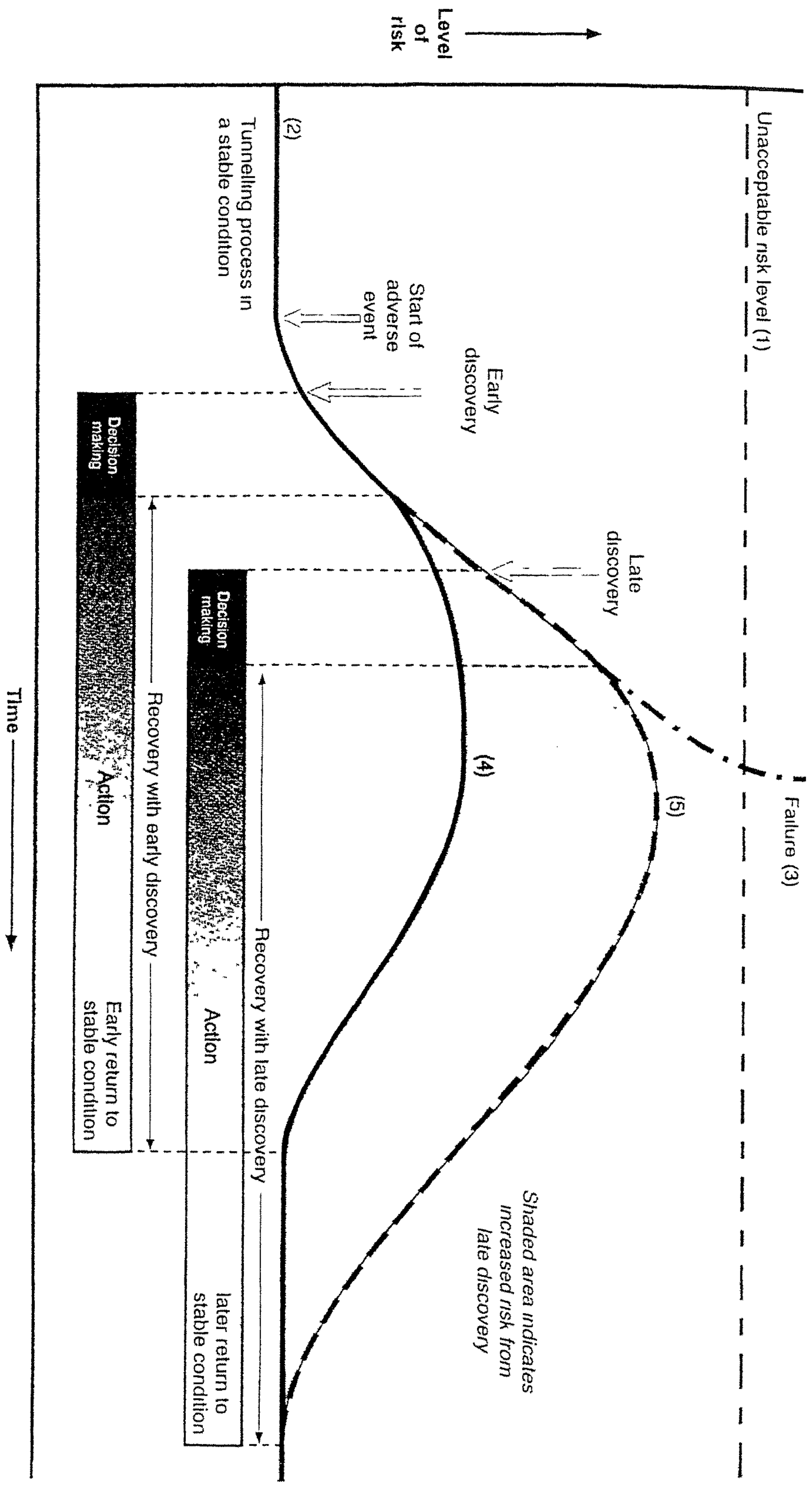
Line (1) indicates the unacceptable risk level

Line (2) is the risk from a tunnelling process that is stable. This risk is well below the threshold of unacceptability

Line (3) shows what happens when increasing risk is not identified until it is too late or no effective action is taken

Line (4) shows what can be achieved where there is early discovery of the adverse event and effective recovery measures are in place through contingency planning

Line (5) shows recovery from an adverse event where discovery was late. This line passes close to and could exceed unacceptable risk levels



(a) Exploration sufficient to establish at least the general nature, pattern and properties of the deposits, but not necessarily in detail.

(b) Assessment of the most probable conditions and the most unfavourable conceivable deviations from these conditions. In this assessment geology often plays a major role.

(c) Establishment of the design based on a working hypothesis of behaviour anticipated under the most probable conditions.

(d) Selection of quantities to be observed as construction proceeds and calculation of their anticipated values on the basis of the working hypothesis.

(e) Calculation of values of the same quantities under the most unfavourable conditions compatible with the available data concerning the subsurface conditions.

(f) Selection in advance of a course of action or modification of design for every foreseeable significant deviation of the observational findings from those predicted on the basis of the working hypothesis.

(g) Measurement of quantities to be observed and evaluation of actual conditions.

(h) Modification of design to suit actual conditions.

The OM has a long history of application in excavation, tunnelling and ground improvement projects. More recently, it has been applied in the field of environmental geotechnics (Morgenstern, 1994). This process of OM has been updated by Nicholson et al. (1997), see Fig. 3. They put emphasis on the need of a definition of the OM and guidelines on its proper use in national design codes. At the corporate level there should be OM-orientated contracts, supported by appropriate specifications. On the basis of policies such as these, the project team will be able to

- achieve economy of design through optimisation of design parameters
- control the risks through a risk-based approach which involves hazard identification, risk assessment and risk control through planned modification
- achieve an equitable sharing of risk, responsibilities and benefits.

Design and construction (including site monitoring) are closely interwoven on OM projects. The OM is an interactive process that binds permanent and temporary works and their designs together. As such, it is important to establish carefully the responsibilities and relationships between organisations and individuals within an organisation or a project team involved in design, construction and monitoring of the work.

In Fig. 3, the trigger criteria are defined as those beyond which contingency measures or emergency measures are implemented. These criteria can be ground conditions, values of forces or movements which can be assessed by calculations or empirical procedures for the range of conditions considered and can subsequently be monitored by instrumentation. Some factors which need to be considered when defining trigger criteria are summarised in Fig. 4.

Trigger criteria are developed from an understanding of the time it

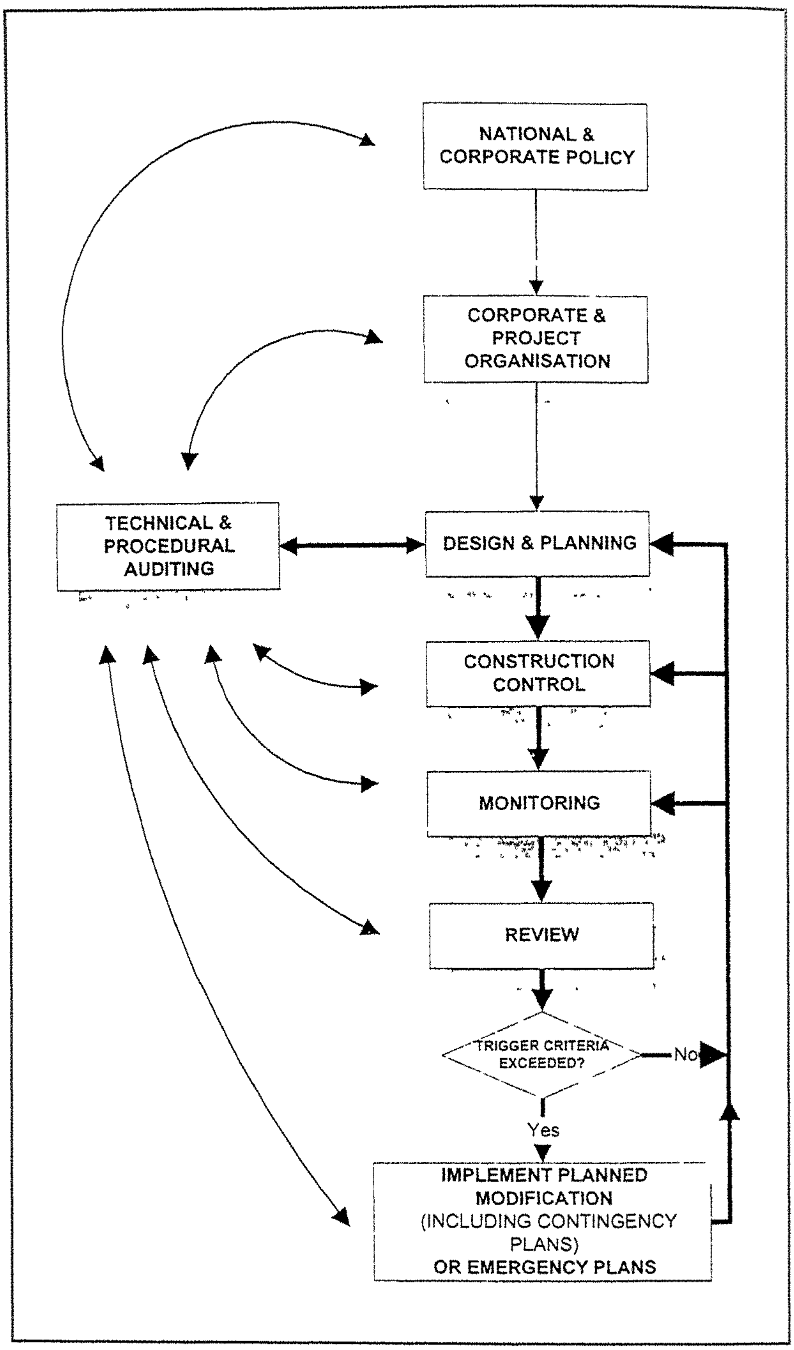


Fig. 3. The observational method (Nicholson et al., 1997)

takes to implement the recovery plan. This includes discovery time, review and decision-making time and the modification implementation time. The time available depends on the rate of deterioration. The OM operates most effectively when conditions deteriorate only gradually to the design limit states. This enables monitoring records to be reviewed so that there is time after discovery for the modification plan to be implemented. For 'greenfield' sites, the serviceability limit and ultimate limit states of the project structures will be the main concern. For projects in built-up areas, the serviceability limit state of adjacent structures will be often impose tighter trigger criteria.

Despite its advantage, the OM should not be used where ground conditions can deteriorate rapidly and there is insufficient time to implement fully, and safely complete, the planned modification or emergency plan. Rapid deterioration of ground conditions can result from the following:

- Brittle soil behaviour - brittle soil behaviour is associated with near constant soil modulus at strains up to the peak strength and a rapid loss of strength with strain past the peak strength. Brittle behaviour often leads to progressive failure. This is associated with the transfer of stress to the adjacent soil, which in turn becomes overstressed leading to progressive and rapid development of an extensive failure.
- Groundwater conditions - examples include (i) rapid pore-pressure increases as a result of heavy rain; (ii) liquefaction of loose saturated soils or where mud flow conditions develop; and (iii) burst water main adjacent to retaining walls.
- Temporary surcharges - temporary surcharges can rapidly apply unexpected loads to a retaining structure or slope.

As such, Nicholson *et al.* (1997) advocate the incorporation of a risk assessment process into the OM. All possible hazards and risks associated with rapid deterioration should be taken into account, starting from the project's inception, including the possibility of 'high consequence-low probability' events. Any limitations imposed by designs and construction sequences and programmes ought to be clearly understood. Safe working methods and contingency and emergency plans should be developed.

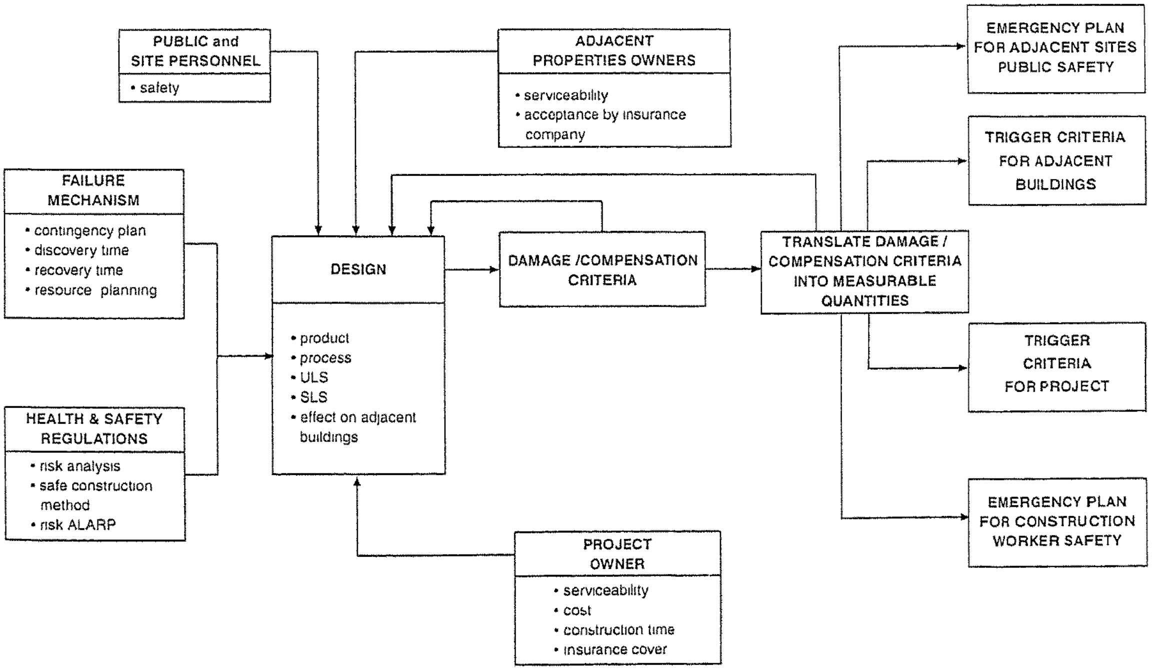


Fig. 4. Defining trigger criteria (Nicholson et al., 1997)

Quantitative Risk Assessment

In the situation of rapid deterioration, there may be no signs of warning prior to failures, e.g. debris avalanche. When such failure occurs, there is practically no time for actions to be taken to recover the 'normal' situation. In this case, it may be more appropriate for the designers to incorporate measures to mitigate the risk associated with the hazards likely to occur during the lifetime of the project. The technique of quantitative risk assessment (QRA) has been used for assisting decision-making for this purpose. The UK Health and Safety Executive (1989) considers that a decision process involving QRA would combine:

(a) quantification of likely risk with an understanding of the inherent uncertainties in this (essentially technical);

(b) reference to the benefits generated by the project and the political and economic considerations associated with it;

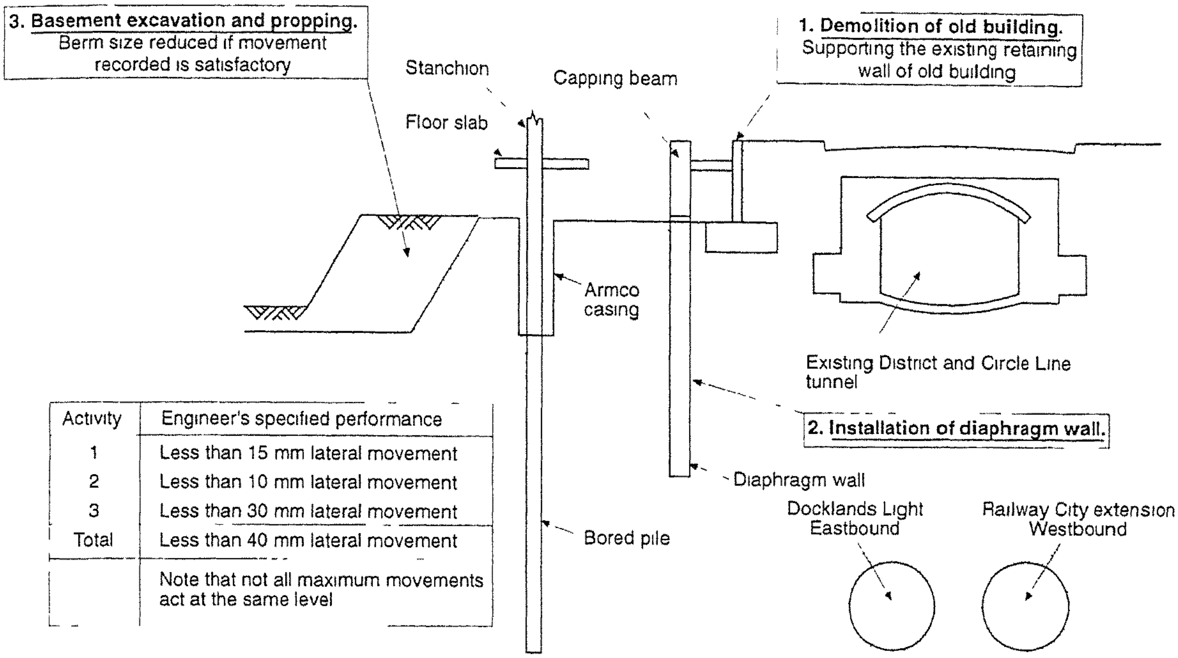
(c) weighing of what might be judged tolerable or intolerable by the public, taking all these considerations into account; and

(d) a decision as to how far risk reduction could reasonably be further attempted, taking cost into account.

Quantitative risk assessment is commonly used to predict the overall risk arising from plant or equipment and to assist in deciding whether the risk is acceptable or tolerable. This is useful for general policy purposes. For example, in Hong Kong there has recently been increasing interest in using a risk-based approach to slope safety management. Table 1 shows the comparison between the conventional 'deterministic approach' and the 'risk-based approach' to slope design (safety assessment).

Table 1. Comparison between deterministic approach and risk-based approach to slope design

	Determainistic Approach	**Risk-based Approach**
Application	This approach calculates the factor of safety for assumed slip surfaces using limit equilibrium methods	this aroach requires the caculation of risk, the making of a decision on whether the risk level is tolerable and if is is not, the taking o action to controal, prevent or reduce failures, weighing cost, including non-financial cost and benefit
Inout Requirements	Best estimated of - ground conditions - strength parameter	Detemination of - hazard - like hihood of occurrence - consequence assessment
Decision Process	the critical slip surface and minimum factor of safety can then be detemined for any slope geometry and the acceptability of design is decided by comoparison of the calculated factor with an acceptable design value	the individual risk and societal risk values are compared to risk acceptance criteria
Acceotabce Cruterua	- for man-made slopes in Hong Kong, GEO Geotechnical Manual for Slopes - None exists for natural slopes	ERM (1998) risk guidelines (for consultation)



Activity	Engineer's specified performance
1	Less than 15 mm lateral movement
2	Less than 10 mm lateral movement
3	Less than 30 mm lateral movement
Total	Less than 40 mm lateral movement
	Note that not all maximum movements act at the same level

Fig. 5. Example of use of the observational method (Tse and Nicholson, 1992). Details of the superstructure not shown

However, it should be noted that QRA is not a *design* tool. It does not (and cannot) replace a proper geotechnical assessment. It does, however, indicate where risk can be reduced. It is also advisable not to rely solely on the results of QRA to determine a decision. This is because there are bound to be omissions and uncertainties in the estimation of parameters involving human behaviour, social attitudes and ground properties. For example, when assessing natural terrain landslide hazards, it is important to supplement the QRA with a detailed assessment of the geomorphology and geology of the site through desk studies, site investigations and field reconnaissance.

Example 1: Risk Management using the Observational Method (after Tse & Nicholson, 1992)

A 9 m-deep basement was formed using a 0.8 m-thick diaphragm wall. About 5 m from one side of the deep basement is an underground tunnel, see Fig. 5. The basement was constructed using a semi top-down construction technique. An earth berm was left to support the retaining wall. Concern was raised about possible movements on the side of the basement adjacent to the tunnel. The following procedures were adopted in the implementation of the OM:

- The allowable movements of the tunnels were agreed between the owners of the deep basement and the tunnels.
- The behaviour of the ground and the diaphragm walls were estimated using analytical methods. The trigger criteria were defined.
- Two berm sizes were designed: A small berm for the 'most probable' ground condition and a large berm for the 'most unfavourable' ground condition.
- Ground movements were measured at an agreed frequency by inclinometers

and extensometers, and by surveying. In-tunnel surveys were also made.

- Construction of the basement proceeded with the excavation to the 'large' berm initially. The cumulative movement at the end of this stage was about 10 mm, which was significantly less than the specified criteria. This gave confidence to the contractor to trim the berm progressively to the 'small' berm.
- The contingency plan was to backfill the berm to its original size in case of large movements.
- The measured wall movement at the end of the excavation of the small berm was about 13 mm and the contingency measured was not required.

Example 2: Risk Management using Quantitative Risk Assessment (after Chiu et al., 1998)

A housing development was proposed for construction adjacent to a natural slope. Like the majority of landslides in Hong Kong, previous landslides at this natural slope occurred in residual soil or weathered rock. These materials form steep slopes, as a result of true cohesion inherent to rock masses or apparent cohesion resulting from negative pore-pressures in partly saturated soil. On failure, either type of cohesion is overcome and major strength decrease occurs. In this project, the engineers used quantitative risk assessment (QRA) for estimating the landslide risk. QRA indicates that the risk level at the periphery of the site is marginally above the Government's safety criteria. It was then decided that a defensive barrier, in the form of an L-shaped retaining wall, should be erected at the site boundary (Fig. 6). Figure 7 shows the QRA process adopted, comprising the following tasks:

(a) Hazard identification - the landslide hazards were identified and documented in a landslide catalogue by aerial photograph interpretation (API), site mapping, brainstorming and other techniques. This has been described in detail elsewhere (Li and Tse, 1998).

(b) Frequency estimation - the likelihood of sliding, expressed in terms of the number of landslides of a certain characteristic that may occur in a study area per year, was identified.

(c) Consequence analysis - the number of potential fatalities and the amount of potential damage to facilities were estimated. This involved population distribution and temporal movements surveys, estimation of landslide debris travel distance and estimation of the vulnerability of the affected facilities and residential areas.

(d) Risk analysis - the likelihood and consequence of each hazard were combined to estimate the risk corresponding to that hazard. Both 'individual risk' (risk to anybody living at a defined radius from the hazard) and 'societal risk' (risk to a population) were considered.

(e) Sensitivity analysis - sensitivity analyses could be conducted by varying the values of the key parameters, including frequency, hazard intensity and consequence.

(f) Comparison of risk levels with safety criteria - the Hong Kong Government (1994) has set risk guidelines for potentially hazardous installations (PHI)

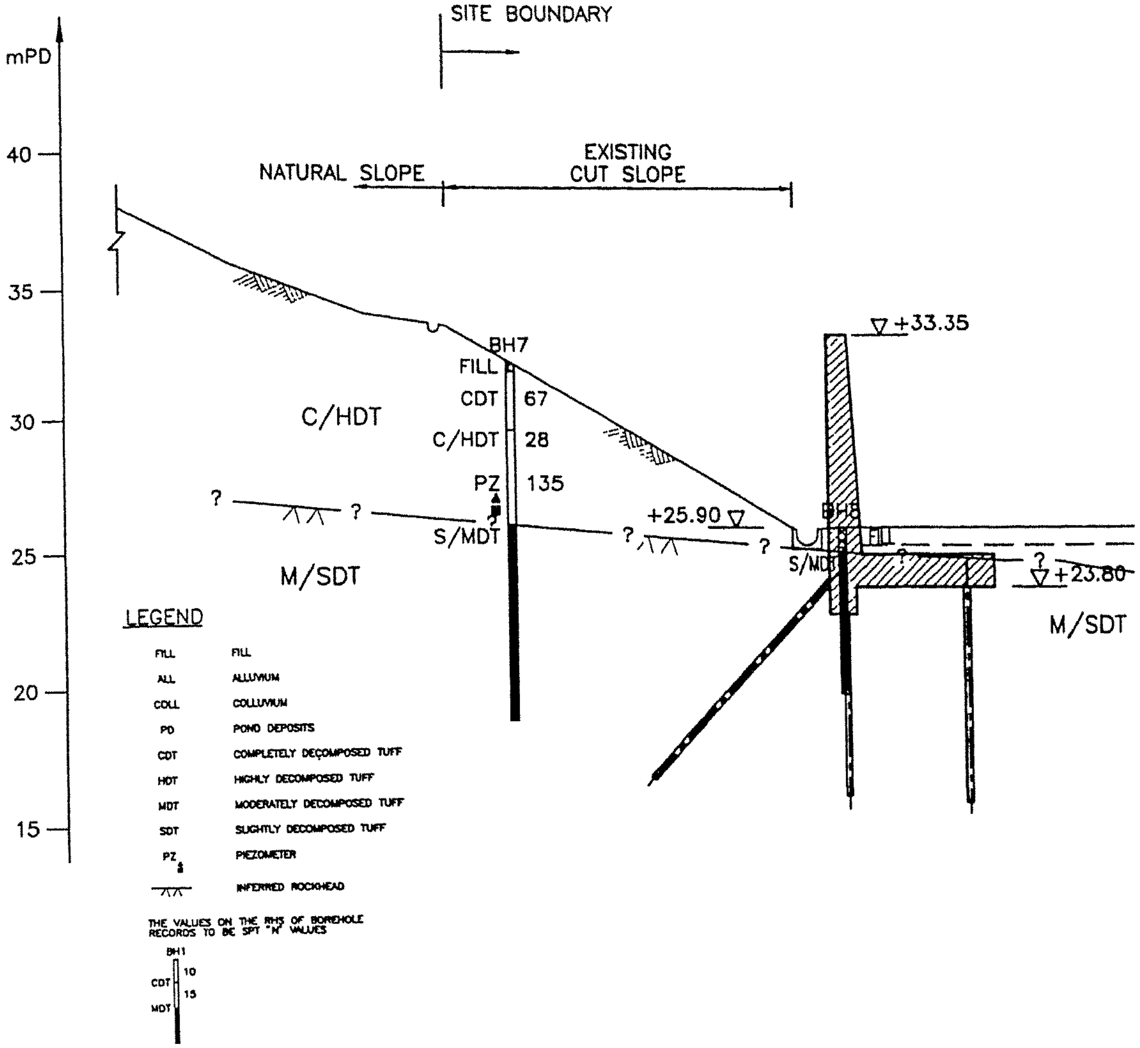


Fig. 6. A landslide hazard mitigation measure design based on quantitative risk assessment (Chiu et al., 1998)

involving the storage or process of toxic or flammable substances, and are used in the decision of land use purposes around the PHIs. More recently, the consultant ERM has been commissioned by the Geotechnical Engineering Office (GEO) to develop risk guidelines for landslides and boulder falls from natural terrain in Hong Kong (ERM, 1998).

(g) Cost benefit analysis - by using a common factor, such as money, the cost-effectiveness of various mitigation measures can be compared. This requires all costs and benefits to be evaluated in terms of money, including human life, injury or disability, damage to plant and machinery, and operational delay.

(h) Recommendation of mitigation measures - in designing the risk mitigation measures, the adopted 'design event magnitude' was based on an extreme design situation. In this case, it is the maximum amount of landslide debris likely to be transported downslope during the lifetime of the housing development.

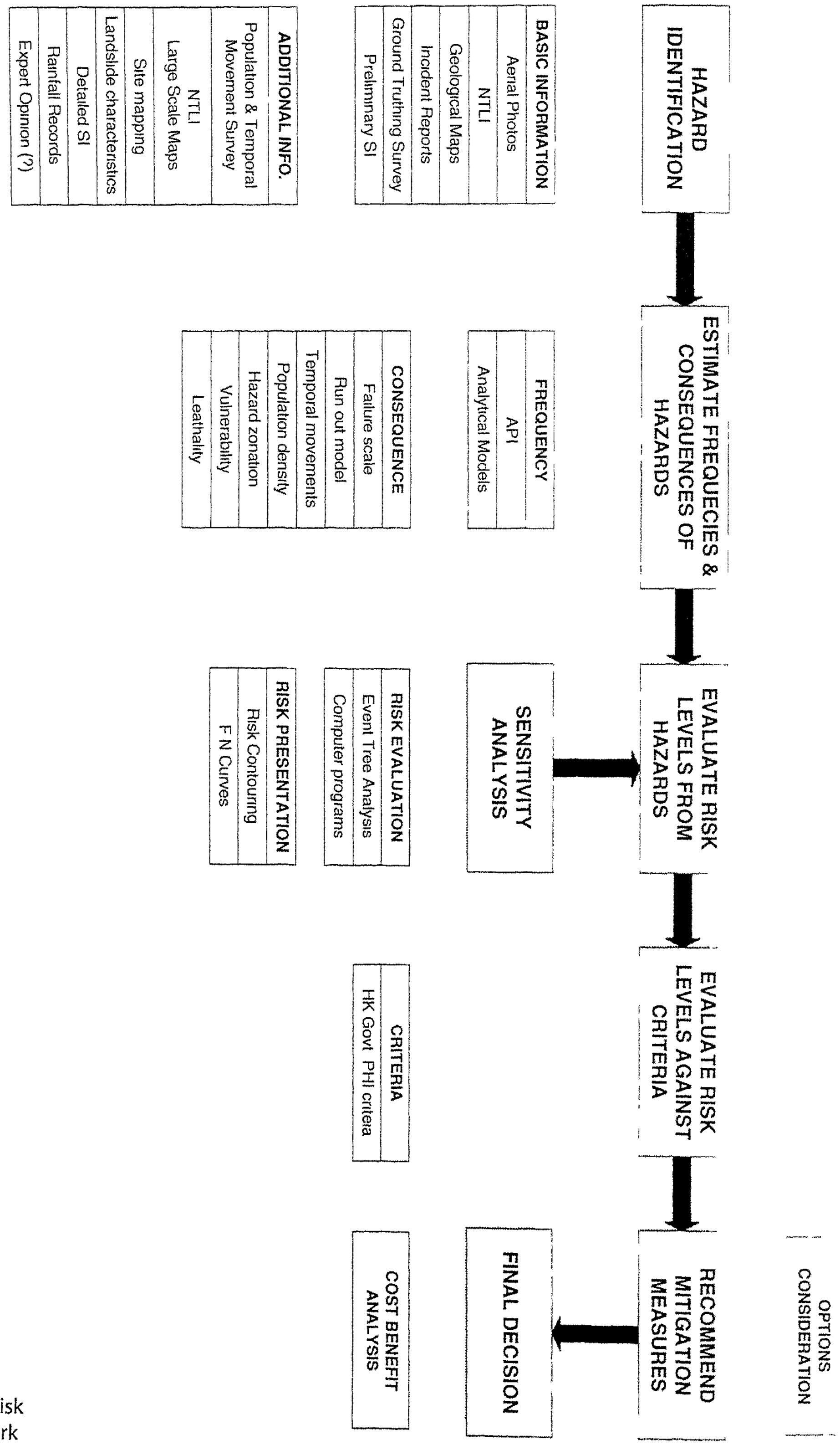


Fig. 7. Quantitative risk assessment framework

Conclusions

The two techniques described above represent the extremes of the range of strategies normally adopted for managing ground risks. The observational method (OM) is used for managing risks associated with hazards which can be monitored and in situations where sufficient time is available for responding to the risks associated with the hazards. Based on the review of the monitoring records, the design can be modified to suit the actual site conditions. However, for risks associated with failures which occur rapidly without warning, the OM is not applicable. It is more appropriate for the designer to consider the reduction of the risk (either the likelihood or the consequence) to as low as reasonably practicable through the use of mitigation measures, and quantitative risk assessment (QRA) provides a methodology.

References

Chiu SL, Tse CM, Chun KM & Cheng LF (1998) The use of retaining structures as natural terrain hazards mitigation measures. *ICE International Conference on Urban Ground Engineering*, November 1998, Hong Kong. In press

ERM (1998) *Landslides and Boulder Falls from Natural Terrain: Risk Guidelines.* Reference GEO 4/97; ERM C1643

Fell R & Hartford D (1997) Landslide risk management. In: Cruden & Fell (eds) *Landslide Risk Assessment.* Balkema, Rotterdam, pp 51-107

Fookes PG (1997) Geology for engineers: the geological model, prediction and performance. The first Glossop Lecture. *Quarterly Journal of Engineering Geology*, 30, (4), November 1997, pp293-424

Health and Safety Executive (1989) *Quantified risk assessment: Its input to decision making.* HSE Books, Suffolk, England

Health and Safety Executive (1996) *Safety of New Austrian Tunnelling Method (NATM) tunnels. A review of sprayed concrete lined tunnels with particular reference to London clay.* HSE Books, Suffolk, England

Hong Kong Government Planning Department (1994) Chapter 11: Potentially hazardous installations. In: *Hong Kong Planning Standards and Guidelines.* Hong Kong Government, Hong Kong, pp12-19

Li D & Tse CM (1998) Natural terrain landslide hazard identification. Pre-prints of *Proceedings of One Day Seminar on Planning, Design and Implementation of Debris Flow and Rockfall Hazards Mitigation Measures*, October 1998, Hong Kong

Morgenstern NR (1994) The observational method in environmental geotechnics. In: *Proceedings of 1st International Conference on Environmental Geotechnics*, Alberta, Canada, pp 965-976

Nicholson DP, Tse CM & Penny C (1997) CIRIA project RP527 report: *The Observational Method in Ground Engineering - Principles and Applications*. Construction Industry Research and Information Association (CIRIA), London 1997

Peck RB (1969) Advantages and limitations of the observational method in applied soil mechanics. *Géotechnique*, 19, (2), pp 171-187

Tse CM & Nicholson DP (1992) The design, construction and monitoring of the basement diaphragm wall at Minster Court, London. *ICE International Conference on Retaining Structures*, Cambridge, July 1992

Scarp Morphology and Development Associated with a Large Retrogressive Compound Landslide at Lai Ping Road, Hong Kong

N.P. Koor[1], S.D.G. Campbell, H.W. Sun and K.K.S. Ho

Abstract

This paper briefly describes and interprets the morphology of scarps associated with a large, slow moving, retrogressive, compound landslide that affected a 40 m-high cut slope at Lai Ping Road, near Sha Tin, in the northeast of Hong Kong. The cut slope failed after intense rainfall on 2 July 1997, and five discrete landslides occurred, with a combined volume of about 4000 m^3. A portion of the relatively mobile debris impacted with a covered service reservoir but no major damage resulted. Surface ground deformation extends up to 50 m into the quasi-natural terrain above the cut slope. This is bounded by a main scarp, up to 4 m high, which indicates the presence of a failed mass with an estimated volume of up to 100 000 m^3. Surface mapping has revealed numerous scarps and tension cracks within the confines of the main scarp. These scarps are of differing ages and structural morphotypes, including horsts, grabens, *en echelon* arrays and duplexes. The scarps and tension cracks were influenced in their development by the relict joint structure, depth of weathering and hydrogeology of the slope. It is established that the slope has had a history of spasmodic, deep-seated deformation dating back to the initial formation of the cut slope in 1978.

Key words: landslide, deep seated, retrogressive, compound, scarps, joints, weathering depth, hydrogeolgy, Sha Tin, Hong Kong.

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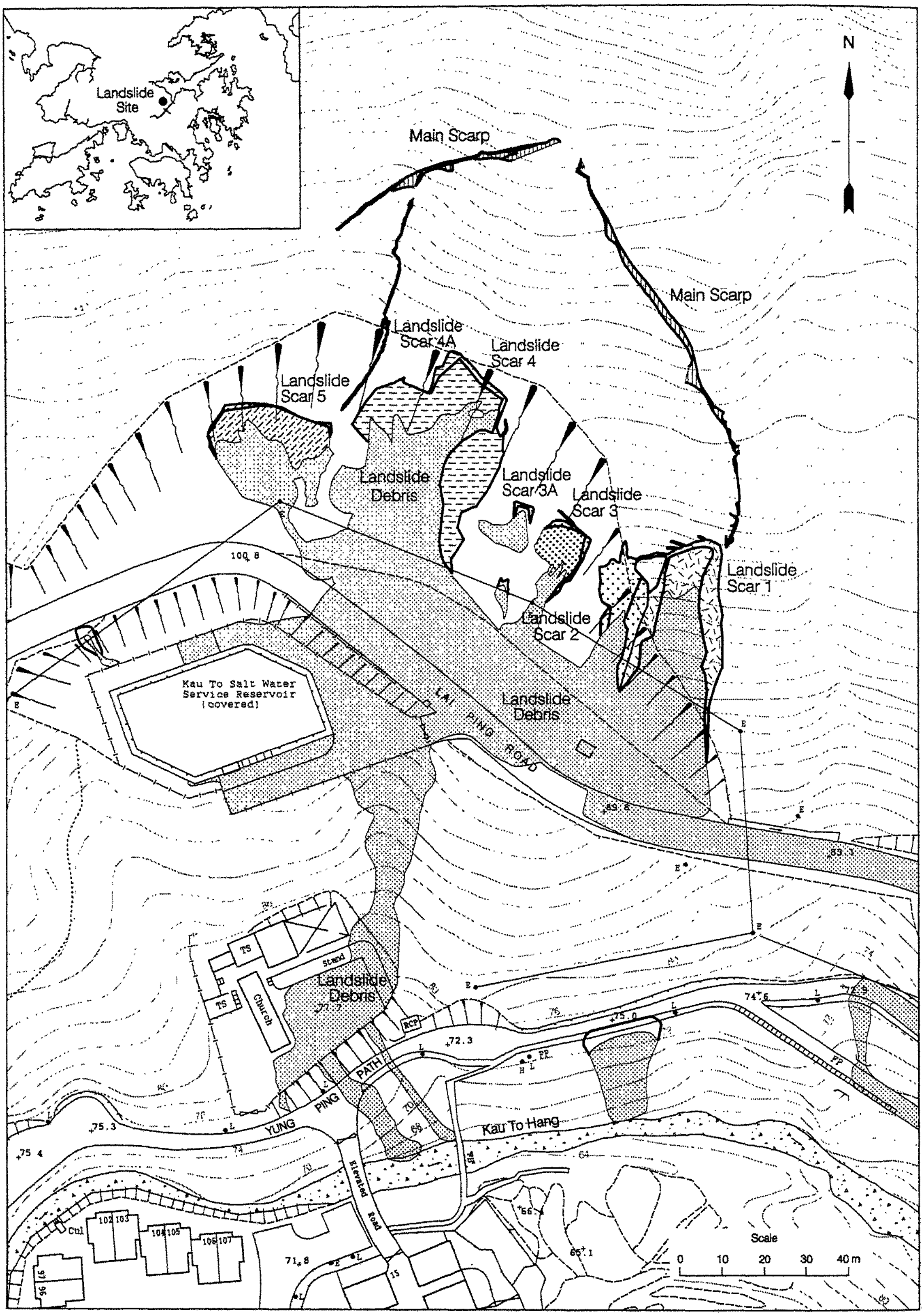
Landslide Site
N
Main Scarp
Main Scarp
Landslide Scar 4A
Landslide Scar 4
Landslide Scar 5
Landslide Debris
Landslide Scar 3A
Landslide Scar 3
Landslide Scar 1
Landslide Scar 2
100.8
Kau To Salt Water Service Reservoir (covered)
LAI PING ROAD
Landslide Debris
83.8
83.1
TS
TS
Church
stand
Landslide Debris
RCP
72.3
75.0
74.6
72.9
YUNG PING PATH
Kau To Hang
Elevated Road
75.3
75.4
102
103
104
105
106
107
97
96
Cul
71.8
66.1
65.1
Scale
0
10
20
30
40 m

Introduction

Fig. 1 (facing). Plan of the landslide

On 2 July 1997, a landslide occurred on a roadside cut slope (No. 7NE-C/C95) on Lai Ping Road, Kau To Shan, Sha Tin (Fig. 1), in the northeast of Hong Kong. The landslide comprised several discrete failures with a total volume of about 4000 m^3. These occurred along a 135 m-long section of the cut slope and the debris completely blocked Lai Ping Road (Fig. 1). There were no casualties and damage was limited. However, during the initial site reconnaissance, a major scarp, extending up to 50 m above the cut slope, was identified in the densely vegetated quasi-natural terrain, which slopes at c.26°. This indicated the presence of a much larger volume, deep-seated landslide, the identification of which led the Geotechnical Engineering Office (GEO) to instigate a comprehensive investigation to study the mechanisms and causes of the failure. The investigation included:

- detailed desk study including a review of documentation and rainfall analysis,
- geomorphological and geological mapping (scale 1:200) of the landslide site and its environs,
- photogrammetric analysis of aerial photographs,
- comprehensive ground investigation,
- seepage and stability analyses and finite difference modelling, and
- diagnosis of the probable causes and mechanisms of failure.

This paper concentrates on the morphology and interpretation of the scarps associated with the landslide, and considers their geological controls. Other findings of the landslide are described in two comprehensive reports (Koor and Campbell, 1998; Sun and Campbell, 1998).

Scarp Morphology

A series of scarps are present on the quasi-natural hillside above the cut slope, and in landslide scars 1 to 5 (Fig. 1). The scarps are interpreted as surfaces of rupture, which have varying degrees of vertical and lateral movement. There are, in addition, open tension cracks, with no significant differential vertical displacement.

A detailed map of the scarp morphology is shown in Fig. 2. The scarps were mapped, prior to a comprehensive topographic survey of the landslide site, with reference to a series of base stations established by a Global Positioning Satellite (GPS) system, accurate to within 0.5 m horizontally and 1 m vertically. Further known points were then added using tape and compass surveying between the GPS base stations. This enabled a relatively accurate base map of the scarps to be compiled rapidly, despite the relatively thick vegetation cover.

The main scarp of the system, marking the apparent up-slope limit of the deformation, extends to a maximum elevation of +156.6 mPD (Fig. 1). The scarps are typically steep (>50°) and have differential vertical offsets of up to 3.8 m (Fig. 3) and horizontal extensions of up to 4.2 m. Most scarps dip directly or obliquely down-slope (south-southeast or southwest), consistent

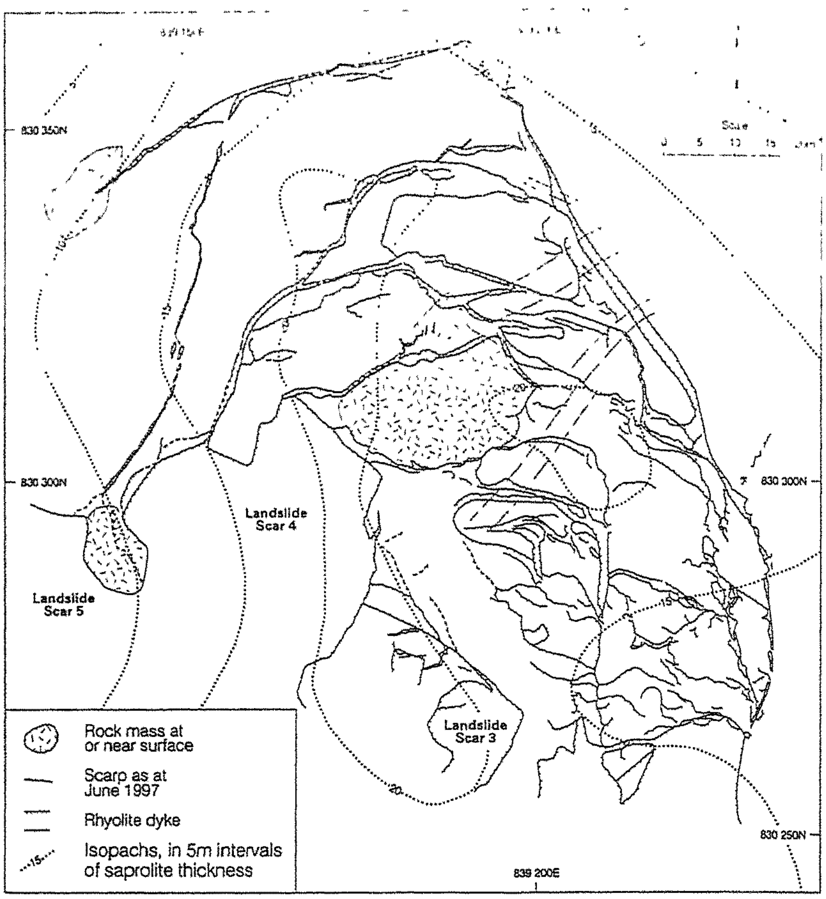

Fig. 2. Landslide scarps, general surface geology and saprolite thickness in the area above the cut slope, July 1997

with the down-slope mass movement. However, a few scars dip up-slope. Some of these are the down-slope margins of extensional grabens. Others reflect locally generated compression, i.e. heave, within the moving mass, or minor toppling failure. Individual scarps extend laterally for up to 100 m, and in plan (Fig. 2) the array of scarps displays a wide range of forms. They vary from curvilinear to rectilinear segments, and include:

(i) bifurcations,

(ii) conjugate shear sets,

(iii) left- and right-stepping *en echelon* arrays,

(iv) S- and Z-shaped inflections,

(v) duplexes, and

(vi) other complex movement transfer zones.

Segments nearer the cut slope are generally shorter (typically <8 m long) than those further up-slope (Fig. 2) and are generally considered to be older features. Most were not activated during the recent slope movements. Their comparatively short strike lengths partly reflect their truncation by younger scarps of different orientation.

There is a relatively regular spacing of the scarps. First order scarps, that can be traced laterally for several tens of metres, are typically about 15 m apart, whereas second order features, that can be traced laterally for up to about 20 m are approximately 7 to 8 m apart. The regular spacing of the first and second order scarps may be controlled either by the spacing of major joints within the rock mass, or by the thickness of the saprolite.

The morphology of the main and minor scarps, and particularly the presence of the steep main scarp, grabens and possible local compressional features, suggests that the large area of deformation can be classified as a compound slide. Compound slides are characterised by markedly non-circular slip surfaces formed by a combination of a steep, curved or planar rearward part and a flatter sole (Hutchinson, 1988). They generally reflect the heterogeneity of a slope, often a weak layer or a boundary between weathered and unweathered rock.

Geological influences on scarp development

Relict Joints

Locally, the scarps follow relict joint surfaces, but generally no such structural control can be observed at ground level. However, deeper-seated structural control of the orientation of the scarps can be inferred if the dip directions of linear segments of the scarps and those of the dominant joint sets are compared.

The main joints sets observed within the scarps and landslide scars 1 to 5 have dip and dip directions of 49°/198° and 86°/098°. Minor joint sets dip towards 28°/001° and 75°/207°. Therefore, all but the northerly-dipping minor joint set appear to have exerted some control on the orientation of main and minor scarp sets.

The main joints sets are generally medium to closely spaced, and are often smooth or slickensided, undulose, and very narrow to tight. They are commonly coated or infilled with manganiferous deposits, limonite, and white or buff kaolin. Locally, and most notably in landslide scar 5 with respect to southwesterly-dipping joints, kaolin-coated or infilled joints have acted as basal surfaces of rupture. Also, within landslide scar 4, subvertical northerly-striking joints have acted as lateral release surfaces. A sheeting joint set, dipping at a low angle parallel to the original natural terrain slope surface was not identified.

Lithology

The main lithology on the site is a grey to bluish-grey, sparsely lapilli-bearing coarse ash crystal tuff, varying to a lapilli ash and locally ash-lapilli tuff. This is consistent with the regional geology shown on the published map of the area (GCO, 1986) which indicates that the tuff is of Jurassic age, despite the fact that it was not assigned to any formation. The tuff exhibits a discontinuous compactional fabric and preferred alignment of lithic clasts and crystals. These indicate a weak stratification that typically dips to the north-northeast, into the hillside, at angles of between 25° and 40°. Although some scarps have a similar strike to the

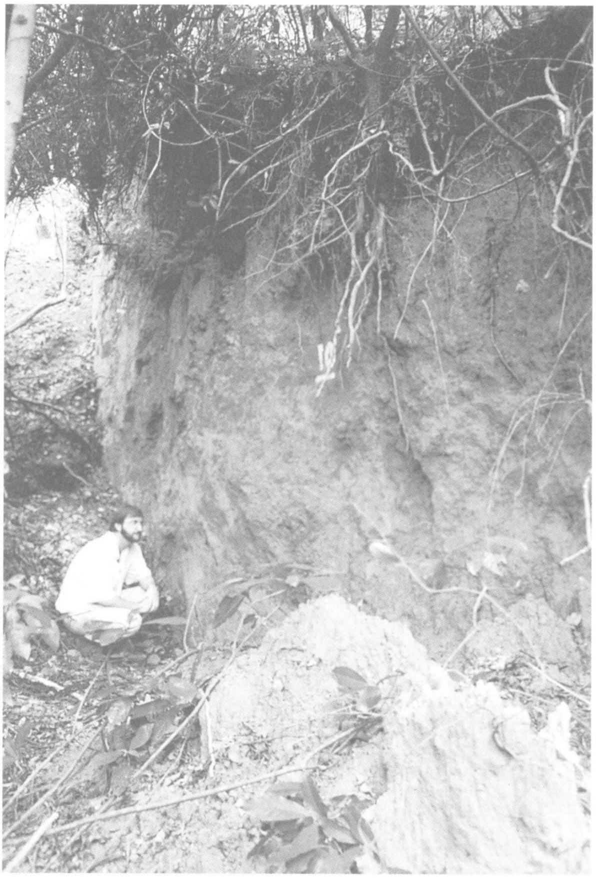

Fig. 3. Main scarp, vertical displacement at this point is 3.8 m (taken 26 September 1997)

stratification, it appears not to have influenced their development.

Aphyric and quartzphyric variably flow-banded rhyolite dykes, up to 4 m wide, can be traced laterally for up to 20 m (Figs. 1 and 2). They occupy several orientations including: steeply dipping (74° to 88°) to the southeast or south-southeast; steeply dipping (62°) to the south-southwest; and moderately inclined (30° to 45°) to the north-northeast. The similarity between the orientations of the two steeply dipping dyke sets and some scarps suggests that the dykes may locally control scarp development. However, there is little evidence of this in the exposed scarps.

Saprolite Thickness

Extensive ground investigation has established that the saprolite thickness across the landslide site is typically 15 to 24 m thick (Koor and Campbell, 1998) but is markedly thinner on the western side of the site (Fig. 2). The ground investigation has also provided evidence of rupture relatively close to the interface between saprolite and rock. Hence, the total volume of the landslide can be estimated as approximately 100 000 m^3. The saprolite thickness may have influenced the extent of the surface deformation, as the main scarp closely follows the 15 m saprolite thickness isopach (Fig. 2).

Cruden (1991) proposed a method for determining the depth of

Fig. 4. A large 1.5 m wide soil pipe at the old colluvium/ new colluvium interface exposed in the main scarp of Landslide Scar 5 - note slight seepage (taken 7 July 1997)

Fig. 5. Close-up of soil pipe in Fig. 4 with heavy flow following recent rainstorm (taken 9 September 1997)

surfaces of rupture of non-circular, translational landslides in clay, based on the width of grabens at surface. For the landslides he studied, a simple ratio of 1.1 times the graben width correlates well with the known depth to the surface of rupture. The observed distance between first order scarps (c.15 m) at Lai Ping Road may therefore be a function of the depth to the surface of rupture. Using Cruden's multiplier of 1.1, a surface of rupture would be predicted at about 16.5 m depth, which is consistent with observations, made during ground investigation, of rupture close to the base of the saprolite.

Fig. 6. Main scarp showing vegetation line indicating at least two phases of movement together with old and recent slickensides on the scarp surface and a rhyolite dyke contact (taken 26 September 1997)

Hydrogeology

Major seepage was observed in landslide scars 1 to 5, and ground investigation provided further evidence of the local groundwater regime.

Soil pipes (0.02 to 1.5 m wide and up to 0.5 m high, Figure 4) are developed at several locations within the main scarp of landslide scar 5. Persistent groundwater flow was noted from several of these pipes after heavy rain (Fig. 5). Site photographs indicate that two of the largest pipes have been present, and actively seeping, for at least 18 years. The soil pipes occur most notably towards the base of colluvium, of which there are two units, with a maximum total thickness of 4 m, exposed in the main scarp of landslide scar 5. Significant thicknesses of colluvium (c. >1 m) are largely restricted to landslide scar 5 (Fig. 1) and the area above it, extending to and beyond the main scarp. Soil pipes have also been observed in Mazier samples, especially those taken close to the base of the saprolite where rupture has also been interpreted.

Minor rhyolitic dykes, of which there are a few at the landslide site, may act as natural dams to ground water flow downslope, causing elevated pore water pressures. However, the discontinuous nature of the dykes suggests any damming effect is likely to be of local significance only.

Rock Mass Weathering, Decomposition Grades and Strength

The rock mass weathering has influenced the mode of failure of the cut slope, and hence the form of the scarps of landslide scars 1-5. Where highly decomposed and completely decomposed tuff and residual soil are predominant,

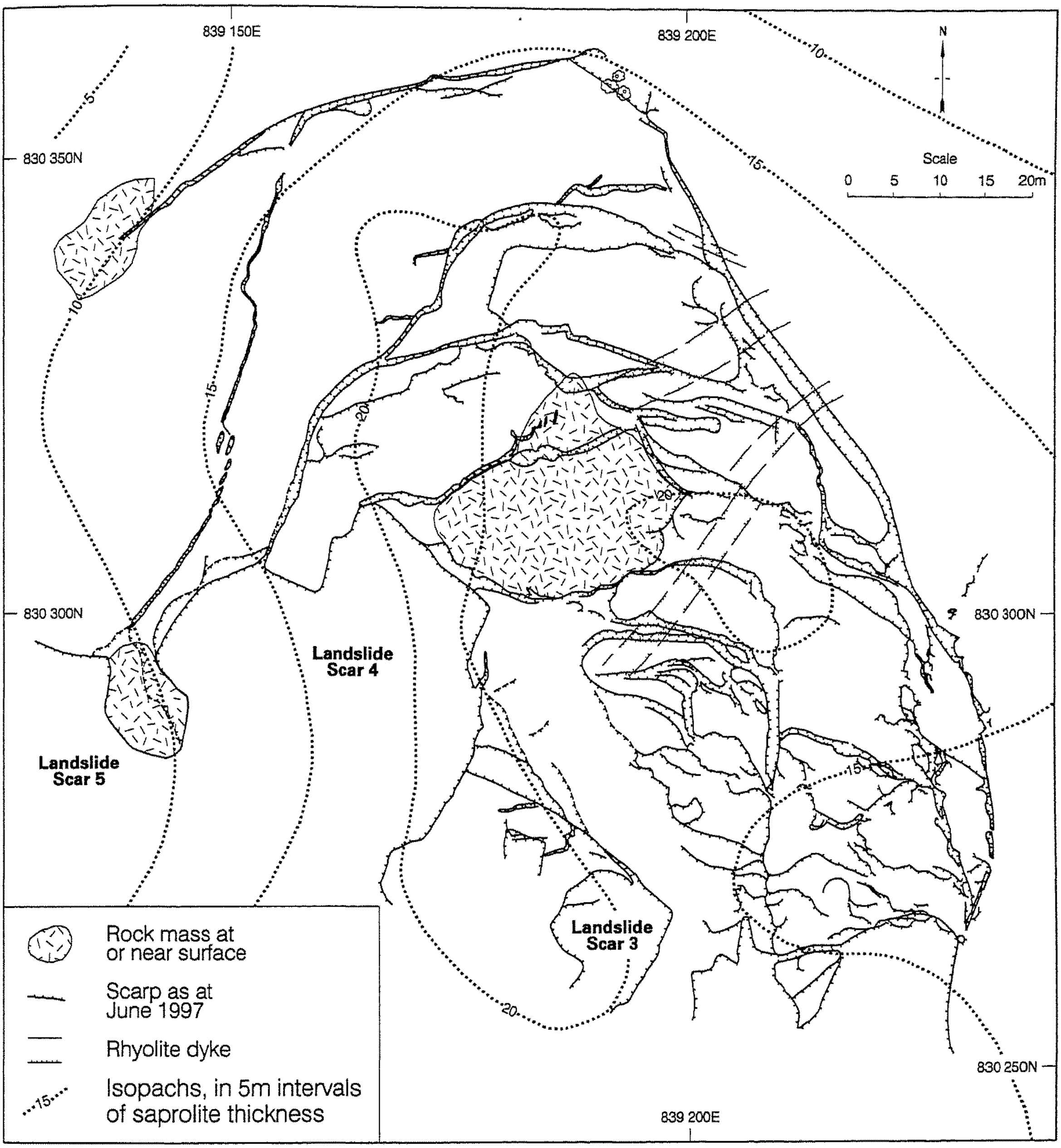

Fig. 7. Composite landslide displacement model, pre-October 1979

as in PW0/30 zones exposed in the scarps of landslide scars 1, 2, 3 and 4A, composite translational slides and gully erosion are typical. However, where rock content was higher, and discontinuities affected the mass strength, as in landslide scar 4, planar rock and soil slides occurred (landslide scars 4A and 5).

Scarp Evolution

Site observations clearly indicate movement predating the most recent phase of failure on and after 2 July 1997. The scarps formed recently lack vegetation and contrast markedly with older vegetated scarps. In some instances, the

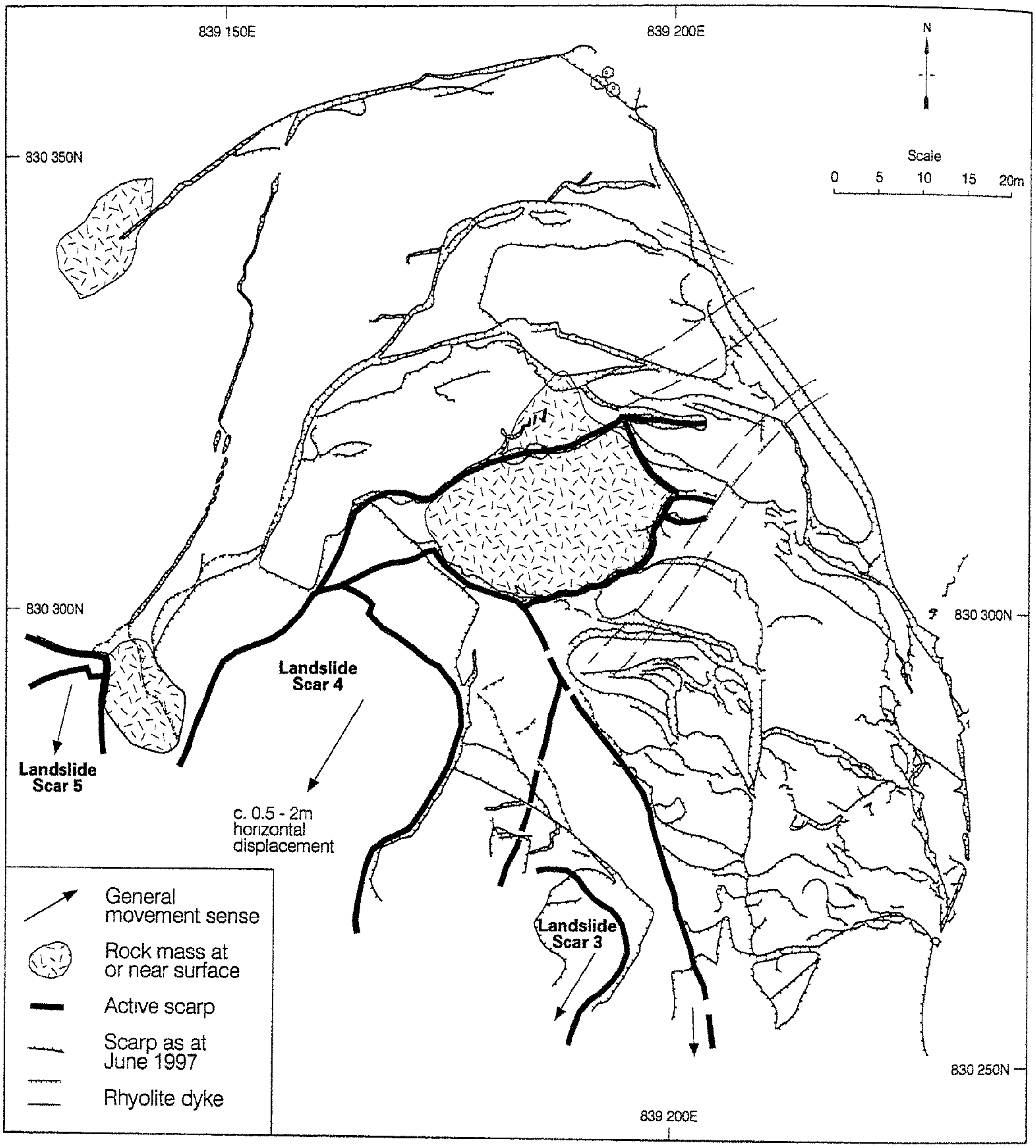

Fig. 8. Composite landslide displacement model 1983-1987, including further activity prior to July 1997

uppermost parts of some scarps have a coating of vegetation (moss, ferns etc.), whereas the lower parts, formed during the most recent activity, are bare. The interface between the vegetated and non-vegetated portions of the scarps is typically abrupt. This indicates recent reactivation of a pre-existing scarp (Fig. 6). Occasionally, it was possible to measure slickensides related to both recent and older phases of movement on the same scarp (Fig. 6). However, the older scarps have generally been eroded to the extent that slickensides are poorly preserved or absent.

Using a combination of evidence derived from detailed site observations, photogrammetry and aerial photograph interpretation, and dendrochronology

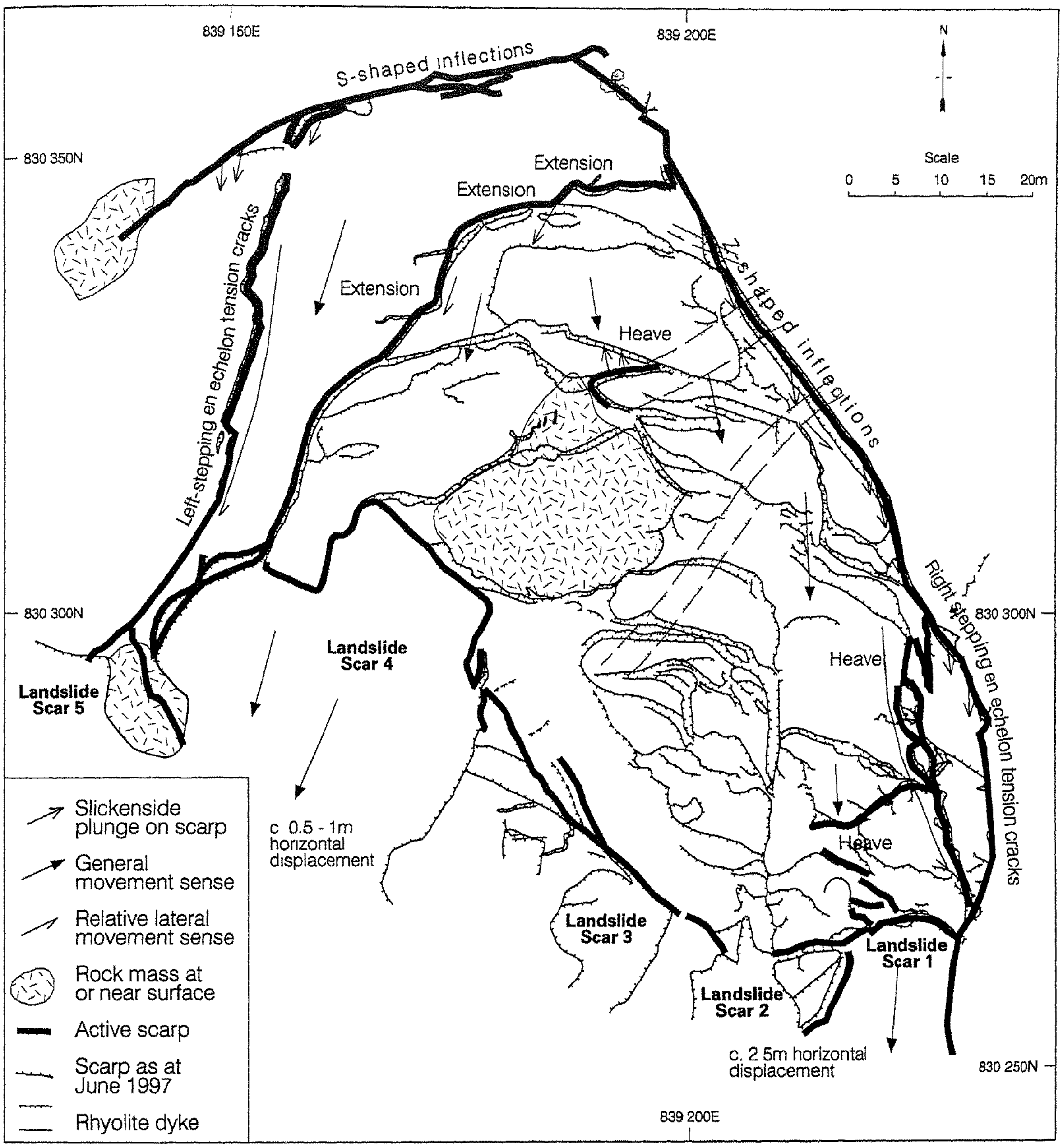

Fig. 9. Composite landslide displacement model, July 1997

(Koor and Campbell, 1998), it has been possible to establish a history of landslide evolution since the formation of the cut slope in 1978 (Figs. 7-9, overleaf) which demonstrates the retrogressive history of the slope failure.

Conclusions

The detailed mapping and interpretation of the scarps has made a significant contribution to the investigation of the landslide in that it;

- defined the limit of deformation.

- demonstrated that much of the deformation preceded 2 July 1997,
- classified the landslide type as compound, suggesting that the location of the surface of rupture may be controlled by the depth of weathering,
- indicated that the surface of rupture may be located at about 16 m below ground level, and
- showed that the orientation of the main scarp was controlled to some extent by the major joint orientations.

Acknowledgment. This paper is published with the permission of the Director of Civil Engineering, Hong Kong SAR Government.

References

Cruden, DN (1991) Observation of graben geometry in landslides. *Slope Stability Engineering*. Thomas Telford, London, pp. 33-35

Koor, NP & Campbell, SDG (1998) *Geological Characterisation of the Lai Ping Road Landslide*. Geological Report No. GR3/98, Geotechnical Engineering Office, Hong Kong, 178 p + 5 drawings

Geotechnical Control Office (1986) *Shatin: Solid and Superficial Geology, Sheet 7*. Hong Kong Geological Survey, Map Series HGM 20, Geotechnical Control Office, Hong Kong

Hutchinson, JN (1988) General Report: Morphology and geotechnical parameters of landslides in relation to geology and hydrogeology. *Proceedings of the Fifth International Symposium on Landslides*, 10-15 July 1998, Lausanne, pp 3-35

Sun, HW & Campbell, SDG (1998) *The Lai Ping Road Landslide of 2 July 1997*. Landslide Investigation Report No. LIR27/98, Geotechnical Engineeering Office, Hong Kong, 138p + 2 drawings

Adverse Ground Conditions at Tung Chung New Town

P.A. Kirk

Abstract

Adverse geological conditions have been encountered in site investigations at the reclamation for the Tung Chung new town. The solid geology is predominantly granite but blocks of metasedimentary rock, including marble, occur as xenoliths within the granite. In places, carbonate dissolution has produced karstic terrain (now buried) and cavities. Locally severe dissolution has led to the development of sediment-filled collapse basins. A new Quaternary unit, the Tung Chung Formation, is proposed for these sediments. The igneous rocks adjacent to the xenoliths are unusually deeply weathered and characteristically have abrupt weathering fronts and steep gradients on rockhead. Drilling and seismic profiling have limitations as investigation methods in this geological environment but gravity surveying has proved effective for identification of the main occurrences of the low-density materials. The Tung Chung marble is one of a series of localised occurrences of metasediment along a northeast-trending structure. Further occurrences are likely elsewhere in this zone, and this should be taken into account in preliminary site investigations for future projects.

Key words: marble, karst, collapse basins, weathering fronts, gravity surveying, Tung Chung, Hong Kong.

Introduction

Tung Chung is situated on the north coast of Lantau Island, close to the new international airport at Chek Lap Kok. Granitoid dykes (feldsparphyric rhyolite, quartzphyric rhyolite, and microgranite) dominate the solid geology, with some small slivers of medium-grained granite that represent remnants of an older pluton. A fault zone is inferred to run along the north Lantau coast (Langford et al., 1995).

Prior to development, marble was unknown from the Tung Chung area. The nearest sedimentary rocks are at the Brothers Islands (with marble in boreholes nearby) and at Tai O (previously both correlated with marble-bearing Carboniferous sequence of the Yuen Long area). Skarn had also been reported

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Fig. 1 (facing). Tung Chung Reclamation, showing locations of adverse ground conditions

from San Shek Wan and Sha Lo Wan (Langford et al, 1995).

According to GEO records, marble was first encountered at the Tung Chung Reclamation in late 1992 in drilling at Housing Development Phase 1 ('Area 10'). Consequent geophysical surveys, undertaken by the GEO during 1993, established the possibility that sedimentary rocks occurred offshore from North Lantau, but were inconclusive for the existing reclaimed area. In 1994, fragments of marble and small voids were noted from several boreholes at the Pedestrian Bridge site in Tung Chung Phase 1. In 1996, drilling for Tung Chung Town Lot 3 ('Site 3') encountered a range of problematic geological conditions including marble with cavities, steep weathering profiles reaching to depths of more than 170 m, and unconsolidated sediment to depths of at least 80 m. Locations of these sites are shown in Fig. 1. The adverse geological conditions at Site 3 eventually led to one of the planned residential tower blocks to be abandoned in late 1996.

The preliminary geological model suggested that the marble and associated metasedimentary rocks occurred as small slivers within a fault zone (GEO, unpublished correspondence). However, the ultimate scale and extent of the problematic ground conditions were unclear. Attempts to understand the geological controls on the distribution of the unusual materials were hindered by inconsistent description and interpretation in borehole logs undertaken by different contractors. This made correlation or comparison between adjacent sites very difficult.

Early in 1997 the Territory Development Department (TDD) gave approval for a geological study to be carried out for the entire Tung Chung new town area. The objectives of the study were to collate all available ground investigation (GI) data; develop a geological model for the occurrence of problem conditions; evaluate the possibility of other areas being affected by similar problems; and provide guidance on the most appropriate GI techniques to enable early recognition and effective delineation of affected areas.

Study of Ground Conditions at Tung Chung New Town

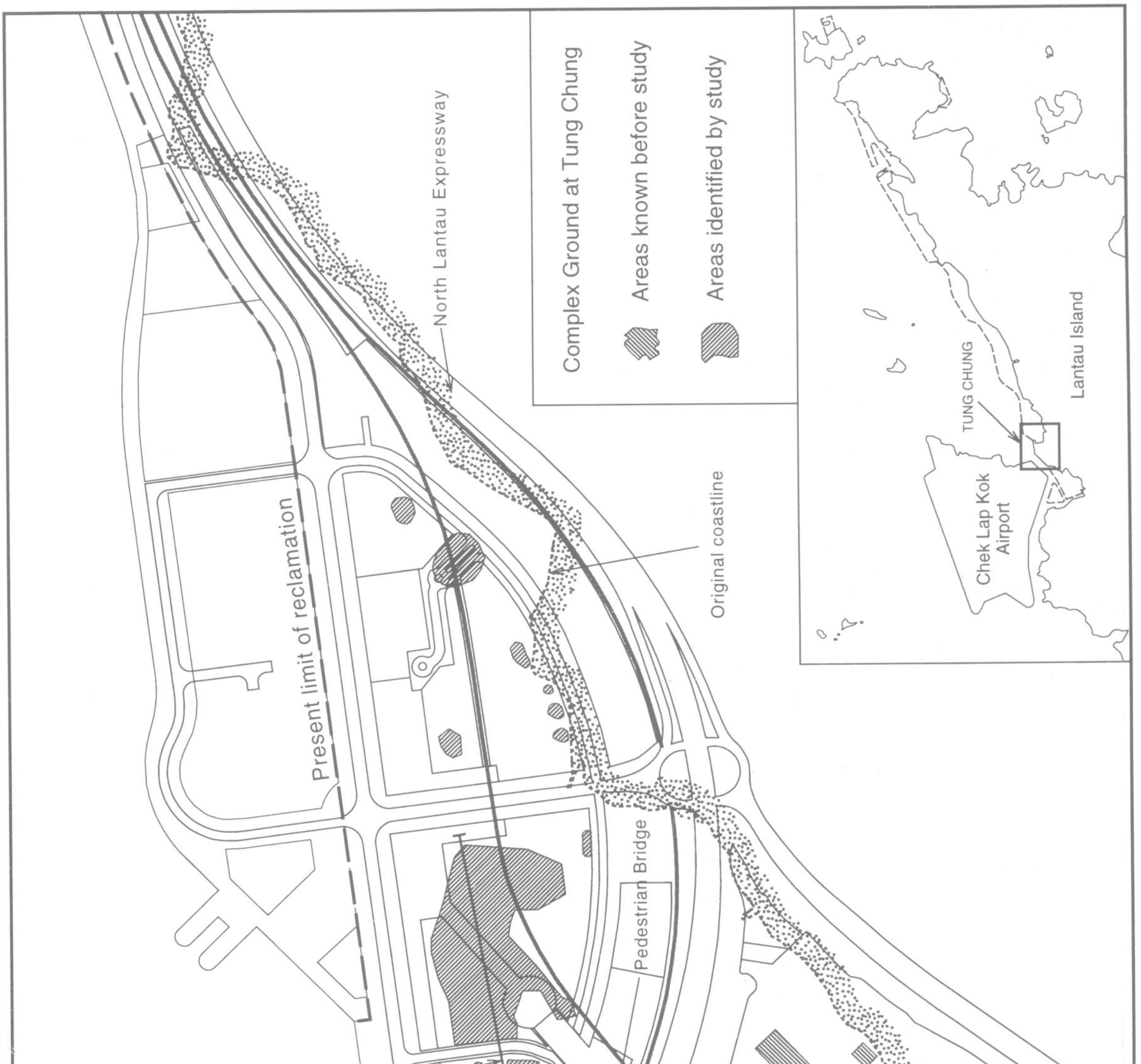
The full scope of the TDD-funded study includes:

- collation of pre-existing borehole, seismic profile, gravity and magnetic survey data;
- a consultancy for relogging and reinterpretation of borehole data;
- limited further ground investigation to test models and test investigation techniques;

    geophysical (gravity) surveys (onshore and marine)
    drilling (onshore and marine); and

- development of a database for all archival and new information.

This paper presents the results of the study up to October 1998. Emphasis here is placed on the two main lines of geological investigation: the borehole relogging, undertaken by the British Geological Survey (Gillespie et al., 1998) under Consultancy Agreement CE 11/97 (commenced September, 1997) and gravity surveying by GEO's Term Contractors, Electronic and Geophysical Services (Hong Kong) Ltd (which started in April, 1997), and subsequent


Complex Ground at Tung Chung
Areas known before study
Areas identified by study
North Lantau Expressway
Original coastline
Present limit of reclamation
Pedestrian Bridge
HA Area 10
Approximate location of cross-section (Figure 2)
MTR Airport Express Line
Site 3
N
Chek Lap Kok Airport
MTR Lantau Line
TUNG CHUNG
Lantau Island
Chek Lap Kok Airport

interpretation of the survey by Cosine Ltd (Electronic and Geophysical Services, 1997, 1998).

Logging and Reinterpretation of Boreholes

Some 2500 boreholes have been drilled in the area over the last 20 years, most within the last few years as the tempo of development has increased. Despite the volume of information there were problems in developing a geological model for the site. Problems arose mainly from the inaccurate or inadequate descriptions of geological materials, and widely differing interpretations of some of the less common lithologies. It was not possible to build up a consistent geological model from the widely differing source information, ranging across many sites.

Logs (and particularly core photographs, where available) of about 2000 boreholes were reviewed, and consistent terminology and classification applied to a revised set of descriptions. About 400 boreholes were completely relogged by re-examination of some or all of the samples from each hole.

New lithological maps and series of new cross-sections were drawn using the improved borehole dataset. The distribution and geometry of each geological material type was investigated and this enabled the development of a consistent geological model for the whole area.

The area is underlain by granite, intruded by numerous granitoid dykes (mainly feldsparphyric rhyolite). The intrusive rocks enclose blocks (xenoliths) of metasedimentary rocks, predominantly marble, sandstone and siltstone. The blocks range in size from a metre across to more than 300 metres across. It is inferred that the blocks were incorporated during (Jurassic) intrusion, as they commonly exhibit effects of contact metamorphism. For example, skarn is well developed where carbonate rock (such as marble) has been in contact with the magma. The structural geology of the area is complex, and faulting further complicates the original distribution of xenoliths.

Late Cenozoic weathering of this complex rock mass has caused the development of the adverse geological conditions.

Where metasedimentary rock was exposed at the middle Pleistocene palaeosurface, thick residual soil has developed. Dissolution has occurred in some of the marble blocks, leading to the development of a range of karstic features. Cavities and fissures are common. Individual borehole intersections range from less than 1 m up to 20 m. Most cavities are infilled with sediment, but voids up to 8 m have been recorded. Some holes have multiple intersections through cavity-infill deposits, and in these areas networks of large caverns are inferred to have existed.

In at least two localities advanced dissolution has led to formation of large sinkholes (or dolines). One feature is interpreted as an infilled solution doline, while the second is most likely a collapse doline. The features exceed 100 m and 60 m across respectively, and are up to 130 m deep. They are infilled with unconsolidated sediment, predominantly boulder and cobble-bearing silt and sand. A new formation, the Tung Chung Formation, is proposed here for these thick, though laterally restricted, deposits. Pollen dates, from serial samples, indicate a mid-Pleistocene age. The Chek Lap Kok Formation unconformably overlies the unit.

Extreme depths of granite weathering are associated with some of the sedimentary rock xenoliths. Typical weathering fronts in the Tung Chung area

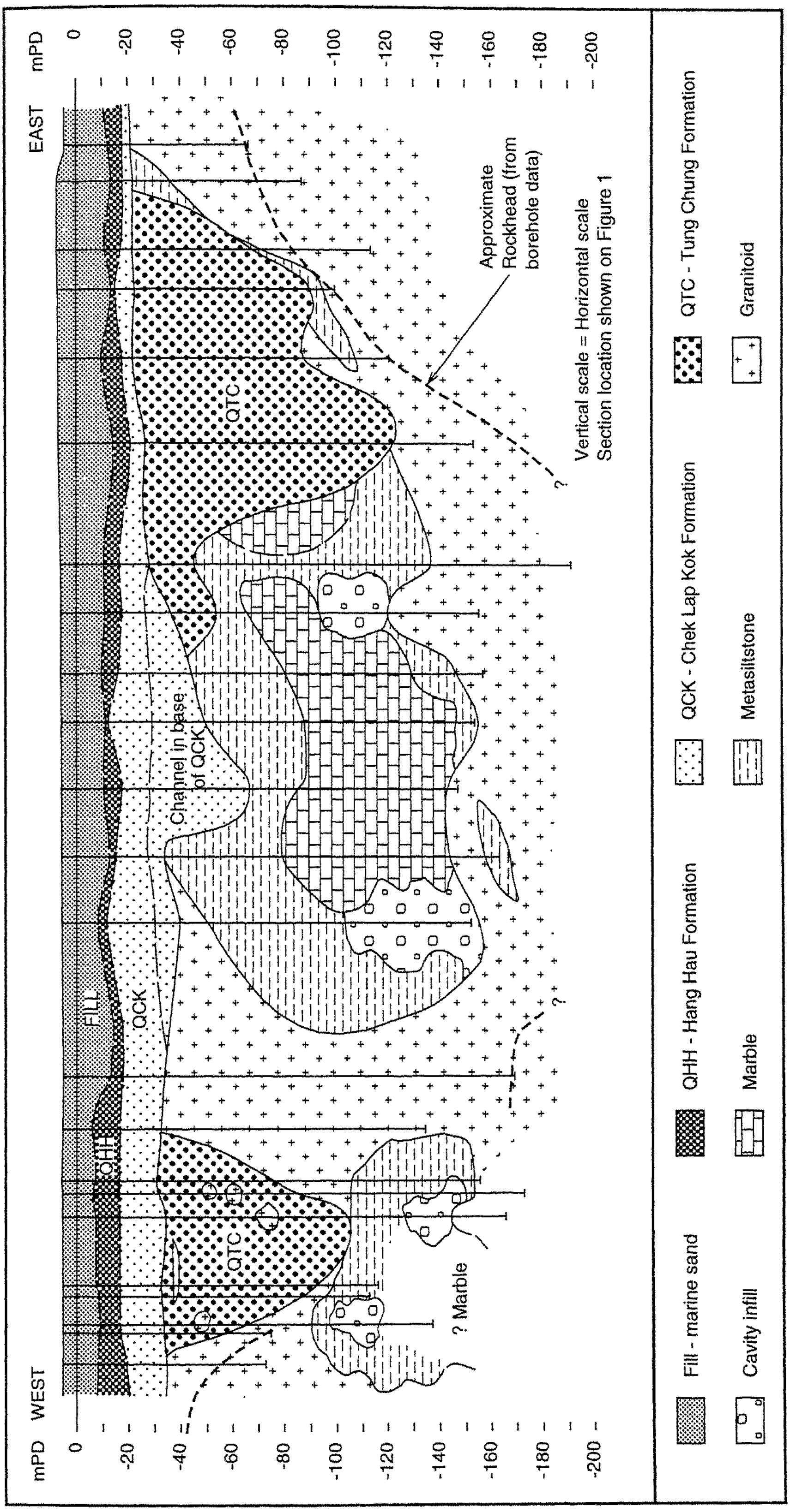


Fig. 2. Cross-Section through Tung Chung Reclamation, showing major geological features

occur at 40-50 m depth. However, in the immediate vicinity of some xenoliths many boreholes were drilled to 150 m or more without reaching fresh granite and at least one borehole exceeds 200 m. These unusual weathering profiles are characterised by abrupt weathering fronts with transitions from completely decomposed granite (CDG, grade V) to slightly or moderately decomposed granite (SDG, MDG, grades II, III) over only a few metres[1]. The gradient on rockhead is also very steep (up to 70°).

The unusual decomposition may be due to increased groundwater movement through cavitous marble, or perhaps increased susceptibility to weathering related to contact metamorphism (the granite may have been altered by circulating fluids).

A representative cross-section (Fig. 2), based on reinterpreted boreholes, shows some of the adverse conditions that occur under the Tung Chung reclamation (marble, cavities, infilled collapse structures, deep weathering of country rock).

The geological history of the area, and the range of lithologies present, are much more complex than those of a typical Hong Kong site. The new model provides a framework for new observations, and will assist future logging and interpretation. A lithological lexicon has also been produced with descriptions and photographs of every lithology (available from GEO, on request).

The model implies local associations of 'problem' materials. A site investigation design that places a heavy reliance on drilling is unlikely to find the problematic material at an early stage (i.e., probably not until dense drilling layout for final design of foundations). However, if any one of these materials is intersected in any borehole, then one should be alerted to the possibility of the occurrence of other materials in the immediate vicinity, and undertake further investigation accordingly.

Gravity Survey

The occurrence of the adverse conditions at Tung Chung is localised, with affected areas measuring from a few tens to a few hundreds of metres across. As noted above, in a phased drilling program problematic materials may not be encountered until a late stage of the site investigation. Other commonly used GI techniques such as seismic profiling may give some indication of adverse conditions, but the signal will be dependent on other factors, including the thickness of other superficial deposits or the presence of 'gas-blanking'.

One of TDD's key objectives for the study was to identify a GI technique that would enable early recognition of the occurrence of similar adverse ground conditions in other areas. Various possible techniques were discussed with several experienced geophysicists. The microgravity technique was suggested as the most promising. The intention was to detect the relatively large masses of weathered granite associated with xenoliths. This utilises the density contrast between CDG and fresh granite, and the favourable geometry (i.e., steep rockhead gradients). Note that the technique was not attempting to identify voids in marble (very low density), nor the marble itself (relatively high density).

A sequence of trials was scheduled to test the viability of the technique, and to optimise sampling station layout. First, two small onshore test areas were surveyed. One used a dense grid (10 m spacing), while the other used a series of profiles (25 m apart). Both areas were known to cross a dramatic

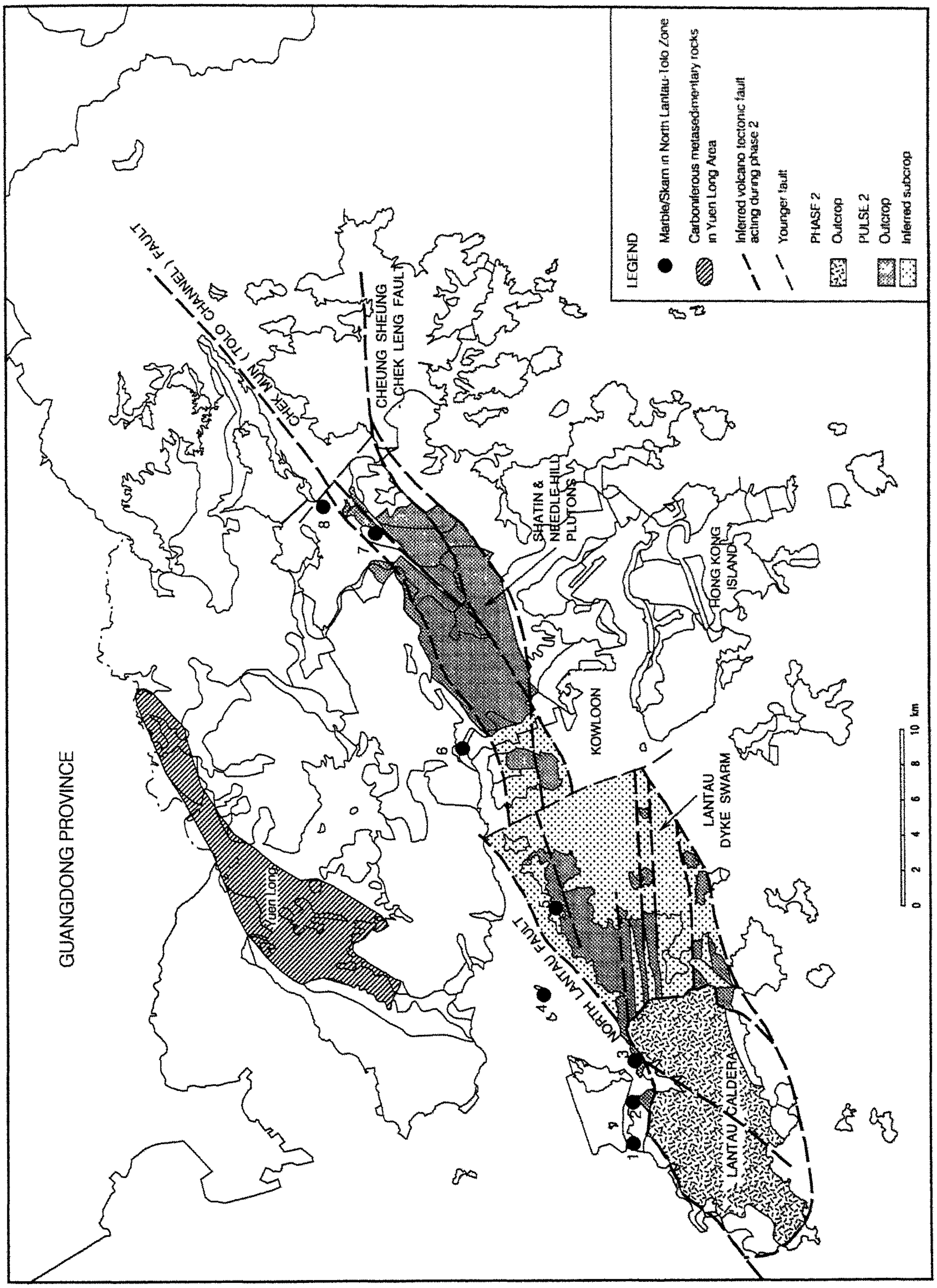


Fig. 3. Distribution of volcanotectonic phase 2 / pulse 2 (after Campbell and Sewell 1997), with locations of metasediment. ***1***, San Shek Wan; ***2***, Sha Lo Wan; ***3***, Tung Chung Reclamation; ***4***, The Brothers; ***5***, Yam O Wan; ***6***, Tsuen Wan; ***7***, Ma On Shan; ***8***, Harbour Island; ***9***, Yuen Long

change in rockhead levels. Existing GI information was made known to the geophysical contractor in one case, but not in the other. Interpretation of gravity residuals correctly identified the location of the changes in rockhead level at both test sites.

The following stage was to survey the entire reclamation (those parts accessible). The stations were spaced semi-regularly, about 25 m apart. This survey correctly delineated rockhead variation known from existing drilling data, and allowed further interpretation of rockhead depths over much of the reclamation. Negative gravity anomalies were interpreted as further sites with depressed rockhead levels. Subsequent drilling confirmed the model, and in one case identified further marble and deep sediment.

Finally, a marine gravity survey was carried out to examine the offshore continuation of the largest anomaly, and to give a better picture of regional gravity trends. Resolution of gravity anomalies is dependent on precise levelling. This is not possible for the marine meter, which therefore operates at rather lower resolution. Much wider spacing is appropriate, and we tried 100 m grid close to shore and 250 m grid over a wider area. The survey results correlated well with some good quality seismic profiles, and further marine drilling again confirmed interpretations of lithological variation and rockhead levels.

Prediction

One of the objectives of the TDD brief was to evaluate the possibility for similar conditions occurring elsewhere along the north Lantau coast (the area is scheduled for considerable further reclamation and development).

To evaluate this, Tung Chung must be viewed in the context of Hong Kong's regional geology. It is noted that the Tung Chung marble is one of a series of small, localised occurrences of metasedimentary rocks, including Ma On Shan, that lie along a northeast-trending structural zone (North Lantau to Tolo Channel). The style of these occurrences contrasts with the laterally extensive Paleozoic sequence of the Yuen Long area. The distribution of the Tung Chung and Ma On Shan type occurrences agrees well with the volcanotectonic reconstruction of that time period. Figure 3 shows Campbell and Sewell's (1997) reconstruction for Phase 2 / Pulse 2 (the period immediately post-dating granite intrusion at Tung Chung) together with reported locations of Palaeozoic rocks. Campbell and Sewell interpret the Phase 2 / Pulse 2 rocks to represent magmatism during crustal extension or transtension. Incorporation of country rock into intrusive rocks (as at Tung Chung) and within controlling structures (as at Ma On Shan) ties in well with this model.

Using this model, it can be inferred that marble may occur, either within fault structures or associated with magmatism, anywhere along the ENE trending zone shown in Fig. 3.

Future Work

This paper describes work in progress. New information is being acquired from active sites, particularly from drilling programs. The new information may require modification to or further development of the geological model.

Further interpretation of gravity data is planned. The near surface materials are well defined by the extensive borehole database. There is considerable density variation in these materials. A more refined interpretation can be obtained if the affect of gravity from the near surface units is 'stripped' from the existing residual model. It is expected that this will result in a better model for granite weathering at depth.

Two further reclamation areas are scheduled on the north Lantau coast. The first is Tung Chung -Tai Ho. The existing gravity survey shows a modest negative anomaly at the western part of this area (close to Tung Chung). The second area is the north shore reclamation (northeastern Lantau), which is beyond the present study area. However, the existing gravity survey shows a strong anomaly trending into the north shore area, and marble is known to occur east of the Brothers Islands. It would be particularly useful to include a marine gravity survey in the preliminary site investigation for this project.

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References

Campbell, SDG & Sewell, RJ (1997) Structural control and tectonic setting of Mesozoic volcanism in Hong Kong. *Journal of the Geological Society, London*, 154, part 6

Electronic and Geophysical Services (Hong Kong) Ltd (1997) *Tung Chung New Town - Gravity Survey. Preliminary Report.* Term contract no. GE/95/05, works order no. GE/95/05.71

Electronic and Geophysical Services (Hong Kong) Ltd (1998) *Study of Ground Conditions at Tung Chung New Town, Offshore Gravity Survey. Final Report.* Term contract no. GE/97/12, works order no. GE/97/12.03

Gillespie, MR, Humpage, AJ & Ellison RA (1998) *Geology of Tung Chung New Town*. A report prepared for Geotechnical Engineering Office, Civil Engineering Department, Hong Kong. British Geological Survey, Keyworth, Nottingham, UK

Langford, RL, James, JWC, Shaw, R, Campbell, SDG, Kirk, PA & Sewell, RJ (1995) *Geology of the Lantau District.* Hong Kong Geological Survey Memoir No. 6. Geotechnical Engineering Office, Civil Engineering Department, Hong Kong Government

Engineering Geological and Geomorphological Aspects of the Western Foothills, Tuen Mun

G.R. Taylor

Abstract

The decomposed volcanics of the western foothills of Tuen Mun beneath Castle Peak (Tsing Shan), on the western side of Tuen Mun new town in the western New Territories of Hong Kong, have posed severe slope engineering difficulties for geotechnical engineers ever since intensive development of the area began in the early 1970s, during the construction of Tuen Mun new town.

In addition, there is the potential for natural slope failures from the Tsing Shan massif above. Until recently in Hong Kong natural slope failures from such locations, and their potential to develop into significant mass movements affecting areas below, have been given less consideration than the stability of man-made slopes. However, recent events, most notably the 1990 Tsing Shan debris flow, which took place within the Castle Peak range, served to focus attention on such phenomena.

This paper considers both these geotechnical engineering aspects in relation to the geological processes which give rise to them. The importance of fully understanding the geomorphology, geology and hydrogeology of an area when formulating an appropriate geological model, where complex geotechnical problems are evident, is emphasised.

Key words: ground instability, weathered volcanic rocks, geomorphology, hydrogeology, highway alignment, Tuen Mun, Hong Kong.

Introduction

As the demand for land in the territory continues, development is taking place in increasingly marginal areas, and frequently in the vicinity of hillsides for which detailed geotechnical information is not available. One such area is the Castle Peak area of Tuen Mun.

The Hong Kong Government is currently promoting the construction of a highway running along the eastern foothills of Tsing Shan (Fig. 1). In view

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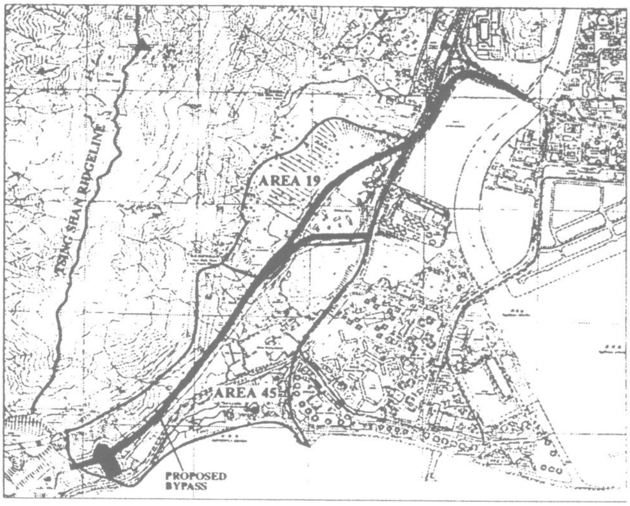

Fig. 1. Location plan, showing Tuen Mun new town and the proposed highway, with the Tsing Shan ridgeline shown to the left

of the recent debris flow activity as well as the longstanding instability within the footslopes of the Tsing Shan range, together with the relative proximity of the proposed alignment of the Foothills Bypass to the toe of the mountainside, an assessment of the likely impact of possible future mass movements on the highway formed an integral part of the geotechnical appraisal associated with this project.

The landscape on the western side of Tuen Mun new town is dominated by the steep granite massif of Tsing Shan. This massif gives way downslope to a distinct set of rounded spurs and associated less steep slopes towards the base of the mountainside. This landform in turn gives way to subdued and gently sloping ground, which extends to and beyond the footslopes. It is within these footslopes that the longstanding instability associated with the decomposed andesitic lava of the western foothills of Tuen Mun is most prevalent. Both aerial photograph interpretation and field mapping indicate that Castle Peak can be divided into two contrasting areas: a northern portion incorporating the steep and rugged Tsing Shan massif and a more subdued southern area, typified by a more rounded, mature topography (Plates 1, 2 and 3).

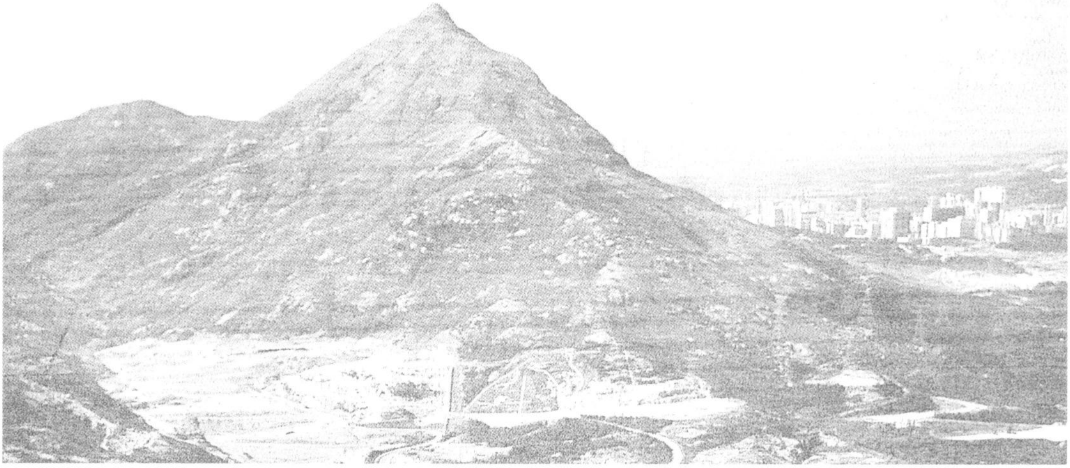

Plate 1. Looking northwards towards Castle Peak (Tsing Shan)

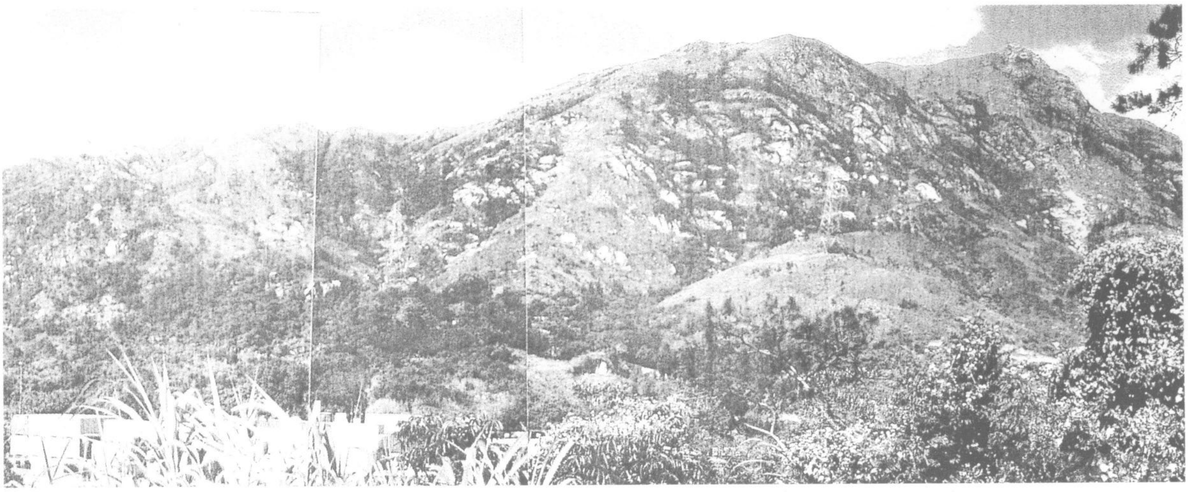

Plate 2. Looking westwards along Castle Peak

Geology and Geomorphology

The geology of the Castle Peak area of Tuen Mun is quite varied and this is reflected in its geomorphology (Hadley et al, 1997). The upper very steep slopes of Castle Peak consist of megacrystic fine- and fine-to-medium-grained granite (Fig. 2, gf, gfm). These slopes are essentially devoid of any superficial cover. The middle less steep slopes are underlain by metasediments of the Tsing Shan Formation and comprise siltstones, quartzites, tuffites and conglomerates (Fig. 2, JTS). These moderately steep slopes are covered by a relatively thin mantle of immature hillwash, largely derived from the metasediments themselves.

Further downhill, and marked by another change in gradient, the footslopes of Castle Peak are underlain by volcanics of the Tuen Mun Formation (Fig. 2, JTU). The volcanic rock consists of andesitic lavas with subordinate pyroclastic units, which in their completely decomposed form typically comprise a firm to stiff becoming very stiff, greenish grey, slightly clayey silt. They are characterised by fairly closely spaced randomly orientated relict joints. These joint surfaces are frequently polished and slickensided as a result of previous slight movement. Additionally, they are often manganese coated. In general these joint surfaces are discontinuous. Continuous through-going slip surfaces, however, have been observed in the uppermost few metres of the decomposed volcanics. The presence of such discontinuities within the soil mass has a significant effect on its overall behaviour. Some of the volcanics have also been subject to dynamic metamorphism, which has altered them to a phyllite.

Large areas of these lower, gentler slopes are covered by Quaternary colluvium Fig. 2, Qd, Qpd) derived chiefly from the upslope granites and metasedimentary strata; an older, weathered and locally cemented colluvium and a younger looser colluvium can generally be distinguished within this mantle. These materials have found their way onto the footslopes both by debris flow and less intense transportation processes and as such illustrate the importance of mass movements in shaping the present-day landscape of Castle Peak. These deposits generally form more distinct landforms in the north than in the south. It seems likely that the

Plate 3. Looking southwards along Castle Peak

volcanic rocks were substantially weathered before deposition of the colluvium occurred as the marked break in slope gradient observed at the interface between the volcanics and the upper metasediments is evident beneath the old colluvium. The break in slope gradient marks the upper limit of deposition of much of the colluvial material. The gentle footslopes underlain by the volcanics continue to the shore and the recent reclamations. The geology of the area is presented in Fig. 2.

To the south, approximately coincident with Area 45 (Fig. 1), the granite massif of Tsing Shan reduces significantly in height with the adjacent slopes becoming less steep and rugged, being composed of weathered and eroded fine to medium grained granite at the surface. This area is considered to be a more mature landform with regard to denudation and mass movement.

Hydrogeology

Artesian groundwater conditions are frequently encountered within the footslopes of mountain ranges, particularly where outflow is hindered by relatively low permeability deposits such as is the case here with the decomposed volcanics. Although previous geotechnical mapping within the foothills has identified an area along the toe of the existing slope in the northern portion of Castle Peak as being constantly wet, with ongoing seepages observed during the wet season, the presence of artesian conditions was not confirmed. Rather, a tendency for groundwater pressures to fall below hydrostatic with increasing depth was identified.

The groundwater conditions within the footslopes below Tsing Shan in the northern portion of Castle Peak, i.e. Area 19, have been monitored extensively, particularly over the period 1978-1986, using a variety of

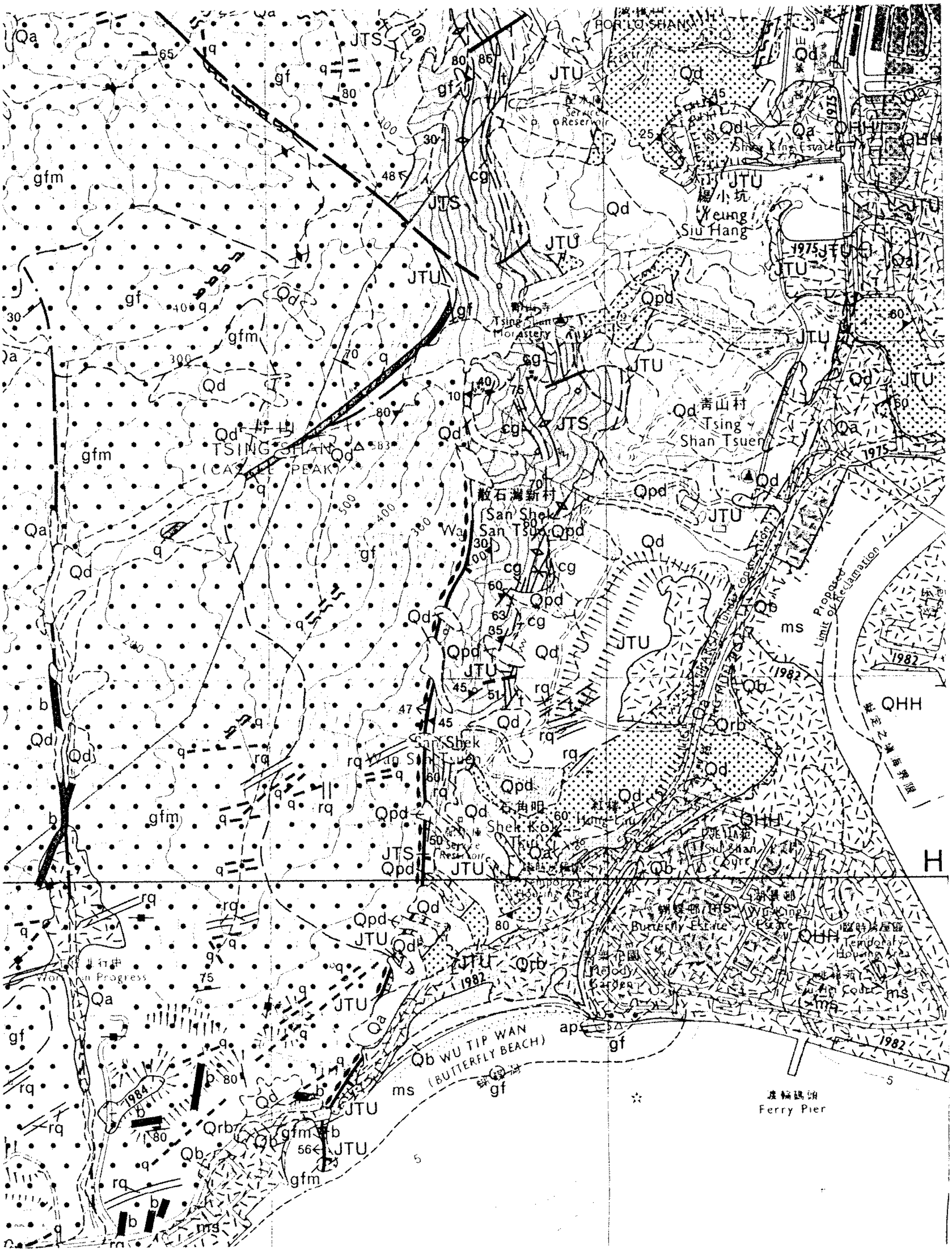

Fig. 2. Geology (reproduced from the Hong Kong Geological Survey's Map Sheet 5, Tsing Shan)

installations. The behaviour observed is summarised below:

a) Groundwater levels within the colluvium and the decomposed volcanics vary both seasonally and in response to individual rainstorms. Generally, however, no large rapid rises in transient groundwater levels in response to individual rainstorms were observed, either within the colluvium or the underlying decomposed volcanics. The responses that do occur tend to be over a period of several days or longer.

b) Perched groundwater levels are often developed within the colluvium, particularly during the wet season.

c) Vertical groundwater flow is generally from the colluvium into the decomposed volcanics below.

Geological Model

As part of the geotechnical design process it is necessary to formulate a geological model to explain the characteristic nature and disposition of the various materials observed within a site. The formulation and subsequent development of such a model is one of the fundamental building blocks upon which the design of a major construction project should be based. This model subsequently becomes an integral part of the engineering solution. A good geological model should enable the design team to fully understand the often complex interactions of the many geological components which make up a site and thus form the basis upon which rational engineering decisions can be made.

A geological model based on that postulated by Langford, Arthurton and Lai (1986) is currently considered to be the most appropriate in explaining the present instability associated with the colluvium-covered decomposed andesite below the Tsing Shan massif in Area 19, Tuen Mun. In this model, it is postulated that during the Quaternary, erosive processes associated with the streamcourses of the hillside resulted in the instability evident today. Erosion and landslipping near downcutting streams are considered to have lowered the ground surface whilst surface and sub-surface waterflow was responsible for extensive reworking of the disturbed ground. The various stages of this geological model were summarised by Whiteside (Scott Wilson Kirkpatrick, 1987) and are presented here as Figs. 3, 4 and 5.

The presence of old, highly weathered colluvium overlying the metasediments in the gullies within the foothills below Tsing Shan implies that there has been little further deepening of the beds of these streamcourses since the deposition of this colluvium. Thus, the pre-colluvium metasediment terrain would have been essentially as it exists today. The presence of substantial deposits of colluvium on the higher interfluves is considered to be the result of the deposition of a large amount of material in a relatively short period of time. In this case the rate of deposition must have been greater than the rate of erosion otherwise such deposits would not exist on the interfluvial spurs today.

Stage 1 - Initial Deposition and Erosion

The likely sequence of events is considered to have commenced with the rapid deposition of an extensive mantle of colluvium. This was followed by a longer period of progressive erosion and downcutting with consequent landslipping concentrated around the associated streamcourses (Fig. 3).

Stage 2 - Subsequent Deposition and Erosion

Following these initial depositional and erosional phases, further colluvial deposition occurred. This subsequent deposition would have tended to have

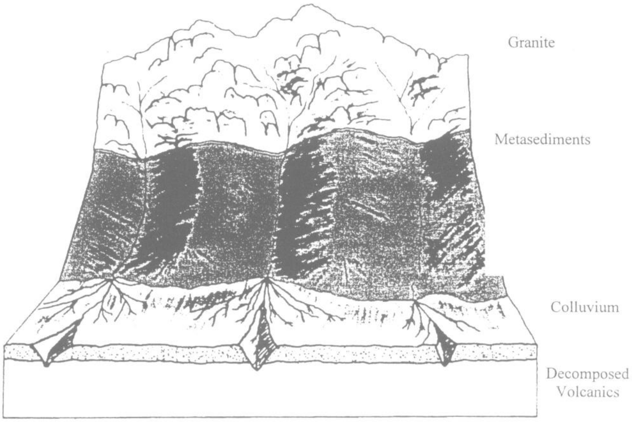

Fig. 3. Stage 1, initial deposition and erosion

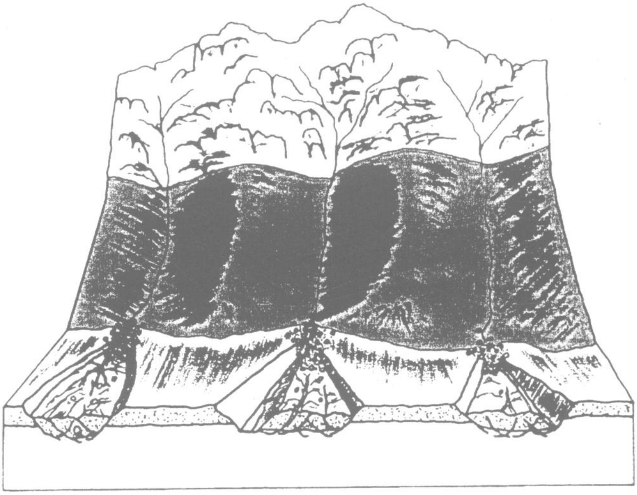

Fig. 4. Stage 2, subsequent deposition and erosion

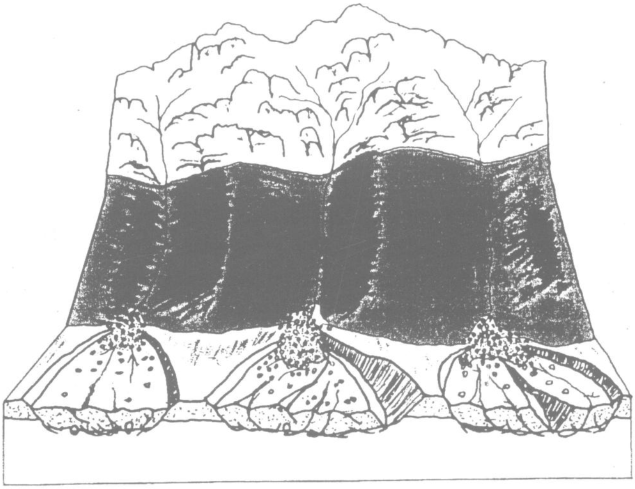

Fig. 5. Stage 3, further erosion and landslipping

been increasingly concentrated around the streamcourses as the colluvium-covered ground in these areas was progressively lowered by continuing erosion and landslipping, forming extensions to the upslope metasediment gullies (Fig. 4).

Stage 3 - Further Erosion and Landslipping

Landslipping which occurred within the steeper banks of the streamcourses during Stage 2 would have migrated back progressively into the decomposed volcanics and overlying colluvium at increasingly flatter attitudes. Continued erosion and migration of these streamcourses would have initiated a subsequent series of landslips, further lowering the adjacent ground surface. These processes have combined to give the completely decomposed andesitic volcanic terrain its characteristic gently dished morphology. The older colluvium is only preserved on the narrow interfluves (Fig. 5).

From this geological model, it can be concluded that the natural slip planes that occurred as a result of the downcutting and erosive processes would, in general, have been inclined approximately perpendicular to the slope of the hillside initially. As landslipping extended, however, subsequent failure planes would have tended to have been oriented approximately parallel to the general slope of the hillside (Fig. 4). They may also have been formed in the volcanics as a result of the rapid deposition of the older colluvium. It is likely that such failure planes are present within the volcanics up to its contact with the metasediments, although less likely within the interfluves.

The recent slips that have been observed have largely occurred at relatively shallow depths and are associated primarily with the completely decomposed volcanics. In addition, both the groundwater and movement monitoring data collected to date indicate in general that movement is confined to the upper few metres of the completely decomposed andesite. Examination of aerial photographs taken before development commenced in this part of the western foothills of Tuen Mun also suggests that instability in the volcanics does not appear to extend to the coast. Inspection of drillholes sunk in connection with adjacent reclamations, and in particular those nearest to the former coastline, further support this postulate. However, on the basis of the available evidence the possibility of deep-seated fossilised coastal landsliding, in the form of a series of retrogressions, having occurred some time in the past and predating the above more near-surface phenomenon cannot be discounted entirely. The worldwide depression of sea levels during, for example, the last glaciation may have enabled marine erosion to attack the coastal slopes of Castle Peak Bay at elevations below present mean sea level causing deep-seated coastal landslides. It may be that there are two geological processes, one superimposed upon the other, giving rise to the present instability. Feint signs of movement have been noted at depth near the interface between the decomposed volcanics and bedrock. This may indicate the presence of deeper-seated incipient slip surfaces.

Metasediment-Volcanic Interface

The interface between the volcanics and the upslope metasediments has generally been acknowledged as delineating the upper boundary of currently unstable ground. This contact extends for a distance of between 2 and 3 km along the eastern footslopes of Castle Peak. It is a major geological feature and in general approximately linear. Although the precise nature of this contact is not clear (whether it is faulted or simply part of the geological sequence or a combination of both) it has been assumed that its nature is essentially the same throughout its length. Past ground investigation, which included a combination of closely spaced and inclined drillholes, has generally identified the zone of contact between the metasediments and the volcanics. Furthermore this work has indicated that the metasediment/volcanic contact dips at about 70° to the west.

Natural Slope Failures

Superimposed on these past geological processes are the continuing denudation and mass wasting processes evident within the Tsing Shan range today and which manifested themselves most recently in the form of the 1990 Tsing Shan debris flow and 1992 Tsing Shan debris flood (Langford and Hadley 1990, Chan et al. 1991, and King, 1996a and 1996b). These incidents served to focus attention on natural slope failures from steep mountainsides in Hong Kong, and their potential to develop into destructive debris flows, floods and torrents at lower elevations. In Hong Kong, fatalities and damage due to natural slope failures have fortunately been relatively few to date.

Aerial photograph interpretation in conjunction with representative field mapping has revealed the presence of colluvial and weathered granite deposits in vulnerable locations within the upper slopes of the Tsing Shan Range, e.g. steep depressions and infilled hollows orientated downslope. In addition, the presence of loose fractured rock and dilated rock masses forming spurs and other promontories, which can fail as a result of progressive weathering or water infiltration, was also noted. Given the intense rainfall that the area frequently experiences together with the erosive processes active these phenomena have the potential to develop into significant mass movements affecting the areas below. Consequently, detailed consideration had to be given to the potential impact of such natural terrain landslides on the proposed development below.

Conclusions

The geological processes considered to be responsible for the instability evident within the decomposed volcanics of the western foothills of Tuen Mun have been described, as have those features which could give rise to future mass movements from the adjacent Tsing Shan Range. The importance of considering the geology, hydrogeology and geomorphology of an area in the formulation of an appropriate geological model for use in subsequent geotechnical engineering design has been emphasised. Only after the geological conditions have been assimilated into a coherent model should the next step in the design process, assigning numbers to the various parameters involved, be contemplated. It should be noted, however, that a geological model is a dynamic tool that changes as more information is gathered during the design and construction process. It is not uncommon and, more importantly, prudent for a geological model to be continuously refined as a project progresses through the various phases of design and construction, thus allowing engineering design to be based upon sound geological reasoning in conjunction with rigorous engineering logic.

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References

Chan YC, Lam CH & Shum W L (1991) *The September 90 Tsing Shan Landslide: A Factual Report.* Volume 1, Technical Note TN 4/91, Geotechnical Engineering Office, February 1991

Hadley D, Hearn GJ & Taylor GR (1997) Debris flow assessments for the Foothills Bypass, Hong Kong. In: *Proceedings of the 16th HKIE Geotechnical Division Annual Seminar, Slope Engineering in Hong Kong*. Hong Kong, May 1997

King JP (1996a) *The Tsing Shan Debris Flow*. Volumes 1-4, Special Project Report SPR 6/96, Geotechnical Engineering Office, May 1996

King JP (1996b) *Tsing Shan Debris Flood of June 1992*. Special Project Report SPR 7/96, Geotechnical Engineering Office, October 1996

Langford RL, Arthurton RS & Lai KW (1986) Geological Survey and Ground Investigations in Tuen Mun New Town, Hong Kong. In: Whiteside, P (ed) *The Role of Geology in Urban Development*, Geological Society of Hong Kong, Bulletin No 3, pp 199-208

Langford RL & Hadley D (1990) New Debris Flow on the Flanks of Tsing Shan. *Geological Society of Hong Kong Newsletter.* Vol 8, Part 3, pp 2-12

Tuen Mun New Town – Area 19, Report on Study of Remedial Measures to Main Slope, Volumes I & II. Scott Wilson Kirkpatrick & Partners (Hong Kong), March 1987

Natural geochemistry and contamination of marine sediments in Hong Kong

Peter G.D.Whiteside

Abstract

As part of Hong Kong's port and airport developments, more than 200 Mm^3 of marine mud was dredged and disposed of in the period 1992 to 1997. On the basis of simple chemical screening for seven metals, approximately 10Mm^3 of this material was classified as contaminated and was isolated by placing in specially dredged seabed pits and capped. The chemical screening dataset of over 4800 analyses has provided an opportunity to review the levels of contamination in relation to the natural geochemistry of Hong Kong's marine sediment. The metal levels in the marine sediments are also compared to those from over 1300 terrestrial sediment samples collected from stream courses throughout Hong Kong, and to average concentrations in local bedrock and typical granites elsewhere. Apart from zinc and nickel, it is evident that the modal values of heavy metal concentrations in the uncontaminated seabed mud and in the uncontaminated onshore stream sediments are similar to each other and to the average levels in Hong Kong bedrock and other granitic areas in the world. Zinc and, to a lesser extent, nickel occur at higher natural levels in the marine mud. Given the natural levels of heavy metals in Hong Kong, the regulatory chemical screening criteria for classifying dredged material seem close to optimum.

Key words: marine mud, contamination, disposal pits, screening standards, background levels, stream sediments, source rocks, zinc, nickel, copper, lead, chromium, mercury, cadmium, disposal cost.

Introduction

Between 1992 and 1997, as part of Hong Kong's port, airport and urban related developments, nearly 200 Mm^3 of seabed mud was dredged either to gain access to underlying sand deposits, to provide a stronger founding layer for reclamations, or for increasing navigable depth. However, many decades of uncontrolled disposal of industrially polluted wastes has resulted in much of Hong Kong's seabed being contaminated. Large amounts of copper and other metals associated with industrial processes such as electro-plating had

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accumulated in the upper layers of marine mud. These metal contaminants, together with smaller amounts of organic pollutants (PCB, PAH, antifouling TBT, etc) and large volumes of raw sewage, have been mixed deeper into the seabed by ships' anchors, resulting in a layer of contaminated mud which can be three or more metres thick.

In 1992, the Environmental Protection Department (EPD) of the Hong Kong Government implemented local legislation in accordance with the London Convention (IMO, 1995) to ensure that badly contaminated dredged material was not disposed of in the open sea (EPD, 1992). To do this the EPD specified criteria, based on the concentration of seven heavy metals, to differentiate between mud that could be safely disposed of at open marine disposal sites and mud that was sufficiently contaminated to warrant special disposal to isolate contaminants from the marine environment (Brand et al., 1994). These criteria have been under review and as part of this review consideration has been given to the natural background concentrations of these seven metals which all occur naturally in Hong Kong sediments. This paper presents data on the natural background levels of these seven metals in seabed mud and compares them with levels found onshore in stream sediments and bedrock. Although much work remains to be done on the pathways and fate of the metallic elements as they migrated from the parent bedrock to the seabed sediment, and although many important questions remain to be answered, there is sufficient information to draw some useful conclusions about the effectiveness of the regulatory levels that have been used so far.

Readers should note that apart from the inclusion of some updated references, this paper is essentially a record of the presentation made at the conference on "Urban Geology" held at Hong Kong University on the 15th of September 1998. The subject matter relating to the regulatory criteria and classification of dredged material has not been updated and readers interested in the current regulatory framework are advised to consult the Environmental Protection Department.

Origin of the Marine Sediments in Hong Kong

Nature of the source material

Some Palaeozoic sedimentary rocks occur in Hong Kong, but the solid geology is dominated by a suite of Mesozoic volcanic and plutonic rocks together with some associated minor sedimentary units derived from this igneous suite (Sewell et al., 2000). Later basic dykes occasionally occur, as do younger sediments in the northeast, although evidence from clasts suggest that the latter are also derived predominantly from the earlier igneous suite. Although a few of the earliest volcanic rocks are of intermediate composition, the main phases of comagmatic volcanic and plutonic rock are dominantly silicic, with major element abundances varying over a narrow range (Sewell and Campbell, 1997). In contrast, the trace element abundances show somewhat greater variation within the rockmass and locally, very high concentrations are present in vein deposits. These vein deposits occur sporadically throughout the territory, and some are rich enough to have been worked, yielding tungsten, lead, silver and copper.

Table 1, which summarises over six hundred volcanic and granitic whole rock analyses, lists the average concentration of five of the seven heavy metals used for classification of dredged material - taken from Sewell (1999).

Element	Cu	Pb	Ni	Cr	Zn
Average whole rock concentration (ppm)	4.2	34	8.6	22	39

Table 1. Average of volcanic and granitic whole rock analyses

Chemical and physical weathering and erosion of the volcanic and granitic rocks have been extensive throughout the Tertiary and Quaternary (Bennett, 1984; Fyfe et al, 2000). Today, weathered products are evident either *in situ* as saprolite or as colluvial and alluvial deposits. Details of the weathering processes are discussed by Irfan (1996) and Fyfe et al (2000), but in broad terms the quartz, although comminuted, mostly remains while the feldspars and mica are largely replaced by clay minerals and iron oxides.

Erosion and Deposition of the Material

The weathering and erosion of the bedrock has left the present mountainous terrain with rocky high ground, a variable thickness of saprolite on ridges and at lower levels, deposits of colluvium which are thickest on the lower hill slopes, and a blanket of alluvium in the valleys. The stream sediment samples discussed later in this paper were collected from drainage lines passing through areas of saprolite, colluvium and alluvium.

The alluvial plains in the valleys were progressively drowned from about 12 000 years BP by the rising Holocene sea which reached its maximum level about 6000 years BP (Geyh, 1979; Fyfe et al., 2000). This rising post-glacial sea initially reworked alluvium on the valley floors (Evans, 1988; Shaw, 1988) which over much of the area of interest were at a local relative level of about –30 mPD (Fyfe et al., 2000). On rising further, the Holocene sea then eroded the saprolite and colluvium-mantled hillslopes and re-deposited the material in the newly marine area together with fluvially transported sediment from the regolith mantle higher up the hillslopes (Whiteside and Cheung, 1996). The basal deposits of this Holocene marine sediment, the Hang Hau Formation (Strange and Shaw, 1986; Fyfe et al., 1997), are generally granular, becoming finer further offshore. The main portion of the Holocene marine sequence is, however, a fairly uniform, slightly sandy, clayey silt typically about ten metres thick away from the coastal area and thinning as is extends to the south of Hong Kong towards the South China Sea. Locally referred to as marine mud, it is generally dark grey in colour due to the action of anaerobic, sulphide-producing bacteria, but bioturbation has oxygenated the near surface portion which as a result is brownish in colour (Valente et al.,1996).

Predominantly Local Nature of the Seabed Mud

Although the marine mud presumably includes some sediment derived from outside Hong Kong - particularly suspended sediment transported into Hong Kong by the neighbouring Pearl River - this author considers that most of it has been derived from the erosion of the local Hong Kong regolith. The three main reasons for supposing this are as follows : firstly, the massive sediment load carried by the Pearl River is presently transported through the estuary to the south and west with little carried into or deposited in Hong Kong (Chalmers, 1983, Ng et al., 1998), and there is no obvious reason why this should have been significantly different during the last 12 000 years. Secondly, almost identical Holocene deposits exist in the eastern waters of Hong Kong, far removed from the influence of the Pearl, as are present in Hong Kong's western waters adjacent to the Pearl (Fyfe et al., 2000). Thirdly, coastal and onshore erosion of the thick regolith, particularly if one allows for a postglacial pluvial period, would have resulted in a very large volume of material being transported into the local marine environment.

Possible Changes in Chemistry of the Material During Erosion and Deposition

In passing from the original unweathered rock to the present-day marine mud it might be expected that some changes have affected the overall chemistry of the material, including the heavy metal concentration. The major effect, however, will have been smoothing of the geochemical variations during transport and mixing of sediment in stream courses and more particularly by further mixing in the marine environment prior to deposition. The passage from rock to marine sediment would nevertheless have provided opportunities for a number of processes to selectively remove chemical components. Dissolution losses of elements, including trace metals, could have been caused by surface water and groundwater acting on the weathered rock material before it was eroded, and also during transport before deposition in the marine environment. Mechanical separation of the tougher quartz component could have affected the overall geochemical balance because trace metals are mostly not held within the quartz. Once in the marine environment, any heavy minerals which survived fluvial transportation would have tended to concentrate in near-shore granular sediments. Even after deposition, the main fine sediment load was subject to the activity of aerobic and anaerobic organisms and this could have resulted in significant changes to the sediment chemistry. Such processes could include sequestering of trace metals from seawater by the fine-grained sulphide produced by the sulphate reducing bacteria, taking in of iron and related sulphates by the same bacteria, and concentration of trace metals into body parts of benthic fauna. None of these processes are examined here, however, nor is any attempt made to estimate what change they might have had on the overall sediment chemistry – rather they are mentioned as areas where further work is needed to put the overall conclusions on a firmer foundation.

Regulatory Framework

In 1992, Hong Kong's EPD adopted a set of chemical screening criteria by which dredged material was classified for disposal (EPD, 1992). In accordance with the London Convention, material passing the criteria was licensed for open sea disposal, while that failing the criteria was placed in specially dredged seabed pits and capped with uncontaminated dredged mud to isolate it from the environment (Brand et al., 1994; Whiteside, et al., 1996). These 1992 criteria are shown in Table 2.

Table 2. EPD's 1992 chemical screening criteria for classifying dredged material

Element	Cu	Pb	Ni	Cr	Zn	Hg	Cd
Concentration - ppm dry weight	65	75	40	80	200	1.0	1.5

Exceedance in even one of the seven metals constitutes failure of the sceening test and between 1992 and 1997 over 10 Mm^3 of such mud was disposed of in the special pits. Commencing in 1997 and taking account of amendments to the London Convention (IMO, 1995), the whole regulatory framework has been under review and *inter alia,* this has taken account of the large amount of test data on the natural background levels of these seven metals. The review is discussed in detail by EVS (1996), and the status in 1998, summarised by Lei et al. (1998). For the current situation the reader should refer directly to EPD.

Sampling and Testing Methods

Marine mud scheduled for dredging and disposal is sampled and tested for comparison with the environmental criteria. Samples are recovered from boreholes mostly using a vibrocoring technique in which a plastic tube, generally 12 m long, is lowered into the soft seabed. Thereafter, sub-sampling is achieved using a smaller diameter cylindrical sampler to avoid testing the outer smeared annulus. The chemical testing is undertaken on the fines content, normally by recognised ASTM (American Society for Testing of Materials) or USEPA (US Environmental Protection Agency) methods preceded by partial acid digestion using aqua regia. Variations of the two methods have been compared and ranges of metal content ± 15% have been found common. This is perhaps in part due to differing levels of digestion. However, as remarked earlier, the trace metals are not predominantly found within the quartz grains and so if the latter mostly account for the undigested material, differing levels of completeness of digestion may not necessarily have a significant effect on the results. Further comparisons have been made between this partial acid digestion method and total digestion (Miles, 1993). Despite these uncertainties, the author is not aware of any systematic bias of the results and therefore it is assumed that the outcome of variations inherent in the testing method is simply to increase the spread of the results rather than change the modal value.

A detailed account of the sampling and testing of the stream sediments is contained in the Geochemical Atlas of Hong Kong (Sewell, 1999). The atlas contains detailed interpretation and discussion of the analyses of sediment from a total of 2246 stream sampling locations. In summary, samples were collected manually, they were sieved and the <150 micron fraction tested mostly by inductively coupled plasma emission mass spectrometry (ICP) or X-ray fluresence spectrometry (XRF) techniques. In all, the concentrations of 36 elements were measured for every sampling location. The overall precision of the analyses was estimated to be better than 5% although this varied between elements. In addition to the chemical analyses, the fraction between 2 mm and 150 microns from selected sites was examined to assist interpretation of the results. In particular, this latter exercise revealed the almost ubiquitous presence of trace quantities of airborne contamination in the form of residue from fossil fuel power stations and industrial plants (Sewell, 1999 and 2000).

Testing for Hg and Cd at the low concentrations found in marine mud and stream sediments is problematic, and the concentration levels for these metals are subject to greater uncertainty than the levels for other metals.

Metal Levels in Marine Mud and Stream Sediments

Results from over 4800 routine tests of marine mud for each of the metals Cr, Zn, Cu, Hg, Pb, Cd & Ni are plotted as frequency distributions in Figs. 1(a) to 7(a) . The samples came from many locations in Hong Kong, most of which are close to existing developments and therefore exposed over many decades to varying degrees of pollution. Although metal levels of many samples are therefore artificially high, a large part of the dataset actually comprises natural uncontaminated material. There are two reasons for this, firstly sampling and testing extend to the full dredging depth which is normally considerably greater than depths of contamination, and secondly, some dredging areas have been distant from the polluted urban area. The opportunity has been taken to extract and combine data from two of these more distant sites which have no polluting sources close by and no history of large ship anchoring. Contamination in these two areas (the central and northern part of the West Lamma Channel) is only surficial and test results from depths greater than one metre below seabed have been used to plot the frequency distribution of natural concentrations of the metals. These are included as Figs. 1(b) to 7(b).

As part of Hong Kong's Geological Survey programme, comprehensive trace element analyses have been undertaken on sediment samples from water courses from all parts of Hong Kong (Sewell, 1999). Data from locations where artefacts were recorded during sampling and also from locations which are downstream of any form of human development have been removed from the main dataset (2246 samples) so as to obtain a subset (1381 samples) which is assumed to be broadly representative of the range of natural concentrations of the seven heavy metals. These are shown in Figs. 1(c) to 7(c).

The EPD chemical screening criteria, together with average concentrations of these metals in the earth's crust and in typical granites (Mason, 1966) are also shown on the frequency distribution plots of Figs. 1 to 7.

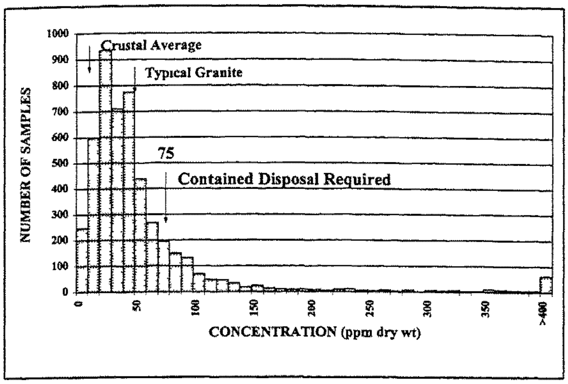
Discussion and Conclusions

It has to be stated that the subject of environmental ecotoxicology and regulatory control is very complex and this paper only covers one aspect, namely the importance of understanding the natural geochemical background concentrations of chemicals of concern. The following remarks are therefore inadequate on their own to assess the appropriateness of chemical screening criteria used in Hong Kong. That said, some pertinent conclusions can be drawn from the results presented here.

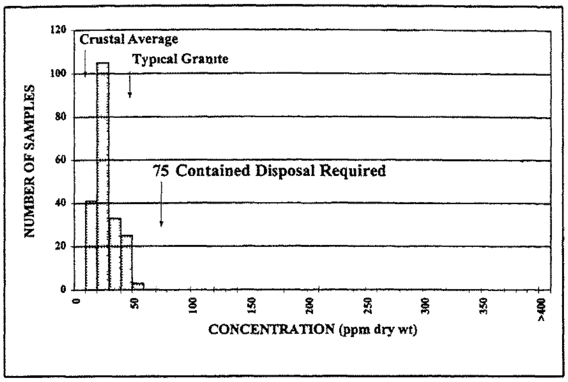
With some exceptions discussed later, Table 1 and Figs. 1 to 7 indicate the similarity of the modal values of heavy metal concentrations in the uncontaminated on-shore regolith and seabed mud, and the average levels in Hong Kong bedrock and other granitic areas in the world. The spread of concentrations about the modal values is assumed to be part real and part related to the testing method.

In attempting to compare the stream sediment geochemistry to that of the uncontaminated Holocene marine mud some factors cannot be discounted nor easily quantified : in stream sediments, the quartz content will be higher than in the marine sediments and this could result in an apparent reduction of relative levels of trace metals; in contrast, where there has been a concentration of detrital heavy minerals especially from locations downstream of metallic

(a) Marine Mud - Contaminated & Uncontaminated



(b) Marine Mud - Uncontaminated



(c) Stream Sediment - Uncontaminated

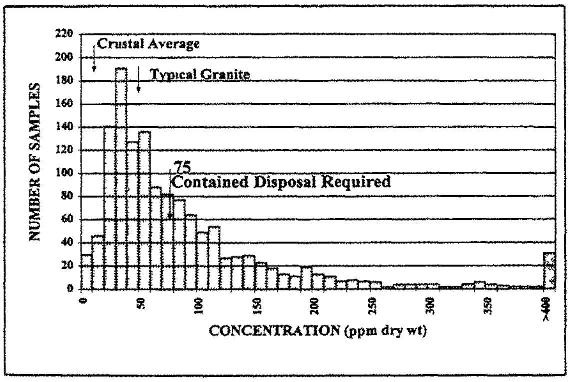
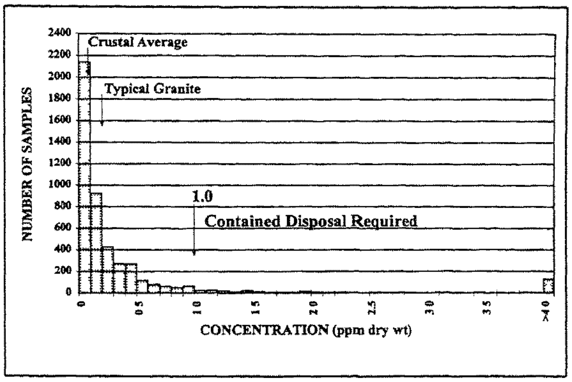
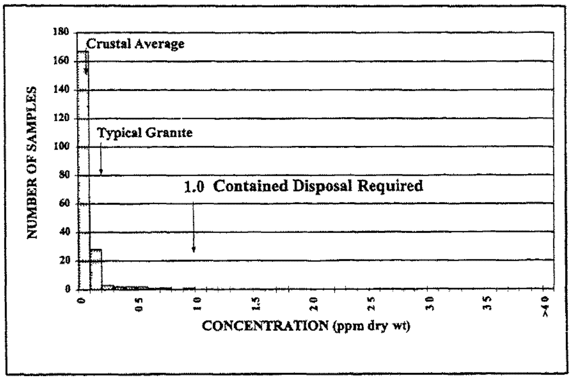


Fig. 1. Comparison of lead (Pb) concentrations onshore and offshore. Sample sizes: (a) 4805 samples; (b) 207 samples; (c) 1381 samples. *Contained disposal required* is the screening criterion introduced in 1992 by EPD to classify dredged material. Comparison of (c) with (b) and Table 1 suggests possible enhancement of (c) by atmospheric sources. *May include airborne contamination

(a) Marine Mud - Contaminated & Uncontaminated



(b) Marine Mud - Uncontaminated



(c) Stream Sediment - Uncontaminated

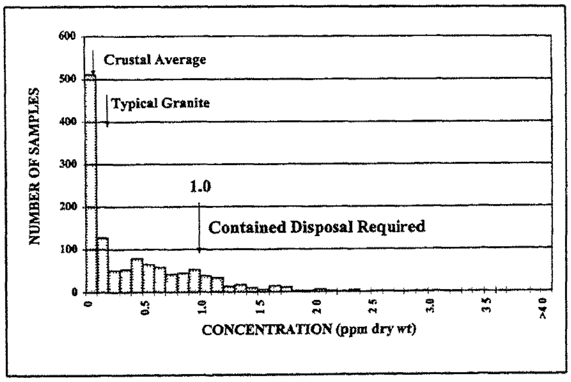
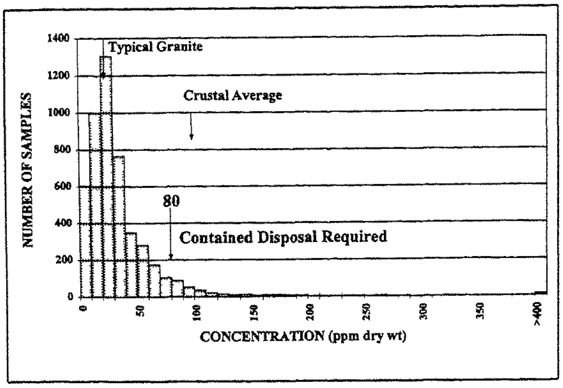
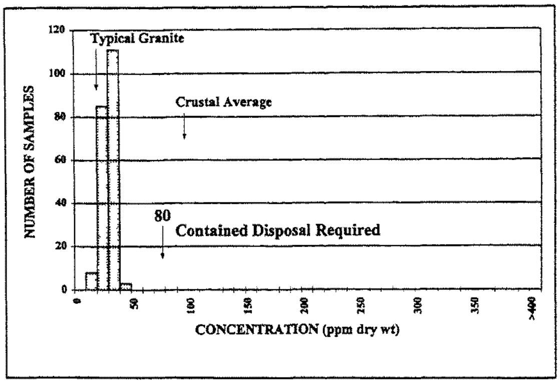


Fig. 2. Comparison of copper (Cu) concentrations onshore and offshore. Sample sizes: (a) 4805 samples; (b) 207 samples; (c) 1381 samples. *Contained disposal required* is the screening criterion introduced in 1992 by EPD to classify dredged material. *May include airborne contamination

(a) Marine Mud - Contaminated & Uncontaminated



(b) Marine Mud - Uncontaminated



(c) Stream Sediment - Uncontaminated

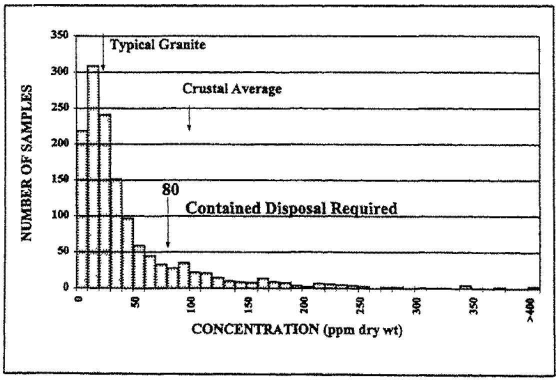
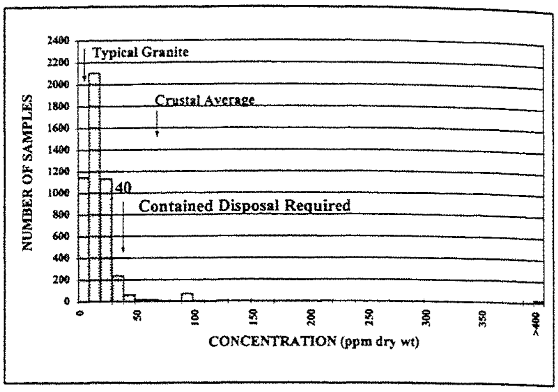
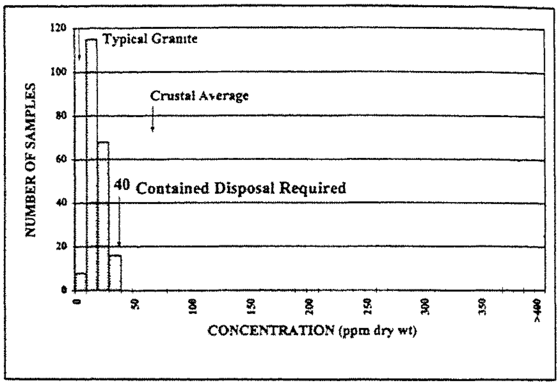


Fig. 3. Comparison of chromium (Cr) concentrations onshore and offshore. Sample sizes: (a) 4805 samples; (b) 207 samples; (c) 1381 samples. *Contained disposal required* is the screening criterion introduced in 1992 by EPD to classify dredged material. Comparison of (c) with (b) and Table 1 suggests possible enhancement of (c) by atmospheric sources. *May include airborne contamination

(a) Marine Mud - Contaminated & Uncontaminated



(b) Marine Mud - Uncontaminated



(c) Stream Sediment - Uncontaminated

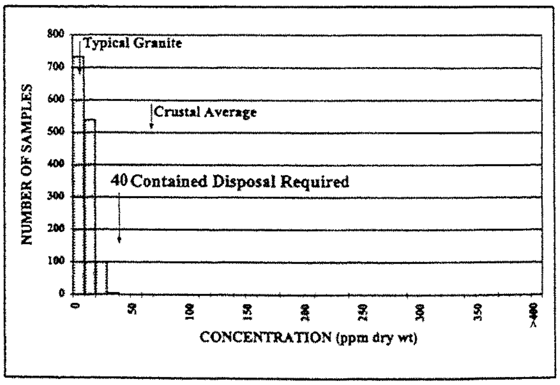
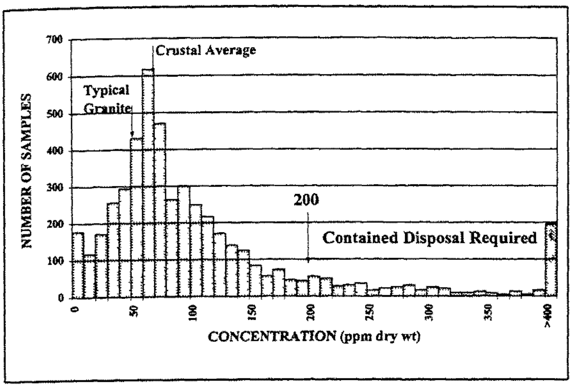
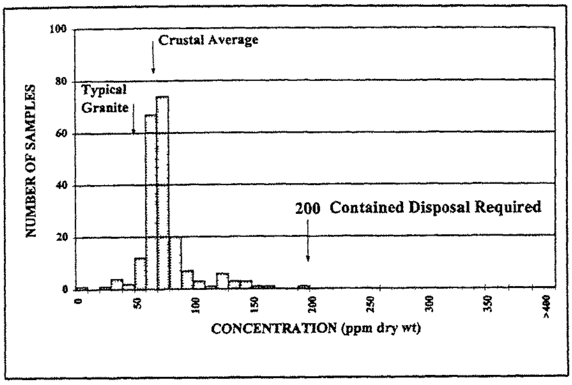


Fig. 4. Comparison of nickel (Ni) concentrations onshore and offshore. Sample sizes: (a) 4805 samples; (b) 207 samples; (c) 1381 samples. *Contained disposal required* is the screening criterion introduced in 1992 by EPD to classify dredged material. Table 1 and (c) suggest that natural processes have enhanced levels in (a) and (b). *May include airborne contamination

(a) Marine Mud - Contaminated & Uncontaminated



(b) Marine Mud - Uncontaminated



(c) Stream Sediment - Uncontaminated

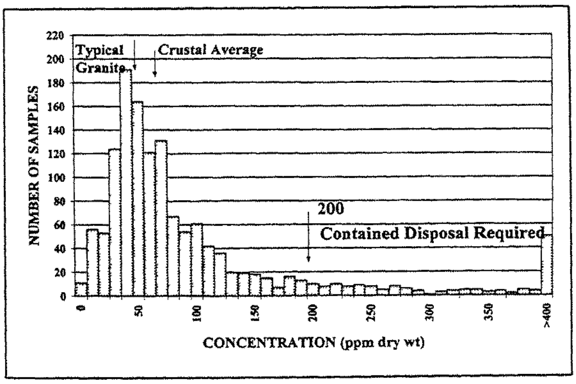
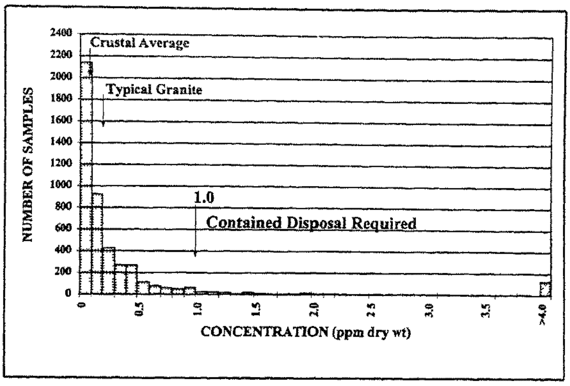
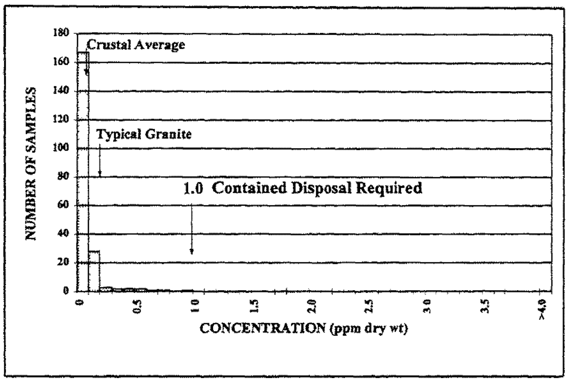


Fig. 5. Comparison of zinc (Zn) concentrations onshore and offshore. Sample sizes: (a) 4805 samples; (b) 207 samples; (c) 1381 samples. *Contained disposal required* is the screening criterion introduced in 1992 by EPD to classify dredged material. Comparison of (c) with (b) and Table 1 suggests possible enhancement of (c) by atmospheric sources. Table 1 and (c) suggest that natural processes have enhanced levels in (a) and (b). *May include airborne contamination

(a) Marine Mud - Contaminated & Uncontaminated



(b) Marine Mud - Uncontaminated



(c) Stream Sediment - Uncontaminated

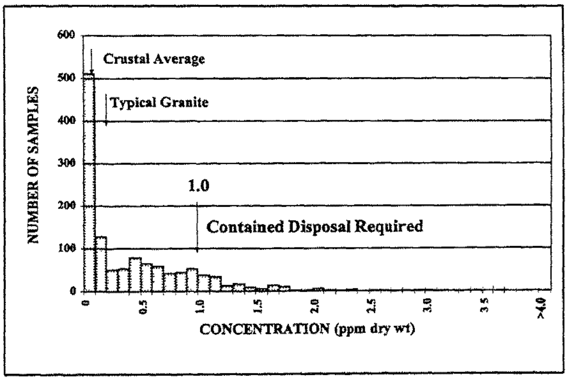
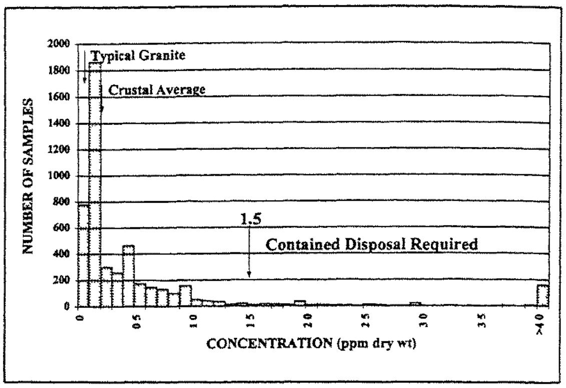
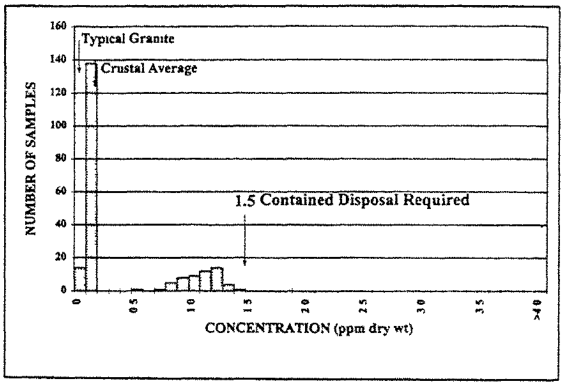


Fig. 6. Comparison of mercury (Hg) concentrations onshore and offshore. Sample sizes: (a) 4805 samples; (b) 207 samples; (c) 1381 samples. *Contained disposal required* is the screening criterion introduced in 1992 by EPD to classify dredged material. Test results subject to significant uncertainty. *May include airborne contamination

(a) Marine Mud - Contaminated & Uncontaminated



(b) Marine Mud - Uncontaminated



(c) Stream Sediment - Uncontaminated

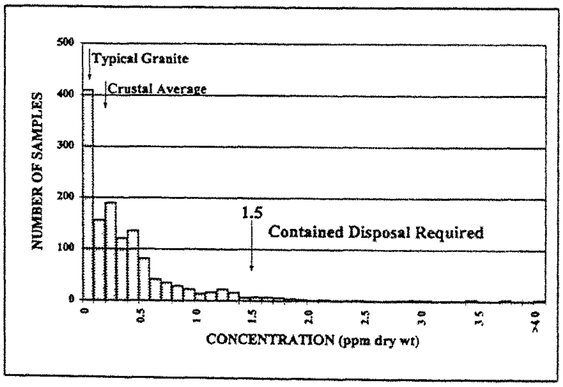


Fig. 7. Comparison of cadmium (Cd) concentrations onshore and offshore. Sample sizes: (a) 4805 samples; (b) 207 samples; (c) 1381 samples. *Contained disposal required* is the screening criterion introduced in 1992 by EPD to classify dredged material. Test results subject to significant uncertainty. *May include airborne contamination

lic vein deposits, higher levels of metallic elements could be present in stream sediments ; and although efforts were made to exclude from the analysis sediments affected by man, certain forms of atmospheric pollution, such as fine fuel ash from power stations and industry, lead from vehicle emission, etc, may have had measurable effects.

The imprint of pollution on the upper layers of marine mud can be gauged by comparing (a) and (b) of Figs. 1 to 7. In most cases the upper bound of metal concentration in the uncontaminated mud is similar to the chemical screening criteria used in Hong Kong to categorise dredged material. Comparison between Table 1 and Figs. 1(b) to 5(b) indicates very similar metal concentrations in bedrock and uncontaminated marine mud with the exception of Zn (and to a lesser degree Ni) which has a noticeably higher modal value in the marine mud. This may be due to the affinity Zn has for organic matter or to some other mechanism which absorbs the metal from seawater. In comparing uncontaminated marine mud to uncontaminated stream sediments, Figs. 1(b, c) to 7(b, c) one finds the expected similarity but also an apparent contamination of the stream sediments by Pb, Zn and to a lesser extent Cr. Atmospheric contamination, such as discussed by Sewell (2000), is possibly indicated by this. In relation to the previous remarks about higher Zn modal levels in uncontaminated marine mud, it is interesting to note that despite the apparent Zn contamination in the stream sediment samples, the modal concentration of Zn in the stream sediments is still similar to that of the bedrock suggesting that there has indeed been some natural process by which the marine mud has taken in Zn from seawater.

The potential cost implications of over-conservative screening criteria for dredged marine mud could be very high. During the period 1992 to 1997, about 10 Mm^3 of dredged mud required special disposal at a cost of about US$7 per m^3. Although the frequency distributions in Figs. 1(a) to 7(a) do not represent volumes actually dredged, they do provide an indication of how quickly the "contaminated" proportion of dredged material would increase if screening criteria were to be significantly lowered. While minor adjustment of some of the screening levels might be appropriate for a number of reasons, as a general principle, setting screening levels below the natural levels would result in rapidly increasing costs for rapidly decreasing benefits. Given the natural levels of heavy metals in Hong Kong, the regulatory screening levels seem close to optimum.

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References

Bennett JD (1984) *Review of Superficial Deposits and Weathering in Hong Kong*. Geotechnical Control Office, Hong Kong, 51 p. (GCO Publication No. 4/84)

Brand EW, Massey JB & Whiteside PGD (1994) Environmental aspects of sand dredging and mud disposal in Hong Kong. *Proceedings of the First*

International Congress on Environmental Geotechnics, Edmonton, Alberta, Canada, pp 1-10

Chalmers ML (1983) Preliminary assessment of sedimentation in Victoria Harbour, Hong Kong. *Proceedings of the Meeting on Geology of Surficial Deposits in Hong Kong*, Hong Kong, pp 117-129. (Published as Geological Society of Hong Kong Bulletin No.1, edited by W.W.S. Yim, 1984). (Abstract published in Geological Society of Hong Kong Abstracts No. 1, 1983, pp 30)

Environmental Protection Department, Hong Kong (1992) Classification of Dredged Material for Marine Disposal. EPD Technical Circular 1-1-92

Evans CDR (1988) Seismostratigraphy of early Holocene sand banks. In: Whiteside PGD & Wragge-Morley N (eds) *Marine Sand and Gravel resources of Hong Kong*, proceedings of the Seminar on Marine Sources of Sand. Geological Society of Hong Kong, pp 45-52

*EVS Environment Consultants (1996) Classification of Dredged Material for Marine Disposal. Report to the Geotechnical Engineering Office of the Hong Kong Government

Fyfe JA, Selby IC, Shaw R, James JWC & Evans CDR (1997) Quaternary sea-level change on the continental shelf of Hong Kong. *Journal of the Geological Society, London*, Vol 154, pp 1031-1038

Fyfe JA, Shaw R, Campbell SDG, Lai KW & Kirk PA (2000) *The Geology of Hong Kong - Quaternary*. Hong Kong Geological Survey, Geotechnical Engineering Office, Government of the Hong Kong SAR

Geyh MA, Kudrass HR & Streiff H (1979) Sea-level changes during the late Pleistocene and Holocene in the Strait of Malacca. *Nature*, Vol 278, p 441-443

IMO (1995) *Dredged Material Assessment Framework (Resolution LC.52 (18))*. Adopted at the 18th Consultative Meeting of the London Convention, 4-8 December 1995. International Maritime Organisation, London

Irfan TY (1996) Mineralogy, fabric properties and classification of weathered granites in Hong Kong. *Quarterly Journal of Engineering Geology*, Vol 29, Part 1, pp 5-36

Lei PCK, Fok AWK, Dawes A & Whiteside PGD (1998) Development of Hong Kong's decision criteria for sediment disposal. *Proceedings of the Seventh International Symposium on River Sedimentation and Second International Symposium on Environmental Hydraulics*, University of Hong Kong

Mason B (1966) *Principles of Geochemistry* (Third Edition). John Wiley and Sons, Inc, New York

*Miles DL (1993) The sampling and analysis of contaminated marine sediments in Hong Kong. British Geological Survey Technical Report WC/93/10/C prepared for the Geotechnical Engineering Office, Hong Kong Government

Ng KC, Whiteside PGD & Kwan SH (1998) Physical and ecological studies on effects of sand dredging and mud disposal in Hong Kong. *Proceedings of the Second International Conference on the Pearl River Estuary in the* *surrounding area of Macao, Guangdong and Macao*, 11-15 May 1998, pp 187-202

Sewell RJ (1999) *Geochemical Atlas of Hong Kong*. Geoechnical Engineering Office, Government of the Hong Kong SAR

Sewell RJ (2000) Baseline geochemical mapping in Hong Kong. *Environmental Geochemistry*

Sewell RJ & Campbell SDG (1997) Geochemistry of coeval Mesozoic plutonic and volcanic suites in Hong Kong. *Journal of the Geological Socety, London* Vol 154, pp 1053-1066

Sewell RJ, Campbell SDG, Fletcher CJN & Lai KW (2000) *The Geology of Hong Kong - Palaeozoic, Mesozoic & Tertiary.* Hong Kong Geological Survey, Geotechnical Engineering Office, Government of the Hong Kong SAR

Shaw R (1988) The nature and occurrence of sand deposits in Hong Kong waters. In: Whiteside PGD & Wragge-Morley N (eds) *Marine Sand and Gravel Resources of Hong Kong*, proceedings of the Seminar on Marine Sources of Sand. Geological Society of Hong Kong, pp 33-43

Strange PJ & Shaw R (1986) *Geology of Hong Kong Island and Kowloon.* Hong Kong Geological Survey Memoir No. 2, Geotechnical Control Office, Hong Kong

Valente RM, Evans NC & Whiteside PGD (1996) Environmental monitoring in Hong Kong using the REMOTS seabed camera. *Coastal Management in Tropical Asia*, No. 6, March 1996, pp 26-29

Whiteside PGD & Cheung PCT (1996) Exploration for offshore sand in Hong Kong: Detailed surveys, dredging and environmental assessments. *Hong Kong Geologist*, 1996, 2 (Spring), pp 28-36

Whiteside PGD, Ng KC & Lee WP (1996) Management of contaminated mud in Hong Kong. *Terra et Aqua*, Number 65, December 1996, pp 10-17

*Reports which can be consulted in the Civil Engineering Library of the Civil Engineering Department of the Government of the Hong Kong Special Administrative Region, 101 Princess Margaret Road, Homantin, Kowloon, Hong Kong.

The Origin and Variability of Suspended Sediment in Hong Kong's Marine Waters

S. Parry

Abstract

Hong Kong is located at the estuary of the Pearl River, China's third largest. This location, together with the constraints on tidal flow induced by numerous islands and distinctive wet and dry seasons, including the regular occurrence of tropical cyclones, results in a highly dynamic hydrological regime. It is within this setting that environmental impact assessments (EIA) for offshore developments are carried out. As one of the main concern of these assessments is the impacts of generated suspended sediments it is critical that correct background levels and the possible variations therein are known.

Key words: marine suspended sediment, origins, variability, natural causes, anthropogenic causes, monitoring.

Introduction

Prior to the commencement of any engineering project it must be demonstrated through an EIA that the resulting impacts can be controlled and mitigated to acceptable levels.

The Water Pollution Control Ordinance 1980 established water control zones (WCZ) for Hong Kong's marine waters. There are currently 10 WCZs and for each zone specific water quality objectives (WQO) are established. With respect to suspended sediments, the WQO for all zones is that "waste discharges shall neither cause the ambient level to be raised by 30% nor give rise to accumulations of suspended solids which may adversely affect aquatic communities". However, the "ambient level" for the zones are not defined in

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the Ordinance. Consequently, the "ambient level", and therefore by definition the impact of generated suspended sediments, is based on professional judgement of the individual consultant. The Agriculture and Fisheries Department (AFD) similarly use the WQOs as a basis for determining the effect of a project on marine life.

In the past, EIA consultants have frequently used the upper 95 percentile of the results from the Environmental Protection Department (EPD) routine water quality monitoring data as the "ambient level". The EPD monitoring is carried out monthly or bimonthly at over 80 monitoring stations. However, it has been noted that more frequent monitoring, such as that undertaken for Environmental Monitoring and Auditing (EMA) purposes during the course of construction works, which are usually monitored twice a day at ebb and flood tide, show higher variations in suspended sediment levels.

In order that the correct assumptions are made with respect to defining "ambient levels" it is important that both the natural and anthropogenic impacts on suspended sediment levels in Hong Kong waters as well as their temporal variations are fully understood.

Natural Impacts on Suspended Sediments

Hong Kong's Seabed

Hong Kong's seabed typically comprises very soft to soft silty clay of the Hang Hau Formation varying between 5 and 20 m in thickness, the majority of which was probably deposited post 5500 yBP (Fyfe et al, In Press). Today sedimentation is limited with the seabed in Hong Kong being in equilibrium and unable to accommodate any further sedimentation. However, sedimentation does occur where the equilibrium is disturbed. Soundings made in the dredged Northern Fairway of Victoria Harbour from 1976 to 1987 indicated that the average sedimentation rate was 50 mm per year (Maunsell Scott Wilson, 1991).

Above the Hang Hau Formation sediments mud suspensions often occur, e.g. during a survey at the East Ninepins Marine a large area of seabed (>12 km^2) was covered by a thin layer between 0.5 and 2.1 m thick with concentrations of between 100 and 2500 mg/l (DRL, 1996a).

This phenomenon was also observed during a study of Hong Kong's eastern waters where three distinct seabed types were noted (BCL, 1995b). These comprised weakly consolidated gelatinous mud occurring as discrete patches with a thickness of 20-60 mm, a "puzzle fabric" comprising loosely packed mud clasts in a mud suspension with a thickness of 20-100 mm, and "normal" compact homogeneous seabed which was only present at 57% of the sampling locations.

Work carried out by Hydraulic Research Ltd (1990) determined critical bed shear stresses for seabed deposits at differing densities. This data, together with the combined effects of waves and currents for eastern waters, suggests that a 0.1 year wave event will erode mud suspensions and may erode consolidating layers, a 1 year storm will erode consolidating mud suspensions and that a 10 year storm will begin to erode in-situ Hang Hau Formation seabed (Selby and Evans 1997).

Consequently a layer of easily remobilised, very soft mud is present over much of Hong Kong's seabed and resuspension of this material is a frequent event.

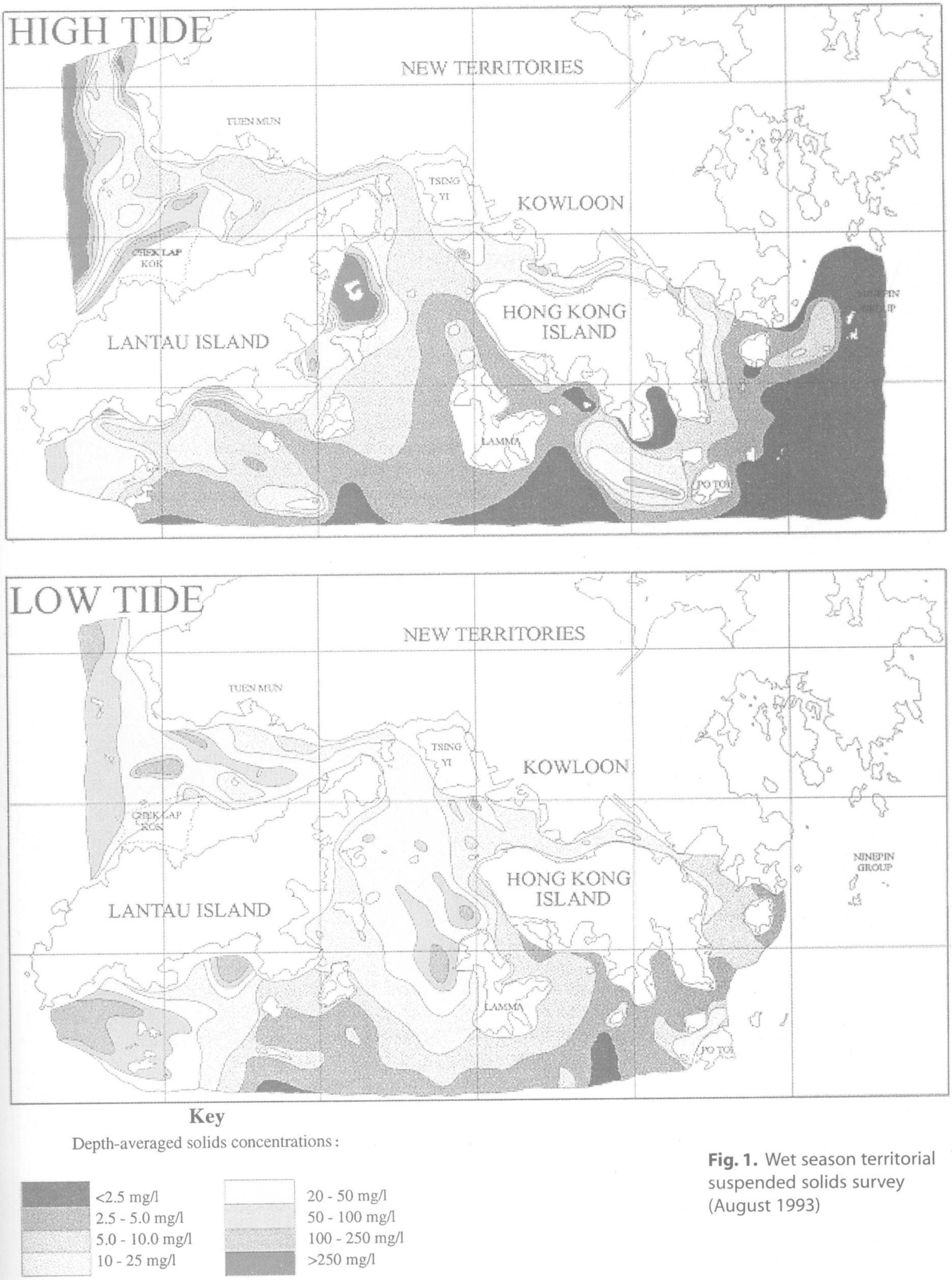

Fig. 1. Wet season territorial suspended solids survey (August 1993)

Figure 2(a) - Neap tide 8-9/2/96

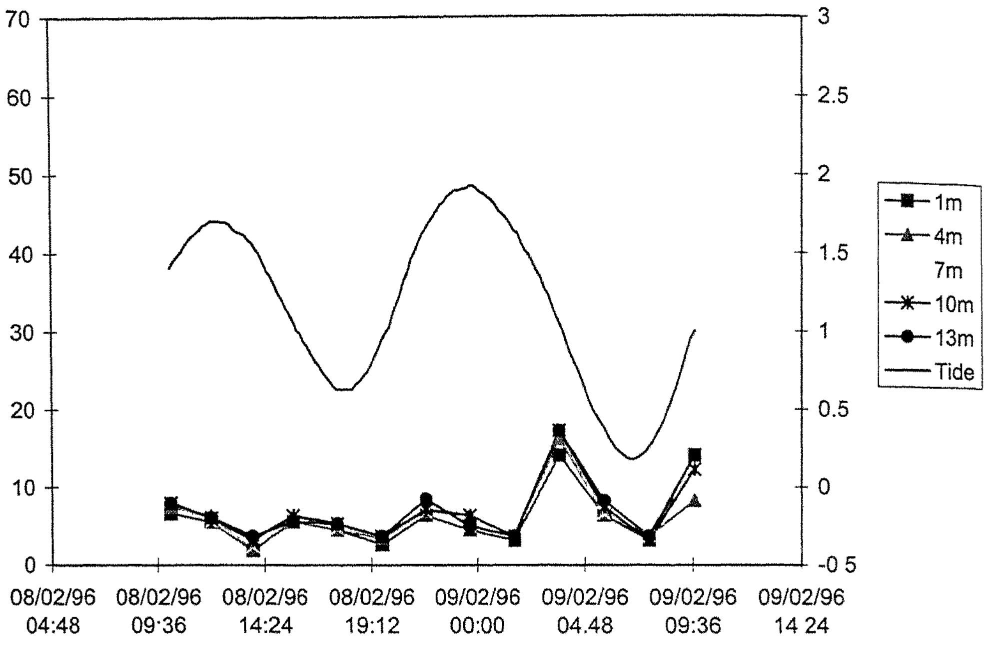

Figure 2(b) - Spring tide 19-20/1/96

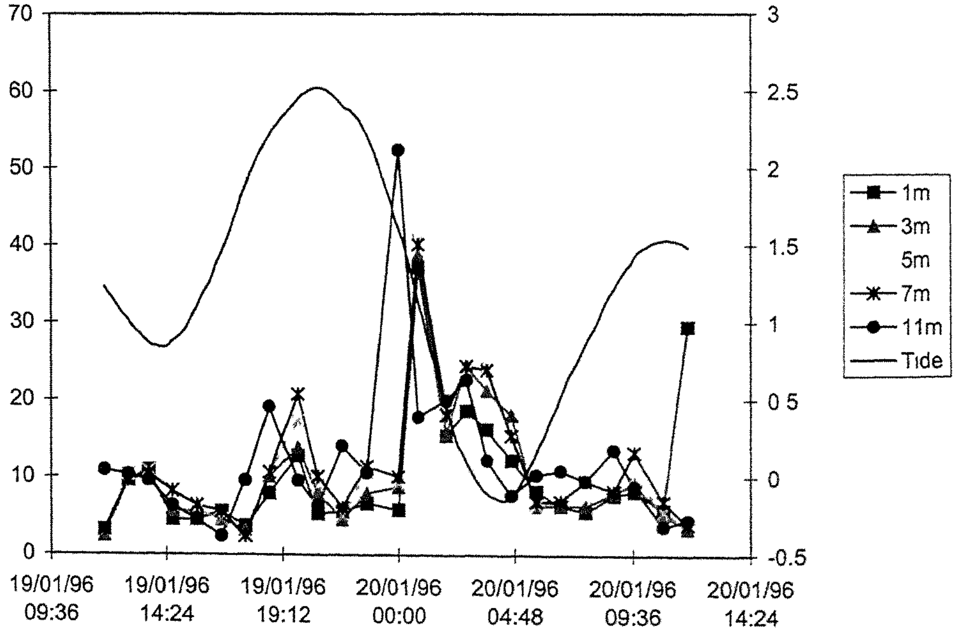

Fig. 2. Dry season suspended sediment concentrations at East Sha Chau. *Left vertical axis*, suspended sediments (mg/l); *right vertical axis*, tidal range (m)

Figure 3(a) - Neap tide 5/8/96

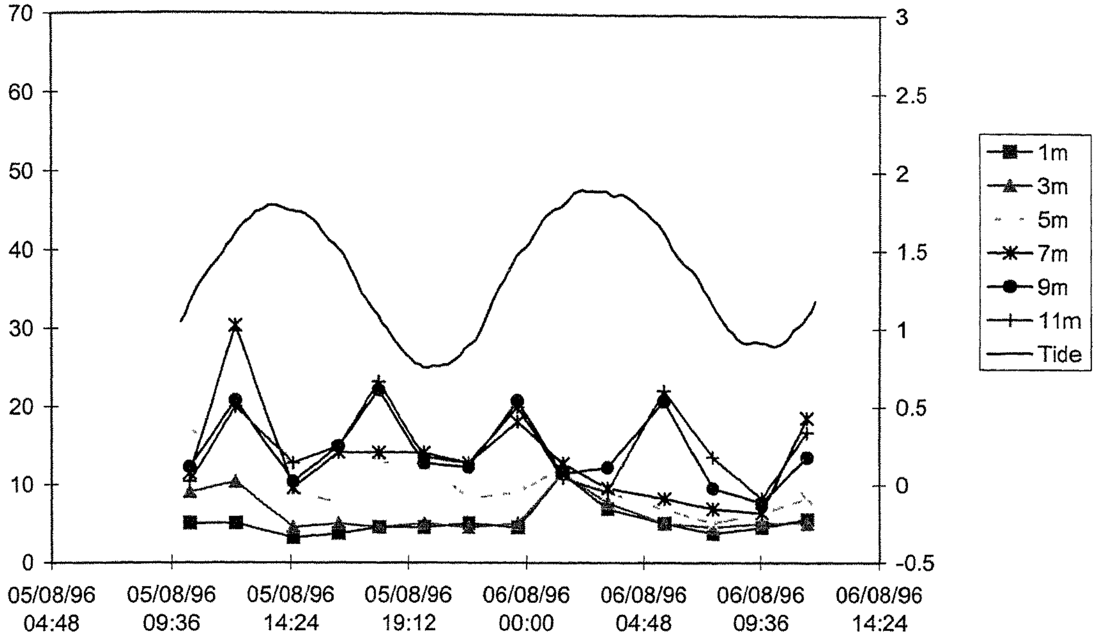

Figure 3(b) - Spring tide 30-31/7/96

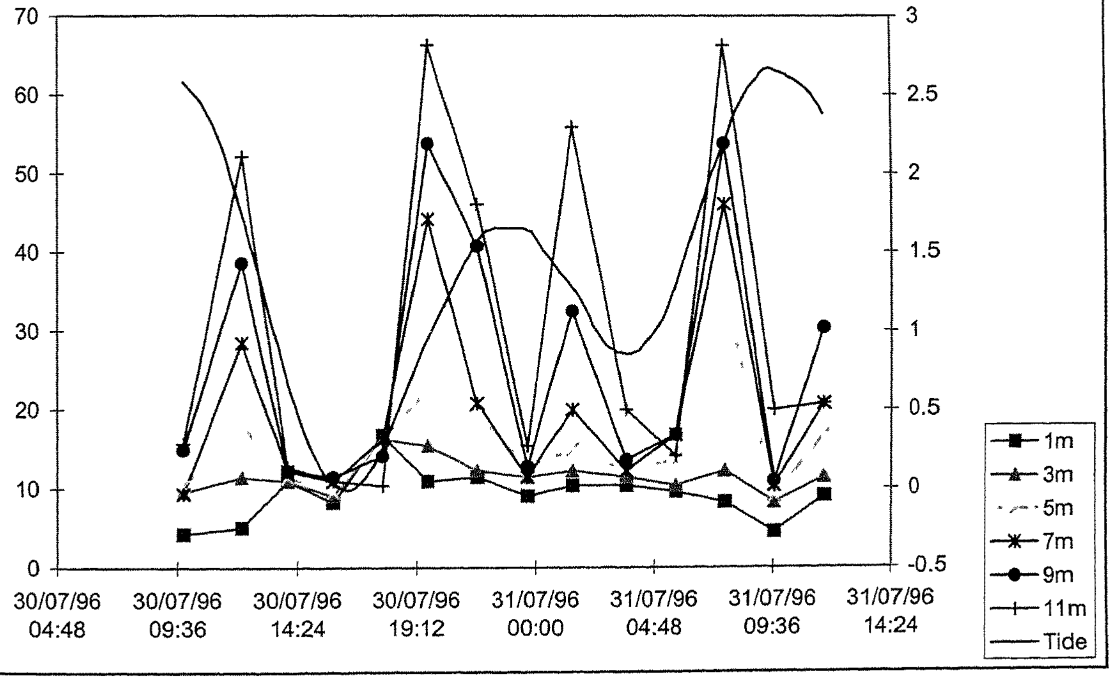

Fig. 3. Wet season suspended sediment concentrations at East Sha Chau. *Left vertical axis,* suspended sediments (mg/l); *rightvertical axis,* tidal range (m)

The Pearl River

It has been estimated that the total annual discharge by rivers of sediment worldwide is about 7x10^9 tons, with Asian rivers carrying in excess of 75% of this (Dyer, 1986). Within China itself the three largest rivers are the Yellow (Huange), the Yangtze (Changjiang) and the Pearl (Zhujiang).

The Pearl River, which is ranked sventeenth in the world in terms of sediment discharge (Milliman & Meade, 1983), is composed of three tributaries, the rivers Xijiang, Zhujiang and Beijiang representing a catchment of over 425,000 km^2, or almost 5% of the surface area of China.

The Pearl River is dominated by sedimentary accretion with the delta advancing seaward at between 50 and 150 m per year (Ravensrodd 1991). Various annual water discharges and sediment loads for all the tributaries are quoted in the literature but are generally in the order of 320x10^8 m^3 of water and 71x10^6 tons of sediment. Ninety percent of runoff occurs in the wet season from May to September. The four channels of the main Pearl estuary which influences Hong Kong discharge approximately 170 Mm^3 of water and some 36x10^6 tons of sediment per year (Chen & Che, 1992).

Kot and Hu (1995) stated that the mean annual sediment content of the estuary is 100-300 mg/l, with a wet season depth average of 300-500 mg/l and a dry season depth average of 20-100 mg/l. Kirby (1992) however reported much larger depth averaged suspended solid concentrations, with values of over 1400 mg/l being recorded.

The low water spring tide, wet season, territorial suspended sediment survey (DRL, 1994) clearly showed the influence of the Pearl, with large amounts of suspended sediment present north of Lantau and extending into the Western Harbour giving values of between 25-50 mg/l and being swept around south Lantau and extending beyond the Soko's with up to 100 mg/l present (Fig. 1). The concentrations were slightly lower at high tide although values in excess of 250 mg/l are still evident in the Pearl. The high concentrations of suspended sediments recorded in the shallow waters of southern and southeastern Lantau are thought to be due to a combination of wave action at high tide and surface runoff .

Tides

The flood and ebb tides form reversing tidal flows which dominate the near shore waters of Hong Kong. In general tidal current speeds are moderate varying from 0.5 m/s in West Lamma Channel to 2.5 m/s at Ma Wan and Kap Shui Mun (Ip, 1995).

Figures 2 and 3 (previous page) show hourly measurements of suspended solids over 24 hour periods during wet and dry season spring and neap tides at East Sha Chau (EGS 1996a, 1996b). All the results clearly show the influence of tides on suspended sediments, with increases in suspended sediments associated with mid ebb and mid flood tides and proportional to the tidal range. As would be expected the smallest fluctuations are associated with dry season neap tides (Fig. 2a). The suspended sediment concentrations are similar at all depths and fluctuate from <2 mg/l to >17 mg/l at mid ebb. A similar pattern is shown for dry season spring tides resulting in suspended sediments typically fluctuating from <5 mg/l to 20 mg/l except on the mid ebb, which has the largest tidal range, where >40 mg/l was recorded (Fig. 2b). Again the suspended sediment levels are similar at all depths, reflecting typical dry season homogenised conditions.

In the wet season similar fluctuations with respect to the ebb and flood tides occur but the suspended sediment concentrations are higher and their variations increase with depth. The neap tides (Fig. 3a) show only slight variations in suspended sediment concentrations in the upper 5 m of the water column, whereas the lower layer shows regular fluctuations from 10 mg/l to 20 mg/l. Similarly with the spring tides (Fig. 3b) the fluctuations in suspended sediment concentrations in the upper 3 m are limited although the actual base levels are elevated in comparison with the neap tides (10 mg/l as opposed to 5 mg/l on the neap tides). However, the lower water layers show rapid increases in suspended sediments with typical basal values of 15 mg/l increasing to in excess of 50 mg/l on the mid ebb and mid flood. It appears that stratification and the associated dampening of turbulence results in the lower waters, which are affected by re-suspension of sediments, being unable to mix with the upper layers.

Storm Events

In 1994, a 1-in-100-year rainfall event in southern China resulted in a 100-year record Pearl River discharge in mid June 1994. The dry season territory-wide suspended sediment survey was carried out in November 1994 (DRL, 1995a) and showed that higher than expected suspended sediment levels associated with the Pearl flood waters were still affecting Hong Kong. Depth average concentrations of >250 mg/l were present north and south of Lantau at low tide; and in more central Hong Kong waters, values of between 25 and 100 mg/l were recorded, with a stream of water extending from Ma Wan through the Western Harbour to Lamma having values of 100-250 mg/l (Fig. 4, overleaf).

In addition to summer monsoons, typhoons also occur, with an average frequency of 5.3 per year affecting the Pearl River area and 1.25 per year making landfall in the area (Kot and Hu, 1995). The typhoons usually last 2-3 days and cause torrential rain and storm surges, raising tidal levels by up to 2.6 m. They also result in mixing throughout the water column, reducing stratification and, at the same time, increasing suspended sediment levels due to the disturbance of the seabed.

During sand dredging near Po Toi Island to the southeast of Hong Kong, continuous suspended sediment monitoring was carried out to detect possible impacts on nearby coral communities. These meters recorded greatly enhanced suspended sediment levels during the passage of Typhoon Sibyl which resulted in the raising of the Tropical Cyclone Warning Signal Number 8. The typhoon passed closest to Hong Kong at about 8am on the 3rd October 1995 when it was 290 km southwest of Hong Kong. The typhoon resulted in maximum gust wind speeds of 113 km/hr and a storm surge of 0.52 m at Waglan Island with up to 272 mm of rainfall (Royal Observatory, 1995). Suspended sediment levels increased from the background value of 20 mg/l to in excess of 350 mg/l. The limited impacts, in terms of duration and magnitude, of the dredging-generated plumes in comparison to those resulting from the typhoon was clearly shown (Fig. 5). Closer examination of the data also shows the influence of tidal conditions on the typhoon-generated suspended sediments with the result that elevated concentrations are present for over 60 hours, including 16 hours after all typhoon signals were lowered (Fig. 6).

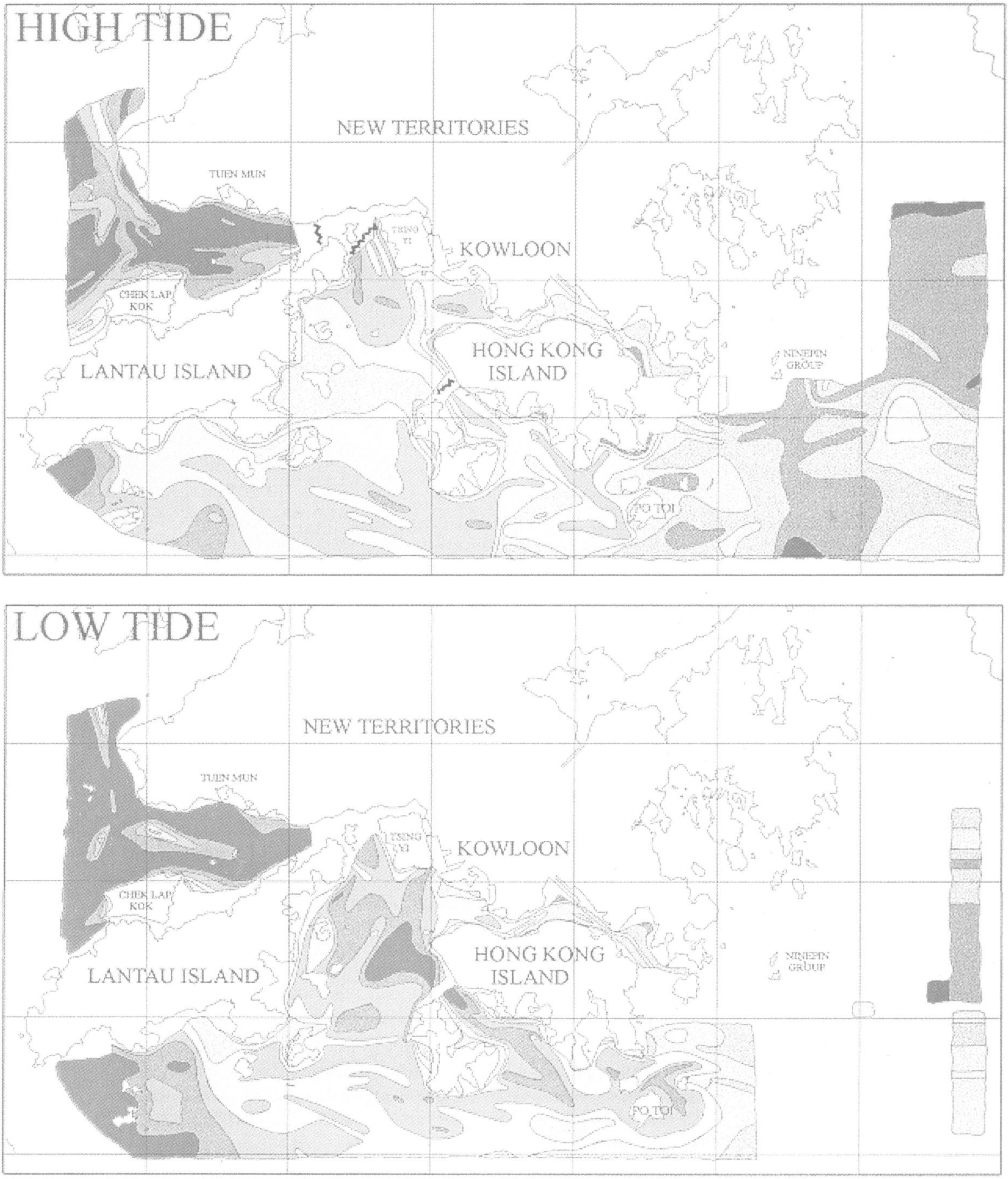

Fig. 4. Dry season territorial suspended solids survey (November 1994)

Key

Depth-averaged solids concentrations :

■ <2.5 mg/l
▩ 2.5 - 5.0 mg/l
▨ 5.0 - 10.0 mg/l
▧ 10 - 25 mg/l
□ 20 - 50 mg/l
▤ 50 - 100 mg/l
▦ 100 - 250 mg/l
■ >250 mg/l

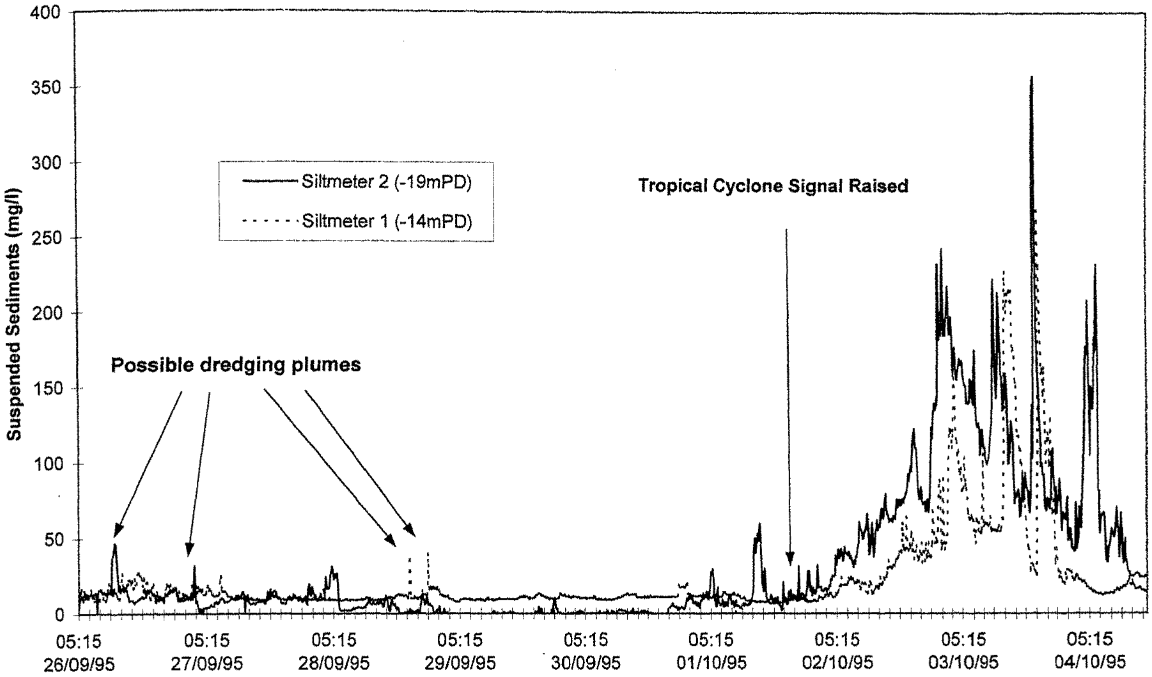

Fig. 5. Dredging plumes compared with the effects of Typhoon Sybil on suspended sediment, October 1995

In addition to typhoons, the strength of the northeast monsoon is sufficient to disturb seabed sediments, with Watts (1973) stating that low visibility occurs in Hong Kong waters in from October to December. He considered that this was at least partly due to the strong wind action of the north east monsoon. The actual wind data for Hong Kong's eastern waters in 1994 was used to recreate the wind induced wave climate from which it is possible to determine wave induced bed shear stress (Hyder, 1997a). Hyder's work showed that the highest mean monthly predicted bed stresses were for November to March associated with the northeast monsoon. Based on the 1994 wind data it was shown that re-erosion of mud suspensions would have occurred for a total of almost 10% of that year, and that even the critical shear stress required to erode in-situ Hang Hau Formation mud would have been exceeded for four hours that year.

The effect of the northeast monsoon is also reflected in the EMA water quality monitoring data for dredging at East Tung Lung Chau. Figure 7 (overleaf) shows the variability of suspended sediment in basal waters at monitoring station B9, approximately mid way between East Tung Lung Chau and Ninepins, remote from the sand dredging area. The dredging itself was relatively small in scale and was completed by July 1995. Using a moving average plot, suspended sediment concentrations are shown as peaking in spring, decreasing until July, slightly increasing until December before increasing rapidly to a peak again in spring. This results in the basal suspended sediment concentrations increasing from a monthly average of 23 mg/l in July to a maximum of 45 mg/l in March. A similar pattern was shown for surface waters with concentrations increasing from 5 mg/l to 21 mg/l over a similar period. It is important to note that even though this data was collected on a daily basis it does not reflect the effects of typhoons, such as Typhoon Sybil, as the monitoring was suspended during these periods.

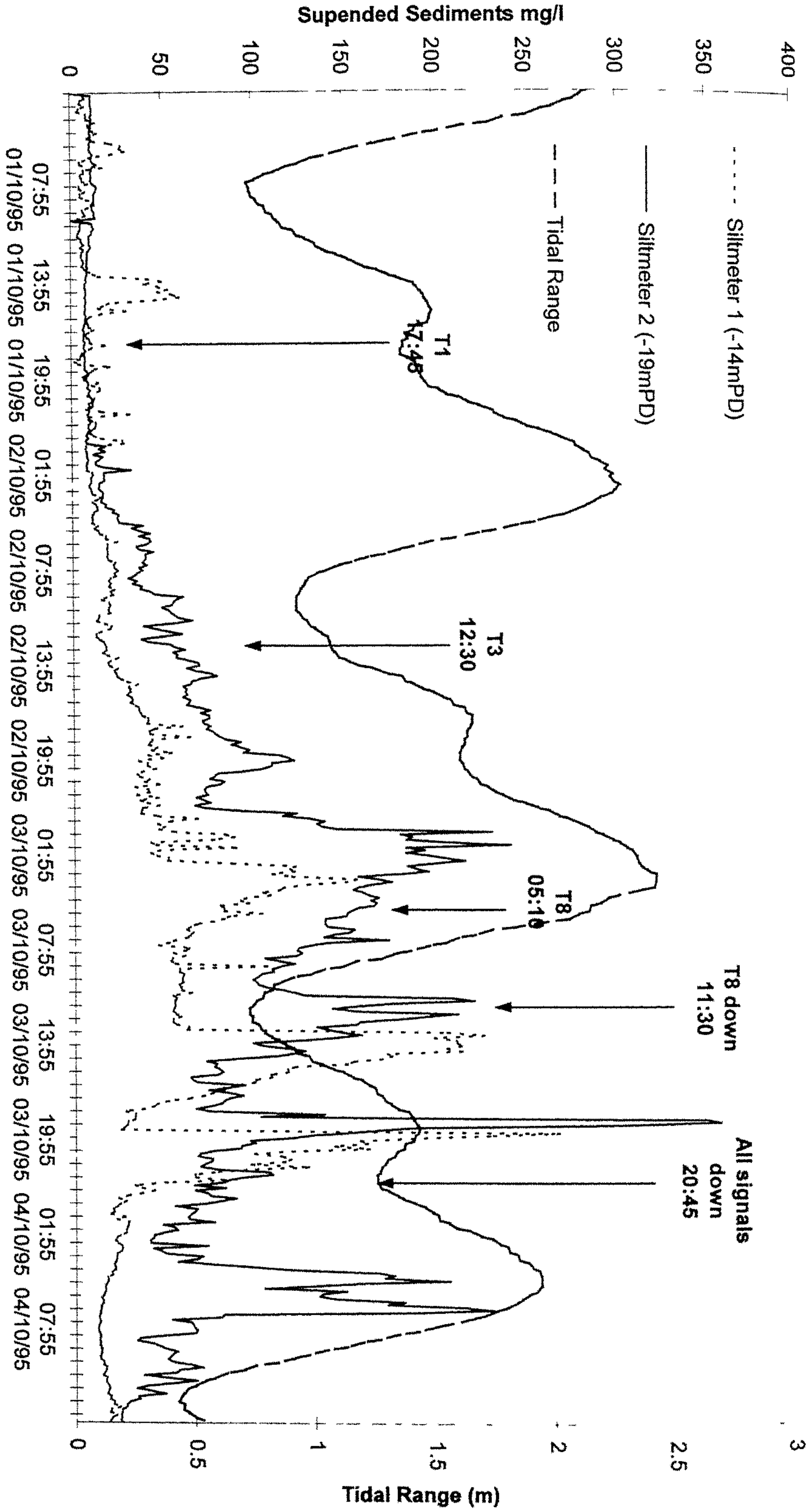

Fig. 6. Typhoon impacts and tidal conditions

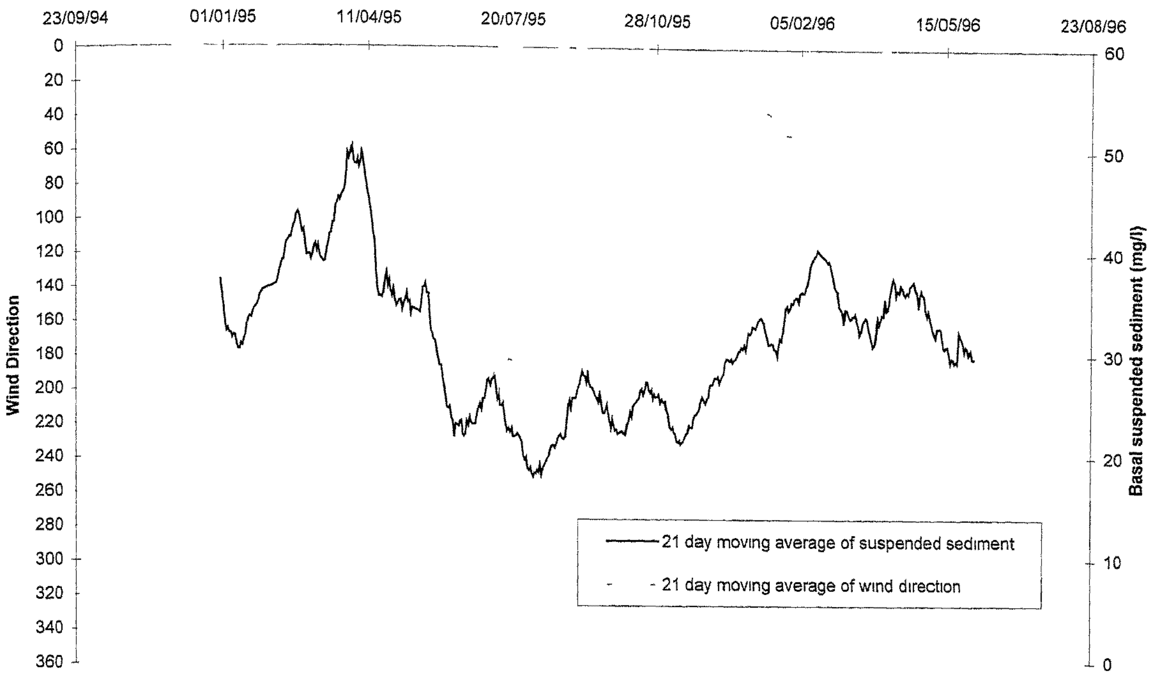

Fig. 7. Variations of basal suspended sediments with wind direction, eastern waters

Hong Kong's Rivers

EPD carries out routine river water quality monitoring at a number of stations throughout Hong Kong, with measurements at the majority of stations carried out on a monthly basis. Consequently it is unlikely that extreme rainfall events, such as typhoons which result in intense runoff, will be recorded. Even without such events being measured significant sediment loads have been recorded throughout Hong Kong, with flows in excess of 4000 l/s and suspended sediment concentrations of up to 1900 mg/l (EPD, 1997). This data only covers natural stream courses and does not include stormwater drains which will also have significant sediment loading during high rainfall events. A number of rivers were also studied as part of the Territorial Land Drainage Flood Control Study (Hyder, 1997b) which estimated an average sediment yield of over 50 000 tonnes, of which 67% was attributed to natural erosion and the remainder from construction/quarries, with 80% to 90% of the sediment yield expected to occur in the period April to October.

Anthropogenic Impacts on Suspended Sediment

Shipping

In 1996, there were over 82 000 ocean vessel movements and over 130 000 Macau and mainland passenger vessel movements in Hong Kong. In addition to these vessels there are numerous ferries, fishing vessels, lighters etc. moving within Hong Kong every day. Marine vessels, especially deep draught and high speed vessels, result in the resuspension of seabed sediments due to the action of propeller wash. However, there is no data available for the extent, duration and cumulative effects of these events.

Sewage and Drainage

Some 1.5 Mm^3 of sewage is released into Victoria Harbour waters every day (EPD, 1995). Assuming the sewage has an average suspended solids concentration of 220 mg/l (Metcalf and Eddy, 1991), this would result in some 120 000 tonnes of sediment per year released into Victoria Harbour.

Reclamation

Between 1990 and 1997 some 390 Mm^3 of fill was used in Hong Kong to create 1875 ha of land, of which 62% was marine-sourced and the reminder from land borrow areas. The General Specification for Civil Engineering Works (CED, 1992) specifies that the fines content for underwater fill for marine works be less than 30%. However, many individual contract specifications stipulated values less than this, often as low as 5%. (Kwan, 1993).

There is limited information with respect to the fines content of dredged sand following extraction but prior to emplacement. DEMAS (1995) measured the average fines content in the hopper of a trailing suction hopper dredger at the Po Toi Marine Borrow Area and found it to be less than 5%. With respect to the fines contents at the reclamation site, these have been reported as varying from 0 to in excess of 20% with the average fines content typically varying from 2 to 4.5% (Shen et al 1997). This is in line with Kwan (1993) who noted that the typical average fines content for 13 reclamation contracts varied from 2% to 8%.

With bottom dumping there is little chance of segregation of fines, whilst with hydraulic placement fines tend to settle further from the discharge point. However, any losses from reclamation sites are minimised by the construction of a seawall in advance of the reclamation.

Dredging and Mud Disposal

As part of an ongoing programme of environmental study work by GEO, the development and decay of dredging plumes has been investigated. A detailed study (DEMAS, 1995) was carried out using four survey boats equipped with acoustic Doppler current profilers (ADCP's), siltmeters and water samplers together with measurements taken on board the dredger. This study showed that approximately 70% of the sediment from the dredger overflow is carried directly to the seabed in the immediate vicinity of the dredger, as a density flow. Any sediment remaining in suspension was found to decay to background levels within two to three hours (Whiteside et al, 1995). Similar results were also observed in a further plume test in 1996 (DEMAS, 1997). Since 1990 some 4900 ha of seabed, or less than 3% of the sea area of Hong Kong, have been dredged for sand.

Losses during mud disposal operations have also been studied for both trailer dredgers and barges. For trailer dredgers (DRL, 1996b) the losses varied from 0.9% to 2.1% for a split-hulled trailer and from 5.3% to 8.7% for a door discharge trailer. Neither vessels were considered "typical" trailers. However, the values measured support the generally adopted value of 5% losses. For barges losses of 1.2% to 3.1% have been recorded (DRL, 1995b). Since 1990 some 3280 ha of seabed, or less than 2% of the sea area of Hong Kong, have been used for the disposal of marine mud.

These studies have shown that, provided the dredging works are properly carried out, the impacts on the environment from sand dredging and mud disposal are transient and are limited to the immediate location of the works. Other studies (ERM, 1998; Leung, 1997) have also shown that development related impacts, such as sand dredging and the generation of suspended sediments, have had little impact on fish stocks in Hong Kong.

Fishing

Whilst there is no published data on the effects of trawling on the seabed in Hong Kong, studies have been carried out elsewhere. Churchill (1989) described how trawling can generate significant amounts of suspended sediments with values between 100 mg/l and 550 mg/l reported 100 m astern of shrimp trawlers, and it was estimated that trawling-generated plumes extend in excess of 10 m above seabed.

During a study of Hong Kong's eastern waters (Selby & Evans 1997), side scan sonar showed extensive disturbance of the seabed. The near seabed sediments in these areas comprised the "puzzle fabric" type of seabed discussed earlier, and it was concluded that this fabric was trawling induced.

The frequency of the trawling probably leads to a continual reworking of the uppermost seabed with clasts and suspensions remobilised to form turbid plumes. It was estimated that during a three hour trawl, a single large shrimp trawler can disturb up to 0.5 km^2 of seabed. AFD's 1997 vessel count recorded 4857 fishing vessels in Hong Kong, of which 54% are less than 5 m in length. Of the remaining vessels in excess of 600 are either shrimp or stern trawlers (ERM, 1998), suggesting the potential for vast areas of the seabed to be disturbed on a regular basis.

In addition to capture fisheries there are 26 mariculture sites throughout Hong Kong producing about 3000 tonnes of fish per annum (Wilson & Wong, 1995). The use of fixed positions for the fish cages in sheltered bays with only 3-5 m of water results in increased localised suspended sediments and sedimentation as a result of fish feeding, especially overfeeding with trash fish, and waste by-products.

Conclusions

In summary, Hong Kong is situated at the estuary of the third largest river in China and is affected by changing oceanic currents, tidal effects, extreme climatic conditions and significant anthropogenic influences. Consequently, monthly or bimonthly data is not considered sufficiently frequent to determine the naturally occurring variations in suspended sediment levels. Figure 8 shows again the continuous suspended sediment values during the passage of Typhoon Sibyl. Also shown are the suspended sediment values recorded on a daily basis from EMA monitoring to the west of Po Toi. No EMA data were collected during the typhoon because of the sea conditions and consequently its impacts are not recorded. Finally the result for EPD's nearest monitoring station is shown for the entire period, comprising a single reading.

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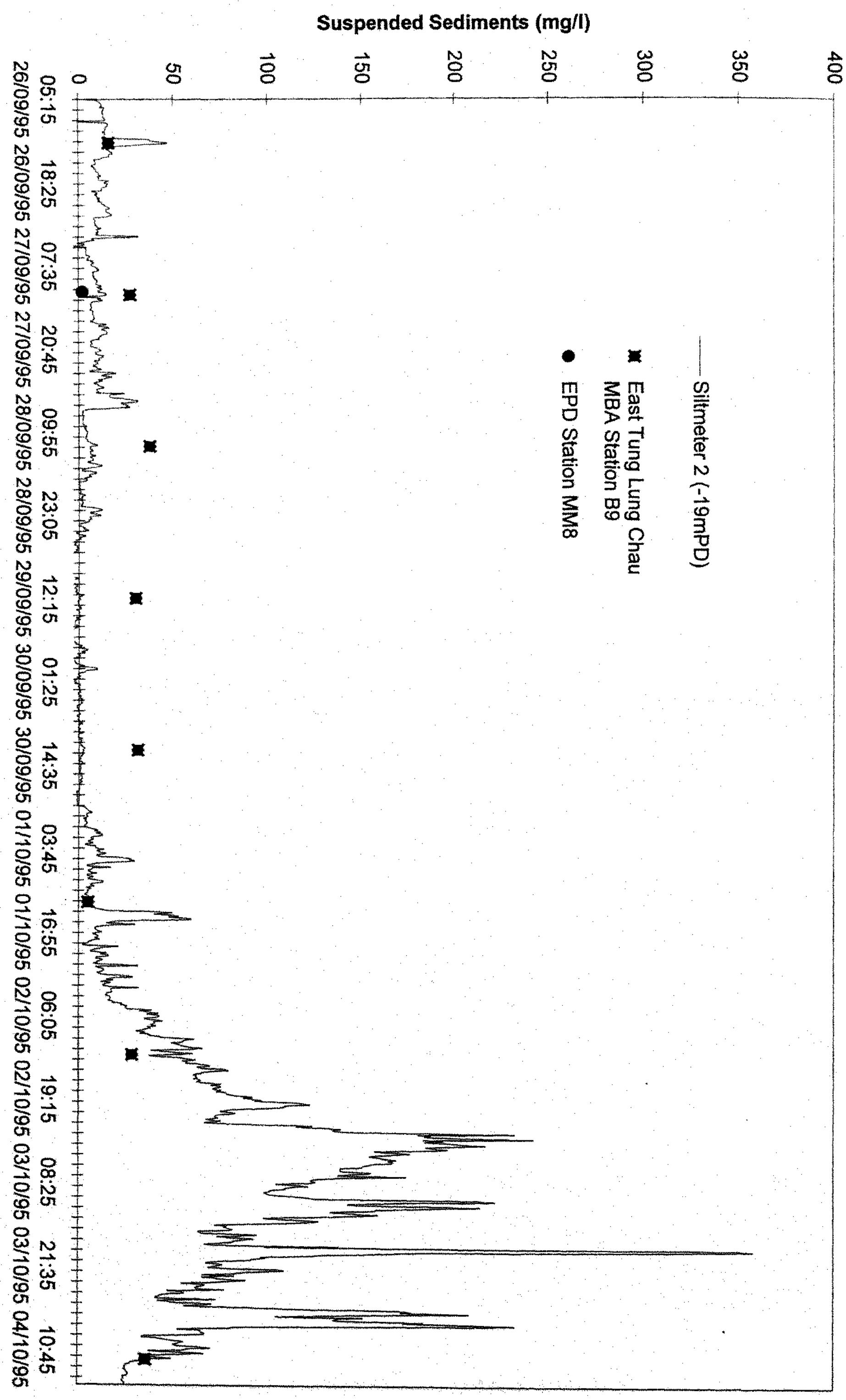

Fig. 8. Comparison of continuous, daily and monthly monitoring

References

*Binnie Consultants Limited (1995b) Fill management study Phase IV investigation and development of marine borrow areas. *Baseline Remots and Benthic Grab Sample Survey of the Eastern Waters Marine Borrow Area.* October 1995

CED (1992) *General Specification for Civil Engineering Works.* 3 Volumes, Civil Engineering Department, Hong Kong

Chen Shangqun & Che Wencai (1992) Analysis of the Hydrological and sedimentary characteristics of the water zone around Macao. *Proceedings of the International Conference on the Pearl River Estuary in the Surrounding Area of Macau*

Churchill JH (1989) The effect of commercial trawling on sediment resuspension and transport over the Middle Atlantic Bight continental shelf. *Continental Shelf Research* Vol 9 No. 9, pp 841-864

*DEMAS (1995) *Suspended Solids Concentrations in Dredging Plumes*

*DEMAS (1997) *Suspended Solids Monitoring During Sand Dredging in the South Tsing Yi MBA, Borrow Pit 1*

*Dredging Research Limited (1994) Study and measurement of dredged materials. Suspended sediment data collection. *Draft Report on the First Territorial Suspended Sediment Survey (August 1993)*

*Dredging Research Limited (1995a) Study and measurement of dredged materials. Suspended sediment data collection. *Second Territorial Suspended Sediment Survey (Dry Season) November 1994*

*Dredging Research Limited (1995b. Study and measurement of dredged materials. *Measurements of Losses During Dumping from Barges at the East Sha Chau Contaminated Mud Disposal Pits (August 1995*)

*Dredging Research Limited (1996a) *Study and Measurement of Dredged Materials*. Suspended sediment data collection. Draft final report

*Dredging Research Limited (1996b) *Measurements of Sediment Transport after Dumping from Trailer Suction Hopper Dredgers in the East Tung Lung Chau Marine Borrow Area, Agreement CE 2/93*

Dyer KR (1986) *Coastal and Estuarine Sediment Dynamics*. John Wiley and Sons

*EGS (1996a) East Sha Chau borrow pits. *EIA for Backfilling of Pits with Contaminated Mud. Collection of Field Data for Calibration of Hydraulic Model Wet Season Measurements*. ERM Hong Kong Ltd

*EGS (1996b) East Sha Chau Borrow Pits. *EIA for Backfilling of Pits with Contaminated Mud. Collection of Field Data for Calibration of Hydraulic Model Dry Season Measurements*

EPD (1995) *Cleaning Up Our Harbour*. April 1995

EPD (1997) *River Water Quality in Hong Kong for 1996*

*ERM (1998) *Fisheries Resources and Fishing Operations in Hong Kong Waters.* Final report, March 1998

Fyfe JA, Selby IC, Plater AJ & Wright M (1999) Erosion and sedimentation associated with the last sea level rise offshore Hong Kong South China. *Quaternary International*

*Hyder Environmental (1997a) *Sand Dredging and Backfilling of Borrow Pits at the Potential Eastern Waters Marine Borrow Area.* Civil Engineering Department Agreement no. CE62/94

*Hyder Environmental. (1997b) *Territorial Land Drainage & Flood Control Strategy Study* - Phase III sedimentation study

*Hydraulic Research Ltd (1990) Port and Airport Development Strategy: Enhancement of the WHAMO mathematical models. Physical Properties of a Bed Sample from the North East New Territories. Report EX2208

Ip KL (1995) Victoria Harbour, Western Harbour and North Lantau Waters. *Proceedings of the Symposium on the Hydraulics of Hong Kong Waters*

Kirby R (1992) Detection and transport of high concentrations of suspensions. *Proceedings of the International Conference on the Pearl River Estuary in the Surrounding Area of Macau.* p67-84

Kot SO & Hu SL (1995) Water flows and sedimentation transport in Pearl River Estuary and waves in South China Sea near Hong Kong, *Proceedings of the Symposium on the Hydraulics of Hong Kong Waters*

*Kwan SH (1993) *Review of Specifications for Marine Fill for Reclamation.* Technical note TN 3/93. Geotechnical Engineering Office

Leung AWY (1997) The impact of dredging and fishing on the benthic fish fauna of the south-eastern waters of Hong Kong. In: Morton B (Ed.) *Marine Fauna and Flora of Hong Kong and Southern China. Proceedings of the 8th International Marine Biological Workshop,* HK University Press, Hong Kong

*Maunsell Scott Wilson (1991) South East Tsing Yi Port Development. Planning & Engineering Feasibility Study for Container Terminal No. 9. Final Report Appendices. Territorial Development Department

Metcalf & Eddy Inc (1991) Wastewater Engineering. Treatment, Disposal and Reuse. 3rd Edition, McGraw Hill.

Milliman JD & Meade RH (1983) World-Wide Delivery of River Sediment to the Oceans. *Journal of Geology.* Vol 91 Number 1 p1-21

*Ravensrodd Consultants Limited (1991) *Hydrological and Sedimentological Regimes of Waters around Hong Kong*

Royal Observatory, Hong Kong (1995) *Monthly Weather Summary October 1995*

Schubel JR (1972) Effects of tropical storm Agnes on the suspended sediments of the North Cheasapeake Bay. In: Gibbs RJ (Ed) *Suspended Solids in Water.* Plenum Marine Science, 4, pp133-132

Selby IC & Evans NC (1997) Origins of mud clasts and suspensions on the seabed in Hong Kong. *Continental Shelf Research.* Vol 17 No 1 pp57-78

*Shen CK, Lee KM & Li XS (1997) *A Study of Hydraulic Fill Performance in Hong Kong - Phase 2.* GEO Report 64

Watts JCD (1973) Further Observations on the hydrology of the Hong Kong territorial waters. *Hong Kong Fisheries Bulletin No. 3*

Whiteside PGD, Ooms K & Postma GM (1995) Generation and decay of sediment plumes from sand dredging during overflow. *Proceedings of the World Dredging Conference.* Amsterdam 1995

Wilson, KDP & Wong CK (1995) Fisheries, mariculture and marine protected areas. *Proceedings of the Symposium on the Hydraulics of Hong Kong Waters*

* These reports can be consulted in the Civil Engineering Library of the Civil Engineering Department, Government of the Hong Kong Special Administrative Region.

Quarrying in Hong Kong: Current and Future Situation

T.S.K. Lam[1] & K.L. Siu[2]

Abstract

Hong Kong has four quarries: Anderson Road, Shek O, Lamma and Lam Tei Quarries. They all produce rock products for the construction industry. These quarries meet about 50% of the local aggregate requirements, in the range of 6 million to 9 million tonnes per annum. The rest is imported from the Chinese mainland. The remaining life span of the four existing local quarries is limited to only a few years, except for Anderson Road Quarry which will last until 2013. By 2003, it is estimated that a total of 76% of Hong Kong's current supply sources will be lost. The need for future quarrying in Hong Kong (i.e. new quarries) should be studied to decide whether Hong Kong should rely solely on external sources or maintain the present balance of deriving 50% (or some other percentage) of its requirements from domestic quarries. A study will be undertaken by the Government to study the need for future quarrying in Hong Kong.

Key words: quarrying, supply, demand, site restoration, new developments, arguments for and against.

Introduction

Despite a land area of only 1090 km^2 and a population of some 6.6 million, Hong Kong has four quarries to serve its construction industry: Anderson Road, Shek O, Lamma and Lam Tei Quarries. The four quarries all have a long history and some date back to the 1950s, providing aggregates for concrete and asphalt production. A historical review of quarrying in Hong Kong can be found in Earle (1990) and Li (1990).

In this paper, the demand and supply of aggregates in Hong Kong, details of quarries in Hong Kong, the methods used to rehabilitate the quarries and the future of quarrying in Hong Kong are discussed.

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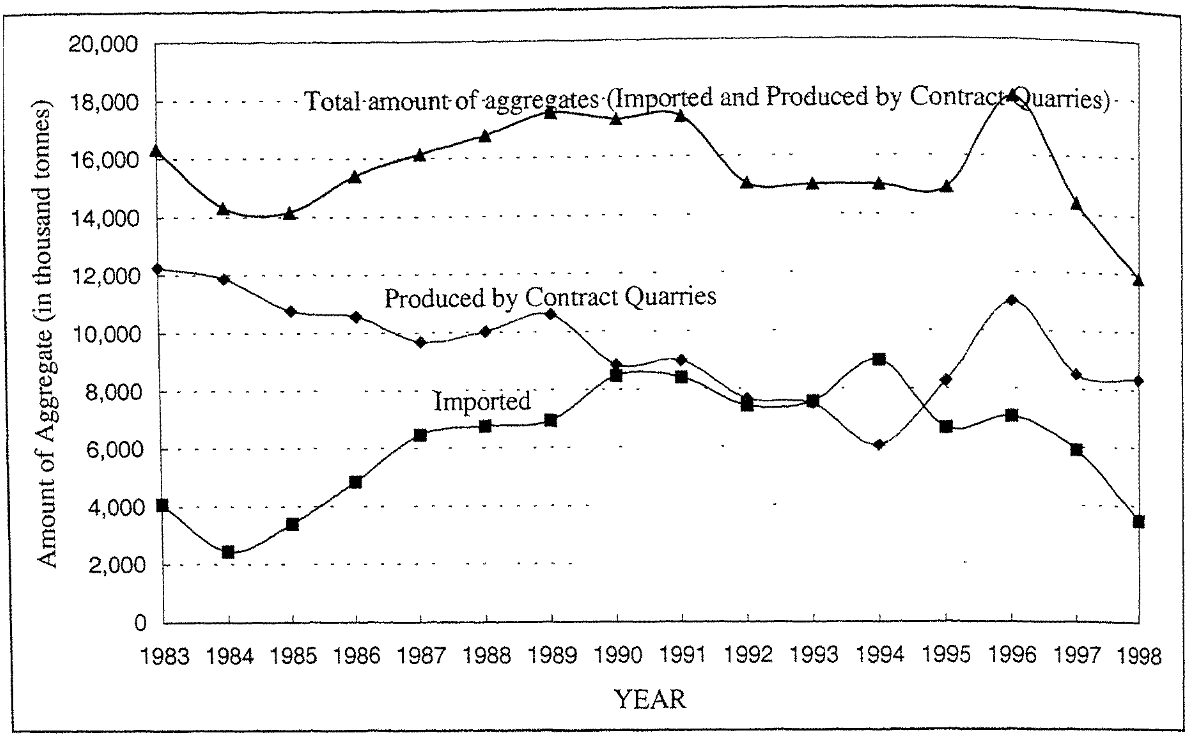


Fig. 1. Amount of aggregates imported and produced by contract quarries in Hong Kong. Data are end-of-year data

Demand and Supply of Aggregates in Hong Kong

The amount of aggregates imported and produced by local quarries is given in Fig. 1. Like rice, aggregates are needed everyday in Hong Kong. In the past 15 years, a total of 229 M tonnes of aggregates were consumed. In 1998 alone, 12 M tonnes were used (equivalent to the amount of aggregates used for constructing nineteen 2.2-km-long Tsing Ma Bridges or three 78-storey Central Plazas). This amounts to about 1.8 tonnes of aggregates consumed per head in Hong Kong in the year.

The quarries in Hong Kong produce about 50% of the local aggregate requirements, in the range of 6 million to 9 million tonnes per annum. The remaining 50% is imported from the Chinese mainland, mainly from quarries located on islands to the south and west of Hong Kong. The amount of imported aggregates has remained fairly constant over the last 10 years, at an average of approximately 7.5 million tonnes per annum. At present, there are 19 quarries in Shenzhen and 12 in Zhuhai, as shown in Fig. 2. Prices of aggregates have also been fairly steady, with locally produced aggregates in the range of HK$40 to $60 per tonne and imported aggregates about $40 per tonne, as shown in Fig. 3.

Quarries in Hong Kong

The locations of the four quarries in Hong Kong are shown in Fig. 2 and the programme for the quarry contracts is shown in Fig. 4. The Lam Tei Quarry contract finished in 1999, and will be followed by the Lamma Quarry contract in 2002, the Shek O Quarry contract in 2005 and the Anderson Road Quarry contract in 2013. The last three quarries are running on new rehabilitation

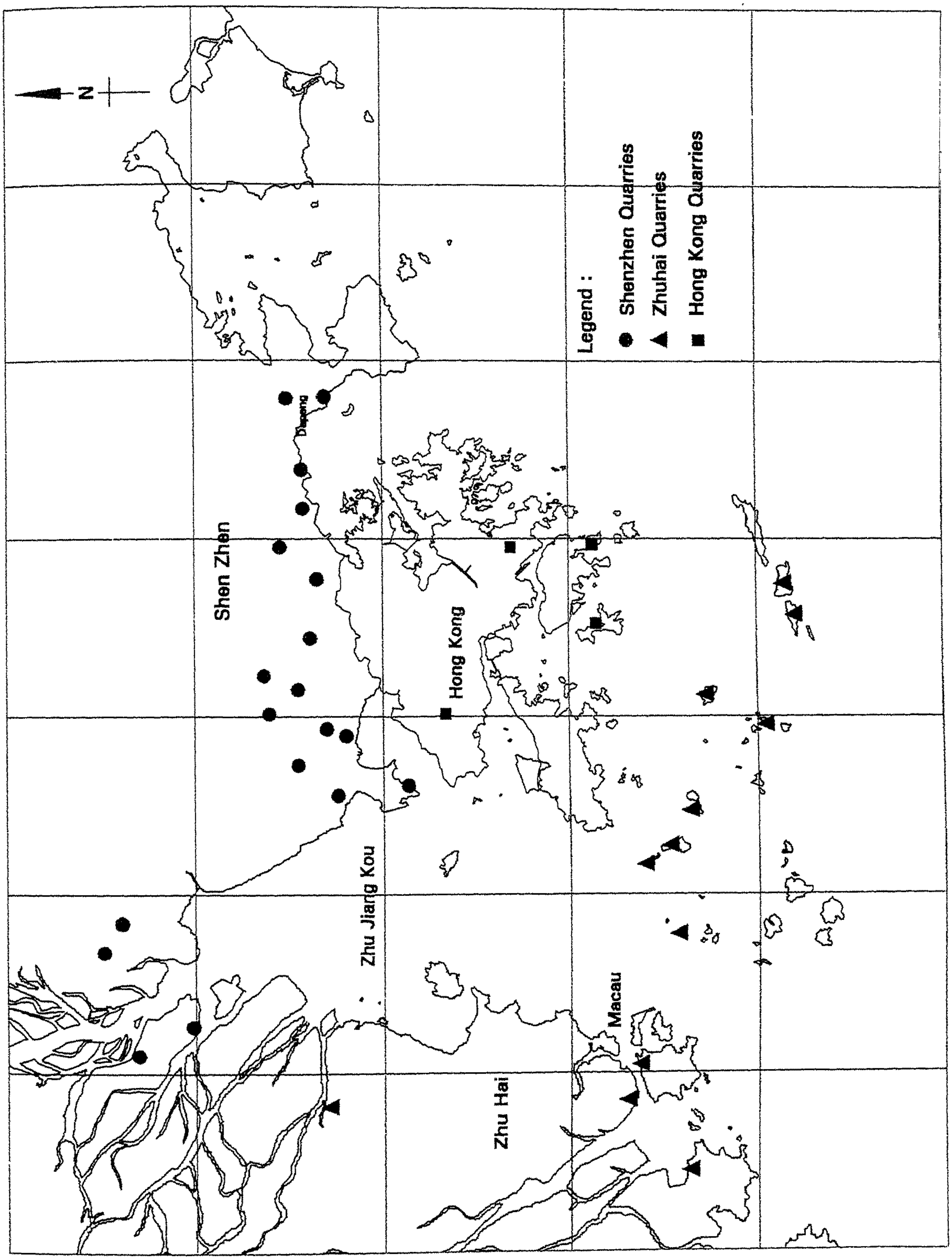


Fig. 2. Location of quarries in Hong Kong and the surrounding Chinese mainland

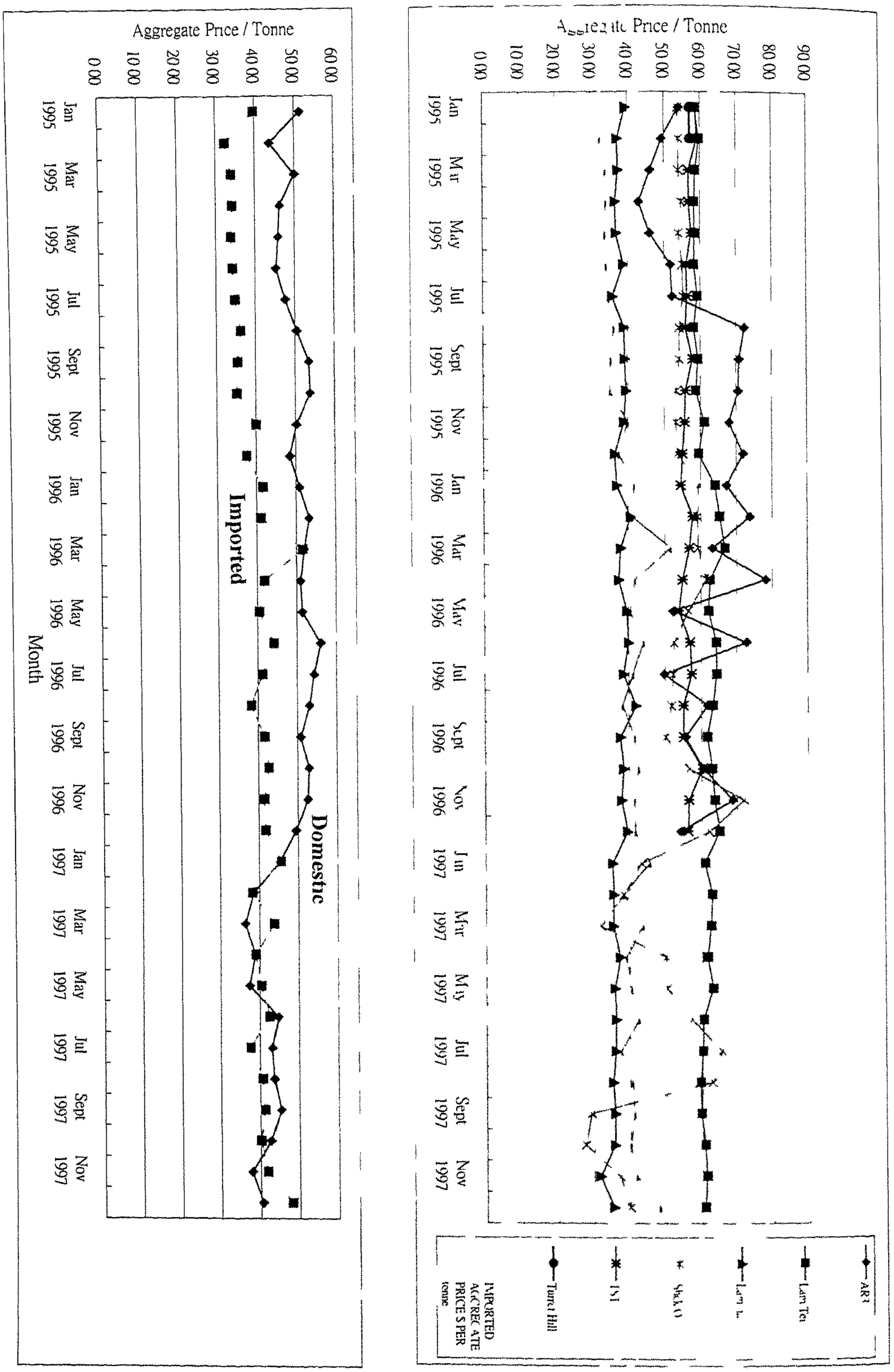


Fig. 3. Price comparison of imported and locally produced aggregate

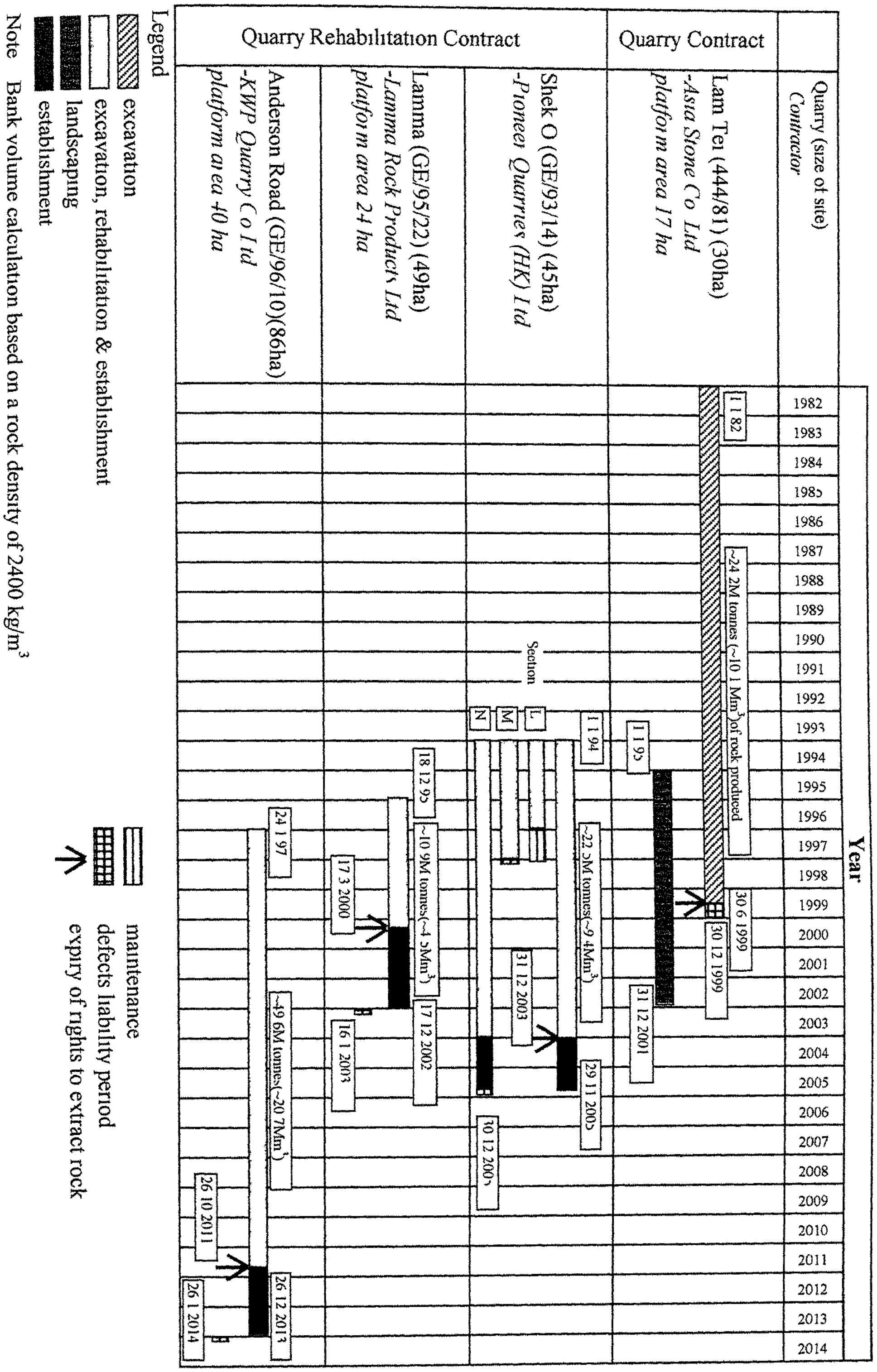


Fig. 4. Programme for the quarry and quarry rehabilitation contracts Bank volume calculation based on a rock density of 2400 kg/m³

contracts, which are for fixed time periods with no rights to rock extraction after the expiry of the contract periods. The first quarry, Lam Tei, operates under the old type of contract with a guaranteed contract volume, requiring the Government to extend the contract period if there are good reasons why the contract volume has not been extracted. A supplementary agreement has been signed for this quarry which specifies that the contractor also needs to complete the rock excavation within a definite time.

A quarry rehabilitation contract is essentially a large site formation contract in nature with rehabilitation (restoration and landscaping) being the main focus. All quarry contracts are design and build and revenue earning contracts, which are different from the normal type of works contract. The contract sum is given by the difference between the value of rights and the cost of works. The types of rights that the operator enjoys in the contract include, for example, selling or removing from the site rock and overburden that are surplus to the requirements of the works, processing of excavated rock for sale, production and selling of ready-mixed concrete and bituminous materials, etc. The cost of works is the amount of works that the operator needs to carry out for the Government in association with the contract, such as site formation, rehabilitation, road works, etc. The contract sum is the amount that the operators need to pay the Government in terms of rental and royalty payments. The Government collects on average a yearly revenue of $50 million from the industry.

Besides aggregates, local quarries also produce fines (<5 mm stone fines) and other rock products which include mainly road sub-base, scalping (inferior rock and clay material removed from the main feed to a mineral-processing plant), crushed/screen fill, pell-mell, armour rock, etc. Fines are used for concrete production as a substitute for sand in some works. In 1998, aggregates constituted 54% of the overall quarry production, fines 34% and other rock products 12%.

As part of the quarry contracts, some notable works that have been or will be carried out are:

(a) Shek O Road at Shek O Quarry (Figure 5). The road has been realigned and improved as part of the quarrying works. The old road had a 180° hairpin bend at Tai Fung Au, its junction with Cape D'Aguilar Road. The bend was eliminated with a turn around as a result of the new road construction. The new road shortens the travel distance by almost 660 m and has improved markedly the traffic conditions with curves of larger radius. As part of the road project, an 3.8 m high amenity earth bund was built on the south side of the road, forming a screen for the quarry operation below, and a series of 10- to 50-m-high man-made slopes comprising 70° rock cut slopes at the bottom and scree slopes above the rock cut were formed on the north side. The new road was opened in mid-August 1997.

(b) Rehabilitation of the quarry face at Anderson Road Quarry. To rehabilitate and flatten the over-steepened slopes, the ridgeline of Tai Sheung Tok needs to be lowered by about 20 m on average. The reduction is less than 10% of the overall height of the mountain (460 m). As a result of the rehabilitation works, a platform of 40 ha suitable for housing development will be formed, and the overall shape and appearance of Tai Sheung Tok will also be improved. Trees and other vegetation will be planted to blend in with the surrounding natural environment.

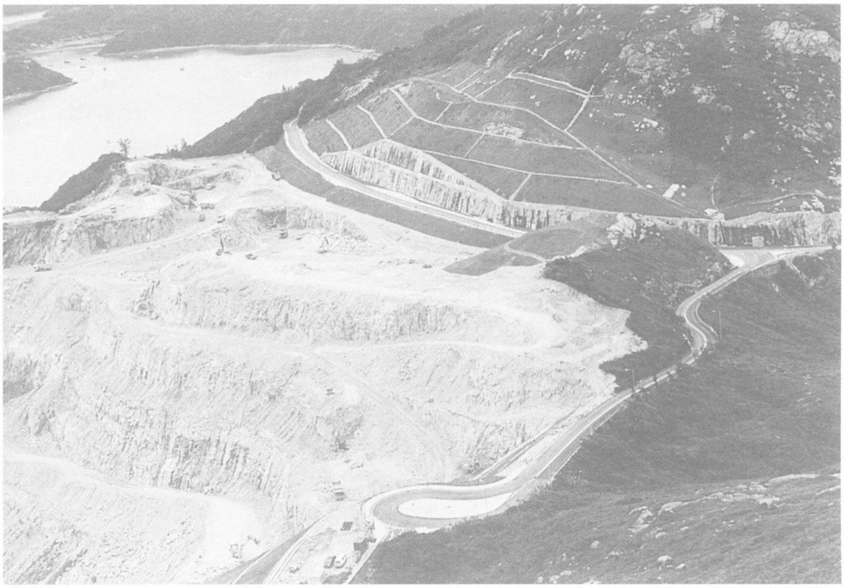


Fig. 5. The new Shek O Road at Shek O Quarry

Quarry Rehabilitation Methods

Quarry rehabilitation methods can be broadly classified into two main categories in terms of the configurations of the final landform produced. These categories are:

(I) Overall slope angle of final landform of about 35° (typical examples are Shek O and Lamma Quarries) (see Coombs, 1990).

(II) Overall slope angle of final landform greater than 55° (typical examples are Anderson Road and Lam Tei Quarries, and Turret Hill Quarry at Shatin, which was completed in 1995).

For Category (I), the scree slope method is used. The procedures employed by this process include:

(a) formation of a final landform of 70° slope typically 10 m high

(b) formation of a 35° scree slope which is composed of broken and shattered rock fragments

(c) placement of a geotextile filter layer

(d) laying of a 500 mm soil mantle composed of completely decomposed granite, organic conditioner and nutrients, encouraging rapid tree growth on the filter layer which prevents the migration of fines from the soil mantle to the scree slope

(e) hydroseeding

(f) placement of a biodegradable mat on top of the soil mantle to retain grass seedlings

(g) placement of an erosion control mat

(h) planting of trees and shrubs.

For Category (II), the bench slope method is used. The procedures include:

(a) formation of a final landform of 60° to 70° slope typically 15 m high

(b) construction of a mortared rock support at slope berm (bench)

(c) construction of drainage channel

(d) formation of rock fill (formed by shot rock) on the bench

(e) placement of a 150 mm thick filter layer of 10 to 50 mm aggregates on top of the rock fill slope

(f) placement of 500 to 600 mm thick completely decomposed granite soil layer (the top 150 mm is mixed with soil conditioner and fertilizer)

(g) placement of an erosion control mat

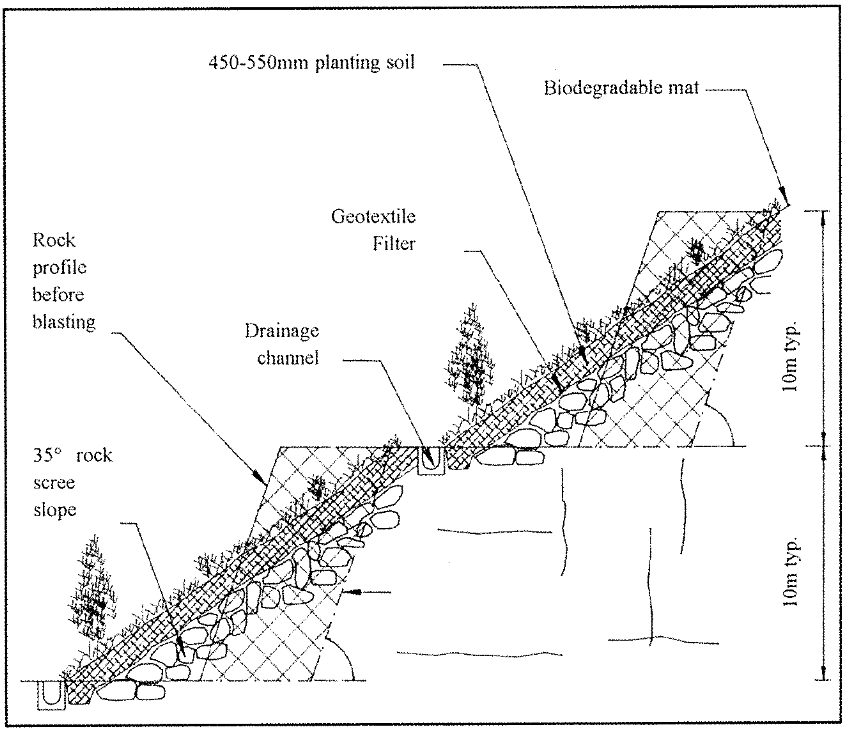
(h) hydroseeding and placement of a biodegradable mat on top of the soil mantle to retain grass seedlings

(i) planting of trees, shrubs and climbers.

Cross-sections of scree and bench slopes are shown in Figs. 6 and 7.

Views of the formed scree slope at Shek O Quarry and the bench slope at Lam Tei Quarry are given in Figs. 8 and 9. The landscape restoration is being undertaken progressively during the course of quarrying. Full cover of grass will be achieved within a few weeks after planting. Trees and shrubs will take 3 to 5 years to establish. It takes 10

Fig. 6. Cross-section of a scree slope



to 15 years for the rehabilitated area to become part of the natural environment. There will be no difference between the rehabilitated area and the natural environment in the long term. The same sort of vegetation and ecological habitats as those in the surrounding natural hill slopes will be established within the rehabilitated areas after rehabilitation. After rehabilitation, a natural self sustaining system and hence a viable ecosystem will be established.

Future of Quarrying in Hong Kong

The remaining life span of the four existing local quarries is limited. By the end of 2000, Lam Tei and Lamma quarries will be closed and 45% of the Hong Kong's domestic aggregate supply will be lost. Three years later, in 2003, Shek O quarry will be closed, by which time a total of 76% of Hong Kong's current supply sources will be lost, leaving Anderson Road as the sole operating quarry in Hong Kong.

The lead time for planning and establishing new quarries is likely to be a number of years, and the establishment of any new quarries can be expected to draw a lot of public concern requiring lengthy consultation.

There is an urgency to assess the need for future quarrying in Hong Kong now to decide whether Hong Kong should rely solely on external sources of aggregates, fines, other rock products and sand, over which the Government has little or no control (in terms of cost, availability and quality) or whether the present balance of deriving 50% (or some other percentage) of its requirements from domestic quarries should be maintained.

There are arguments for and against new quarries in Hong Kong as summarised below:

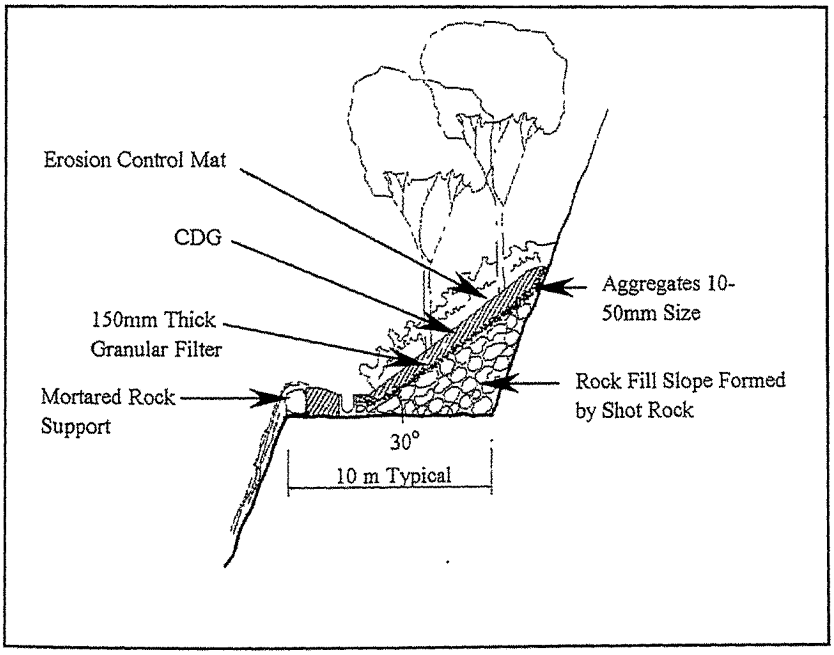


Fig. 7. Cross-section of a bench slope

For New Quarrying in Hong Kong

(a) Economic gain. This is one of the oldest industries of Hong Kong originating as far back as the 1950s. In 1998, the four quarries provided employment to more than 600 people. The Government currently receives an average yearly revenue of $50 million from the industry in rental payments and royalties.

(b) Market demand. The demand for aggregates will continue as Hong Kong enters into the twenty-first century with the planned development for housing and infrastructure.

(c) Self-sufficiency. The Government will have little or no control (in terms of cost, availability and quality) if Hong Kong is to rely solely on external sources of aggregates, fines, other rock products and sand. By maintaining several active quarry operations in Hong Kong, the Government has the flexibility of quickly increasing production at a reasonable price in the event of a sudden shortfall from the mainland quarries.

(d) More facilities to handle imported aggregates. More facilities, such as piers, barging and loading points, and storage and transfer stations will be needed to handle imported aggregates if Hong Kong has no quarry. These facilities give rise to environmental nuisance.

Against New Quarrying in Hong Kong

(a) Environmental impact. Quarry operation could have a substantial impact on the environment.

(b) Supply from mainland quarries. If there are large reserves of rock from various locations relatively close to but outside Hong Kong, the need for new quarries in Hong Kong is reduced.

Fig. 8. View of the formed scree slope at Shek O Quarry

(c) Scarcity of land. Identification of sites for quarries may not be easy as land is scarce in Hong Kong and most sites may have been reserved for other more important uses, such as residential development. Any new quarries identified should be located in sites composed of intrusive acidic granitic rocks, and away from urban areas (Government of Hong Kong, 1989), country parks, tunnels, firing ranges, pylons, power lines, etc.

The Government will carry out a study to assess the need for future quarrying in Hong Kong based on the arguments above and other factors. It is expected that the study be completed by December 2000. The following work will be included in the study:

(i) review supply and demand over the medium and long term (i.e. in 5, 10 and 20 years time) and quarry policy;

(ii) review arguments for and against new quarrying in Hong Kong;

(iii) recommend the need for future quarrying in Hong Kong based on the assessments above;

(iv) to allow for the possibility that new quarrying is needed, identify and study possible alternative sites in Hong Kong for quarry establishment;

(v) to allow for the possibility that new quarrying is not needed, identify alternative arrangements; and

(vi) recommend follow-up actions.

Conclusions

The following conclusions can be made from this review:

(a) The quarry rehabilitation works aim to turn degraded land into valuable sites through a rehabilitation process. Through the process, gains in terms of engineering, industry and economics are achieved by the

Fig. 9. View of the formed bench slope at Lam Tei Quarry

Government. The process brings revenue to the Government and sustains employment, and the land becomes a valuable resource at the expense of quarrying. Industry can make good use of the excavated rock and turn it into useful products for construction (e.g. concrete, asphalt, etc.), while making profits. This is also good in terms of conservation of natural resources.

(b) Quarry rehabilitation projects also aim to turn once-bare eyesores into areas covered with trees and vegetation, in harmony with the natural environment and suitable for future development. Many features, such as peregrine falcon nesting sites, natural-looking cliffs, marine coves, man-made lakes, etc., may be included in the final landform.

(c) The lifespan of the four existing local quarries is limited. There is an urgency to assess the need for future quarrying in Hong Kong now to decide whether Hong Kong should rely solely on external sources of aggregates, fines, other rock products and sand, or whether the present balance of deriving 50% (or some other percentage) of its requirements from domestic quarries should be maintained. The Government has undertaken to carry out a study to assess the need. It is expected that the study be completed by December 2000.

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References

Coombs A (1990) A Bioengineering Approach to Quarry Restoration. In: Houghton DA, Earle QG, Holley KG (eds) *The Hong Kong Quarrying Industry 1990-2000 A Decade of Change*, Hong Kong

Earle QG (1990) A Historical Review of Quarrying in Hong Kong. In: Houghton DA, Earle QG, Holley KG (eds) *The Hong Kong Quarrying Industry 1990-2000 A Decade of Change*, Hong Kong

Government of Hong Kong (1989) White Paper: *Pollution in Hong Kong - A Time to Act*

Li UK (1990) Hong Kong Legislation on Stone Quarries. In: Houghton DA, Earle QG, Holley KG (eds) *The Hong Kong Quarrying Industry 1990-2000 A Decade of Change*, Hong Kong

Weathering Profile Development Over Volcanic Rocks in the Tuen Mun Valley, Hong Kong

R.B. Owen[1] and R. Shaw[2]

Abstract

Deep weathering is a characteristic feature of tropical and subtropical regions. However, very little is known about the morphology of the weathering front at the base of the weathering profile, largely because most tropical areas lack sufficient borehole information to enable this surface to be mapped. Hong Kong is uniquely placed in this regard as intensive urban development has been accompanied by numerous ground investigations. Approximately 375 000 borehole records are held in the library of the Civil Engineering Department of the Hong Kong Government. Using these records, a recent investigation of the depth of weathering over the granite of the Kowloon Peninsula found a strong correlation between the topography of the weathering front and the main structural trends. Local variations in the pattern of weathering were found to be primarily a function of the geometry and infilling of joints. This study has extended that investigation to the Tuen Mun Valley, another area for which concentrated borehole data are available. Attention has been focussed on examining the style of weathering of the volcanic rocks, which are exposed over about 48% of the land area of Hong Kong. Over 4000 borehole logs from Tuen Mun valley have been interpreted and entered in a computer database. These data have been used to model variations in the thickness of weathering over the mainly volcanic lithologies in the area, and to examine the influence of the major structures that run through the Tuen Mun Valley. Other features, such as corestone development and distribution, have also been considered. The results of this study will further our understanding of weathering patterns in Hong Kong and have important practical applications in helping to refine and improve engineering ground models derived from borehole interpretations.

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Fig. 1 (facing). Location and geology of the Tuen Mun study area. Bedrock on the main valley floor is dominated by volcanic rocks, with sedimentary and granitic lithologies underlying valley side slopes (from Hong Kong Geological Survey maps Sheet 5 [GCO, 1988b] and Sheet 6 [GCO, 1988c])

Key words: weathering profile, subtropical weathering, volcanic rocks, 3D modelling, surface topography, corestones, faults, Tuen Mun, Hong Kong.

Introduction

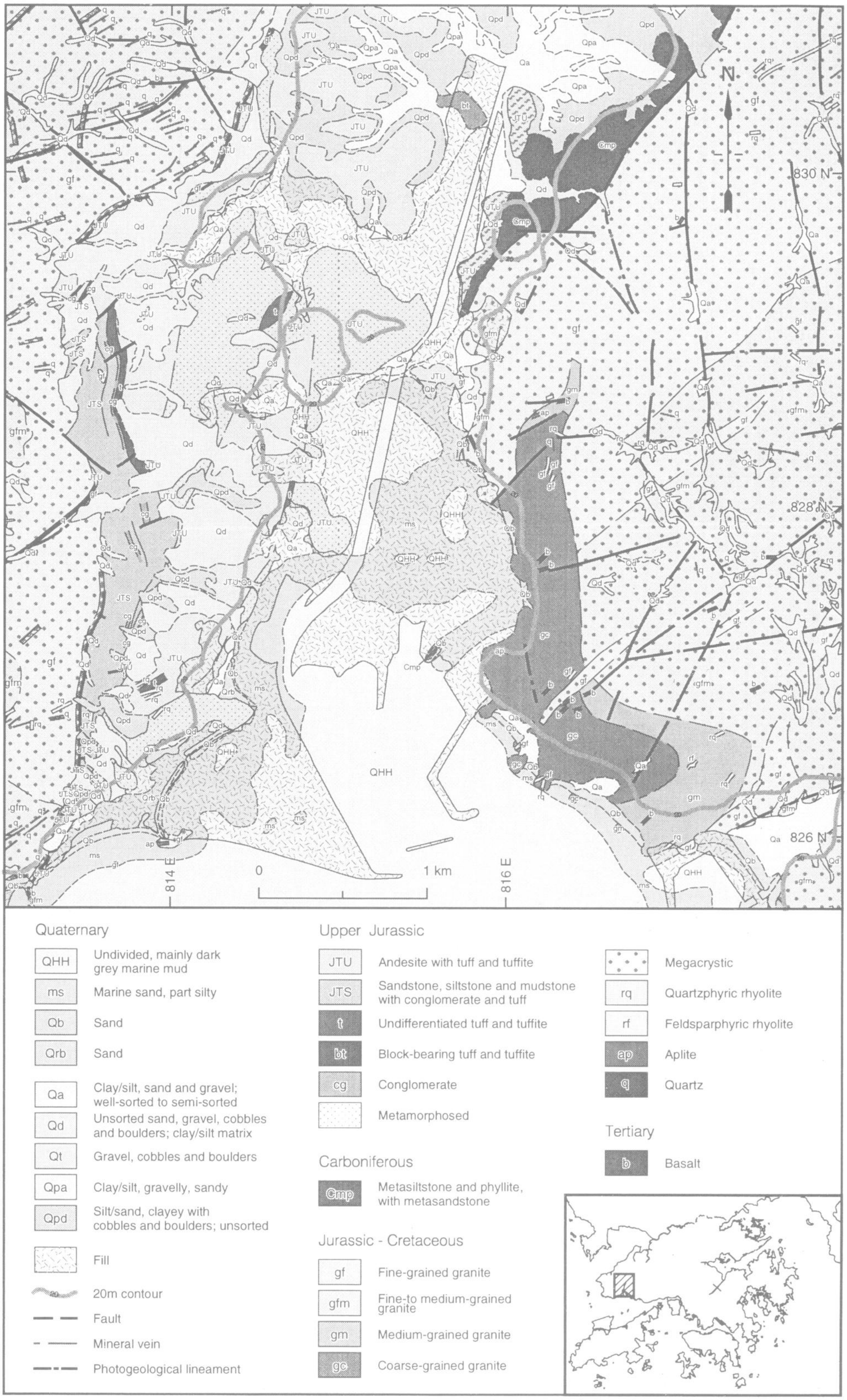
Tropical and subtropical landscapes are characterised by the development of deep weathering profiles overlying the bedrock, especially on igneous rocks. These residual mantles vary in their thickness and physical characteristics, variations that broadly depend upon the local lithology, geological structure, topography, and groundwater conditions. Factors such as the morphology of the weathering front, the thickness of the weathered mantle, the influence of weathering on the physical properties of the rocks, and their engineering implications are of practical concern to both geologists and geotechnical engineers. However, despite the importance of these variations for engineering designs, there have been very few studies of the regional patterns of weathering profile development. Most studies of tropical weathering have been site specific, largely because most tropical areas lack sufficient borehole information to enable mapping to be carried out. However, Hong Kong is exceptional in possessing a very large archive of borehole records from numerous ground investigations that have been carried out in the urban areas.

Recently, Shaw (1997) examined the spatial variations of weathered mantle over uniform granite of the Kowloon Pluton, using data from 4730 boreholes. Owen and Shaw (2000) have modelled weathering profiles near Yuen Long. The present study has extended that investigation to assess weathering over volcanic lithologies in the low-lying Tuen Mun corridor (Fig. 1). Borehole records were retrieved from the Geotechnical Information Unit (GIU), an archive of borehole data in the Civil Engineering Library of the Hong Kong Special Administrative Region (SAR) Government. A search of these records retrieved 4070 logs of boreholes drilled in the project area (Fig. 2). Location data and interpreted geological details were extracted and entered into a computer database. Absolute level of the ground surface, base of superficial deposits or fill, the highest positions of corestones in the profile (if present), and base of the weathered mantle were identified. Contours on the weathering front and isopachs of the weathered mantle were generated to establish a model of variations of the regolith in the study area.

The Tuen Mun Study Area

The Hong Kong SAR has a total land area of about 1075 km^2 that supports a predominantly urban population of 6.3 million people (1995 census), living mainly on Hong Kong Island, the Kowloon peninsula, and in eight new towns in the New Territories. Approximately 65% of the population live in towns built on granite bedrock, therefore the majority of ground investigations and construction projects are carried out on granitic rocks.

Although several of the new towns are underlain by volcanic rocks, no studies to date have examined the regional characteristics of weathered profiles in volcanic lithologies. Intensive ground investigations for Tuen Mun new town have provided an opportunity for an examination of weathering profile development over these lithologies in this area. The present study has assembled and assessed borehole information for the Tuen Mun valley in the western New Territories, an area that has a dense concentration of boreholes. Investigations


N
830 N
828 N
826 N
814 E
816 E
0
1 km
QHH
Cmp
Quaternary
QHH Undivided, mainly dark grey marine mud
ms Marine sand, part silty
Qb Sand
Qrb Sand
Qa Clay/silt, sand and gravel; well-sorted to semi-sorted
Qd Unsorted sand, gravel, cobbles and boulders; clay/silt matrix
Qt Gravel, cobbles and boulders
Qpa Clay/silt, gravelly, sandy
Qpd Silt/sand, clayey with cobbles and boulders; unsorted
Fill
20m contour
Fault
Mineral vein
Photogeological lineament
Upper Jurassic
JTU Andesite with tuff and tuffite
JTS Sandstone, siltstone and mudstone with conglomerate and tuff
t Undifferentiated tuff and tuffite
bt Block-bearing tuff and tuffite
cg Conglomerate
Metamorphosed
Carboniferous
Cmp Metasiltstone and phyllite, with metasandstone
Jurassic - Cretaceous
gf Fine-grained granite
gfm Fine-to medium-grained granite
gm Medium-grained granite
gc Coarse-grained granite
Megacrystic
rq Quartzphyric rhyolite
rf Feldsparphyric rhyolite
ap Aplite
q Quartz
Tertiary
b Basalt

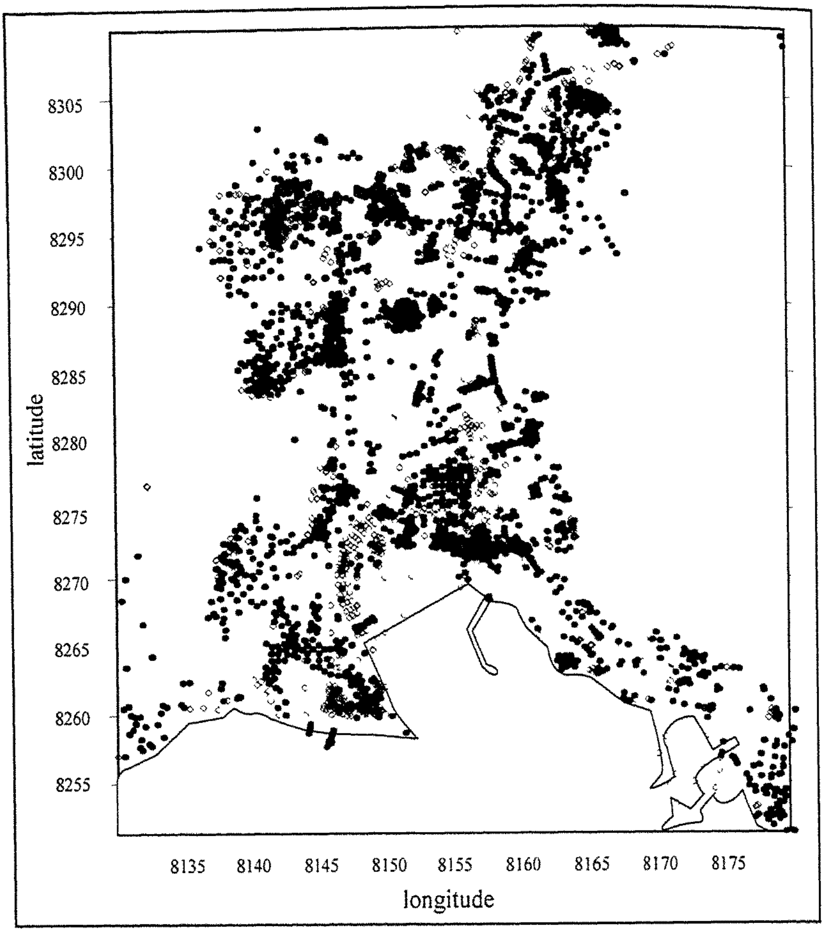


Fig. 2. Map of borehole locations. Data for 4070 boreholes shown, but with many overlapping in densely investigated areas. ***Open diamonds***, boreholes not reaching bedrock; ***filled circles***, boreholes that intersect the weathering front

were restricted to an area bounded by the co-ordinates 813000 east and 818000 east, and 825100 north and 830100 north, an area of about 28.5 km^2.

Geology

Geologically, the site comprises a low-lying, north-trending structurally controlled corridor of volcanic rocks located between the Tsing Shan (Castle Peak) range of granite hills to the west and the Tai Lam granite uplands to the east (Fig. 1; GCO, 1988b, 1988c; Langford et al., 1989). The volcaniclastic rocks belong to the Jurassic Repulse Bay Volcanic Group, which are faulted against Jurassic to Cretaceous granites in the west and east. Narrow outcrops of Palaeozoic metasediments and Jurassic sediments occur at the margins of the valley. A variety of Quaternary superficial deposits cover the solid geology over much of the valley floor.

Rocks of the undivided Tuen Mun Formation (JTU on Fig. 1) are the dominant lithology exposed on the valley floor. These consist mainly of andesites with tuffs and tuffites. Sedimentary rocks of the Tsing Shan Formation (JTS) crop out below the Tsing Shan (Castle Peak) range in the southwest of the study area, in fault contact with the granites. These rocks comprise a range of lithologies including sandstone, siltstone, and mudstone, with conglomerates and tuffs. In the northwest, narrow outcrops of block-bearing tuffs and tuffite of the Tuen Mun Formation (bt) occur.

In the northeast, sedimentary rocks of the Mai Po Member of the Palaeozoic Lok Ma Cha Formation (Cmp) are faulted against the granites of the Tai Lam hills. These rocks consist of metasiltstones and phyllites, with subordinate metasandstones.

The Tuen Mun Valley is a fault-controlled structural depression. The feature is controlled by northeast-trending faults and folds of the Lo Wu-Tuen Mun fault and fold belt (Langford et al., 1989). The Yuen Tau Shan Fault determines the western margin of the valley. A northeast-trending Palaeozoic fold belt underlies the valley floor.

Quaternary superfical deposits mask much of the solid geology of the valley floor. Two narrow, dendritic splays of Holocene alluvium (Qa) occur near the centre of the valley, deposited along the courses of the north- and south-flowing rivers. Extensive Pleistocene fluvial terraces have been mapped (Qpa), adjacent to the river channels. Overlying these and originating from the flanking valley slopes are large areas of old and indurated colluvium, identified as Pleistocene debris flow deposits (Qpd). In the south, concealed beneath reclamation fill (Qf), are marine muds (QHH), marine sands (ms), and sandy beach deposits (Qb) of the Holocene Hang Hau Formation (QHH). A small area of raised beach (Qrb) has been mapped in the extreme southwest.

These varied and complex lithologies make up the substrate that has been subjected to humid subtropical weathering, perhaps since the Early to Middle Tertiary Period (Ruxton and Berry, 1957). The weathering profile can be expected to be intricate and variable, reflecting the contrasting weathering responses of the different lithologies.

Geomorphology

The Tuen Mun valley is aligned NNE, running from the coast in the south to open out into the Yuen Long Plain in the north. Topographically, the study area ranges in elevation from a low of –8.15 mPD on the seabed in the south, to a maximum of 418.72 mPD on the granite hills in the west. The low-lying valley floor does not rise above 20 mPD. Therefore, because of its gentle gradient, the valley floor is not subject to the mass movements and vigorous fluvial activity experienced by the adjacent steep slopes. These conditions could be expected to have favoured the development and preservation of deep weathering profiles, as the area is not subject to significant soil loss. Conversely, seasonally high water tables may have precluded or slowed down the rates of weathering .

Prior to the commencement of reclamation for the Tuen Mun new town the valley was undeveloped and Castle Peak Bay was a long, narrow, north-south estuary. Marine deposits have been mapped extending northwards under the reclamation to a location about 4.5 kilometres from the present harbour breakwater (Fig. 1). Reclamation designs were first prepared in 1959 for a new town site with a potential area of 283 hectares of new land. Preliminary engineering works began on the site in March 1964. Today the site has a thick and extensive cover of reclamation fill, largely weathered granite extracted from borrow areas in the adjacent granite hills. Development of the new town has considerably modified the natural landscape, with extensive reclamation and cutting back of the adjacent hillslopes to create sites for housing and urban amenities.

Deeply Weathered Profiles

Weathering affects rocks in all climates. Although most authors agree that weathering is a dominant process in tropical landscapes (e.g. McFarlane, 1976), some authors question the existence of a distinctive tropical geomorphological zone (e.g. Thomas, 1994). A major distinguishing feature of the tropics is the lack of the glaciations that occurred in the northern latitudes. Absence of this period of major bioclimatic disturbance has resulted in a continuity of weathering and erosion in the tropical regions (Thomas, 1974).

Characteristics of Weathered Profiles

The nature of the base of weathered profiles depends to a large extent upon lithology. In massive igneous rocks such as granite, a sharp contact usually exists. This irregular and dynamic surface was termed the weathering front by Mabbutt (1961). However, in some lithologies the weathering grades imperceptibly to unweathered rock. Immediately above the weathering front the lower, sedentary part of the weathering profile is usually termed a saprolite. This zone has been subject to only minor volume changes and characteristically preserves undisturbed original structures such as joint planes and quartz veins. Depending largely upon topography, a mobile zone of variable thickness occurs near the top of the weathered profile. The mobile zone has been disturbed by processes such as gravitational creep, loss of material by leaching and eluviation, and bioturbation. Across most of the landscape, an overlying surface layer of entirely transported superficial material is present. This is most commonly colluvium on hillslopes and in the steeper upland valleys, with alluvium on the floors of more gentle valleys.

Classification of Weathered Profiles

Based on work in Hong Kong, Ruxton and Berry (1957) devised a detailed zonal scheme for the description of weathering profiles developed on granitic rocks. This scheme, based primarily on the percentage of corestones in the profile, has been adopted as the model for many engineering classifications (e.g. BSI, 1981; GCO, 1988a). However, several studies of weathering profiles on granitic rocks, both in Hong Kong (Gamon and Finn, 1986; Shaw, 1997) and overseas (Ollier, 1965), found rapid transitions and considerable irregularity in the occurrence and distribution of corestones on which the zones are defined. Greater reservations apply to the application of this classification scheme to the more variable, and less well documented, weathered profiles observed on volcanic rocks.

Determination of Rockhead for Engineering Studies

Defining the boundary between geological materials defined as soil and those defined as rock, *i.e.* the weathering front or engineering rockhead, is an important objective for engineering ground investigations, particularly in areas of deep weathering such as Hong Kong. Ground investigations seek to determine such factors as the thickness and engineering properties of the regolith, and the depth and topography of the weathering front. Detailed regional modelling of the depth and topography of the weathering front, and determination of the geological factors that control local variations, will assist in refining the techniques for engineering investigations and classification.

Weathering Characteristics of the Tuen Mun Area

Characteristics of the weathered mantle were studied by reference to the borehole records that were available for the area up to December 1998. A total of 4070 boreholes penetrated the superficial deposits to reach weathered rock or bedrock. Data from these boreholes have been used to compile maps that illustrate the characteristics of the weathering profile and overlying superficial deposits in the Tuen Mun Valley (Figs. 4 to 6).

Borehole Data

Locations of the boreholes used in the study are shown in Fig. 2. Clearly these are concentrated along the valley floor, which is the major development area. Consequently the maps that have been compiled to portray the results of the study have been masked to exclude the western and eastern granitic uplands for which no borehole data are available.

The standard of geological logging and data recording styles employed in the borehole records was found to vary considerably, from descriptive and factual, to sparse and rudimentary. Only in the more recent ground investigations was there any reference to the rock types or stratigraphical units portrayed on the published Hong Kong Geological Survey 1:20 000 scale map of the area (Geotechnical Control Office, 1988b, 1988c; Fig. 1).

Investigations that predated the publication of these maps adopted an interesting range of descriptions and terminology. Consequently, problems were encountered in determining the exact lithology that was penetrated by many of the boreholes. Clearly, this difficulty presented a degree of uncertainty in the study, particularly for determining the weathering characteristics of the individual lithologies.

However, the bedrock descriptions contained in the borehole logs have been resolved into 35 different categories. These categories were classified into 4 major groups, volcanic, granitic, sedimentary and metamorphic rock types, with a minor intrusive group that contained only seven records (Table 1). The depth of the weathering front in each of the four major groups is illustrated graphically in Fig. 4a. Overall it can be seen that the depth of weathering was found to be greatest in the volcanic lithologies, and successively less in the granitic and sedimentary rocks, with the metamorphic rocks being the least deeply weathered.

Boreholes were further subdivided into those that reached the weathering front and those that terminated within the weathering profile. The former category provided absolute datum points for contouring the weathering front and the latter category gave minimum depths that could be used to assist with the contouring. The thickness of the weathering profile was recorded directly from the borehole logs with no allowance being made for the gradient of the ground. Because the study area was relatively flat this was considered to be an acceptable procedure. However, in areas of steeply sloping ground, such as the valley sides, a geometrical correction should preferably be applied as vertical boreholes would penetrate the profile obliquely and not record the true profile thickness (Fig. 3b).

Determination of the weathering front was relatively straightforward. Engineering practice in Hong Kong dictates that, for foundation purposes,

Table 1. Lithological relationships with weathering parameters and superficial materials

BEDROCK LITHOLOGY	WEATHERING FRONT mPD		MANTLE THICKNESS		SUPERFICIAL THICKNESS		BOREHOLES		
	MIN	MAX	MIN	MAX	MIN	MAX	# BORE-HOLES	# CORE-STONES	% WITH CORE-STONES
GRANITIC									
1 COARSE-GRAINED (Gc)	-81.2	+122.0	00.0m	70.7m	00.0m	25.5m	349	41	12%
2 MEDIUM-GRAINED (Gm)	-35.6	+115.0	00.0m	42.7m	00.0m	25.0m	114	09	08%
3 MEDIUM TO COARSE (Gmc)	-51.7	+406.0	00.0m	37.5m	00.0m	27.5m	108	11	10%
4 GRANITE	-54.3	+062.9	00.0m	59.0m	00.0m	13.5m	053	08	15%
5 FINE-GRAINED (Gf)	-80.0	+055.5	00.0m	84.5m	00.0m	25.3m	044	07	16%
6 FINE TO MEDIUM (Gfm)	-24.0	+220.0	00.0m	30.6m	00.0m	09.5m	036	05	14%
7 FINE TO COARSE (Gfc)	-44.0	+021.0	00.0m	84.5m	00.0m	21.5m	013	04	31%
8 PORPHYRY	+00.8	+020.6	13.2m	29.4m	03.3m	06.2m	006	01	17%
9 GRANODIORITE	-31.0	+067.1	08.4m	14.7m	03.0m	22.0m	004	00	00%
10 PORPHYRITIC GRANITE	-58.0	+012.1	10.0m	39.5m	00.5m	13.5m	003	00	00%
SUMMARY	**-81.2**	**+406.0**	**00.0m**	**84.5m**	**00.0m**	**27.5m**	**730**	**86**	**12%**
VOLCANIC									
11 VOLCANIC	-86.7	+112.0	00.0m	91.4m	00.0m	46.4m	1 040	61	06%
12 JTU	-65.7	+075.0	00.0m	62.7m	00.0m	25.4m	503	42	08%
13 JSL	-78.7	+000.5	00.0m	84.0m	00.0m	16.0m	051	06	12%
14 BLOCKY TUFFITE (bt)	-54.9	+000.1	11.3m	51.6m	01.0m	12.0m	019	04	21%
15 ANDESITE	-40.9	-005.2	12.0m	52.8m	00.7m	13.2m	018	05	06%
16 JSM	-42.2	-006.0	05.1m	30.5m	01.0m	18.5m	011	02	20%
17 JTS	+00.9	+104.0	01.4m	22.0m	00.0m	23.0m	009	01	12%
18 PYROCLASTIC BRECCIA	-72.9	-012.9	11.2m	29.4m	07.5m	12.5m	005	00	00%
19 TUFFITE (t)	-42.5	-030.4	28.3m	31.2m	08.0m	10.0m	004	00	00%
20 SEDI-VOLCANIC	-25.5	-022.9	22.9m	38.5m	00.0m	09.9m	003	02	66%
21 JHI	-03.1	-003.1	05.5m	05.5m	06.0m	06.0m	001	00	00%
SUMMARY	**-86.7**	**+112.0**	**00.0m**	**91.4m**	**00.0m**	**46.4m**	**1 664**	**123**	**07%**
METAMORPHIC									
22 LOK MA CHAU Fm (cmp)	-23.0	+046.0	00.0m	35.0m	00.0m	11.5m	057	11	19%
23 METAMORPHIC	-00.0	+102.0	00.0m	33.2m	00.0m	10.0m	049	02	04%
24 META-TUFF	-47.6	+007.1	08.5m	51.7m	00.0m	20.5m	037	08	22%
25 META-SILTSTONE	- 32.4	+003.5	09.0m	36.8m	00.0m	15.0m	035	08	23%
26 META-SILTSTONE/SCHIST	+41.4	-055.9	14.4m	03.3m	00.0m	12.0m	021	00	00%
27 PHYLLITE	-14.5	+014.6	00.0m	27.5m	00.0m	12.7m	011	01	09%
SUMMARY	**-47.6**	**+102.0**	**00.0m**	**51.7m**	**00.0m**	**20.5m**	**210**	**30**	**14%**
SEDIMENTARY									
28 SILTSTONE	-83.0	+082.3	00.0m	78.0m	00.0m	25.0m	233	24	10%
29 SHALE	-32.4	+032.8	00.0m	30.2m	00.0m	16.5m	027	06	22%
30 SANDSTONE	-63.2	+001.8	00.0m	57.0m	00.0m	17.5m	023	05	22%
31 SEDIMENTARY	-38.9	-016.6	10.9m	39.0m	07.5m	12.9m	005	02	40%
32 CONGLOMERATE	-53.7	-030.9	30.8m	41.1m	04.5m	20.5m	003	00	00%
33 BRECCIA	-24.4	-023.0	13.3m	22.8m	09.0m	16.0m	002	01	50%
SUMMARY	**-83.0**	**+082.3**	**30.8m**	**78.0m**	**00.0m**	**25.0m**	**293**	**38**	**13%**
INTRUSIVE									
34 BASALT	-34.0	+035.0	07.2m	23.9m	00.6m	18.5m	006	00	00%
35 DOLERITE	+46.0	+046.0	07.0m	07.0m	14.5m	14.5m	001	00	00%
SUMMARY	**-34.0**	**+046.0**	**07.2m**	**23.9m**	**00.6m**	**18.5m**	**007**	**00**	**00%**

bedrock is proved by drilling for at least 5 metres (GCO, 1987) into Grades I to III rock material (GCO, 1988a). Therefore, this criterion was also adopted to define the weathering front.

Distinguishing corestones from borehole records is less well defined. Following the procedure of Shaw (1997) corestones in boreholes were defined

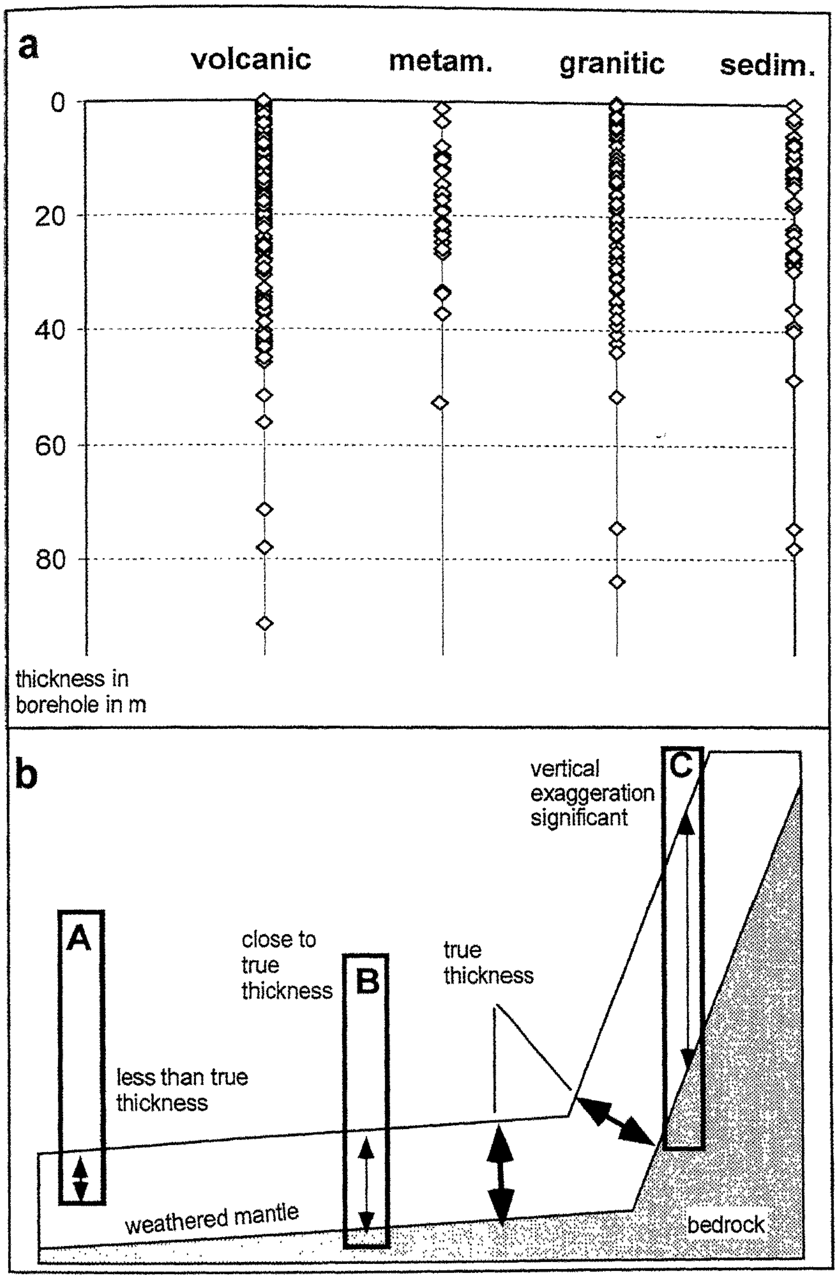
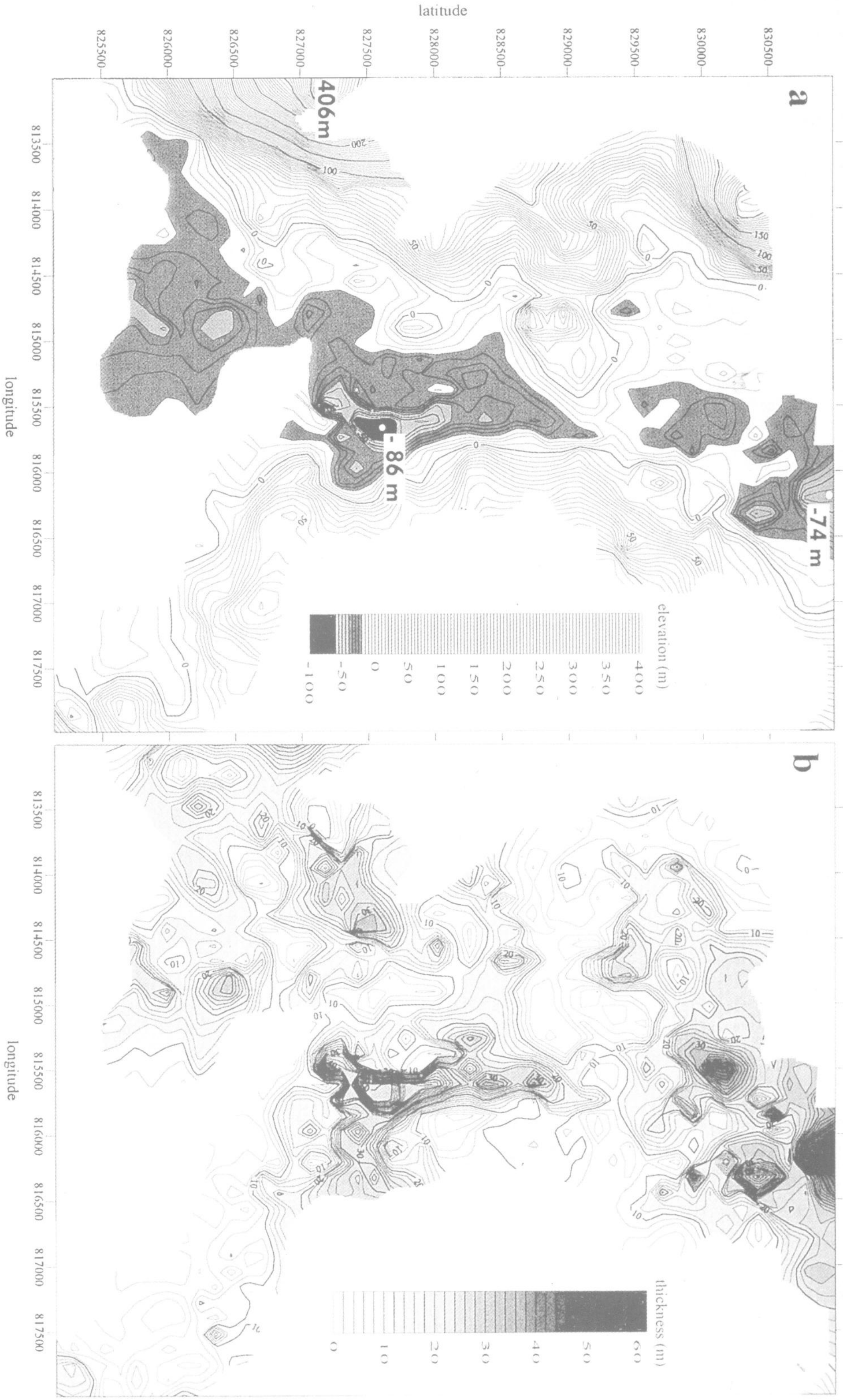


Fig. 3. Lithology and weathered mantle thickness. ***a***, graph showing data for volcanic, metamorphic, granitic and sedimentary rocks in the Tuen Mun area. The thickness of weathered mantle in each borehole is plotted (many plots overlap), yielding an impression of weathering thickness for each major lithology. ***b***, diagram showing topographical effects on borehole data. Borehole 'A' underestimates weathering (not included in data sets used to produce the maps in this paper). Borehole 'B' produces a good approximation of reality. Borehole 'C' overestimates weathering thickness and will tend to occur more commonly on valley side slopes than on the relatively flat valley floor. Some examples of in very thick weathered mantles may represent this situation

as occurrences of Grades I to III rock material that were separated from each other, and from the weathering front, by at least 1 m of weathered rock material. Bands of weathered rock less than 1 m thick were considered to be widened joints. Corestones have a limited lateral extent and, particularly in granitic rocks, a characteristic rounded shape. This feature is impossible to determine in borehole records. Therefore, in the bedded or layered sedimentary, metamorphic and volcanic rocks, the possibility exists that some of the rock occurrences here classified as corestones could be extensive bedding layers separated by widened bedding planes or the differential weathering of softer interbeds.


a
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latitude
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816500
817000
817500
406m
- 86 m
-74 m
elevation (m)
400
350
300
250
200
150
100
50
0
-50
-100
thickness (m)
60
50
40
30
20
10
0

The Weathering Front

Fig. 4 (facing). Contours on the weathering front and isopachs of the weathered mantle. ***a,*** weathering front height in mPD, emphasising areas of low relief (<0 m). Areas with poor data coverage are masked. ***b,*** isopachs of the weathered mantle with thicker sequences shaded. Note the close relationship with low relief areas of the weathering front

Of the 4070 borehole records retrieved from the GIU, a total of 2938 reached bedrock. The remaining 1132 boreholes penetrated the superficial deposits and terminated within the weathered profile, providing minimum values for the depth to the weathering front. These data were used to compile a contour map of the weathering front (engineering rockhead) at 5-metre contour intervals (Fig. 4a).

Inspection of the map (Fig. 4a) reveals that relatively unweathered bedrock reaches an altitudinal maximum of 406 mPD at 813125E, 827175N on medium- to coarse-grained granite. The lowest bedrock encountered in the study area lies at -86 mPD at 815673E, 827491N on volcanic material, concealed below 62 m of weathered rock and a cover of 25 m of superficial deposits and fill materials. Thus the weathering front has a total altitudinal range of 492 m in the study area. Although this is a significant variation, a more important finding for foundation engineering is the topography of the weathering front on the main valley floor.

Figure 4a shows that there is an abrupt break of slope between the steep valley sides and the main valley floor. This is defined by the 20-metre weathering front contour. Within the main valley floor, below the 20-metre weathering front contour, the topography of the weathering front forms a well defined, NNE-oriented valley. This alignment is generally consistent with the main structural trends in the area (Fig. 1), suggesting that the deep weathering has preferentially exploited a major fault that is concealed below the thick weathered mantle and the thick cover of superficial deposits. The main trough is widest in the south, narrowing northwards.

Four weathering lows, or basins, with floors below –40 mPD can be clearly recognised along the bedrock valley. One low occurs in the south, offshore, and descends to over –50 mPD. A second elongate low is located in the centre of the study area, reaching the lowest recorded depth of –86 mPD. The other two lows are located in the north of the study area, the most northerly depression reaching a depth of –74 mPD.

The Weathered Profile

As pointed out previously, weathered profile thicknesses are subject to errors caused where boreholes cut obliquely across a weathered mantle that occurs either on a steep hillslope or on a steeply inclined weathering front (Fig. 3b). This geometrical effect tends to exaggerate the recorded weathering thickness, being most significant on the valley sides where steeper rock head slopes tend to occur, although it still affects the flatter valley floor. Consequently the following data should be regarded as maximum values.

Several broad patterns can be recognised in the variations of weathered profile thickness on the valley floor, that is the area defined as lying below the 20 mPD contour. The average weathering profile thickness calculated from all the boreholes is 13.9 m, which serves as a useful basis for comparison. Isopachs of the weathered mantle (Fig. 4b) show that there is considerable lateral variation in weathered profile thickness across the Tuen Mun valley axis. The thickest profiles occur along the axis of the valley floor, over the volcanic rocks, generally reaching up to about 50 m. However, they are thicker locally. Profiles are thinnest on the valley slopes.

Weathered profiles were found to be thickest over the volcanic lithologies (Figs. 3a, 4b; Table 1), being up to 55 m thick over most of the area, but reaching 91 m locally. The thickest profiles occur along the main axial line of the valley. Granitic rocks supported slightly thinner weathered profiles that, being away from the main fault traces, were probably joint controlled. Profile thicknesses on the granites were generally up to 50 m, but locally reached 84 m. In contrast, the sedimentary and metamorphic rocks weathered less deeply. Weathered profiles over the sedimentary rocks were generally up to 30 m thick, but reached a maximum of 78 m. The thinnest profiles were encountered on the metamorphic lithologies, being generally less than 30 m thick but locally reaching 52 m.

Corestone Distribution

A knowledge of corestone distribution is important for engineering projects such as excavation contracts and cutslope design, but is critical for piling contracts and the location of foundation levels. Weathered granite profiles characteristically contain corestones, rounded to subrounded blocks of relatively unweathered rock up to several metres in diameter. In contrast, corestones are less commonly described from the volcanic or other lithologies. This study has allowed their occurrence to be objectively examined.

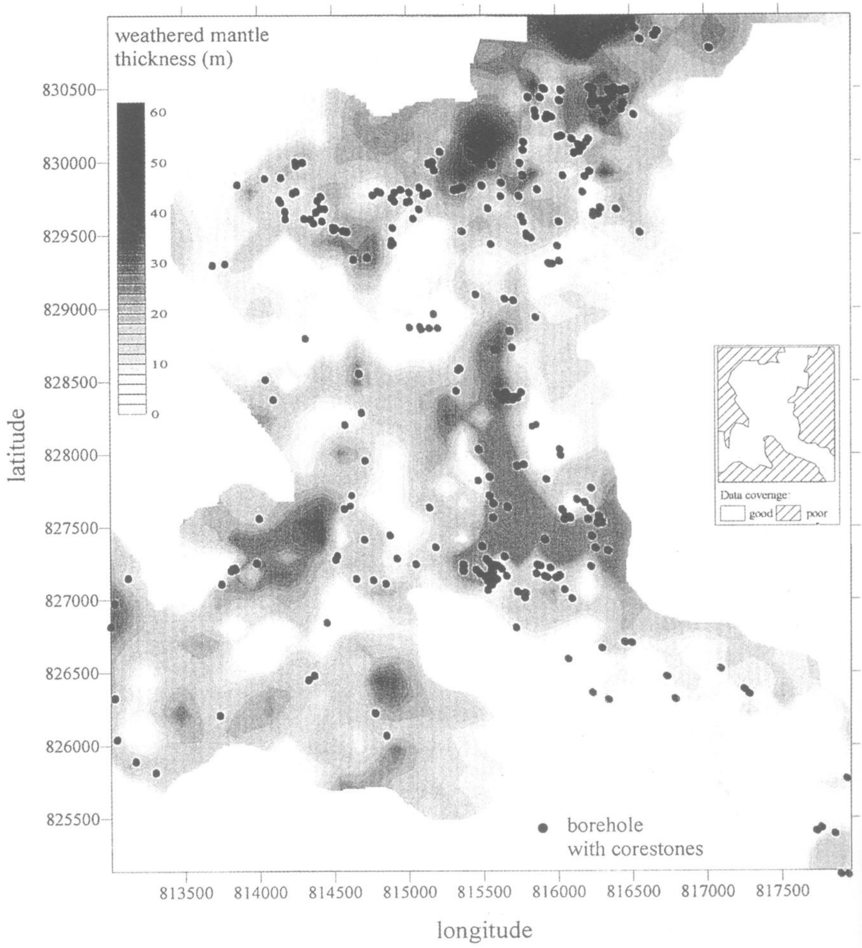

Fig. 5. Corestone locations. Locations of boreholes that encountered corestones are shown together with a shaded representation of the weathered mantle. Note the distribution partly reflects the density of borehole sampling

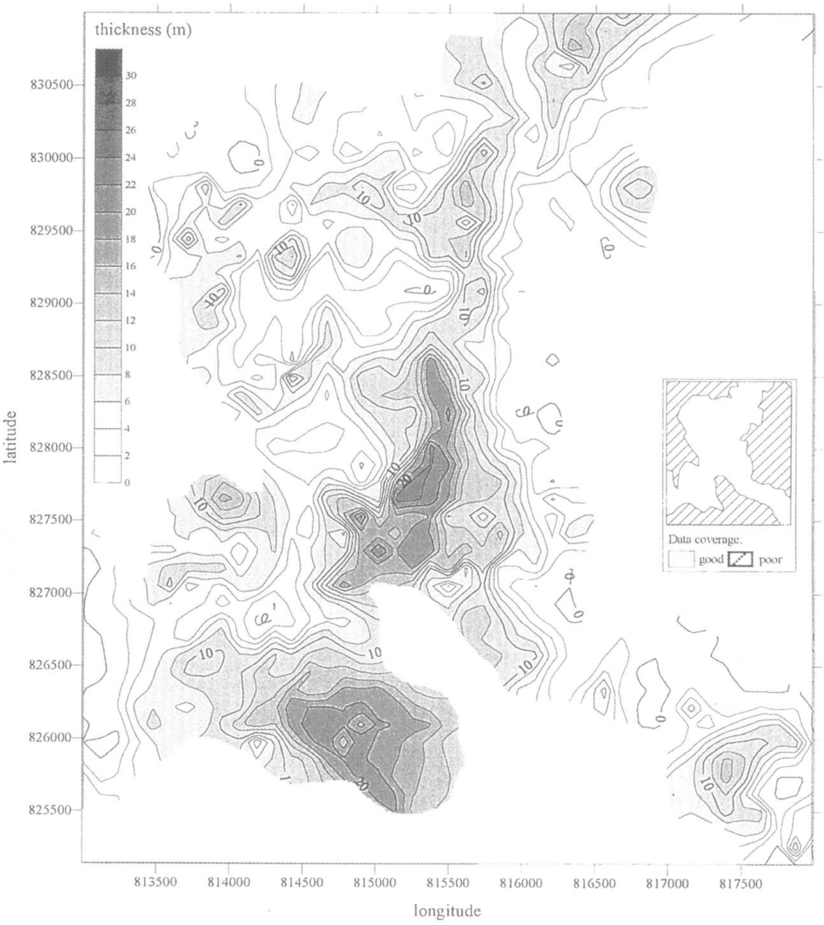

Fig. 6. Isopachs of the superficial deposits. Note the NNE-trending linear zone of thickest sediments

Overall, corestones were found to occur in only 10% of the boreholes examined. Of the igneous lithologies, they were most common in the granitic rocks, occurring in 12% of the boreholes that penetrated this rock type (Table 1). Corestones occurred in 7% of the boreholes in volcanic rocks. Surprisingly, corestones occurred in 14% of boreholes in metamorphic lithologies and 13% of boreholes in sedimentary rocks. However, as discussed previously, this finding should be interpreted cautiously as these layered and foliated rocks are more prone to the widening of bedding planes or the differential weathering of less resistant interbeds. This weathering phenomenon is different to true corestone development.

Figure 5 illustrates the areal distribution of corestones in the Tuen Mun valley related to the thickness of the weathering profile. In general it can be seen that corestones are widespread across the study area with no clearly discernible pattern. However, corestones most commonly occur where the weathering profile is more than about 20 metres thick. They are even present in the areas of particularly deep weathering where the deepest depression in the weathering front occurs, in what have been interpreted as the structurally controlled, linear zones of deep weathering. This distribution of corestones found in the volcanic and associated lithologies is similar to that previously determined in the granites of the Kowloon peninsula (Shaw, 1997). There, although large concentrations of corestones were found below the upland areas

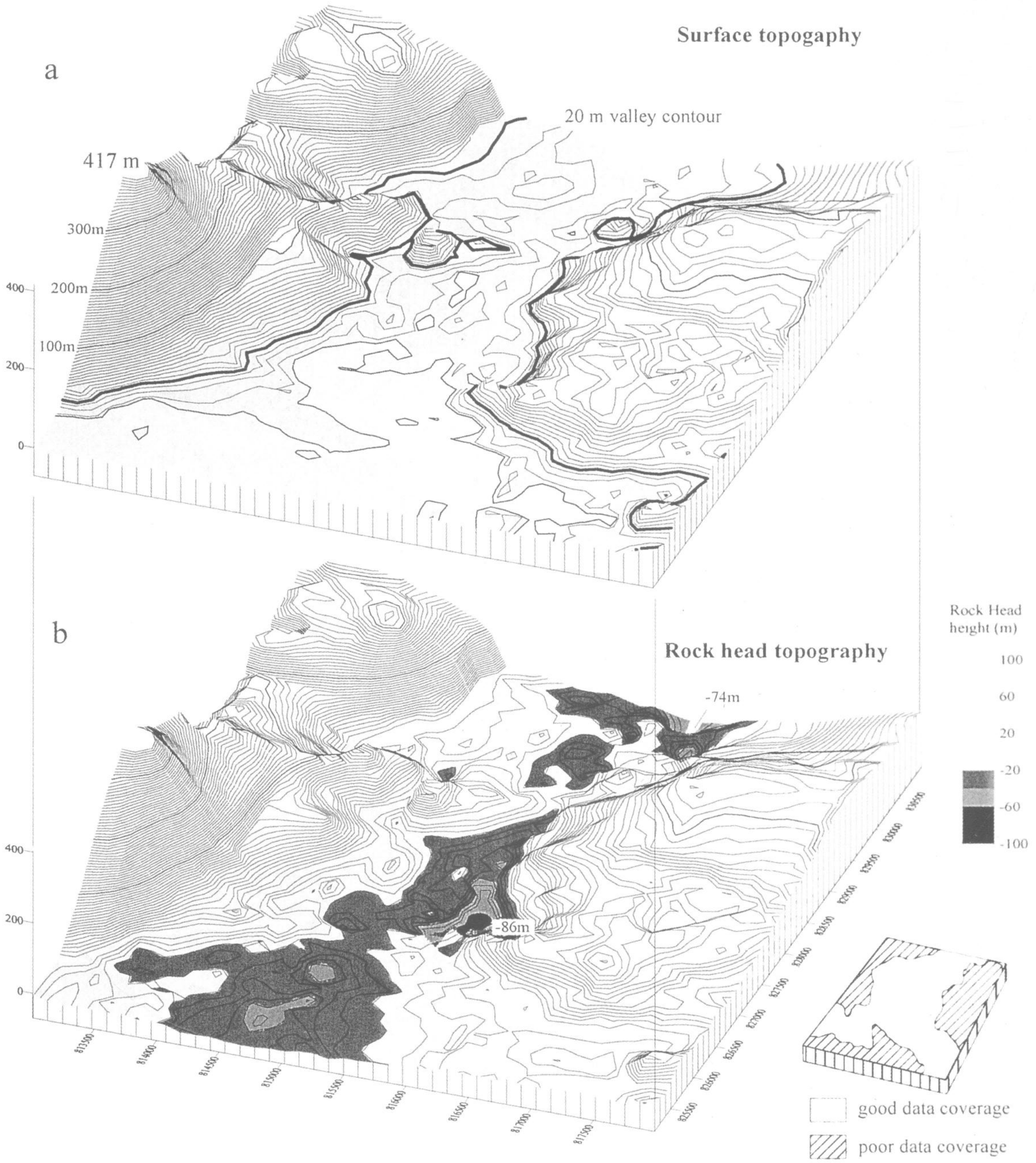

Fig. 7. Isometric views of the surface topography and the weathering front topography. ***a,*** surface topography is based on borehole data records and may not match exactly with topographic maps. ***b,*** weathering front topography, using the same borehole reference heights

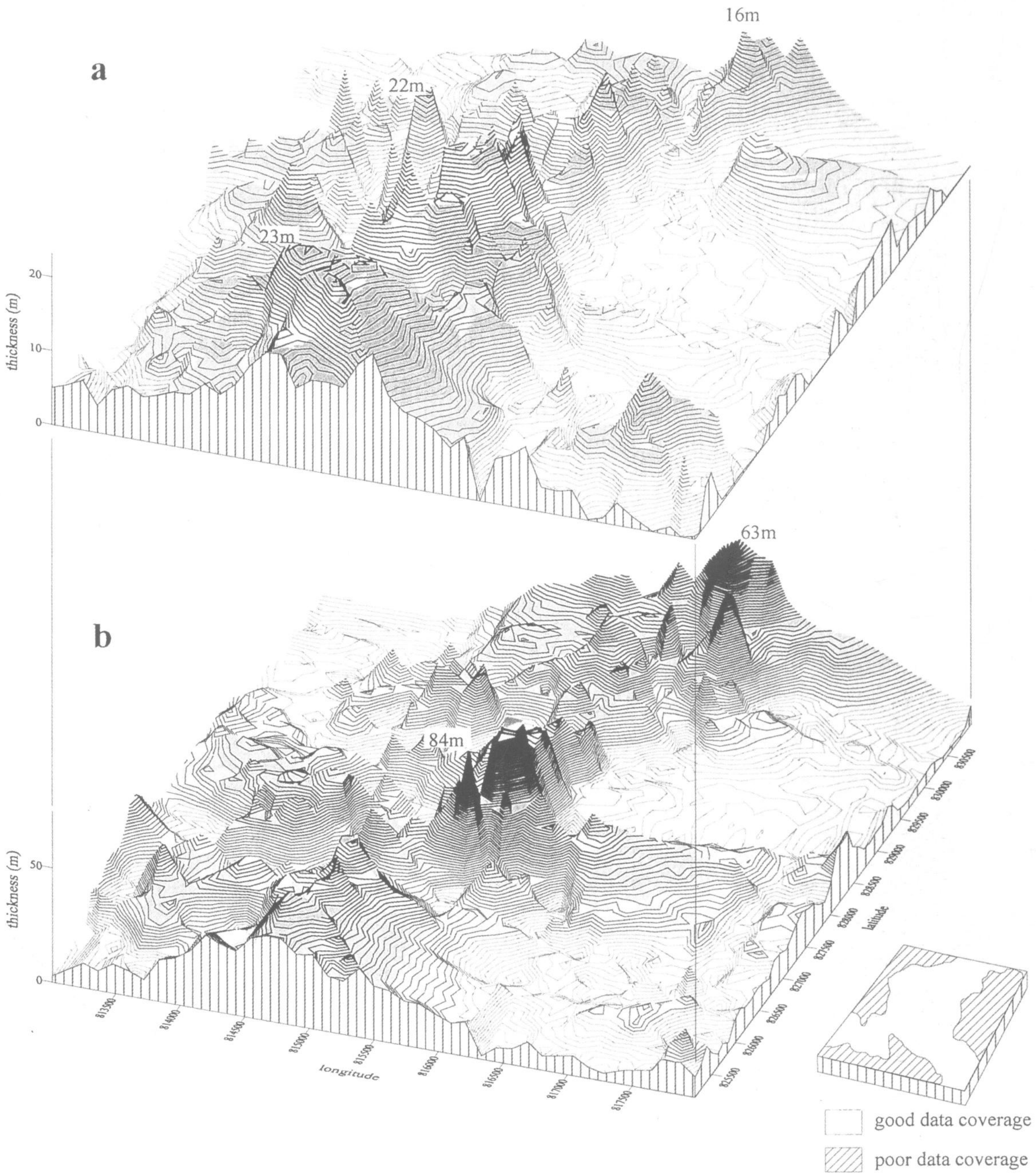

Fig. 8. Diagrammatical isometric representation of the superficial deposits thickness and weathered mantle thickness. ***a,*** superficial thickness at 0.5 m intervals; ***b,*** weathered mantle thickness at 1 m intervals. Areas of thick material show as "highs". Both models show rapid thickness variations and a general NNE-trending zone of thicker materials

where the weathering front was high, corestones were also encountered in the structurally controlled zones of deepest weathering where the weathering front descended to around –60 mPD.

Superficial Deposits

The borehole data also allowed the compilation of an isopach map of the distribution of superficial deposits in the study area (Fig. 6). Fill was not examined. Alluvium blankets much of the valley floor and colluvium mantles the valley sides. Marine deposits occur offshore in the south of the study area. Thicknesses range from zero to over 20 metres, with the thickest deposits being concentrated along the main valley axis, which also corresponds to the course of the river channel.

Summary and Conclusions

This study has revealed that the weathering front forms a NNE-oriented linear depression up to 100 m below the modern valley floor. The topography of the present landscape compared with the deeply weathered bedrock trough is pictorially illustrated in the isometric views in Fig. 7. The trends of the linear features correspond to the main structural trends mapped in the area (GCO, 1988b, 1988c; Langford et al., 1989), indicating that preferential weathering along structural discontinuities is the most likely mechanism to explain the morphology of the weathering front in this area.

The thickness of the weathered mantle and the overlying superficial deposits are diagramatically illustrated in Fig. 8, displayed as piles of sediments on a horizontal surface. Both mantles were found to be thickest along the axial line of the valley. Volcanic lithologies are the most deeply weathered, but probably because they occur along the main structural trend and have been fractured and preferentially weathered. The adjacent granitic rocks, which are not faulted to the same extent, attain almost the same weathering depths. Sedimentary and metamorphic lithologies have been shown to be less deeply weathered.

Corestones were found to occur in all lithologies, and to be fairly evenly distributed across the study area. They tend to occur in weathered profiles that are at least 20 m thick. However, reservations are held about the apparently more common occurrence of corestones in the sedimentary and metamorphic lithologies. In these lithologies, bands of Grade IV to VI weathered rock greater than 1 m wide probably represent widened bedding planes or differential weathering rather than true corestones.

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References

BSI (1981) *Code of Practice for Site Investigations (BS 5930 : 1981).* British Standards Institution, London, 148p

Gamon TI & Finn RP (1986) Simplified descriptive scheme and classification system for the logging of cut slope faces. In: Hawkins AB (ed) *Site Investigation Practice: Assessing BS 5930*, Engineering Group of the Geological Society, Special Publication No 2, pp 253-260

GCO (1987) *Guide to Site Investigation: Geoguide 2.* Geotechnical Control Office, Hong Kong Government, 362p

GCO (1988a) *Guide to Rock and Soil Descriptions: Geoguide 3.* Geotechnical Control Office, Hong Kong Government, 189p

GCO (1988b) *Tsing Shan (Castle Peak): Hong Kong Geological Survey Map Sheet 5, Solid and Superficial Geology.* 1:20 000 scale, Series HGM20, Geotechnical Control Office, Hong Kong Government

GCO (1988c) *Yuen Long: Hong Kong Geological Survey Map Sheet 6, Solid and Superficial Geology.* 1:20 000 scale, Series HGM20, Geotechnical Control Office, Hong Kong Government

Langford RL, Lai KW, Arthurton RS & Shaw R (1989) *Geology of the Western New Territories:* 1:20 000 Sheets 2, 5 & 6. Hong Kong Geological Survey Memoir No. 3, Geotechnical Control Office, Hong Kong Government, 140 p

Mabbutt JA (1961) 'Basal surface' or 'weathering front'. *Proceedings of the Geologists Association*, 72: 357-358

McFarlane MJ (1976) *Laterite and Landscape.* Academic Press, 151p

Ollier CD (1965) Some features of granite weathering in Australia. *Zeittschrifte fur Geomorphologie*, 9: 285-304

Owen RB and Shaw R (2000) Weathering profile development below the Yuen Long Plain, western New Territories, Hong Kong. *Hong Kong Geologist*, 5: 1-11

Ruxton BP & Berry L (1957) The weathering of granite and associated erosional features in Hong Kong. *Bulletin of the Geological Society of America*, 68: 1263-1292

Shaw R (1997) Variations in sub-tropical deep weathering profiles over the Kowloon Granite, Hong Kong. *Journal of the Geological Society of London*, London, 154:1077-1085

Thomas MF (1974) *Tropical Geomorphology.* MacMillan Press, 332p

Thomas MF (1994) *Geomorphology in the Tropics.* Wiley, 460p

Archaeology and Geology in Hong Kong's Developing Urban Environment

P. Rumball Rogers

Abstract

A fundamental relationship exists between past human societies and the geological environment in which they lived, moved, and subsisted. With time, stone and soil covers and preserves the evidence of these societies, forming stratified deposits. Archaeology has widely adopted and adapted geological models and methods to excavate and interpret this data. In this paper we will briefly review this relationship and then focus on the particular situation in Hong Kong today. The introduction of archaeology into the environmental impact assessment (EIA) process has highlighted the importance of geologists and archaeologists working with development interests to carry out the required assessments while moving projects forward towards completion. At the same time it is important that assessments be designed to maximise research potential and to address issues of importance to local archaeology. We will discuss the ways in which archaeology and geology can achieve this through the assessment process, from preliminary studies, through field survey and evaluation to analysis of artifacts and environmental data.

Key words: environmental impact assessment, archaeology, geology, interaction, sediments, habitation, geophysics, soil stratigraphy, absolute dating, material sources.

Archaeology and the Earth Sciences

A geoscientific approach to evaluating the archaeological record began with a shared concern in the eighteenth and nineteenth centuries for chronology and the development of basic principles. In the early twentieth century a collaborative interest evolved in palaeoenvironmental studies moving into the present with a shared focus on the processes by which prehistoric action enters the archaeological record and becomes archaeology. The culmination of this convergence of disciplines has been the creation of a field of archaeology called "geoarchaeology", which aims to solve archaeological problems using Earth science techniques, concepts and data (Rapp and Hill, 1998).This

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geoarchaeological approach has been widely used in Europe and America.

Although its application in Hong Kong has been limited, it is hoped in this paper to illustrate ways in which archaeology and the Earth sciences can combine in the field and in the lab to the benefit of heritage preservation and understanding.

In the Specific Environment of Hong Kong's Rapidly Changing Urban Environment

There is probably nowhere in Asia, or perhaps in the world, where we see development move at such a furious pace and on such an overwhelming scale as we see in Hong Kong. Mountains are flattened and dumped in the sea to construct an airport and highways span expanses of water and fly over and under the city. The Chief Executive has announced that 85,000 flats per year will be built until housing needs are met and at the same time old and dilapidated sections of the urban centre are being levelled and modernised. New towns rise in mangrove swamps to house three-quarters of a million people where previously egrets and oyster farmers lived in comfortable proximity.

For all of this progress a price is paid in terms of stress on what remains of Hong Kong's cultural and archaeological heritage. In fact, so great is Hong Kong's fame as an engineers' paradise that people are unaware that historic architecture, cultural landscapes and archaeological sites even exist.

In fact, there are more than 200 archaeological sites identified in Hong Kong, primarily located in present and past coastal areas. The number and location of these sites inevitably means that proposed infrastructure development for the territory has and will continue to have serious impacts on the archaeological heritage of the territory.

The sites in question date from approximately 4500 BC, through what is referred to locally as the Middle Neolithic, the Late Neolithic, into the Bronze Age dated from ca. 1500 BC until the arrival of the Han Chinese in approximately 100 BC, and on into the historical period. Sites from the prehistoric periods are characterised by minimal architectural remains, beyond postholes and compacted surfaces; by evidence of fires and other activities in the form of pottery, ceramic and stone implements; deposits of organic refuse such as shell and fishbone; and the burial of human remains. To date, excavated historical remains have included lime kilns, ceramic manufacturing sites, walled city remains, fortifications, human burials and tombs.

The Antiquities Authority in Hong Kong is the Director for Home Affairs of the Hong Kong Government, who is advised on antiquities policy and procedures by an appointed body called the Antiquities Advisory Board. The day to day implementation of this policy is carried out by its executive arm, the Antiquities and Monuments Office (AMO). Within the AMO are two sections dealing solely with archaeology: a field unit which carries out rescue excavations and prepares reports, and a monitoring section which evaluates threats to sites, both natural and developmental.

Unlike most developed countries, the legal framework for the preservation of cultural heritage in Hong Kong up to March 31 1998 has been built upon only one simple piece of legislation. This is the Antiquities and Monuments Ordinance, Chapter 53 of the Laws of Hong Kong, which provides for two main areas of heritage protection:

- by the declaration of monuments which include historical buildings, archaeological and palaeontological sites by notice in the gazette; and
- by subjecting archaeological excavations to a system of licensing.

On April 1, 1998, a new Environmental Impact Assessment Ordinance was implemented, which for the first time requires that the assessment of impacts to heritage resources be a formal part of the EIA process (Annex 10 of the Technical Memorandum on Environmental Impact Assessment Process). Every development project above a defined size is now required to timetable and finance an archaeological assessment before engineering work commences. This legislation has had enormous and far-reaching effect upon the way that archaeology is approached in Hong Kong. In effect, it is bringing about the commercialisation of what was previously an academic pursuit, with all the restructuring and reorganisation which this implies.

Evaluation Process

The stated aim of archaeological impact assessment is :

- to establish an inventory of all known and potential sites within the impacted area of the proposed site by means of a baseline study;
- to propose and implement a field evaluation strategy in areas where information is inadequate or where the potential for archaeological material is deemed to be high;
- to analyse the resulting data; and
- to recommend mitigation measures for partial or complete preservation, or where required, by record – in other words, through full excavation and recording to extract maximum data.

As archaeologists we aim ideally to perform this assessment function while at the same time expanding the local data base, and if possible to answer research-based questions concerning the area under study.

Role of Geology in this Exercise

This section examines some of the ways in which geology and the earth sciences in general can aid archaeologists in performing the above tasks.

Baseline Study

The baseline study is designed to accumulate data on all known sites, but also to predict where as yet unknown archaeological resources are likely to occur within the study area. There is a variety of ways in which geology and geomorphology assist the archaeologists in the formulation of such a predictive model of archaeological potential.

With the help of topographical and geological maps, landforms are identified which have known archaeological potential. Consolidated sandbars, and the juncture of sandbar and hillslope when accurately identified, frequently prove to be locations of prehistoric archaeological deposits (Fig. 1). Other

Fig. 1. View of Yung Long, a Late Neolithic site on Deep Bay

local palaeoenvironments with high potential are tombolo and lagoonal formations. Studies of sea level changes and sedimentation rates combined with information from bore holes can aid in the location of these former coastlines and coastal features.

At the same time, portions of the study area which can be shown to be landforms that post-date the periods of archaeological interest can be eliminated from the assessment. This is particularly relevant in the northwestern New Territories and Castle Peak area, where large portions of the present land environment were shallow sea or marsh environments until well into the historical period. Such environments offered rich economic opportunities, and identification of their margins could isolate areas of high prehistoric archaeological potential.

The geology of an area affects the hydrology and thus the flora and fauna resource bases available to the prehistoric inhabitants. More work is needed to correlate local geology with information on broad ecological conditions and their variation across different parts of the landscape. This is vital in reconstructing human activity within ancient landscapes. Most multidisciplinary archaeological projects now begin with the mapping of the present vegetation, which when combined using geographical information systems (GIS) with soil maps and geological, palaeoecological and palaeopedogenic studies from drill cores, the pattern of ecological change and land use should emerge. In combination with archaeological survey, the human rationale for past land use, settlement patterns and exploitation of flora and fauna can be determined.

With a clearer picture of the geological and morphological environment of the area, the archaeologist is better able to design an appropriate field programme to systematically evaluate the predictive model of site location. This field evaluation employs a number of techniques and theoretical approaches from the Earth sciences.

Field Evaluation Phase

The field methodology recommended by the AMO consists of systematic field walking of the study area, along regularly spaced lines; systematic auger testing at intervals along this grid; and excavation of test pits where justified by the finding of cultural soils or material in the auger samples.

In more arid and less densely vegetated areas of the world, the emphasis of field survey is on the discovery and recording of archaeological material on the ground surface. However, in Hong Kong local conditions mean that the emphasis must be placed on methods which reveal information concerning any sub-surface deposits; thus the focus on auger sampling and test pit excavation .

It is important to understand the soil matrices in which any cultural material is found and to identify the chronological events which resulted in their deposition and any subsequent alteration. This is related to the geological base rock and the rate at which its erodes, creating soil deposits. Local geological events will also be evident in the stratification. Both archaeology and geology "read", as it were, the complex sequential strata created by nature and man; the time scale represented by these strata may vary dramatically from weeks or months in the archaeological record to millions of years in the geological record, but the principles of superposition apply equally to both (Harris, 1989). Although the archaeologist may be able to explain the cultural deposits found, the help of a geomorphologist is regularly sought to explain the sequence of events represented by the strata revealed.

Cultural soils from auger testing or test pit excavation are identified by particle size analysis and testing for pH value and by geochemical testing for sulphates, phosphates and organic material. The most useful of these is the testing for phosphates. There can be a close correlation between ancient settlement and high concentrations of phosphates in the soil when phosphates are diagnostic of the organic components of former occupation debris (Holliday 1992) .

Auger testing and test pit excavation suffer from two drawbacks. Firstly, they are intrusive and destructive methods. Secondly, if the area being evaluated is extensive, they have a limited chance of revealing meaningful evidence in relation to their cost. Geophysical prospecting techniques can prove a useful alternative in the field. Geophysical methods can detail the location, extent and character of modified terrain. Surface geophysical surveys can be combined with magnetic analysis of soils and geochemical prospecting to give a good picture of the extent of the anthropogenic context of a buried site or feature (Renfrew and Bahn, 1991).

The most frequently used methods, magnetometry, electrical resistivity, electromagnetic conductivity and ground penetrating radar, are most effective in reading the presence of structural remains and larger scale landscape modification. This limits their usefulness for recording the smaller scale scatters and deposits characteristic of prehistoric sites in Hong Kong, but supports their increased use in the identification of early historical period material.

In the assessment of maritime archaeological potential, geophysical survey methods are of fundamental importance. Seismic methods of investigation provide the raw data which is interpreted by a maritime archaeologist (Draper-Ali, 1996). The field of maritime archaeology is new in Hong Kong and will expand rapidly as assessments are required for the numerous offshore developments.

Analysis

Having designed and carried out a field evaluation programme, the archaeologist must next analyse the resulting data to assess the meaning and value of the deposits found. We will briefly describe three uses of geological method and theory which play an important role at this stage.

Estimating the age of archaeological materials and Quaternary strata is one of geoarchaeology's main tasks. Relative dating is based on the position of material in the stratigraphic sequence, but what we refer to as "absolute dating" relies on the use of chronometric techniques adopted from the earth sciences. These include methods such as radiocarbon dating, thermoluminescence and archaeomagnetic dating. These are all techniques which require sophisticated lab conditions and methods provided by scientific specialists; at the same time they require that the archaeologists involved understand the requirements of the technique. Collection and presentation of samples must follow strict rules. Similarly, there must exist a clear chronological and depositional association between the sample being dated and the artefacts and features to which the date will be applied.

Fig. 2. Rock carving at Po Toi Island, dated to the first millennium BC

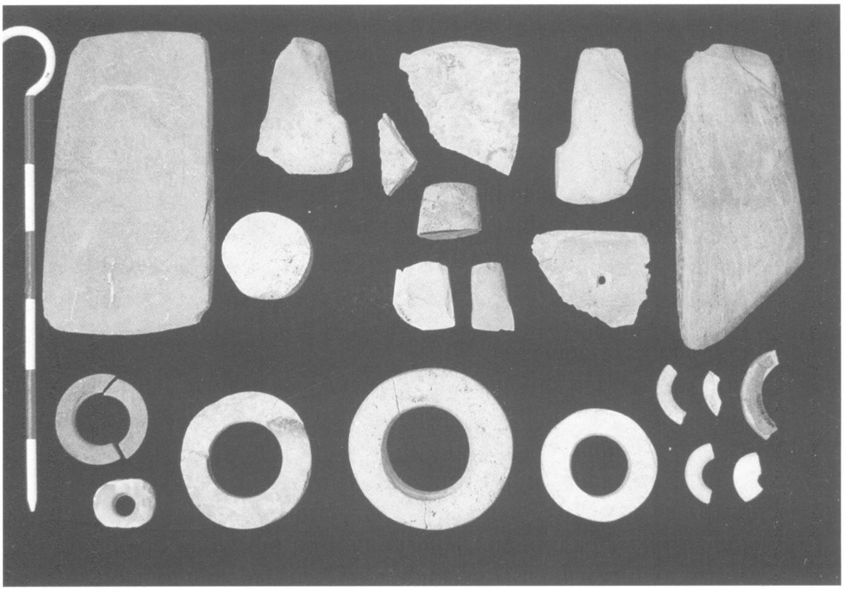

Fig. 3. A group of stone implements of various materials, excavated from a Bronze Age site at Tung Wan Tsai, Ma Wan Island

Eight groups of rock carvings have been recorded in Hong Kong, carved into rock faces near the coast (Fig. 2). On the basis of style they have been dated to the Bronze Age, when similar motifs can be found on ceramic vessels. No scientific dating has been attempted, although a dating method exists, adopted from geology, for the dating of rock carvings or petroglyphs. Cation ratio dating based on weathering and chemical alteration of the rock surface has been successful in dating similar petroglyphs in America (Rapp and Hill 1998).

Stone implements and artefacts form a major part of the archaeological record, ranging from unaltered pebbles with evidence of use wear, to highly polished blades and tools (Fig. 3). Geologists aid archaeologists in identifying rare or problematic raw materials, and in explaining the inherent qualities of specific stones which may have affected their selection and treatment in antiquity. It is important to know whether stone materials found in an archaeological context occur in the local environment, or whether they have been collected or imported from distant sources. Studies of stone provenance help in the reconstruction of economic and social networks which existed in prehistory (Andrefsky,1998).

The final example of geological methodology informing the analysis of archaeological data is the use of petrographic analysis in the study of ceramic fabrics. Thin sections of ceramic fabrics are studied with a polarising microscope to identify the mineral constituents and their relative abundance, alignment and state of alteration. The aims of petrographic analysis are to identify the nature of the clays used; to understand the methods by which the clay was processed into ceramic vessels; and most importantly, to determine whether the resulting vessels could have been manufactured locally or whether they came from other geological regions (Vincent, 1998). There is a great need in Hong Kong for archaeologists and geologists to design and implement a programme of petrographic analysis of local ceramic fabrics in order to better understand the nature and extent of local ceramic production and links to production centres in the region.

Mitigation Recommendation

This review of some of the ways in which geology and the Earth sciences as a whole aid and inform archaeology has been of necessity brief and general. However, we hope that it has shown something of how both disciplines can work together within the assessment system to identify Hong Kong's archaeological heritage. The use of methods and techniques absorbed from the Earth sciences helps the archaeologist to evaluate data collected in the field. Integration of this data using GIS systems allows us to clearly present this data and to recommend appropriate measures for mitigation of negative impacts on important archaeological sites. In the end, Hong Kong's past and present benefit equally from the co-operation of our two disciplines.

References

Andrefsky, W (1998) *Lithics: Macroscopic approaches to analysis.* Cambridge University Press, Cambridge

Draper-Ali, S (1996) *Marine Archaeology and Geophysical Survey.* The Hampshire and Wight Trust for Maritime Archaeology, Southampton

Environmental Protection Department (1997) *Technical Memorandum on Environmental Impact Assessment Process.* Hong Kong Government, Hong Kong

Harris, E (1989) *Principals of Archaeological Startigraphy.* Academic Press, London

Holliday, VT (ed) (1992) *Soils in Archaeology.* Smithsonian Institution Press Washington DC

Rapp, G & Hill, CL (1998) *Geoarchaeology: The Earth-Science Approach to Archaeological Interpretation.* Yale University Press, New Haven

Renfrew, C & Bahn, P (1991) *Archaeology: Theories, Methods and Practice.* Thames and Hudson, London.

Vincent, BA (1998). *Prehistoric Ceramics of Northeastern Thailand.* BAR International Series 461, Oxford

Magnetic Survey of the Offshore Areas of Hong Kong: Results, Interpretation and Significance

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Abstract

Marine magnetic surveys for geological applications first commenced in Hong Kong in 1991, however the majority of the offshore areas were only surveyed very recently in connection with the regional geological mapping programme. A brief summary of the theory of magnetic surveying and the analytical techniques employed to interpret these data is provided. The magnetic survey data collected from the central and western Hong Kong offshore areas have been amalgamated and analysed, and the corrected magnetic intensities displayed as a residual magnetic anomaly map. Numerous magnetic anomalies and lineaments have been recognised and an initial interpretation of their geological significance is presented. Marine magnetic surveying has already proved to be a cost-effective, rapid and highly informative technique for use in ground investigations related to the planning and construction of infrastructure and development projects.

Key words: marine magnetic surveys, subsurface mapping, residual anomalies, corrections, plutons, dykes, volcanic plugs and faults, infrastructure projects.

Introduction

The acquisition of marine magnetic data for geological applications in Hong Kong was initiated by the Geotechnical Engineering Office (GEO) in 1991 to assist in the location of marble beneath planned reclamations in Tolo Harbour,

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northeastern New Territories, and as part of the geological investigations for the Hong Kong International Airport at Chek Lap Kok (Electronic and Geophysical Services Ltd, 1991, 1993). However, the majority of offshore areas of Hong Kong have only been surveyed within the last two years in connection with the regional geological mapping programme (EGS (Asia) Ltd, 1999b, c, e, g, h). These regional surveys have been enhanced by more detailed surveys in selected areas to assist with the planning and construction of tunnels for the Strategic Sewage Disposal Scheme (EGS (Asia) Ltd, 1999a, d, f). Cosine Ltd has undertaken the compilation, levelling and processing of the marine magnetic data. Commonly, the data had to be 'cleaned' in order to take out the effects of electromagnetic noise, and influences of steel ships, infrastructure materials and marine debris. The preliminary geological analysis has been carried out in conjunction with GEO.

This paper summarises the principles of magnetic surveying and analysis, and provides a preliminary geological interpretation of the data from the central and western offshore areas of Hong Kong.

Rock Magnetism

Most rocks have some degree of magnetisation which, although normally very weak in small samples, can amount to a significant and readily measurable magnetic effect when summed over the enormous volumes of the rock mass. This magnetisation derives mainly from the traces of iron (Fe), either as small grains of the oxide magnetite or in the rock-forming ferromagnesian silicate minerals (e.g. amphiboles, pyroxenes, iron-bearing micas), that are common in the more basic igneous and metamorphic rocks. Less commonly, massive concentrations of iron and nickel oxides and some sulphides may be readily recognised by their locally strong magnetic influence. Massive magnetite-bearing skarns have been mined in the Ma On Shan area, northeastern New Territories, but it is unlikely there are substantial concentrations of nickel oxides or magnetic sulphides in Hong Kong.

There are essentially two types of rock magnetism: induced magnetisation that results from the incidence of the Earth's magnetic field upon the rock mass at the present time and secondly, but sometimes greater, a magnetisation that the rock acquired as a result of the magnetic field prevailing at the time of rock cooling, alteration or even during the lithification process. Although those different forms of rock magnetisation can be identified separately in the laboratory, in practice their influences are additive according to their directions. In normal magnetic surveys the quantity measured is the total response of the rock magnetisations superimposed upon the background of the Earth's magnetic field. The Earth's magnetic field is usually very much greater than the response of the rock magnetisations, so for convenience the total magnetic field is usually assumed to lie in the direction of the Earth's undisturbed magnetic field. The resultant local variations of the total magnetic field intensity due to lateral contrasts of the rock magnetic properties are termed magnetic 'anomalies'.

Magnetic Measurements

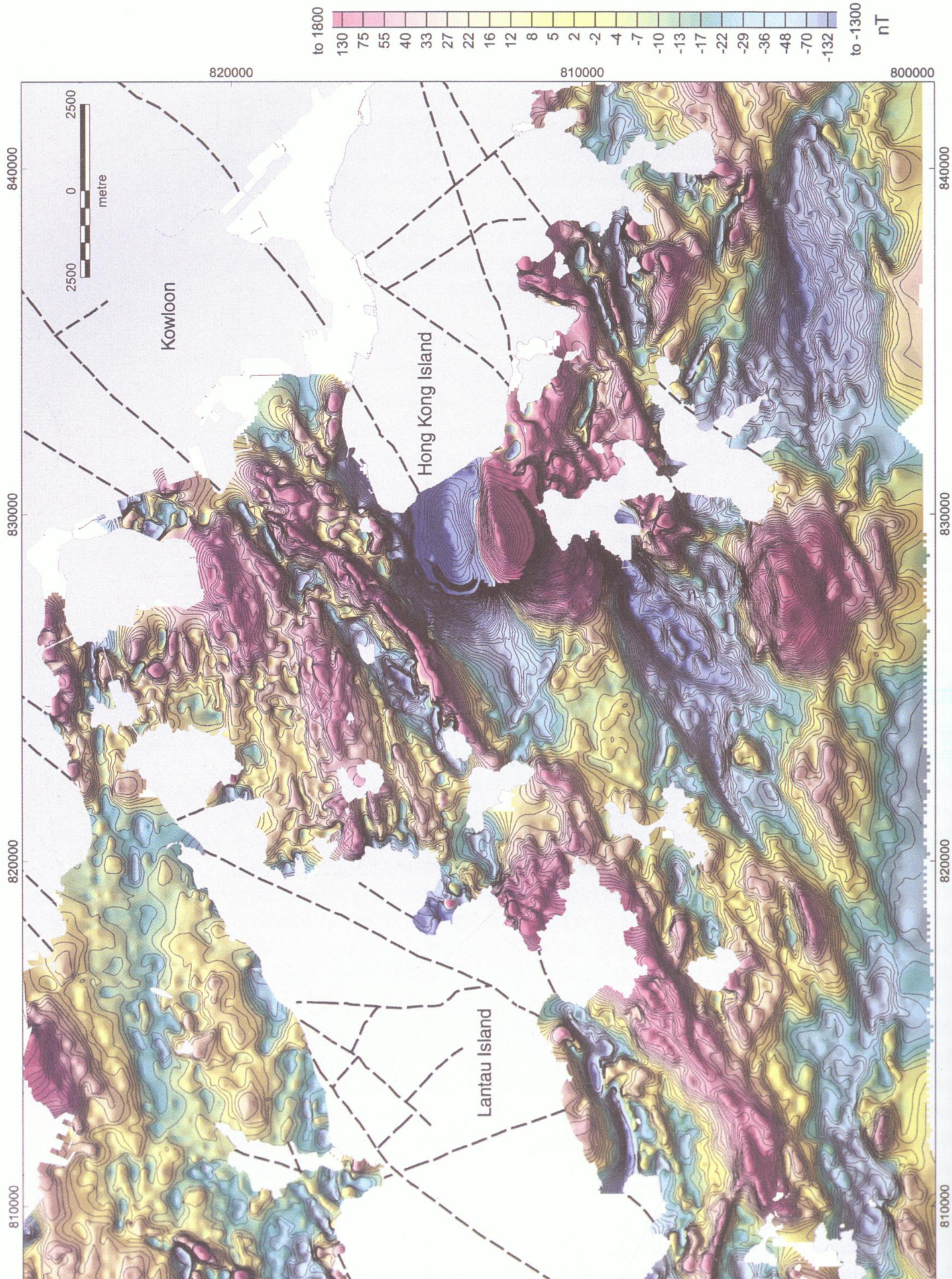
Using sensitive magnetic survey equipment, the total influence of the rocks upon the Earth's magnetic field can be measured very accurately. The commonly adopted unit of the magnetic field intensity is the nanoTesla (nT). With a few significant local exceptions the Earth's magnetic field in Hong Kong typically has a range of 44,500 to 44,700 nT at sea level, of which lateral magnetic contrasts within shallow rocks might on average contribute ± 50 nT in any locality. The modern survey equipment records with a resolution of ±0.01 nT and is capable of taking measurements at 10 readings per second. Thus the method, with appropriate control and data analysis, can be used very effectively as a geological mapping support tool, especially in offshore areas (see below). The objective of the magnetic survey is, therefore, to define variations in the Earth's total magnetic field that are controlled by local changes in rock magnetism of the various geological sources.

Marine Magnetic Surveys

The marine survey is undertaken from a suitable vessel, towing a magnetometer 'fish' sensor at a fixed, magnetically remote distance from the boat, and at an appropriate depth. The magnetic data are recorded digitally and the track of the vessel is defined using a Global Positioning System. A network of magnetic profiles can therefore be defined quite rapidly over a large area to generate a detailed map of magnetic variations. Subsequent data interpretation techniques can resolve the data into groups or bodies of magnetically contrasting rocks. In Hong Kong, the zone of interest is the first few hundred metres of the geological section, although marine magnetic surveys are also applicable to deeper targets, and are used routinely in offshore oil and gas exploration in support of seismic profiling.

Marine magnetic surveys in Hong Kong are subject to several problems. Within the main shipping lanes and in anchorages the passage of the survey vessel is commonly restricted and therefore consistent survey coverage is not always possible. Extraneous magnetic material, including anchored steel vessels, buoys, coastal structures and steel debris on the sea floor, affect the magnetic data. Whereas complete removal of the affected data would have resulted in large gaps in the data set, application of a filter would also have removed much of the magnetic anomaly attributable to shallow geological contrasts. The problem was minimised during these surveys by careful logging of the anchored and passing vessels and buoys. Subsequent generation of appropriate simple 3-D theoretical models of these iron bodies, and subtraction of the theoretical magnetic influence from the observed data, significantly reduced the magnetic distortion without any loss of the geological influence. Further interference of the magnetic readings has recently come from an unidentified source of strong (presumed) electromagnetic signal that couples with the magnetometer system in certain offshore areas. This has produced severe magnetic 'noise' in the data records, but fortunately this interference almost ceases during the early hours of the morning, and therefore night-time surveying largely overcomes this problem.

So far over 2000 line-kilometres of marine magnetic data profiles have been measured in Hong Kong waters along lines spaced at between 50 and 600 metres. The magnetic readings are processed with reference to onshore magnetic base stations. Small line to line natural discrepancies were minimised through magnetic line 'levelling' utilising tie line data.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Magnetic Maps

The final output of 'cleaned' magnetic data were first contoured as a total magnetic field intensity map that shows how the intensity of the Earth's magnetic field varies at sea level in response to magnetically contrasting rocks. The patterns shown by the total magnetic field intensity map were clarified by subtraction of the regional magnetic gradients that are due to deep geological influences and to the normal variation of the Earth's magnetic field. These were defined firstly by fitting a smooth, second order polynomial function to the 'cleaned' total field magnetic data and applying a controlled wavenumber filter. The resultant residual magnetic anomaly map is derived dominantly from the lithological contrasts within the uppermost 1000 m. Figure 1 presents a contoured residual magnetic anomaly map for western Hong Kong. The map has been computer enhanced by illuminating the intensity 'surface' from a northerly direction in order to give 'topographic' effect.

Fig. 1 (facing). Residual magnetic anomaly map of the central and western offshore areas of Hong Kong. The fine contour interval of the magnetic intensity is 5 nT, except in areas of high magnetic amplitude where contour interval is 100 nT. The colours used to depict the broad magnetic intensities are shown on the right-hand side of the figure. The 'topographic' effect displayed on the residual map has been computer-generated by simulating illumination from a northerly direction. The main onshore faults are taken from the 'Geological Map of Hong Kong' (1:200 000 scale) (Geotechnical Engineering Office, 2000)

Geological Interpretation

A preliminary geological interpretation of the residual magnetic anomaly map (Fig. 2, overleaf) reveals a large number of magnetic anomalies and lineaments that can be attributed to lateral magnetic contrasts within the rocks, either as a result of contrasting lithologies or to varying degrees of weathering of the magnetic mineral components. Many of these features correlate with the known geology of the onshore areas, but some do not, and extensive work will be necessary to provide a more complete interpretation. One technique that can be employed to interpret the data is analysis by theoretical 2-D and 3-D modelling. This method generates possible geological cross-sections by comparing the observed and calculated magnetic profiles (see Figures 11 and 12, in Fletcher et al., this volume). However, at this juncture only the main features that can be recognised on the residual magnetic anomaly map are described below.

Granite Plutons

Most of the seabed in the survey area is underlain by granite. It is recognised that tuffaceous volcanic rocks may be present locally, but they can not be distinguished from the granites by their magnetic signatures alone. The granites are magnetically variable, mainly due to the relative percentage of contained magnetite in the various granite bodies. It has been possible therefore to map out granites that are magnetically positive in comparison with those that are more magnetically neutral (Fig. 2). However, superimposed hydrothermal alteration will also affect the magnetic properties of the granites and thus the boundaries of some of the granites can only be mapped approximately.

Sedimentary Rocks

A slightly magnetically positive zone can be distinguished along the northwest coast of Lantau Island. This zone includes the Palaeozoic, metasedimentary, argillaceous rocks that crop out on The Brothers islands and areas of marble that have been proved in offshore boreholes.

Volcanic Plugs

Two dipolar anomalies with positive values to the south and negative values to the north are present close to Lamma Island. The anomaly to the north of Lamma Island is extremely strong with a magnetic range of over 3000 nT. The source has been interpreted as a steeply plunging, highly magnetic, basic/ultrabasic plug that rises to within 250 m of the sea floor beneath a cover of volcanic rock (Electronic and Geophysical Services Ltd, 1993). The modelled plug is slightly elliptical in horizontal section, measuring 2200 m by 1300 m with the major axis orientated ENE-WSW. The anomaly trends of the surrounding host rocks have largely been masked by the intense magnetic field of the plug. To the southeast of Lamma Island a more diffuse dipolar anomaly is observed, through which the magnetic response from regional structures can be discerned. Although not modelled at this time, the source of this anomaly is conjectured to be another basic/ultrabasic plug; however it would be slightly larger and have a thicker rock overburden than the plug to the north of Lamma Island.

Rhyolite Dykes

The series of ENE-trending anomalies to the east of northern Lantau Island form a set of bands of different levels of magnetic intensity. These anomalies may be correlated directly with the offshore extension of the Lantau Dyke Swarm that consists of a series of composite feldsparphyric rhyolite dykes, commonly over 50 m wide. The dykes are intruded into the medium-grained Lantau Granite that appears to be magnetically positive in contrast with the dykes. The dyke swarm is truncated to the east by the extension of the Tolo Channel Fault.

Monzonite Dykes

Several linear positive magnetic anomalies can be correlated with the monzonite dykes that crop out along the southeast coast of Lantau Island and on Lamma Island. The most persistent monzonite dyke parallels the offshore extension of the NE-trending Tolo Channel Fault for several kilometres, and may be associated with a similarly oriented dyke further to the southwest. Several shorter, NW-, NE- and NNW-trending monzonite dykes have been identified between Lamma and Hong Kong islands.

Faults and Fractures

Many persistent linear magnetic trends can be traced across the magnetic map. Some of these lineaments are evident through zones of contrasting magnetic intensity, whereas others appear simply as local troughs in the magnetic levels. These features are interpreted as faults or fracture zones, and several can be extrapolated directly to known mapped faults in the onshore areas. However, it should be noted that faults will only be observed on the magnetic map where there is a contrast in the magnetism of the rocks on opposing sides of the fault, or where alteration, either hydrothermal or weathering, has significantly reduced the original magnetism of the rocks within the fault/fracture zone. NE-, NNE- and NW-trending sets of linear anomalies are dominant, but easterly trending lineaments are present in the southern part of the map.

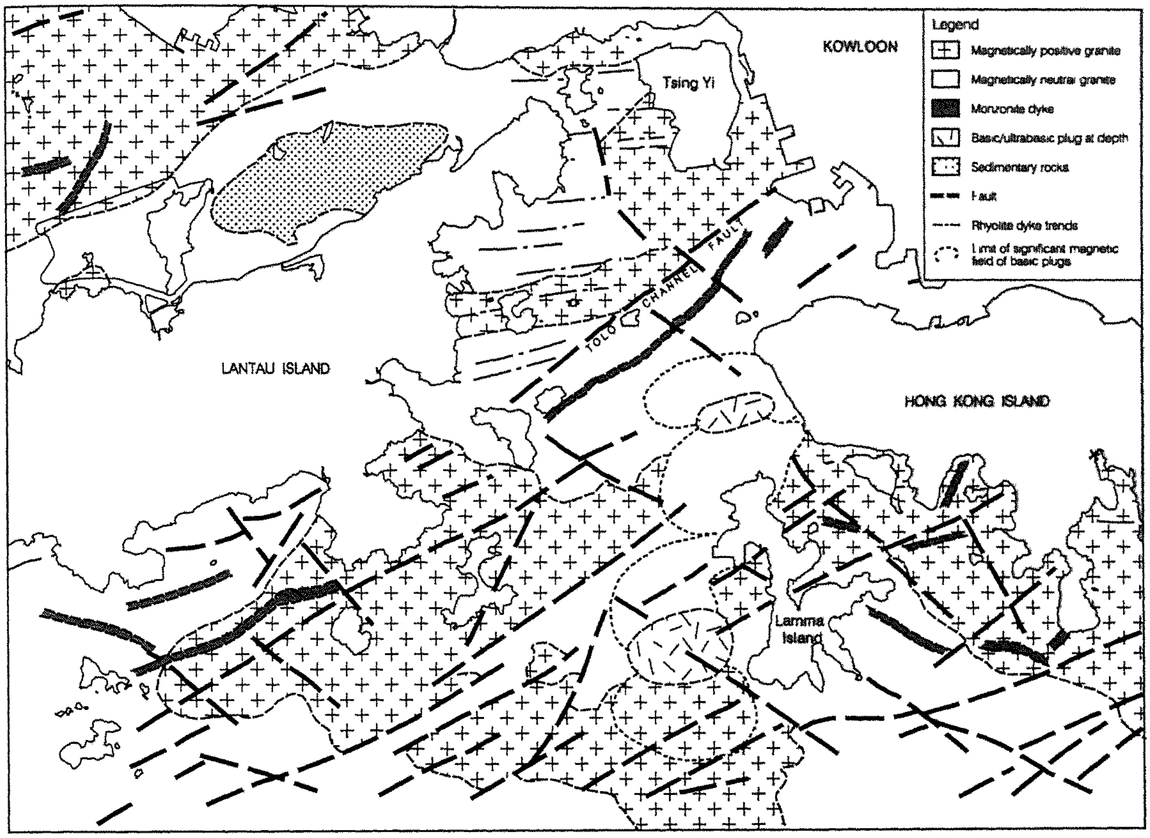

Fig. 2. Main geological features of the central and western offshore areas of Hong Kong that have been identified from the residual magnetic anomaly map

The most significant NE-trending linear magnetic trough is associated with the extension of the Tolo Channel Fault (see also Fig. 11, in Fletcher et al. this volume). This trough can be traced for over ten kilometres and has been modelled as a zone of depleted magnetism, up to 150 m wide, that is considered to be related to deep weathering and hydrothermal alteration along the fault zone. In places, the trough is sinistrally displaced by NW-trending faults. Relative timing of movement on the differently orientated faults can also be determined between Lamma and Hong Kong islands. There, the magnetic evidence mainly implies that it is the NW-trending faults that are displaced by the NE-trending and WNW-trending faults.

Discussion

The residual magnetic anomaly map of Hong Kong provides for the first time a regional picture of the complex geology in the offshore areas of western and central Hong Kong. However, this is just the first stage in the interpretation of the magnetic data, and theoretical computer modelling, combined with correlated onshore, tunnel and borehole geological information will greatly improve this preliminary interpretation. This survey has shown the usefulness of the marine magnetic technique, which has already been successfully applied to the construction and planning of certain infrastructure and development projects: for example the Strategic Sewage Disposal Scheme tunnels, reclamation at Ma On Shan (Tolo Harbour), the platform for Hong Kong

International Airport at Chek Lap Kok and Route 9 Highway on Hong Kong Island. It is envisaged that detailed magnetic surveys will become a standard technique in offshore ground investigations, as it provides a quick, cost-effective and highly informative method to assist in the interpretation of the geology, and in the siting of costly, marine boreholes.

Acknowledgements. This paper is published with the approval of the Head of the Geotechnical Engineering Office and the Director of Civil Engineering, Hong Kong SAR Government. The Directors of Drainage Services and Environmental Protection have allowed the data collected during magnetic surveys in the Rambler and East Lamma channels respectively to be incorporated into the offshore magnetic dataset presented in this paper.

References

Electronic and Geophysical Services Ltd (1991) Replacement airport at Chek Lap Kok, offshore magnetometer survey, geophysical surveys. *Report for Geotechnical Engineering Office, Job Number HK67892, Contract Number GC/91/01, Works Order Number PW7/2/31.25*

Electronic and Geophysical Services Ltd (1993) North Lamma offshore gravity and magnetometer geophysical surveys. *Report for Geotechnical Engineering Office, Job Number HK69292-2, Contract Number GC/91/01, Works Order Number PW7/2/31.29*

EGS (Asia) Ltd (1999a) Rambler Channel between Tsing Yi Island and Kwai Chung Container Terminal, marine magnetic survey. *Report for Geotechnical Engineering Office, Job Number HK132798, Contract Number GE/97/12, Works Order Number GE/97/12.36*

EGS (Asia) Ltd (1999b) Green Island, Tsing Yi and Peng Chau, marine magnetic survey. *Report for Geotechnical Engineering Office, Job Number HK132898, Contract Number GE/97/12, Works Order Number GE/97/12.37*

EGS (Asia) Ltd (1999c) Green Island, Tsing Yi and Peng Chau, marine magnetic survey – data interpretation. *Report for Geotechnical Engineering Office, Job Number HK137399, Contract Number GE/97/12, Works Order Number GE/97/12.53*

EGS (Asia) Ltd (1999d) Interpretation on marine magnetic survey in Rambler Channel. *Report for Geotechnical Engineering Office, Job Number HK137999, Contract Number GE/97/12, Works Order Number GE/97/12.54*

EGS (Asia) Ltd (1999e) Cheung Chau, Lamma Island and the Po Toi islands, marine magnetic survey. *Report for Geotechnical Engineering Office, Job Number HK136898, Contract Number GE/97/12, Works Order Number GE/97/12.55*

EGS (Asia) Ltd (1999f) Strategic Sewage Disposal Scheme Stage II, Preliminary Project Feasibility Study, desk study and geophysical surveys, Job Number HK144799, Contract Number GE/97/12 Works Order Number GE/97/12.68

EGS (Asia) Ltd (1999g) Soko Islands, Deep Bay, Tathong Channel and selected nearshore areas around Lantau, Hong Kong and Lamma islands, marine magnetic survey. *Report for Geotechnical Engineering Office, Job Number HK144899, Contract Number GE/97/12, Works Order Number GE/97/12.69*

EGS (Asia) Ltd (1999h) Additional data interpretation, geophysical survey. *Report for Geotechnical Engineering Office, Job Number HK145599, Contract Number GE/97/12, Works Order Number GE/97/12.70*

Fletcher CJN, Campbell SDG, Kirk PA, Parry S, Sewell RJ, Li XC, Lai KW & Liu YS (this volume) The role of the geological model in the urban development of Hong Kong. In: A Page & SJ Reels (eds) *The Urban Geology of Hong Kong*. Geological Society of Hong Kong Bulletin No. 6

Geotechnical Engineering Office, (2000) *Geological Map of Hong Kong*, 1:200,000 scale

Geophysical and Radiometric Properties of Weathered Saprolites in Hong Kong

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Abstract

Apparent resistivity, permittivity, and natural gamma intensity can be shown to be effective indicators of the degree of saprolitisation. Field trials at a study site in Hong Kong reveal relatively lower resistivity and higher permittivity values in more weathered rocks. Both total gamma intensity and gamma emission from potassium bearing minerals also decrease with increasing weathering grade. A radiometric survey conducted on a borehole in weathered volcanic tuff has demonstrated a good correlation of natural gamma intensity with weathering grade description. The results suggest that these properties can be used to characterise the degree of weathering and identify subsurface clay-rich layers.

Key words: saprolites, weathering grade, resistivity, permittivity, total gamma ray intensity, gamma emission, ground investigation.

Introduction

The characterisation of weathered saprolites is a fundamental concern for engineering geologists in undertaking geotechnical ground investigations. Most engineering geologists in Hong Kong are familiar with the 6-degree scale for descriptions of weathering grade (Table 1). While the scale is popular because of its simplicity, it requires a subjective judgement of the observer and does not provide a continuous scale for quantitative correlation with other parameters. Weathering indices that are based on geochemical composition, such as the Parker weathering index (Parker, 1970) or the silica-sesquioxide ratio (Selby, 1993), require laborious sample preparation and laboratory measurements. Therefore, there is a need for the development of a more quantitative and efficient means of characterising weathered rocks. Geotechnical assessments of rock masses are often based on mechanical parameters; the geophysical and

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Table 1. Weathering and rock grade classification for Hong Kong rocks

Grade	Degree of Decomposition	Diagnostic Features in Samples
VI	Residual soil	Original rock fabric is completely destroyed; no recognisable rock texture; surface layer contains humus and plant roots
V	Completely decomposed	Rock is discoloured and changed to a soil, but original fabric is preserved; sample may disintegrate when placed in water
IV	Highly decomposed	Rock weakened so that fairly large pieces (50 mm diameter) can be broken and crumbled in the hands; rock is discoloured; discontinuities may be open and have discoloured surfaces, and the original fabric of the rock near the discontinuities may be altered
III	Moderately decomposed	Rock is discoloured; discontinuities may be open and will have discoloured surfaces with an alteration starting to penetrate inwards; intact rock is noticeably weaker, as determined in the field, than the fresh rock, but large pieces cannot be broken by hand
II	Slightly decomposed	Rock maybe slightly discoloured, particularly adjacent to discontinuities, which may be open and will have slightly discoloured surfaces; the intact rock is not noticeably weaker than the fresh rock; yellow-brown limonite staining and some decomposition of feldspars
I	Fresh rock	Parent rock showing no discolouration, loss of strength or any other weathering effects

radiometric properties of weathered rocks are relatively less well known. We have been undertaking field trials to examine the feasibility of using selected geophysical and radiometric properties to quantify weathered saprolites in Hong Kong. At a cut slope in Siu Sai Wan on Hong Kong Island, we carried out measurements of apparent resistivity, permittivity, and gamma spectroscopy along two traverses that exhibit different degree of weathering. In a separate study, a downhole gamma survey was conducted on a borehole that cut across layers of different degree of decomposition. The objective of the studies was to evaluate the interrelations between the geophysical and radiometric properties and weathering grade. The results of these studies have been reported by Chen et al. (1999) and Chen and Chan (2000). The present paper presents a summary of the relation between the observed geophysical and radiometric properties and the degree of weathering.

Geophysical and Radiometric Properties

This present study is founded on the idea that potassium-bearing minerals such as K-feldspar and micas are commonly dissociated during chemical weathering processes, resulting in a gradual leaching of K-cations and an accumulation of clay minerals in the residue (Krauskopf and Bird, 1995). In a partially weathered saprolite, silicate grains are conceivably coated with an outer shell from which the K-cations have been preferentially removed. In the process, clay minerals depleted in K-cations form and accumulate in the weathered material. Since several electrical and electromagnetic properties, notably resistivity and permittivity, are sensitive to the presence of clay, the accumulation of clay minerals in the rock may cause measurable changes to these parameters.The depletion in K-cations may also result in a lower gamma-ray emission rate by more weathered rocks. In theory, therefore, these geophysical and radiometric parameters may be used as a measure of the degree of saprolitisation. While such geophysical and radiometric parameters are routine in exploration for petroleum and mineral resources, they have not been extensively used to study weathered saprolites. Bisdorf (1995) and Paniszczyn (1988) applied electrical resistivity to characterise subsurface weathering profiles. Neto (1998, abstract) described the interrelationship between gamma-ray intensity and certain engineering parameters, including shear wave velocity. Cromwell (1992) demonstrated that electrical resistivity, permittivity, and natural gamma spectroscopy could be used in a combined manner to identify geological deposits. Although preliminary in nature, these studies have pointed to the potential applications of the radiometric and geophysical methods to geotechnical investigations.

Apparent resistivity

The electrical resistivity of a material, given in ohm-m, depends on the material's mineralogy, porosity, degree of saturation, and chemistry of soil water (Sharma, 1997). Massive crystalline rocks, e.g. granites and volcanic rocks, have resistivity values several orders of magnitude greater than sedimentary and clay-rich rocks. Soil moisture and groundwater, however, can modify the resistivity value of a formation. A low resistivity is often attributable to high soil moisture. Since clay minerals have a high capacity for adsorbed water, low resistivity zones are thus an indirect indication to the presence of clay-rich materials (Lewton, 1989). For that reason, the electrical resistivity method is sometimes used to locate clayey or shaly formations (Takakura et al., 1997; Globe et al., 1997; Mullarkey and Dolly, 1997; Abu et al., 1996).

The measurement of resistivity in the field can be carried out using a resistivity meter and a set of four electrodes. In the Wenner configuration, the four electrodes are positioned at equal spacing along an array. A small current is introduced into the ground through the outer pair of electrodes, and the potential difference between the inner pair is measured. The resistivity of the material is calculated based on the measured potential difference, the current intensity, and the electrode spacing. The resistivity value obtained is given for the midpoint of the array and at a depth approximately equal to the electrode spacing. In the constant separation traversing (CST), the array of electrodes is progressively moved along a traverse line to determine the variations in resistivity along the traverse. The electrode spacing is kept constant during the survey and the array may be oriented either normal or perpendicular to the traverse line.

A more elaborate imaging procedure, the dipole-dipole method, may be used to obtain resistivity cross-sections. This imaging procedure involves field measurements of the resistivity values and inverse modelling of the obtained results. In this method, the current and the potential electrode pairs have equal spacing and are separated from each other by a distance equal to a multiple of the electrode spacing. The resistivity measured is given for the point of intersection of the two lines subtended at an angle of 45° from the midpoints of the electrode pairs. The two electrode pairs are progressively migrated along the traverse during the survey to obtain a resistivity profile, known as a 'pseudosection', which is subsequently inverted to obtain a resistivity cross-section.

Permittivity measurements

Permittivity (or dielectric constant) is a fundamental electromagnetic property of materials. It represents the 'ease' with which electromagnetic waves propagate within a medium. In principle, the velocity of electromagnetic wave in a medium is given by

$$v = c/\sqrt{\varepsilon}$$

in which e is the permittivity of the material and *c* velocity of light. Most of the previous studies on the permittivity of geological materials were related to the application of ground penetrating radar technology. Typical permittivity values are about 4 for dry porous materials and 20 for moist or clay-rich soils (Daniels, 1996).

Natural gamma spectroscopy

The natural gamma spectroscopy method is based on the idea that geological material contains a certain amount of radiogenic isotopes. Such isotopes may be concentrated or leached out during geological processes (Krauskopf and Bird, 1995). In humid conditions, chemical weathering of potassium-bearing minerals can lead to a progressive loss of potassium ions. Since naturally occurring potassium contains about 0.1% radiogenic K, the progressive loss of potassium through chemical weathering can therefore result in a decrease in the radioactivity associated with potassic minerals. Since the gamma radiation emitted by a certain isotope has a specific energy level, it is possible to tune a gamma ray detector to a particular energy window to detect the abundance of the isotope. Overlapping energy windows of some radiogenic isotopes, however, render the determination of the concentration of an individual isotope based on a single energy window difficult. In practice, multiple energy window counts are subjected to a series of stripping equations to determine the contents of individual radiogenic isotopes (Durrance, 1986).

Study Site

The study site at Siu Sai Wan is part of a cut slope located on the northern and western side of Siu Sai Wan Estate in the eastern part of Hong Kong Island (Fig. 1). The cut slope itself comprises a number of levels and subsections. The major section, designated S18|C2, consists of seven 10- to 12-metre-high slopes separated by approximately 2-metre-wide berms. The northeastern section, designated S9|C2, consists of three levels each about 8-10 m long. The native rock of the slope is a fine-grained dacitic ash tuff mapped as part of the Shing

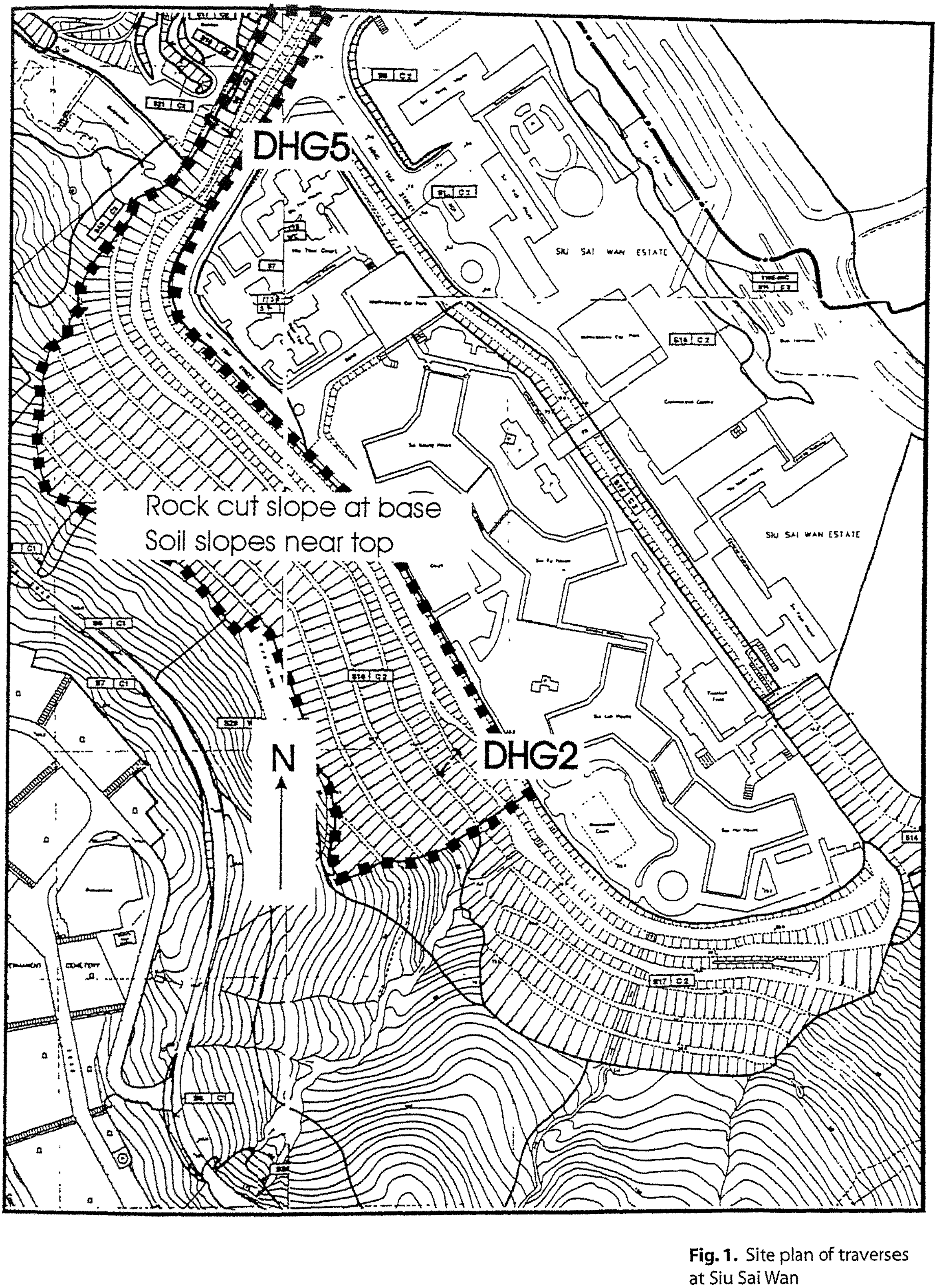


Fig. 1. Site plan of traverses at Siu Sai Wan

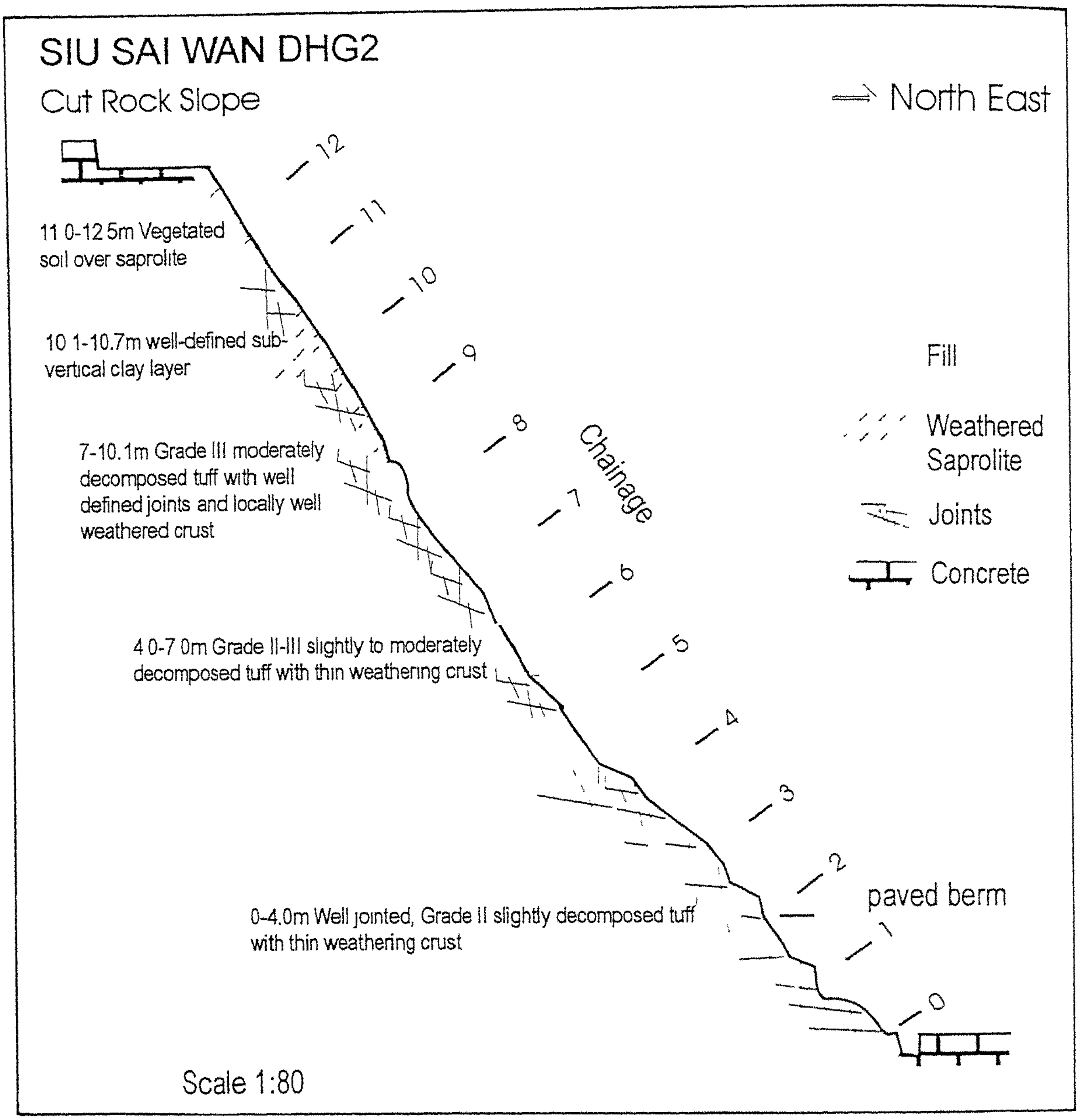


Fig. 2. Detailed characteristics of traverse DHG2

Mun Formation (GCO, 1986). The lower part of the slope was cut into relatively fresh rocks rated Grade II (slightly decomposed) to Grade III (moderately decomposed). Several sets of joints are present, with joint faces coated by a thin weathered crust a few mm thick. The degree of weathering and the thickness of soil cover increase toward the top of the slope. The upper sections of the slope consist of Grade III-V (moderately to completely decomposed) tuffs. Several clay-rich zones up to half a meter thick were also observed. Two particular slope traverses were chosen in the present study.

DHG2 (Fig. 2), located on the third level of S18|C2. The traverse is 13.5m long and inclines at 55° towards the northeast. The slope consists of slightly weathered volcanic tuff (Grade II) in the lower 8 m and highly to completely decomposed tuff in the upper 4 m. A sub-vertical, 60-cm-thick clay

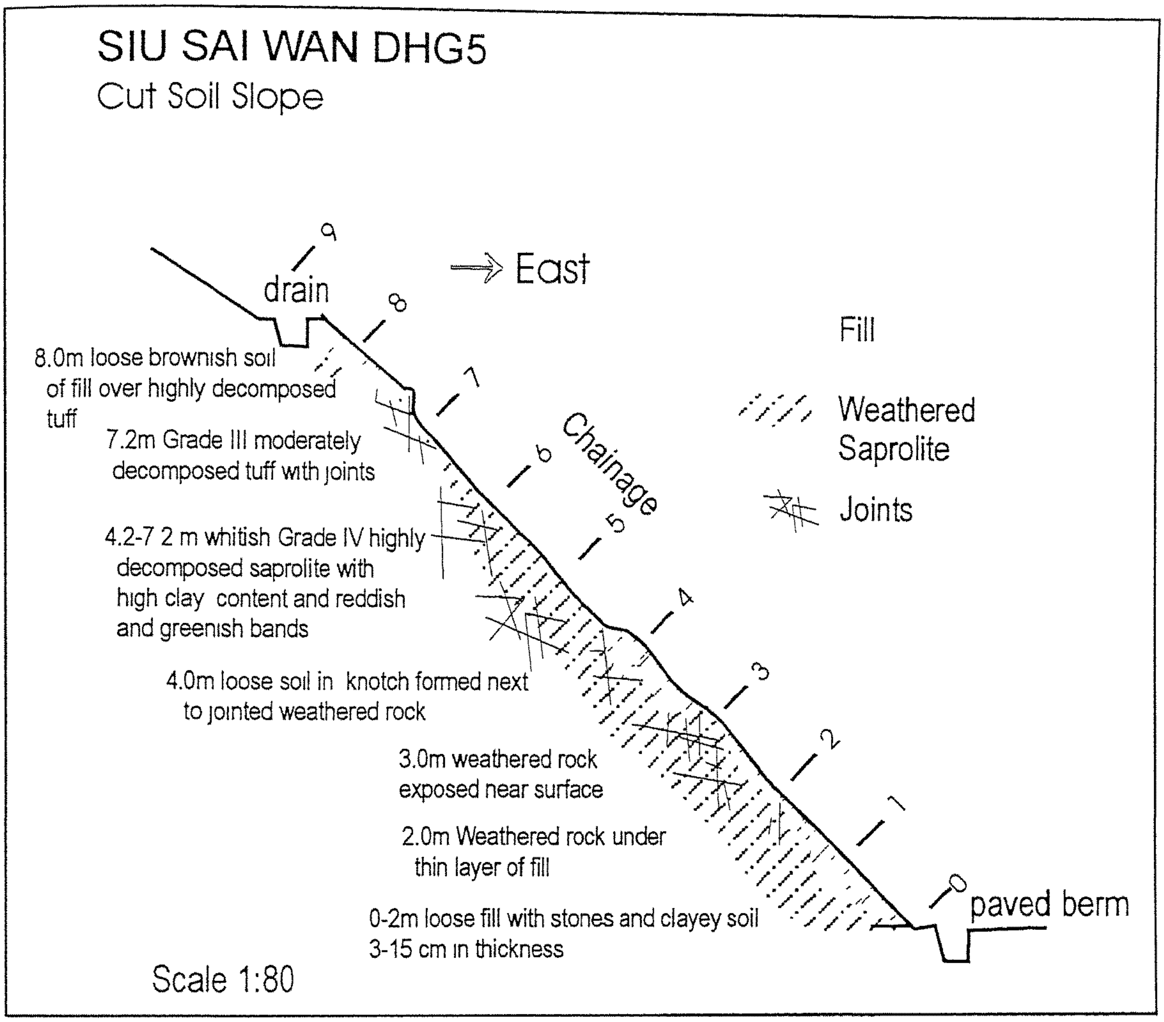


Fig. 3. General site characteristics of traverse DHG5

layer occurs at chainage 9.5-10.3 m along the traverse.

DHG5 (Fig. 3), located on the uppermost level of slope S9|C2. The slope is about 8.4 m long and inclines at an angle of 40° towards the east. The lower part of the section is Grade III-IV decomposed tuff covered by a 3- to 15-cm-thick layer of silty soil. Occasional jointed rocky layers protrude through the soil cover. The upper 4 m is primarily a Grade III-IV whitish-green clay-rich saprolite with a thin soil cover.

Since the two slopes show different degree of weathering, they were used to study the effects of weathering on the geophysical and radiometric properties.

Field Measurements

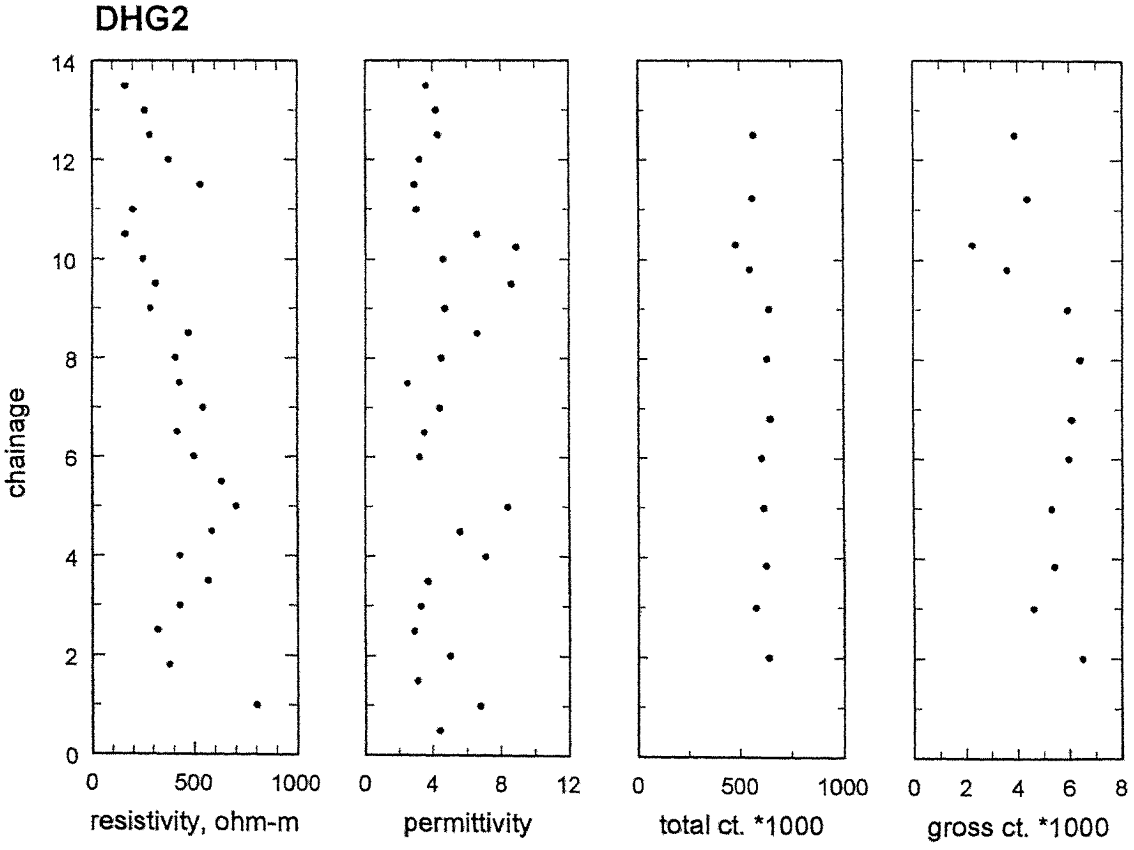
Constant separation traversing, permittivity and gamma intensity measurements were conducted along the two traverses. The CST was conducted with the Wenner electrode configuration oriented perpendicular to the traverse line using a 0.25 m spacing. A dipole-dipole profile was also carried out on DHG5. The measurements were done using a Sting R1 Earth Resistivity Meter. Steel or aluminium electrodes were used on the softer surfaces and split plugs inserted into predrilled holes on indurated, unjointed rock surfaces as electrodes.

For the dipole-dipole survey at DHG5, the electrodes were inserted into the ground at 0.4 m spacing (a=0.4) along the dip of the slope. A multi-electrode cable and a channel switch box were used to direct the current to different electrode pairs during the operation. Resistivity readings were taken at up to eight times the electrode spacing (n=8). The inversion of dipole-dipole resistivity data was done using RES2DINV which employs an iterative procedure that stepwise modifies the resistivity model according to the deviations of the computed resistivity section from the pseudosection.

Permittivity and contact conductivity measurements were done at 0.25 m intervals using an ADEK percometer and two sensors, one of them a surface sensor for hard rock and the other a penetrative sensor for soft soil. The penetrative sensor allowed measurements of materials located about 4-5 cm beneath the surface.

Direct measurements of gamma intensity up to 2200 KeV were done with an EG&G NaI ScintiPack low-level detector and a NOMAD system. A live time of 15 minutes was used in the counting. Two different counts were computed for each sample. The total gamma count and the count associated with the K-window were obtained, respectively, by integrating the intensity curve over the entire energy range and the peak at 1460 KeV (peak energy for

Fig. 4. Apparent resistivity, permittivity, and gamma intensity counts of DHG2



potassium-generated radiation).

In addition to the quantity of radiogenic isotopes in the measured samples, several other factors also control the natural gamma intensity, such as the sensitivity of the detection system and the sensing volume during the field measurement. In the present study, the sensitivity of the detection system was controlled by using a fixed gain of measurement and by calibrating the energy and output voltage against potassium chloride powder and specific radiogenic sources. Moisture and clay contents within the sensing volume may also reduce the recoil distance of the gamma radiation and hence the sensing range of the detector. Since both moisture and clay contents tend to increase with increasing weathering grade, more weathered rock would yield a lower gamma emission rate. All of these factors were taken into consideration in the present survey.

Results of Measurements

The results of the resistivity, permittivity and gamma intensity measurements for the two traverses are shown in Figs. 4 and 5. The CST result of DHG2 reveals apparent resistivity ranging from 200 to 800 ohm-m. The lowest value was recorded at chainage 10.5 m in the clay-rich layer and near the top of the section. In DHG5, the apparent resistivity of DHG5 ranged from 60 ohm-m to 250 ohm-m. The section also shows a gradual decrease in apparent resistivity values towards the top of the section. Such a decrease was confirmed in the inversion model of the dipole-dipole resistivity section (Fig. 6). The lower portion of the section has generally higher apparent resistivity values in the range of 100 to 600 ohm-m; the section at 3.4-6.8 m is underlain by a zone of relatively lower apparent resistivity.

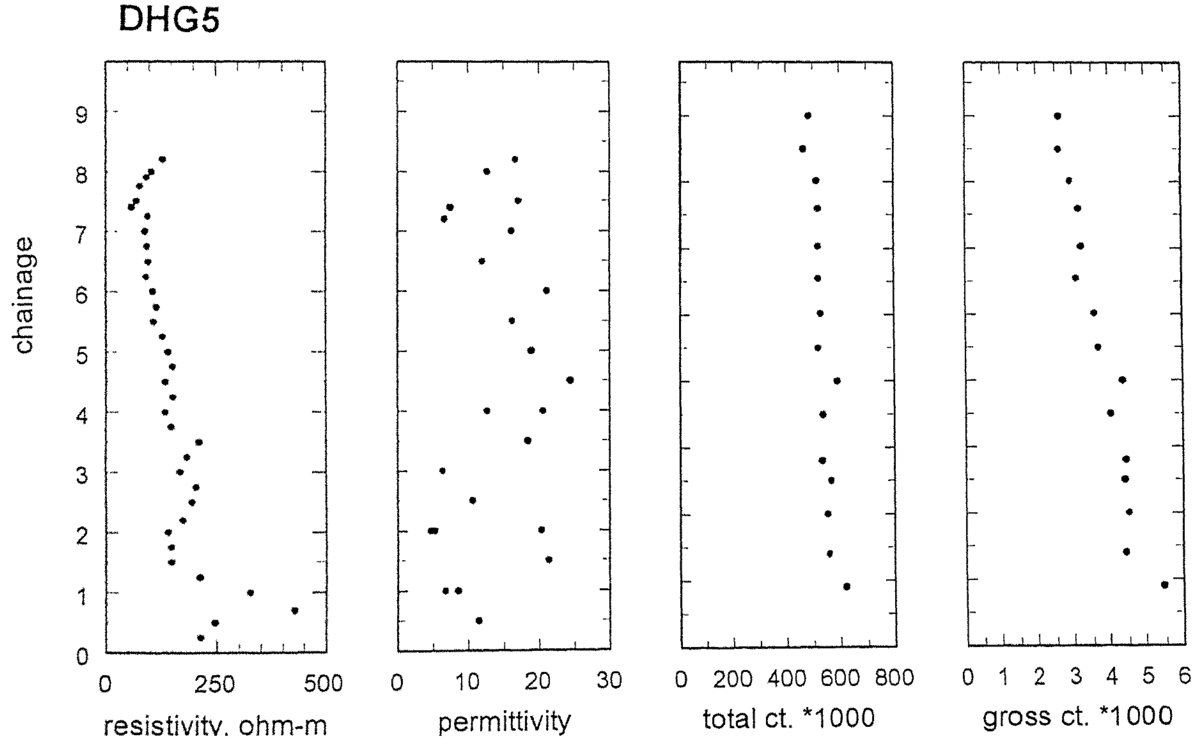


Fig. 5. Apparent resistivity, permittivity, and gamma intensity counts of DHG5

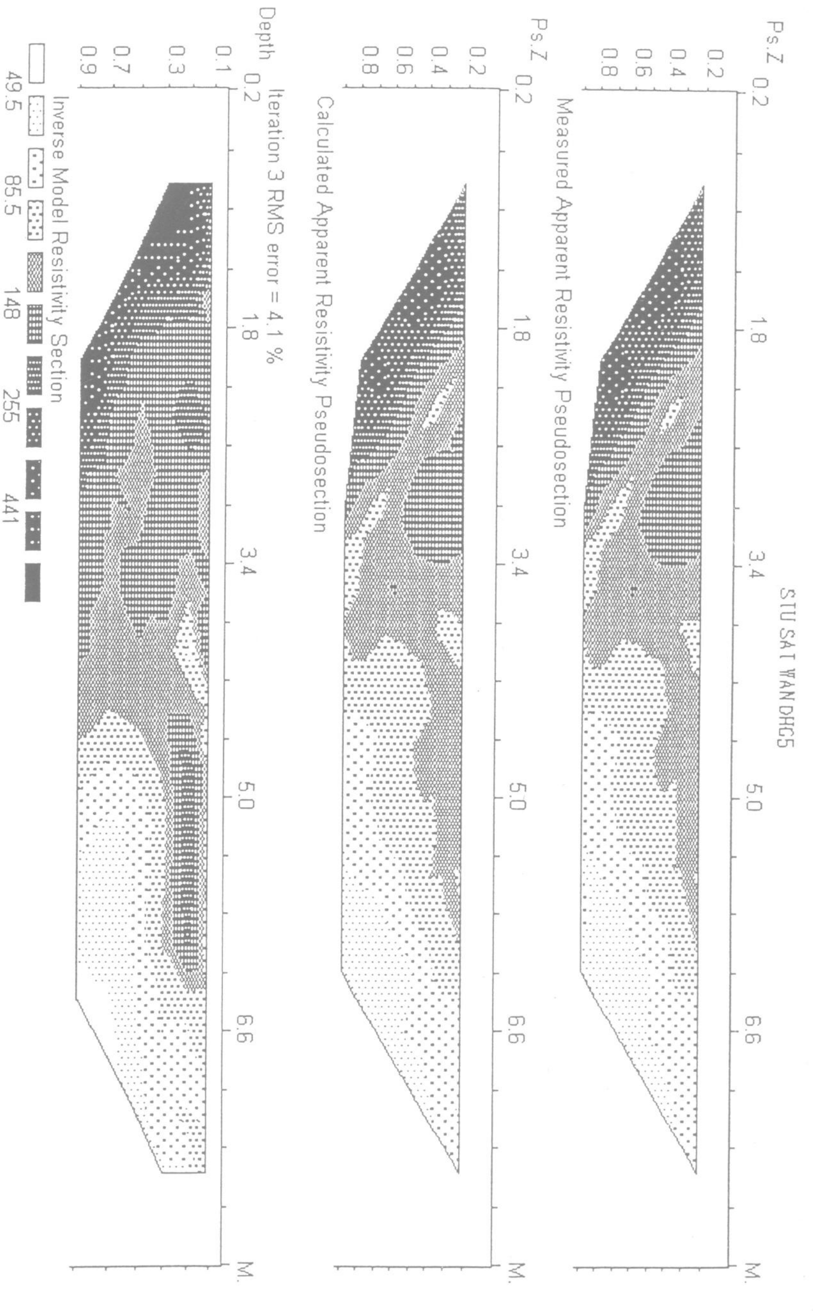


Fig. 6. Inverse model of resistivity profile of DHG5. The uppermost figure is the pseudosection, the lowermost the inverse model, and the middle one the computed resistivity section based on the inverse model

The permittivity of DHG5 ranged from 6 to 25. DHG2 shows a relatively lower permittivity between 4 and 10. Relatively higher permittivity was recorded in the clay-rich zone between 9.5 m and 10.3 m. A comparison of the results from the two slopes reveals generally higher permittivity in the more weathered materials.

The natural gamma radiation counts for the two traverses show substantial differences. For DHG2, 80% of the samples yield a total gamma intensity above 550 000 counts per 15 min. The clay-rich layer at 10.1-10.7 m shows a significantly lower total gamma intensity of 460 000 counts per 15 min and a similar reduction in the gamma intensity associated with the K energy window (designated K-gross count here). The relatively less weathered rocks reveal K-gross counts above 5000, while the K-rich zone has low K-gross counts of less than 2000. Both the total and K-gross counts for DHG5 are significantly less than those of DHG2 (Figs. 4 and 5). In summary, the radiometric survey reveals lower gamma intensities emitted by more weathered rocks.

Downhole Gamma Survey at Lai Ping Lane

To further examine the potential application of the radiometric method to ground investigation, a downhole natural gamma intensity survey was carried out on a drillhole at Lai Ping Lane in Shatin. The specific purpose of the survey was to determine if the natural gamma intensity profile is consistent with the description of weathering grade in the core log.

Borehole TT2A was installed near the crown of a landslide and where a system of tension cracks was exposed. The borehole has a diameter of 15 cm and is cased with galvanised iron. The top soil, about 1-2 m thick, was dominantly a clayey-silty soil. The drillhole record reveals completely decomposed tuff between the base of the top soil and a depth of 15.5 m (Fig. 7). Two levels of relatively less weathered tuff present at depths of 6.9-7.64 m and 8.04-9.00 m are probably corestones. The section between 15.5 m and 19.5 m consists of Grade II to Grade V rocks. The lower part of the drill core is mainly completely decomposed tuff at 19.5-21.88 m overlying slightly decomposed tuff. At the time of the survey, the water level was located at a depth of 7.3 m.

An MGXII logging system, equipped with a 2PGA-1000 polygamma probe was used in the survey. The probe was centered over the drillhole on a winch system and lowered down into the drillhole with a steel cable. The downhole survey was conducted at a speed of 4.0-4.5 metres per minute and data were collected at a 5 cm interval.

The 5-point running-average profile of the total gamma intensity is shown in Fig. 7. A number of zones can be recognized on the gamma intensity profile. The gamma intensity increases from about 80 cps to over 150 cps within the top 3 m (A). Two peaks are present at 3-4.8 m (B) and 6.6-7.3 m (D). A less prominent peak can be observed at 8.5-9.3 m (F). The intensity then drops below 150 cps between 9.3 m and 17.0 m (G). The intensity increases slightly to about 170 cps at a depth of 17.0 m (H) and shows an abrupt increase to over 250 cps at a depth of 22.0 m .

A comparison of the gamma intensity profile with the drillhole record provides a preliminary interpretation of the variations in the observed gamma intensity. The top soil within the uppermost 2-3 m yields a low gamma intensity. The slightly elevated intensity zones D and F are associated with corestones; low intensity zones E and G are characteristics of completely decomposed rock. Relatively high gamma intensities (I) are attributable to the least weathered rocks.

The natural gamma profile generally agrees with the weathering grade description in the drillhole record. Based on the recorded gamma profile, less weathered rocks show higher gamma intensities. For this borehole, Grade III and IV tuffs show gamma intensity in the range of 150-200 cps. Grade V tuffs are generally below 150 cps and Grade II rocks show a relatively greater gamma intensity above 250 cps. The gamma ray emission rates have also been converted into gamma-ray American Petroleum Institute (API) units as shown in Figure 7.

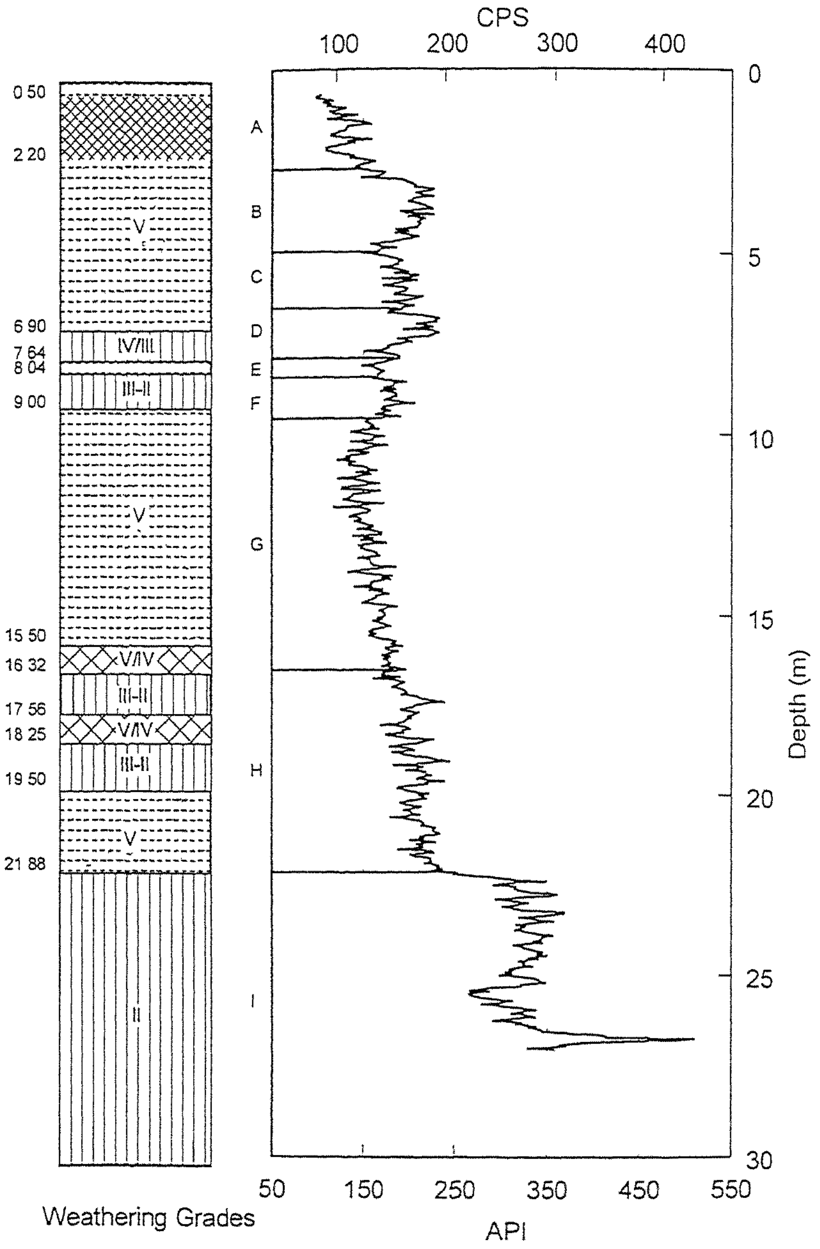


Fig. 7. Core description and total gamma intensity profile of drillhole TT2A, showing correlation between weathering grade and natural gamma intensity

These ranges of values can perhaps serve as a reference for characterisation of the degree of weathering of volcanic tuffs.

Conclusions

The results from the studies can be summarised as follows:

1. Saprolitisation of the studied rock was associated with a decrease in resistivity and an increase in permittivity.
2. Clay-rich saprolite shows permittivity values in the range of 10-20.

3. Both total gamma intensity and gamma emission by potassium-bearing minerals decrease with an increasing weathering grade.
4. The radiometric survey at one borehole has revealed a good correlation between borehole description of weathering grade and the gamma intensity profile.

The three geophysical and radiometric properties can be used as a means of characterisation of weathered rocks. Since the three parameters are easy and inexpensive to measure, they can potentially be used as supplementary techniques for engineering geology ground investigations.

References

Abu HZ, Benson CH & Blotz LR (1996) Electrical resistivity of compacted clays. *Jour Geol Engineering*, 122, 397-406

Bisdorf RJ (1995) Correlation of electrical geophysical data with lithology and degree of alteration at the Summitville Mine site. *Proc Summitville Forum '95*, 70-74, Colorado Geol Survey Report 38

Chen Q, Chan LS & Ie S (1999) Radiometric study of clay-rich zones in weathered volcanic tuff in Hong Kong. *Pro. 2nd Asian Symp Eng Geol and the Environ*, 23-25 Sept. 1999, Malaysia, 7/13-19

Chen Q, & Chan LS (2000) Gamma radioactivity differentiation of weathered volcanic tuff in Hong Kong. *Conf Proc SAGEEP*, Arlington, 1137-1146

Cromwell R (1992) *An Evaluation of Using Electrical Resistivity, Dielectric Constant, and Natural Gamma Radiation for Mapping Quaternary Deposits in Savuloski, Finland.* Master's thesis, Univ Wisconsin-Madison

Daniels DJ (1996) *Surface Penetrating Radar.* Inst Electrical Engrs, Exeter, 300p

Durrance EM (1986) *Radioactivity in Geology.* Ellis Horwood Limited

GCO (1986) *Geology of Hong Kong Island and Kowloon.* Civil Engineering Services Department, Geotechnical Control Office

Globe MJ, Camp WK & Hairr RD (1997) Resistivity calibration techniques for micro-resistivity image logs; applications for thin-bedded, shaly sand reservoirs, Gulf of Mexico. *Abstracts, Amer Assoc Petrol Geol, Annual Meeting*, 6, 41

Krauskopf KB & Bird DK (1995) *Introduction to Geochemistry.* McGraw-Hill, New York

Lewton WA (1989) *Sedimentology and Diagenesis of a Pleistocene Low Resistivity Reservoir, Louisiana Offshore, Gulf of Mexico.* Master's thesis, Univ Texas

Mullarkey JC & Dolly ED (1997) Causes of low contrast, low resistivity in hydrocarbon productive reservoirs of the Rocky Mountain and Mid-continent regions. *Abstracts, Amer Assoc Petrol Geol, Annual Meeting*, 6, 86

Neto AA (1998) *Relationships Between Physical Properties and Sedimentologial Parameters of Near Surface Marine Sediments and their*

Applicability in the Solution of Engineering and Environmental Problems. PhD Thesis, 122 pp, Univ Christian Albrechts, Germany

Paniszczyn F (1988) A resistivity method used for the recognition of vertical weathering zones in overconsolidated clay shale, central Texas. *Assoc Eng Geol 31st Meeting, Abstr & Progm*, p 55

Parker A (1970) An index of weathering for silicate rocks. *Geol Mag*, 107, 501-504

Selby MJ (1993) *Hillslope Materials and Process*, 2nd edn, Oxford Univ Press, London

Sharma PVC (1997) *Environmental and Engineering Geophysics*. Cambridge University Press, 330-351

Takakura S, Nishizawa O, Aoki M & Kozake K (1997) Influence of smectites on resistivity of rocks and soils. *Geophysical Exploration*, 50, 161

Towards sustainable coastal development in Hong Kong

W.W.-S. Yim

Abstract

The coastal zone of Hong Kong has been utilised for a range of conflicting purposes including coastal reclamations, port activities, offshore waste disposal, offshore sand exploitation, marine parks, coastal reserves, coastal fisheries, mariculture and coastal recreation. Problems are created, including the declining coastal water quality, the increasing frequency of coastal flooding and the failure of seawalls during storms. Based mainly on learning from past experience, a policy towards sustainable coastal development is outlined. In this policy, the coastal waters of the Hong Kong Special Administrative Region (SAR) are divided into a western zone, a central zone and a eastern zone based on their present characteristics. Different types of current coastal utilisation are permitted in at least one of the three zones while the conditions of the naturally clean eastern zone are maintained. In the densely populated central zone where land demand is the greatest, a 'cost-effective' strategy is to allow regulated effluents from storm drains and sewage outfalls to be contained within typhoon shelters in order to reduce their environmental impact. Such typhoon shelters may be reclaimed every twenty to thirty years to create new land needed as part of a long-term coastal development plan. In the eastern zone, offshore sand exploitation and marine waste disposal should be banned to permit use of at least part of the zone for mariculture, coastal fisheries and coastal recreation. In the naturally high-turbidity western zone, regulated offshore waste disposal and offshore sand exploitation can be permitted. Since the implementation of any coastal development policy in the Hong Kong SAR will also affect the adjacent Guangdong coast, it is important to involve the Guangdong authorities in discussions to seek mutually beneficial solutions.

Key words: coastal development policy, eastern, central and western zones, effluent discharge, waste disposal, sand exploitation, mariculture, fisheries, recreation, Hong Kong, Guangdong.

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Introduction

The coastal zone is one of the most important of the world's finite resources (Apsimon et al., 1990). It is the area where much of the world's population lives and obtains its food. Currently it is under the threat of the combined effects of population growth, urban and agricultural development, industrial expansion, recreational pressures, offshore waste disposal, the exploitation of marine resources, coastal erosion, and the effects of a rising sea level. This threat will grow in the future as the population of the coastal zone continues to increase rapidly. It is therefore essential for major coastal cities in the world to adopt a sustainable coastal development policy.

According to a paper prepared for public consultation on Australia's ocean policy (Anonymous 1998), ecologically sustainable development is 'development that improves the quality of life, both now and in the future, in a way that maintains the ecological processes on which life depends'. For coastal development, the desirable natural attributes of the coastal zone should be maintained as long as possible. It is important to enhance individual and community well being and welfare by following a path of economic development that safeguards the welfare of future generations and at the same time protects biological diversity and maintains essential ecological processes and life-supporting systems. In the present study, based mainly on learning from past experience, a policy towards sustainable coastal development for the Hong Kong SAR is outlined.

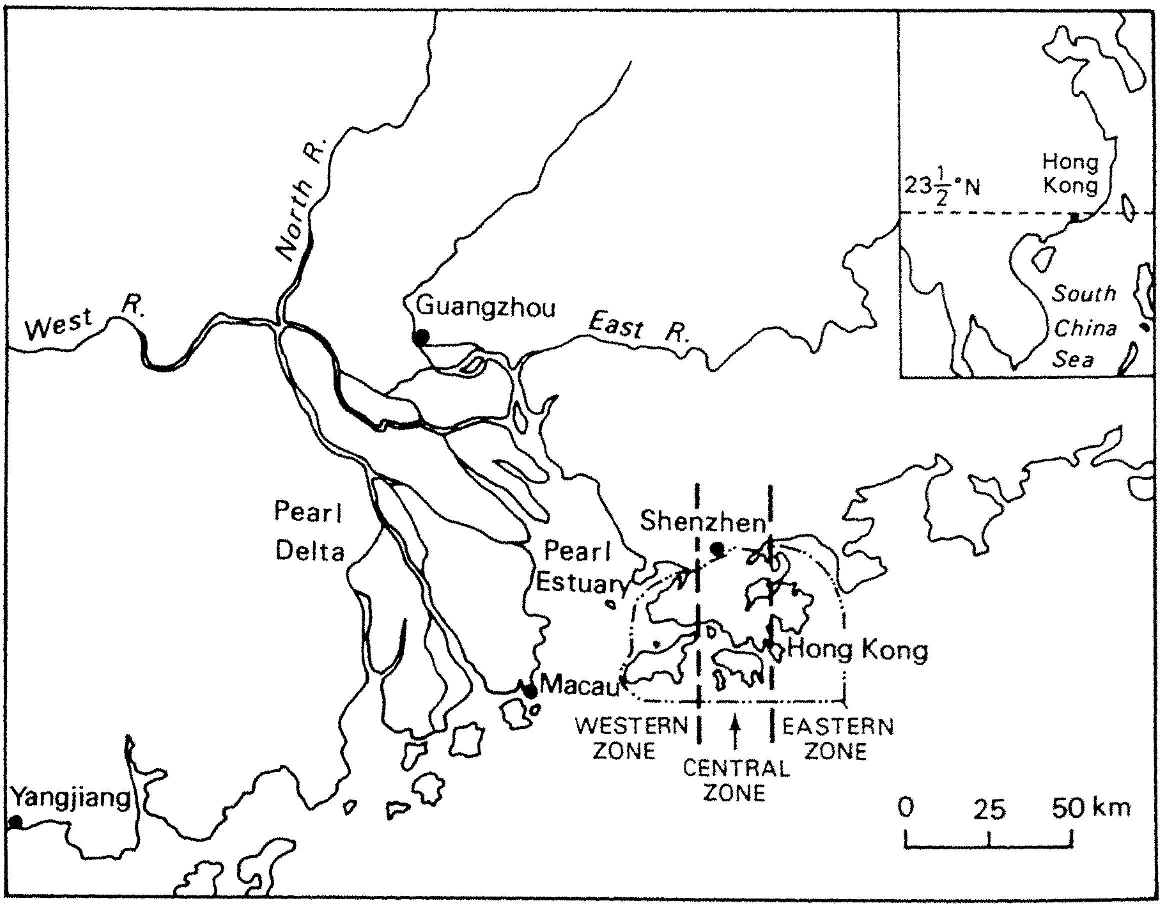


Fig. 1. Map showing the location of Hong Kong, its three hydrographic zones (after Watts [1973] and Morton [1985]), the Pearl Delta and the Pearl estuary

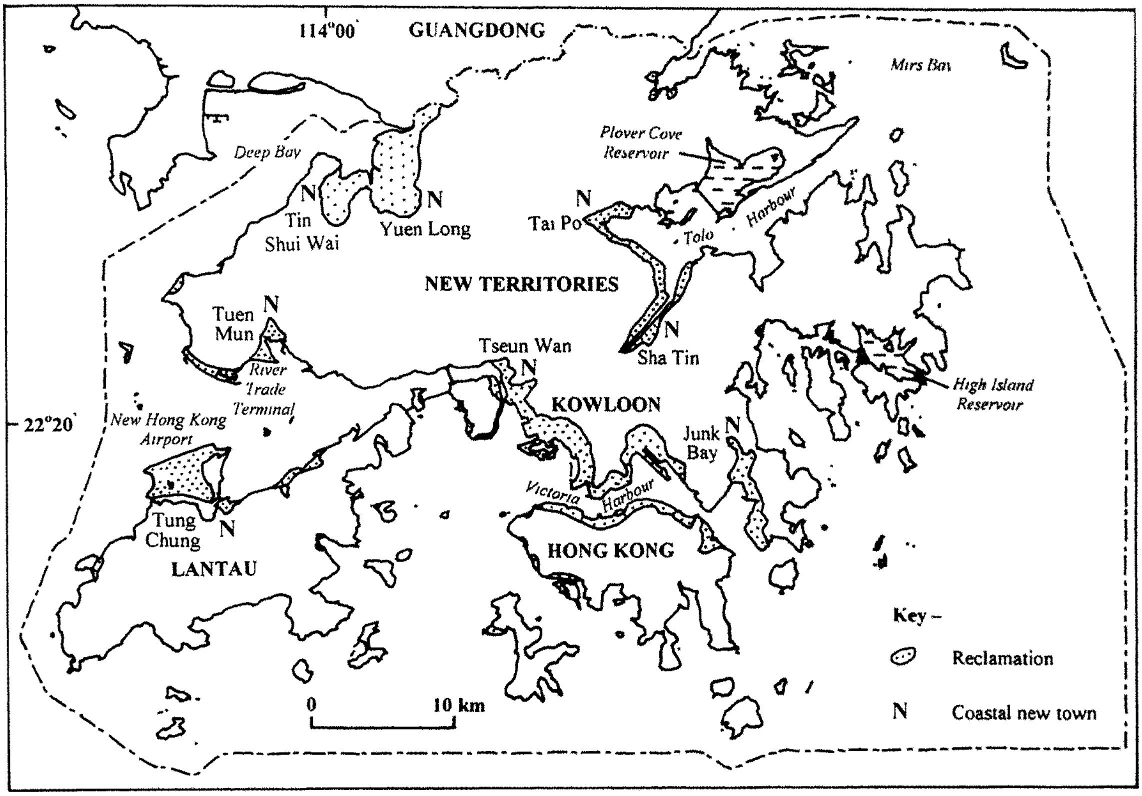


Fig. 2. Map of Hong Kong showing coastal reclamations and other selected coastal features

Environmental Background

Hong Kong lies east of the Pearl River Delta on the fringe of the Pearl River estuary to the south of the Tropic of Cancer in the northern part of the South China Sea (Fig. 1). It has a subtropical climate characterised by hot wet summers and cool and dry winters associated with the southwest monsoon and the northeast monsoon respectively. In spite of the generalisation, enormous variability of rainfall is known to exist (Yim, 1996) with the highest annual precipitation associated with El Nino/Southern Oscillation (ENSO) years. The two strongest ENSO years in 1982 and 1997 were also the two wettest year ever recorded.

Out of Hong Kong's present total land area of about 1100 km^2, about 10% was estimated by Peart and Yim (1992) to have been reclaimed from the sea. The need for coastal reclamation was caused partly by the shortage of low-lying land and the difficulty in developing hilly terrain prone to landslides.

Hong Kong is naturally a highland area without major rivers, formed largely of volcanic and intrusive igneous rocks of Mesozoic age. The rugged terrain does not appear to have undergone any significant changes since the late Mesozoic but the coastline of some 870 km in length (So, 1985) is highly indented with numerous headlands, bays and offshore islands. There are a number of relatively large, sheltered bodies of water including Victoria Harbour and Tolo Harbour (Fig. 2). Evidence obtained from the study of offshore sediments by Yim (1994) indicated five high and five low stands of sea level related to interglacial and glacial periods during the Quaternary period. The present day sea level was attained between 6000 and 7000 years ago as a consequence of the termination of the last ice age (Yim, 1986).

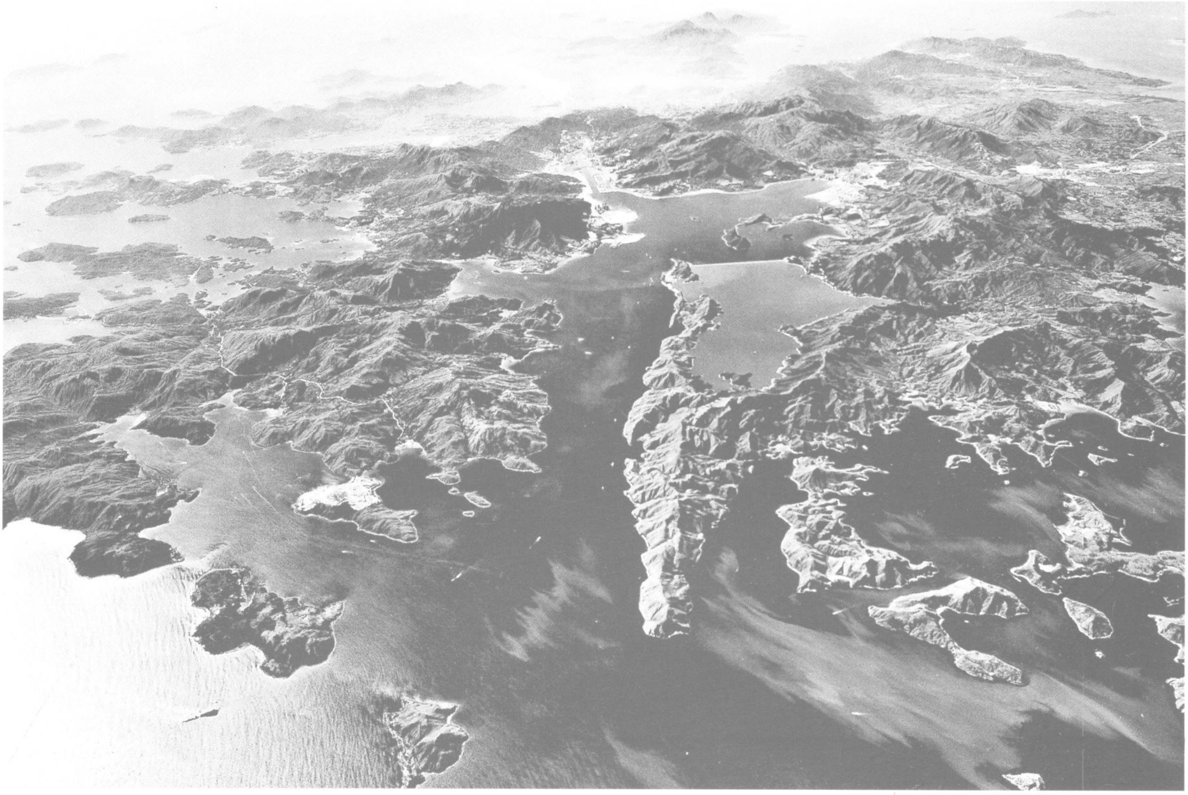


Fig. 3. Oblique aerial photograph of Hong Kong taken in a southwesterly direction from the northeast at an elevation of about 6000 m. The rugged terrain has been partially drowned by the Holocene transgression with naturally low-lying land very limited in extent. Tolo Harbour with a narrow exit into Mirs Bay can be seen in the centre. Source: Department of Lands © Hong Kong SAR Government

Because of freshwater discharges from the Pearl River, the coastal waters of Hong Kong show major differences in salinity and turbidity from the Pearl River estuary eastwards. This led Watts (1973) and Morton (1985) to divide the Hong Kong waters into an eastern zone, a central zone and a western zone based on the hydrological characteristics (Fig.1). The eastern zone is under the strongest oceanic influence and the salinity is only marginally below normal seawater. The waters are also the cleanest because the zone is furthest away from the influence of Pearl River. In contrast, the western zone is dominantly estuarine with low salinity and high turbidity while the central zone is transitional in nature. Victoria Harbour and Tolo Harbour, both located in the central zone, show sharply contrasting characteristics. The former is regularly flushed by strong tidal currents entering through a number of narrow channels while the latter, with a narrow exit into Mirs Bay (Fig. 3) is poorly flushed.

Main Types of Coastal Usage and their Problems

A map of the proposed coastal reclamations, sand burrow areas, mud disposal areas, marine parks, coastal reserves, fish culture areas, coastal landfills and selected coastal features in Hong Kong is shown in Fig. 4. In just over two millenniums, Hong Kong has developed from a sparsely populated area relying mainly on coastal fisheries and sea-salt manufacturing into a coastal city with a population of over 6.5 million and the busiest container port in the world. There is therefore much to learn from Hong Kong's past experience in coastal development. In this section, the main types of coastal usage and their associated problems are examined.

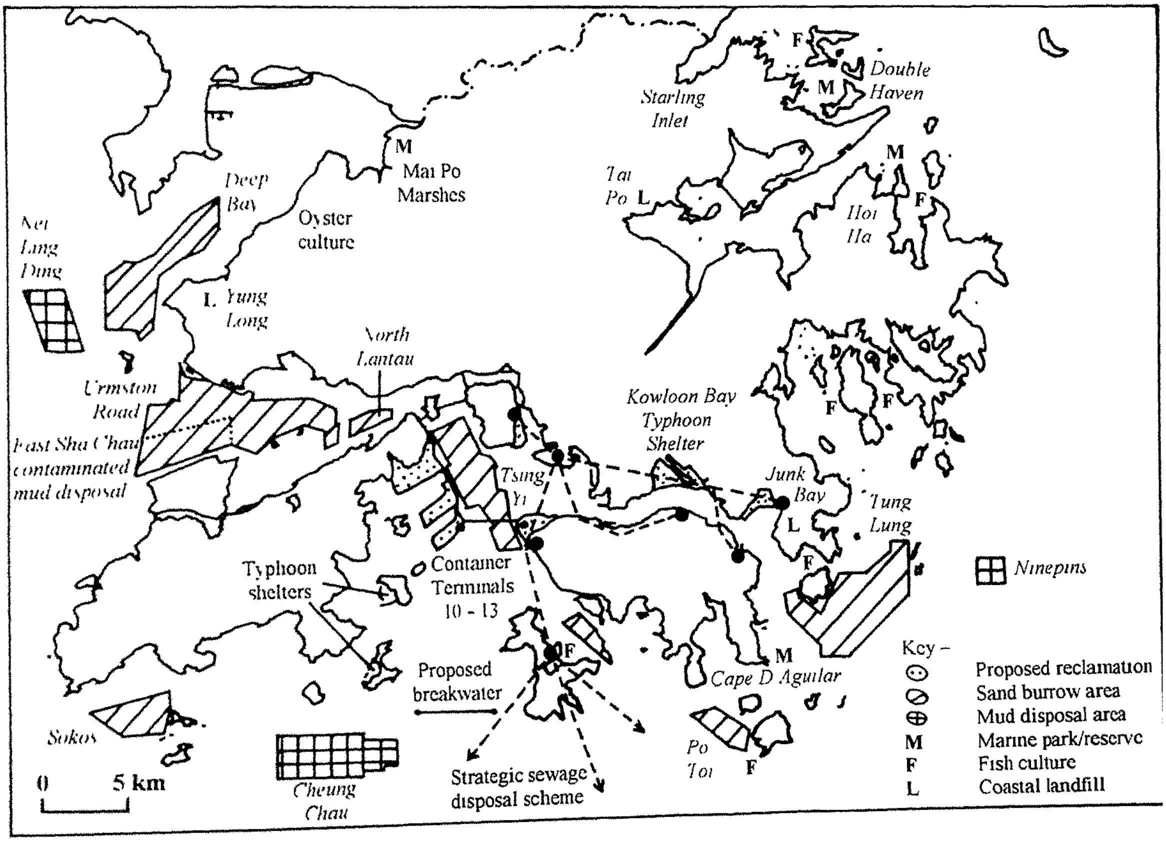
Port activities

The success of Hong Kong as a leading international port owes much to its naturally deep-water harbour. Prior to the last quarter millennium, even sheltered inshore areas like Victoria Harbour possessed sufficiently good water quality for environmentally sensitive organisms such as corals. This is indicated by the discovery of both coral remains and living corals within the harbour. Coral remains were found during the construction of the Choi Hung housing estate in Kowloon Bay (the late P. Lumb, personal communication) and the construction of the Western Harbour Crossing (W.W.-S. Yim, unpublished work) while living corals were found in the Ma Wan Channel and in the vicinity of Green Island (W.N. Ridley Thomas, personal communication).

Since port development is of great importance to the economic well being of Hong Kong, port activities have to be tolerated and the marine environment, at least in some areas, has to be sacrificed. The necessity to control pollution from ships including oil, noxious liquid substances, harmful packaged substances, sewage and garbage was recognised by the @Marine Policy@ (MARPOL) convention in 1973. However enforcing the convention is a major problem even now. For example, the discharge of ballast water contaminated by oil is still widespread.

Ships are also a major contributing source of heavy metals to sea-floor sediments. The high mean concentration of 93 parts per million dry weight for Pb found in Victoria Harbour sediments (Yim and Fung, 1981) is best explained by shipping contamination through paint chippings as red lead is widely used

Fig. 4. Map of proposed coastal reclamations, sand burrow areas, mud disposal areas, marine parks, coastal reserves, fish culture areas, coastal landfills and selected coastal features in Hong Kong. Based partly on Anandasiri (1998)



for rust proofing the hull of ships. This is supported by the strong correlation found between magnetic susceptibility and the heavy metals Pb, Cu, Zn and Cr in surficial sea-floor sediments of the harbour (Chan et al., 1998). The high magnetic susceptibility is consistent with an origin through rust fragments while the heavy metals have derived from paints. Because of the nature of shipping activities, the most contaminated areas are likely to be the anchorage areas, shipyards, piers, container terminals, typhoon shelters and the main shipping channels.

Coastal reclamations

Early coastal reclamations in Hong Kong prior to Hong Kong becoming a British colony were predominantly for sea-salt production, fish and shellfish farming, and for agricultural uses. Yuen Long, Tai O and Mui Wo were formerly centres for such activities. After Hong Kong became a British colony, rapid population growth and the development of Hong Kong into a deep-water port have led to major coastal reclamation schemes in the sheltered parts of Victoria Harbour. A map showing the shifting position of the coastline in Victoria Harbour as the result of episodic coastal reclamation is shown in Fig. 5. Since the 1960s, eight new towns with coastal locations (Fig. 2) were constructed to cater for population growth and other development.

Flooding is an increasingly common problem in coastal reclamations. It is exacerbated by a combination of factors including:

(1) The creation of large areas of low-lying land adjacent to steep hillslopes. This is made worse by episodic coastal reclamation schemes along the natural coastline (Fig. 5).

(2) Long-term ground settlement in coastal reclamations. A settlement rate averaging about 5 mm/year was found by levelling of the North Point tide gauge to nearby bench marks during the period from 1954 to 1991 (Yim, 1991a). Because of long-term ground settlement in the older coastal reclamations, they may also be lower in elevation than the newer reclamations creating a 'trough effect' for the surface runoff. Such low-lying areas are particularly prone to rainstorm and storm surge flooding (Peart and Yim, 1992).

(3) Intense rainfall over short duration of time. The record 1-hour and 24-hour rainfall at the Hong Kong Observatory station is 108.2 mm and 697.1 mm respectively (Yim, 1996). In urban areas where the infiltration is minimal due mainly to concrete pavements, the bulk of this rainfall will form surface runoff to cause flooding in the low-lying areas particularly when the drainage network is obstructed.

(4) Storm surge associated with the passage of typhoons. The height of the maximum sea level attained during a storm surge is largely determined by the coastal configuration and the typhoon track (Yim, 1993a). In Tolo Harbour, the highest maximum sea levels are known because of the special coastal configuration, namely its dimension, orientation and the narrow eastern exit into Mirs Bay (Fig. 3). Additionally because the sea level is abnormally elevated during a storm surge, gravity drainage in coastal reclamations through the storm drainage networks would become ineffective.

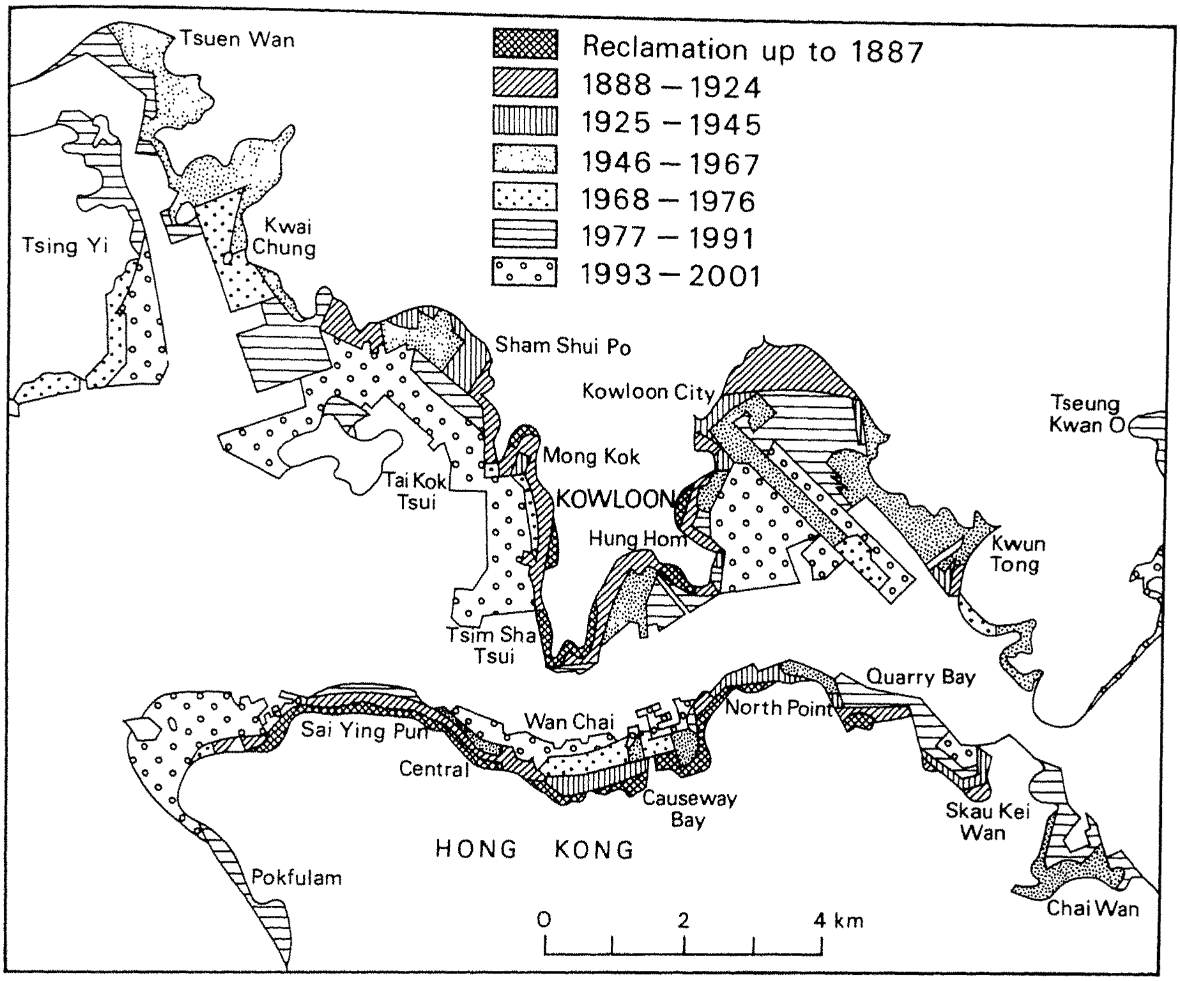


Fig. 5. Map showing the shifting position of the coastline in Victoria Harbour as the result of episodic coastal reclamation schemes. Redrawn after Kwong and Hacker (1993) with modifications

(5) Inadequate design of storm drainage networks in the coastal land reclamations. This is caused by the adoption of rainfall return periods based on an instrumental record too short to reflect the long-term variability.

(6) Poor maintenance of storm drainage networks.

(7) Future sea-level rise resulting from global warming. However, previous investigations (Yim, 1991b and 1993b) have not revealed a rising eustatic sea-level trend. In fact, slow crustal uplift may be taking place (Yim, 1993b) causing the relative sea level in Hong Kong to fall. Consequently coastal reclamations subsiding at rates exceeding the uplift rate are expected to be the most susceptible to flooding.

From the above, it can be seen that coastal reclamations are prone to flooding. Because of the lack of information on the rates of long-term ground settlement in coastal reclamations, a monitoring programme involving levelling on the ground and surveying using satellite altimetry at regular intervals is needed to permit the better estimation of settlement rates (Yim, 1991a). This should help to identify areas requiring attention.

Offshore waste disposal

Four main types of wastes are currently disposed of into the coastal waters. They include:

(1) Screened sewage and wastewater from sewage treatment plants discharged via submarine outfalls.

(2) Sewage sludge from sewage treatment plants. These wastes are disposed of at a site about 3 km east of the Ninepins dumpsite shown in Fig. 4.

(3) Constructional wastes including uncontaminated dredged spoils where the content of heavy metals, including Cd, Cr, Cu, Hg, Ni, Pb and Zn, are below the preset limit of the Environmental Protection Department (Reed, 1992) shown in Table 1. These wastes are disposed of at the designated marine dumping grounds at Nei Ling Ting, Cheung Chau and Ninepins shown in Fig. 4.

(4) Contaminated dredged spoils with contents of heavy metals exceeding the preset limit shown in Table 1. These wastes are disposed of in trenches at East Sha Chau (Fig. 4).

In addition to the above categories of wastes, domestic, industrial and agricultural effluents may also find their way into the coastal waters via streams and storm-water drains and leacheates from coastal landfills.

Up to the early 1970s, sewage was discharged into the coastal waters without treatment other than screening via seawall-type outfalls. During the 1970s, these outfalls were converted into submarine-type outfalls aiming at better dispersion of sewage by dilution within the seawater column. However, whether the submarine-type outfalls are superior to the seawall-type outfalls for dispersing sewage is uncertain. A comparison between the two types of sewage outfalls is shown in Fig. 5. Based on monitoring work of the Environomental Protection Department (1993) from 1976 to 1992, the level of dissolved oxygen in Victoria Harbour waters has declined. The eutrophicaion trend may be explained by the conversion to submarine-type outfalls for three possible reasons. First, effluents entering typhoon shelters via seawall-type outfalls and storm-water drains are poorly dispersed due to the weak tidal circulation. In typhoon shelters such as Kowloon Bay (Fig. 4), sewage and other land-derived effluents are efficiently trapped because of the weak tidal

Table 1. Classification of uncontaminated and contaminated dredged sediments in Hong Kong based on the heavy metal content. After Reed (1992)

		Heavy metal content (mg/kg dry weight)						
Class	Category	Cd	Cr	Cu	Hg	Ni	Pb	Zn
A	Uncontaminated	<0.9	<49	<54	<0.7	<34	<64	<140
B	Moderately contaminated	1-1.4	50-79	55-64	0.8-0.9	35-39	65-74	150-190
C	Seriously contaminated	1.5 or more	80 or more	65 or more	1 or more	40 or more	75 or more	200 or more

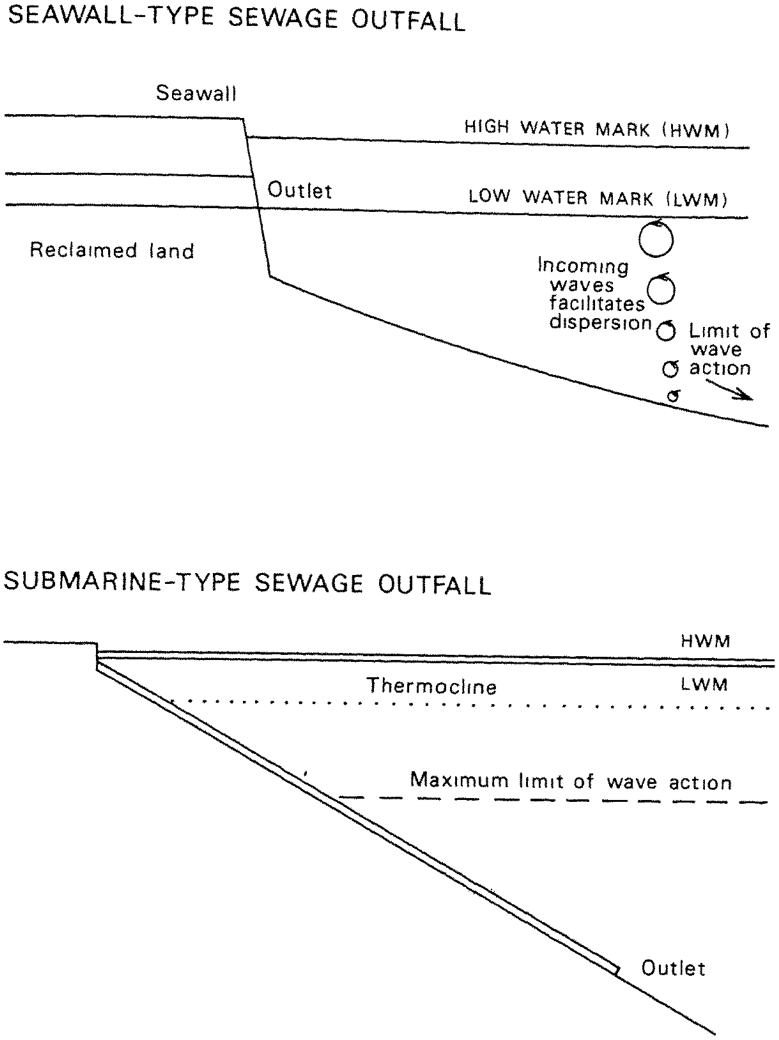


Fig. 6. Simplified diagrams showing the main difference between the seawall-type and submarine-type of sewage outfalls in Victoria Harbour

currents. They are unable to spread into other parts of the harbour. Second, seawall outfalls permit sewage to be broken down more readily through natural means. Because the surface water receives more sunlight, is better oxygenated and better mixed by wind and ship-generated waves than waters at depth, the conditions are more favourable to the breakdown of organic matter present in sewage through bacterial action. The development of a thermocline during the wet summer season also means that sewage present in the surface layer is dispersed further out to sea through the tidal circulation. Third, since submarine outfalls release sewage into the deeper bottom waters of the harbour, the conditions may already be anoxic unless strong bottom currents are present. Additionally, coastal reclamations destroy the natural coastal habitats including mangroves in the intertidal zone and replace the shoreline either with a vertical or inclined seawall rising from the seabed. Eutrophication through the build-up of sewage is therefore a more serious problem in Victoria Harbour due to the long history of sewage discharge and coastal reclamations.

The disposal of sewage into oceans using long outfalls was seen as a cost-effective way of dealing with these wastes without causing noticeable pollution because of the dilutions achieved (Koop and Hutchings, 1996). However, the long-term effects of ocean disposal of sewage can only be determined reliably using systematic monitoring studies a long time after the construction of the outfalls. The Strategic Sewage Disposal Scheme (Fig. 4) (Smith-Evans and Dawes, 1996), at an estimated cost of HK$10 billion, is thought to provide the long-term solution. However, the construction of the scheme is well behind schedule and costs are mounting rapidly due to unforeseen ground conditions encountered in the submarine tunnels. Whether the scheme is feasible is now open to questions. There is for example doubt over whether the high cost of the scheme should be spent instead on sewage treatment facilities as they are clearly a more environmentally friendly option.

Construction wastes are produced in large quantities through the development of new infrastructures. In 1991, a peak of 16,374 tonnes per day of construction wastes categorised into roadwork material, excavated material, demolition waste, site clearance and renovation waste were received at landfill sites (Environmental Protection Department, 1993). The shortage of landfill sites onshore is the main reason for dumping these wastes into the sea. At the South Cheung Chau mud disposal site (Fig. 4), continuous dumping has resulted in major changes of sea-floor topography (Nash and Yip, 1988) making the site hazardous to shipping in addition to impacting marine life. At the East Sha Chau contaminated mud disposal site (Fig. 4), abandoned sand burrow pits are used for the disposal of contaminated dredged spoils, then capped with uncontaminated mud to isolate the spoils. There is, however, conflict because the area is a known habitat for pink dolphins and possesses strong tidal currents. The latter makes it difficult to contain the contaminated muds within trenches prior to their capping.

The current practice of offshore dumping of sewage sludge, produced by the sewage treatment plant at Sha Tin, in the eastern zone is against the principle of sustainable coastal development. It is accelerating eutrophication in an area with naturally the best water quality and conflicts with a number of coastal utilisation activities best carried out in the zone. Therefore a less sensitive site should be found.

Three currently operating coastal landfills are located in Tai Po, Junk Bay and Yung Long (Fig. 4). These sites are areas where toxic leachates may escape into the coastal waters. Hong Kong produces enormous quantities of wastes requiring landfill sites for disposal, and there is limited storage capacity at the landfills. The long-term solution is to reduce the volume of wastes through recycling and incineration.

Stability of coastal structures during storms

Coastal reclamations have shifted the natural coastline seawards, replacing beaches and headlands with either sloping or vertical sea walls. The change in coastal configuration and the seabed profile inevitably modifies the wave regimen and other coastal processes (So, 1984) including the current flow pattern (So, 1986a and 1986b). During the passage of typhoons, newly constructed sea walls of coastal reclamations are known to have failed because of inadequate design. There are two examples of sea wall failures. In 1960, the sea wall of the Royal Hong Kong Yacht Club was destroyed by typhoon Mary. In 1983, the Kwai Chung Road sea wall was partly destroyed by huge waves approaching from a southwest direction during typhoon Ellen. Future coastal reclamations in greater water depths must therefore be more adequately designed to withstand typhoons.

Offshore sand exploitation

The major offshore burrow areas are shown in Fig. 4. Over the past 12 years, there has been a dramatic increase in the exploitation of offshore sand needed for coastal reclamations because of major infrastructural projects including Hong Kong International Airport (1,248 ha) and the West Kowloon reclamation (330 ha). During the period of peak activity in 1993, 24 dredging vessels or 75% of the world's fleet were involved in removing mud and placing marine sand for the construction of Hong Kong International Airport (Wallis, 1998).

The exploitation of offshore sands has given rise to a number of coastal management problems (Bowler, 1985). Objections to offshore sand exploitation by the fishing industry and green groups such as the Marine Conservation Society have taken a long time for the Hong Kong Government to act on. Because the sand burrow areas are distributed in all three hydrographic zones of Hong Kong (Fig. 4), the environmental impact is not the same in each zone. In the eastern zone, coral reefs are sensitive to the increase in turbidity caused by the release of suspended solids during dredging. Since the annual mean seawater temperature in Hong Kong and the freshwater discharge of the Pearl River already make conditions marginal for coral growth, increased turbidity through sand exploitation would lead to an increase in environmental stress. The chances of survival of corals would be further reduced. However, in the western zone where oyster cultivation has been carried out for at least 50 years in Deep Bay (Fig. 4), the effect appears to be minimal. Because the seabed is heavily trawled, it is difficult to predict the long-term impact of dredging. There is likely to be a decrease in nutrient availability, an increase in sedimentation rate and destruction of spawning grounds of benthic organisms in and close to dredged sites. This would help to account for the decline in the benthic molluscan community found by Morton (1996).

Marine parks and coastal reserves

Marine parks and coastal reserves are mainly aimed at preserving marine and coastal habitats such as for corals and migratory birds. Marine parks include Hoi Ha and Double Haven while coastal reserves include the Mai Po Marshes and Cape D'Aguilar (Fig. 4).

Both marine parks and coastal reserves should ideally be located as far away as possible from populated or developed areas to prevent conflicts. For marine parks, the eastern zone offers the best natural conditions but offshore sand exploitation and mud disposal would create problems. The Mai Po Marshes located downstream of the polluted Shenzhen River near the border between the Hong Kong SAR and Guangdong is semi-enclosed by the cities of Shenzhen to the north and Yuen Long to the south. Its survival is in doubt and a possible solution worthy of consideration is to relocate the reserve to Starling Inlet (Fig. 4) where the pressures from development are less severe.

Coastal fisheries and mariculture

The coastal waters support a traditional inshore fishing industry based mainly on trawling which results in major disturbance of the sea-floor sediments Mud clasts discovered on the seabed using remotely operated cameras were interpreted by Selby and Evans (1997) as proof of regular trawling Because of high prices and demand for fish, a number of inlets and bays shown in Fig 4 had been developed for mariculture using floating cages over the past 20 years In 1994, the production was 3080 tonnes with a value of HK$185 million or about 7% of the total value of the Hong Kong fisheries production (Wilson and Wong, 1996)

The hydraulic requirements of the mariculture industry in Hong Kong were described by Wilson and Wong (1996) Most important, the sites should be located away from industrial centres and areas with dense population in water of high quality

Coastal fisheries and mariculture are both highly sensitive to pollution Wu (1988) estimated some 270 tonnes of fish were lost by the mariculture industry through pollution in 1987 Out of this total, a loss of 12 tonnes was attributed to coastal development including reclamation and silting Red tides caused by pollution are harmful for two reasons (Environmental Protection Department, 1993) First, they deplete oxygen levels in the water causing marine life to perish Second, they may produce toxins that enter the food chain resulting in contamination of shellfish In April 1992, one of the largest blooms on record occurred covering nearly the whole of Hong Kong's eastern waters resulting in mass mortality of fish (Environmental Protection Department, 1993) Such events are linked to the increase in nutrient load discharged into the coastal waters through sewage outfalls and agricultural effluents Since the eastern zone has naturally the best conditions for both coastal fisheries and mariculture, offshore waste disposal should be banned in this zone to prevent conflicts

Table 2. Recommended utilisation of the three hydrographic zones in Hong Kong shown in Fig 1 Modified after Yim (1995 and 1997)

Western zone	Central Zone	Eastern zone
Land reclamation for development	Land reclamation for development	Recreation e.g. bathing, fishing
Container terminals	Limited container terminals	Marine parks
Sand exploitation	Limited sand exploitation	Coastal reserves
Sewage disposal	Limited sewage disposal	Water sports e g scuba diving, yachting
Uncontaminated mud disposal	Typhoon shelters	Coastal fisheries
Contaminated mud disposal	Stormwater drains	Limited mariculture
Coatal landfills	Seawater extraction	Seawater extraction
Typhoon shelters		
Landfill sites		
Power stations		
Stormwater drains		
Pulverised fuel ash lagoons		
Industrial estates		
Incineration plants		

Coastal recreation

As a coastal city, Hong Kong has its share of coastal recreational activities including sea bathing, yachting, wind surfing, snorkelling, scuba diving and recreational fishing. Due to the popularity of sea bathing in the summer, the government places a high priority on monitoring the water quality of the most popular bathing beaches. A system of beach grading based on the indicator bacteria *Escherichia coli* is enforced to provide health-risk warning. However, many gazetted swimming beaches located in the western and central zones are influenced to some degree by submarine sewage outfalls. It is therefore advantageous to locate all bathing beaches in the naturally clean eastern zone.

An increase in the turbidity of seawater through offshore sand exploitation, offshore dumping of constructional wastes, offshore disposal of sewage and sewage sludge, quarrying onshore, and, increase in shipping activity conflicts with coastal recreation. All such activities should be banned in the eastern zone in order to maintain the water quality for coastal recreation.

Towards sustainable coastal development

Based on past experiences, it can be seen that problems have arisen mainly because of conflicts between the different types of coastal utilisation. In order to have a policy towards sustainable coastal development, it is necessary to group the non-conflicting types of coastal utilisation and to carry them out in the naturally favoured zone in order to minimise their environmental impacts. The three hydrographic zones in Hong Kong should therefore be used to the best advantage.

The recommended coastal utilisation in each of the three hydrographic zones is presented in Table 2. Offshore waste disposal and offshore sand exploitation should be banned in the eastern zone because of the naturally clean environment. It should be kept for limited coastal fisheries, mariculture, coastal recreation, marine parks and coastal reserves. The central zone can continue to be used for coastal land reclamations including container terminals, typhoon shelters, and limited amounts of sand and gravel dredging. This follows the philosophy of continuing an activity in an area clearly affected by environmental deterioration rather than exposing a new unaffected area to pollution pressures. On the other hand, since the western zone is already heavily influenced by the estuarine conditions brought by Pearl River, offshore sand exploitation, the disposal of uncontaminated and contaminated wastes, and the disposal of sewage sludge may be carried out with a smaller environmental impact. The policy for coastal utilisation outlined above is favoured by the coriolis force which is causing a net westerly drift of sediment along the south China coast. The types of coastal utilisation suggested for all three hydrographic zones should help to maintain the naturally clean conditions of the eastern zone. At the same time, the potentially polluting coastal utilisations in the western zone will to a certain extent be diluted by the water discharge of the Pearl River through estuarine mixing.

Since typhoon shelters are excellent traps for land-derived effluents, they may be used cost-effectively in controlling polluting effluents. For long-term sustainable coastal development, the coastal management plan should be divided into stages of reclamation on a smaller scale than that of the West Kowloon reclamation at about 20- or 30-year intervals (Fig. 6). Each stage is to be accompanied by urban renewal of the onshore coastal area and reclamation of typhoon shelters. In this plan, effluents other than sewage should be treated at the source while typhoon shelters are used to prevent their spread as a last line of defence. This 'containment' approach is deemed to be more environmentally friendly than the 'dilution' approach of the Strategic Sewage Disposal Scheme (Fig. 4). Recent work has suggested that sewage is too valuable a resource to be disposed of in the oceans. For example, Lottermoser (1998) identified potential benefits including possible use of sewage sludge as agricultural fertilisers, production of noble and heavy metals, saving of expensive waste repository space, conserving of primary geological metal resources, and prevention of possible environmental impacts on both continental and marine ecosystems. Furthermore, the effectiveness of ocean disposal is in doubt and may lead to impacts on the neighbouring regions of Guangdong.

Much hydrological, sedimentological and geochemical information obtained on the marine environment in Hong Kong is now available to suggest that the policy towards sustainable coastal development outlined in this paper is pointing in the right direction. These include the distribution of metallic elements in sea-floor sediments (Yim and Fung, 1981; Yim, 1984), sediment characteristics (Yim and Leung, 1987; Hodgkiss and Yim, 1995), Holocene sedimentation rate (Yim et al., 1996) and the hydrology of the coastal waters (Watts, 1973; Morton and Wu, 1975; Ridley Thomas, 1985; Broom and Ng, 1996). The policy is based on widely recognised earth science principles and attempts to work in harmony with nature. It should also be possible to further refine this policy as part of an overall integrated long-term coastal management plan similar to those used in the Netherlands by Waterman (1989).

Conclusions

The policy of coastal development outlined for Hong Kong is sustainable because it works in harmony with nature. Because many types of coastal utilisation are catered for while the most desirable characteristics of the coastal environment are preserved, the policy is cost-effective. Other advantages include using nature to the best advantage and that it is based on widely recognised earth science principles. However, it is necessary to relocate some of the current types of coastal utilisation and a continuous effort is needed to reduce wastes at the source especially through recycling. Since the implementation of the policy will also affect other parts of the Guangdong coast, there should be dialogue between the two government authorities from an early stage in order to work out a mutually beneficial long-term sustainable coastal development policy for both.

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References

Anandasiri K compiled (1998) *Fill resources, mud disposal areas and major reclamations*. Drawing FMC/1-1G. Fill Management Division, Civil Engineering Department, Hong Kong Government, Hong Kong

Anonymous (1998) Australia's Ocean Policy – An Issues Paper. *Environment Australia*, Canberra, May 1998

Apsimon H, Thornton I, Fyfe W, Hong Y, Leggett J, Nriagu JO, Pacyna JM, Page AL, Price R, Skinner B, Steinnes E & Yim W (1990) Anthropogenically induced global change - report of Working Group 3, IUGS Workshop on Global Change Past and Present. *Global and Planetary Change*, 82: 97-111

Bowler RA (1985) Coastal pollution due to land formation - a case history. In: *Pollution in the Urban Environment.* Elsevier Applied Science, London, pp 581-590

Broom MJ & Ng AKM (1996) Water quality in Hong Kong and the influence of the Pearl River. In: *Coastal Infrastructure Development in Hong Kong - A Review*. Civil Engineering Office, Civil Engineering Department, Hong Kong Government, Hong Kong, pp 193-213

Chan LS, Yeung CH, Yim WW-S & Or OL (1998) Correlation between magnetic susceptibility and distribution of heavy metals in contaminated seafloor sediments of Hong Kong. *Environmental Geology*, 36: 77-86

Environmental Protection Department (1993) *Environment Hong Kong*. Hong Kong Government, Hong Kong

Hodgkiss IJ & Yim WW-S (1995) Chapter 5 A case study of Tolo Harbour, Hong Kong. In: McComb AJ (ed) *Eutrophic Shallow Estuaries and Lagoons*. CRC Press, Boca Raton, pp 41-57

Koop K & Hutchings P (1996) Disposal of sewage to the ocean – a sustainable solution? *Marine Pollution Bulletin*, 33: 121-123

Kwong K & Hacker A (1993) Lost horizons – how Hong Kong has grown. *South China Morning Post Saturday Review*, 21st August

Lottermoser BG (1998) Golden sewage. *Abstracts, 1st Asia Pacific Symposium on Environmental Geochemistry.* Department of Civil and Structural Engineering, The Hong Kong Polytechnic University, Hong Kong, pp P21

Morton BS (1985) Marine pollution induced environmental changes in Hong Kong - the Tolo Harbour case study. In: *Pollution in the Urban Environment.* Elsevier Applied Science, London, pp 548-558

Morton B (1996) The subsidary impacts of dredging (and trawling) on a subtidal benthic molluscan community in the southern waters of Hong Kong. *Marine Pollution Bulletin*, 32: 701-710

Morton B & Wu SS (1975) The hydrology of the coastal waters of Hong Kong. *Environmental Research*, 10: 319-347

Nash JM & Yip PYK (1988) Infilling by marine dumping of a spoil ground south of Cheung Chau, Hong Kong. *Proceedings of Seminar on Marine Sources of Sand Hong Kong*. Marine Studies Group, Geological Society of Hong Kong, Hong Kong, pp 184-190

Peart MR & Yim WW-S (1992) Flood hazards in the coastal land reclamations of Hong Kong. In: *Proceedings 2nd US-Asia Conference Engineering for Mitigating Natural Hazards Damage*, Yogyakarta, pp F14.1-F14.8

Reed SB (1992) *Classification of dredged sediments for marine disposal*. Environmental Protection Department Technical Circular, no. 1-1-92, Hong Kong Government, Hong Kong

Ridley Thomas WN (1985) Oceanographic studies in the Pearl River mouth. *Proceedings Seminar on marine Geology of Hong Kong and the Pearl River Mouth*, Marine Studies Group, Geological Society of Hong Kong, Hong Kong, pp 85-88

Selby I & Evans NC (1997) Origin of mud clasts and suspensions on the seabed in Hong Kong. *Continental Shelf Research*, 17: 57-78

Smith-Evans M & Dawes A (1996) Early experiences in monitoring the effects of Hong Kong's new generation of sewage outfalls on the marine environment. *Marine Pollution Bulletin* 33: 317-327

So CL (1984) The effect of reclamation on coastal processes. *Proceedings 25th International Geographical Congress*, Paris, pp 136-145

So CL (1985) Hong Kong. In: *The World's Coastline*. Van Nostrand Reinhold, New York, pp 823-828

So CL (1986a) *Reclamation and its impact on current flows in Hong Kong - 1.* The Dock and Harbour Authority (London), 67: 117-122

So CL (1986b) *Reclamation and its impact on current flows in Hong Kong - 2.* The Dock and Harbours Authority (London), 67: 149-155

Wallis K (1998) Reclamation project involved 75 pc of world's dredging fleet. *South China Morning Post*, April 27th

Waterman RE (1989) *Integrated Coastal Policy via Building with Nature*. Ministry of Transport and Public Works, The Netherlands, The Hague

Watts JCD (1973) Further observations on the hydrology of the Hong Kong territorial waters. *Hong Kong Fisheries Bulletin*, 3: 9-35

Wilson KDP, Wong ECK (1996) Fisheries, mariculture and marine protected areas in Hong Kong. In: *Coastal Infrastructure Development in Hong Kong - A Review*. Civil Engineering Office, Civil Engineering Department, Hong Kong Government, Hong Kong, pp 215-231

Wu RSS (1988) Marine pollution in Hong Kong: a review. *Asian Marine Biology*, 5: 1-23

Yim WW-S (1984) Geochemical mapping of bottom sediments as an aid to marine waste disposal in Hong Kong. *Conservation and Recycling*, 7: 309-320

Yim WW-S (1986) Radiocarbon dates from Hong Kong and their geological implications. *Journal of Hong Kong Archaeological Society*, 11: 50-63

Yim WW-S (1991a) Relative sea-level change and long term ground settlement in coastal land reclamation - their assessment and future monitoring. In: *Reclamation - Important Current Issues*. Geotechnical Division, Hong Kong Institution of Engineers, Hong Kong, pp 139-151

Yim WW-S (1991b) An analysis of tide gauge and storm surge data in Hong Kong. *Hong Kong Meteorological Society Bulletin*, 1/1: 16-23

Yim WW-S (1993a) Future sea level rise in Hong Kong and possible environmental effects. In: *Climate and Sea Level Change: Observations, Projections and Implications*. Cambridge University Press, Cambridge, pp 249-376

Yim WW-S (1993b) Recent sea-level changes in Hong Kong and their implications. *Proceedings International Workshop on Sea level Changes and Their Consequences for Hydrology and Water Management, UNESCO IHP-IV Project H-2-2, Session IV Socio-economic Impacts*, Noordwijkerhout, pp 89-98

Yim WW-S (1994) Offshore Quaternary sediments and their engineering significance in Hong Kong. *Engineering Geology*, 37: 31-50

Yim WW-S (1995) Sustainable development of the waterfront in Hong Kong. In: Bellwood O, Choat H & Saxena N (eds) *Recent Advances in Marine Science and Technology '94*. Pacon International and James Cook University of North Queensland, Townsville, pp 743-752

Yim WW-S (1996) Vulnerability and adaptation of Hong Kong to hazards under climate change conditions. *Water, Air and Soil Pollution*, 92: 181-190

Yim WW-S (1997) Coastal management problems in Hong Kong and towards sustainable development. *Pacon 97 Proceedings*, Pacon International, Honolulu, pp 378-387

Yim WW-S & Fung KW (1981) Heavy metals in marine sediments of Hong Kong. *Hong Kong Engineer*, 9/10: 33-39

Yim WW-S, Huang G & Li Q-Y (1996) Hydrological information on Hong Kong waters obtained from the study of Holocene sediments. In: *Coastal Infrastructure Development in Hong Kong - A Review*. Civil Engineering Office, Civil Engineering Department, Hong Kong Government, Hong Kong, pp 97-113

Yim WW-S & Leung WC (1987) Sedimentology and geochemistry of seafloor sediments in Tolo Harbour, Hong Kong - implications for urban development. *Geological Society of Hong Kong Bulletin*, 3: 493-510

The Urban Geology of Hong Kong

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