Drilling process monitoring for a wealth of extra factual data from drillhole site investigation

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Abstract: This paper presents a method for obtaining valuable additional information from automatic drilling process monitoring in conventional drillhole site investigation. A digital drilling process monitor (DPM) is developed and used to automatically and continuously monitor and record the operational process while a hole is being drilled in ground using a hydraulic rotary machine. The DPM data are examined in detail for an enhanced recording and understanding of the ground profile while drilling. The extra information from the DPM is validated with information from conventional manual drillhole logging. The DPM results can improve geotechnical knowledge and engineering practice in Hong Kong and other mountainous regions.

Résumé: Cet article présente une méthode d'obtenir des informations supplémentaires valables d'un processus de monitorage automatique de perçage dans l'investigation du site de forage conventionnel. On a développé un moniteur numérique de procédé de perçage (DPM – « drilling process monitor ») qui contrôle automatiquement et enregistre le processus opérationnel lors du perçage d'un trou dans la terre avec un appareil hydraulique rotatif. On examine en détail les données du DPM pour un enregistrement amélioré et une compréhension du profil de la terre lors du perçage. Les informations supplémentaires du DPM sont confirmées avec les données obtenues d'un registre manuel conventionnel de forage. Les résultats du DPM peut améliorer la connaissance géotechnologique et la pratique en génie à Hong Kong et dans d'autres régions montagneuses.

Keywords:. Drilling, in situ test, monitoring, penetration tests, site investigation, strength

INTRODUCTION

Over last eight years, the Department of Civil Engineering of The University of Hong Kong has launched and completed a research and development project in automatic monitoring of the full drilling process in geotechnical engineering (Sugawawa *et al*. 2002a, 2002b, 2002c, 2003; Tan *et al*. 2005; Yue *et al*. 2001, 2002, 2003, 2004a, 2004b, 2004c; Yue 2004, 2005). The research and development have resulted in the invention of a digital drilling process monitor (DPM) and an associated simple data analysis method. The DPM can automatically, objectively and continuously measure and record the drilling progress and operation while a hole is being drilled in the ground. This paper is intended to introduce the research and development of the DPM and discuss some testing results obtained by using the in-situ device in drilling holes for ground investigation in Hong Kong.

BACKGROUND

Drilling for subsurface geotechnical investigation has a long history of more than four thousand years (ADITCL 1997). Drilling a hole for subsurface exploration using a hydraulic rotary drilling machine is one of the most common and basic tasks in geotechnical engineering. Drilling practice for ground investigation is normally regulated by government standards and guidance (GEO 1987; BSI 1981). Hydraulic rotary drilling for the recovery or non-recovery of soil or rock samples is the most commonly used method for ground investigation in Hong Kong and elsewhere.

The initial measurements and logging of the findings from a drillhole are usually conducted by the driller. The final geological logging of the findings from the drillhole is usually prepared by an engineering geologist. Drilling logs provide the basic data on the ground conditions for geotechnical design and construction. The logging report usually includes the sampling depths, testing depths, boundaries of different soils and rocks, rock discontinuities, core recovery, and description of materials at the corresponding depth.

For many years, it has been recognized that drilling itself can be considered as an in-situ testing for ground characterizations (Horner & Sherrel 1977; Liu et al. 1998). A number of researchers have attempted to develop electronic systems for the measurement of drilling parameters while drilling (MWD). Originally, the MWD was introduced to tackle cooked hole problems in oil and gas industry in 1929 (Jackson 2000). It was intended for measurement of drillhole orientation in connection with deep vertical or long directional hole drilling. A measuring device is usually installed near the drill bit and transmits the data to the ground surface for directing the drilling. The MWD systems and the associated drilling machines for oil and gas industry are sophisticated and expansive

(Somerton 1959; Chugh 1992; Jackson 2000; Luthi 2001). These systems are not directly applicable to the simple drilling rigs that have been used in geotechnical investigation.

Literature review indicates that there are a few cases of investigating and applying instrumented drilling techniques for geotechnical investigation. Soletanche-Bachy in France developed a digital recorder Enpasol in the early 1970s for measuring eight penetration parameters of typically continuous non-coring rotary rigs (Hamelin *et al*. 1982). This has been used for soil/rock identification at dredging sites (Smith 1994), soil improvement projects (Pfister 1985; Pazuki & Doran 1995), and subsurface investigation in London (Gui *et al*. 1999; 2002). Peck and Vynne (1993) reviewed some drill monitoring systems used in Canadian mining industries. Fortunati & Pellegrino (1998) introduced the Papero system, developed in 1985 by Rodio S.p.A. in Italy, for drilling parameter recording in geotechnical investigation. It has also been applied to continuous non-coring rigs for soil grouting treatment checking and rock geotechnical characterization for fast construction (Fortunati & Pellegrino 1998; Colosimo 1998). A similar system was also used by Garassino & Schinelli (1998) for continuous minotoring of tricone drillholes to detect cavities in a power plant project in Italy. Suzuki et al. (1995) developed a soil survey system vehicle for seismic cone penetration test in combination with a rotary percussion drill without coring. A MWD logging device is equipped in the vehicle for measuring the soil resistance to the high-speed rotary percussion drill (Nishi *et al.* 1998). Schunnesson (1996a, 1996b, 1997, 1998) and Schunnesson & Holme (1997) carried out studies for using percussive drilling in rock characterizations with application in rock tunnelling. Benoît & Sadkowski (2004) used a MWD technique to characterize rock and rock fractures for application of in situ bioremediation techniques. Möller et al. (2004) developed a hard soil-rock sounding technique with MWD. These systems record the drilling parameters such as penetration rate, rotation speed and thrust pressure at a pre-selected bit advancement depth (Yue *et al*. 2004a). Such sampling method is also used in the oil and gas industry (Nguyen 1996).

Despite the obvious advantages in such drilling parameter recording and some successful cases for ground characterization, however, the relevant techniques and methods have not become a common or standard ground investigation tool in the civil and mining industries (Yue *et al.* 2004a). Drilling parameter recording (or instrumented drilling) is still a comparatively new concept in terms of regular implementation in geotechnical engineering (Gui *et al*. 2002; Yue *et al*. 2004a). Attempts to have general correlations between soil and rock properties and electronic drilling parameter data have been unsatisfactory. Hydraulic rotary drilling rigs have not been equipped with a device to monitor and record the full drilling process in real-time. The present manual recorded results leave ample room for variance and errors.

It is, therefore, necessary to further develop in-situ devices and associated data analysis methods for automatically monitoring the full drilling process of drilling machines and for accurately and effectively zoning soil and rock profiles. We have developed an innovative in-situ device, namely, the drilling process monitor (DPM) for automatic recording (Sugawawa *et al*. 2002a, 2002b, 2002c, 2003; Tan *et al*. 2005; Yue *et al*. 2001, 2002, 2003, 2004a, 2004b, 2004c; Yue 2004, 2005). For cost-effectiveness, this DPM can be easily and non-destructively mounted onto existing drilling machines. It can automatically, objectively and continuously measure and record drilling parameters in real time at any given time intervals. It can record the full drilling process and operations that are experienced by a drilling machine when drilling a hole in the ground. We have found that the electronic data from the DPM can be used to zone and to characterize the structural geometries of weathered rock and soil profiles in depth without difficulty.

In this paper, we describe the DPM for monitoring and recording the full drilling process associated with ordinary hydraulic rotary drilling machines. DPM data will be presented to show that a wealth of extra factual data can be obtained from ordinary hydraulic rotary drilling in ground investigation. These extra data can be used for construction management and ground characterization.

Figure 1. Hydraulic rotary drilling machine equipped with drilling process monitor for ground investigation

HYDRAULIC DRILLING MACHINE

Hydraulic rotary drilling is the most common method for ground investigation in Hong Kong. Figure 1 shows the actual operation of a typical hydraulic rotary drilling machine in Hong Kong. It comprises the four main parts: (a) a hydraulic rotary drilling rig; (b) a number of drill bits, steel rods and steel casings with different sizes; (c) water tank and water pump; and (d) a diesel generator for electricity power. The drilling rig is usually footed on a wooden platform (sleeper) for minimizing ground settlement.

At least two operators are needed to operate the drilling machine during ground investigation. The primary operator uses the control panel to manually control and operate the drilling rig. The secondary operator assists the primary operator in connecting the rig with drill rods and other components for drilling. On the control panel, there are a main clutch lever, an oil pump clutch lever, an oil pressure control handle, a feed control lever, an oil pressure gauge, a water flow control valve, a water pressure gauge, a gearshift lever, a spindle/hoist drum clutch lever, a slide base clutch lever, and a hoist and brake lever. The primary operator operates these levers and handles to direct the rig operations for drilling.

The main clutch lever is to turn on or turn off the drilling rig. The oil pump clutch lever is to start or to turn off the oil pump. The oil pressure control handle is to adjust the oil pressure during drilling. The feed control lever is to control oil circulates for pushing down the piston in the swivel cylinder and lifting up the spindle. The oil pressure gauge is to display the oil pressure. The water flow control valve is to control the flow of water supply into the bottom of the drillhole through the drill rod. The water pressure gauge is to display the water pressure. The gearshift lever is to set the speed of rotation of spindle and winding speed of hoist drum. The spindle/hoist drum clutch lever is to switch the function between spindle and hoist drum. The slide base clutch lever is to move the rig forward and backward horizontally. The hoist and brake lever is to control the hoisting wire to lift a material upward or let it downward.

Each process for drilling one core-barrel length may have eight operations as follows: (a) lowering down rods and core-barrel into the hole with the hoist; (b) sliding the rig main body on the horizontal drag skid base forward for drilling; (c) fixing the rod with the drill chuck; (d) moving down swivel drill head together with connected rod and core-barrel to core the soil/rock; (e) moving up swivel drill head up along and then repeating the operation (d) until the completion of the core-barrel length; (f) detaching the rod from the chuck; (g) sliding the rig main body on the horizontal drag skip base backward; (h) lifting upward the rods and core-barrel out of the hole for samples and; (i) the operations (a) to (h) are then repeated.

The above drilling process and operations can contain a number of sub-operations. In addition, the flush liquid (water or air-form mixing) is pumped to the core-barrel via the drill rod inner hole. It then flows into the hole and fully or partially returns the ground surface. Casing may be used to stabilize the hole in weak and unstable soils and rock zones.

DRILLING PROCESSING MONITOR

Based on the design and operation of the hydraulic drilling machine in ground investigation described above, the full drilling process of the drilling operations can be determined from the automatic monitoring of the following drilling parameters in real time: (a) the downward or upward movement of the swivel drill head along the two vertical drill spindles; (b) the forward and reverse rotation of the drill rod; (c) the thrust force in the drill rod; (d) the torque in the drill rod; (e) the forward or backward sliding of the rig main body on the horizontal drag skid base; (f) the upward hydraulic pressure for moving the swivel drill head upward; (g) the downward hydraulic pressure for moving the swivel drill head downward; (h) the two hydraulic pressures for sliding the main rig body on the horizontal drag skid base forward and backward respectively; (i) the pressure and flow rate of the flush liquid pumping into the drill rod and; (j) the pressure and flow rate of the flush liquid sucked from the settling pit back into the water tank.

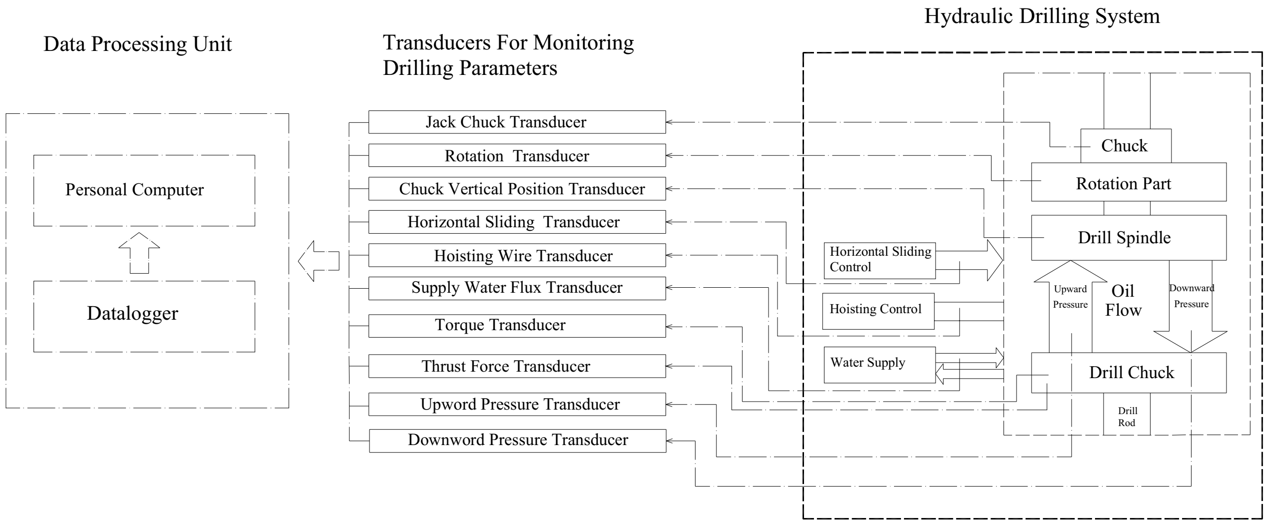

Figure 2. Design sketch of the in-situ drilling process monitor for automatic monitoring of hydraulic rotary drilling

The drilling process monitor (DPM) has been developed to monitor the above drilling parameters to represent the full drilling process in real-time sequence and in a digital manner. The DPM comprises of a transducer unit and a data micro-control and processing unit. Figure 1 illustrates the actual automatic monitoring of a hydraulic drilling machine while it was being used for ground investigation in Hong Kong. Figure 2 shows the design flow sketch of the in-situ DPM system.

The transducer unit includes ten transducers to measure the following drilling process parameters: (1) a position transducer that measures the vertical position of drill chuck; (2) a rotation transducer that measures the rotation of rod and bit system; (3) a pressure transducer that measures the oil pressure for pushing rods downward; (4) a pressure transducer that measures the oil pressure to pull rods upward; (5) a flow meter that measures the discharge of water flux into the water swivel; (6) a hoist transducer that measures the movement of the hoisting wire on top of the derrick; (7) a torque transducer that measures the torque in the drilling rods; (8) a thrust transducer that measures the thrust in the drilling rods; (9) a pressure transducer that measures the chuck action of chuck head; (10) a position transducer that measures the horizontal movement of the drilling rig on the platform.

These transducers are mounted on the drilling machine non-destructively. The data processing and logging unit controls the sampling of signals from the ten transducers. It collects the ten signals simultaneously in the forms of voltage output or electrical pulses at a pre-selected time-sampling interval in real-time sequence. The time-sampling interval can be 0.01 to 1 second. The data acquisition cables are used to transmit the data from the transducers to the data micro-control and processing unit for store. After completion of all the monitoring in one day, the electronic data and their sampling time can be then downloaded into a personal computer for further processing and analysis.

The transducer and data processing and logging units are small in size and are portable. Mounting the transducers on an existing hydraulic drilling machine and removing the transducers from the machine are a simple task and can be completed within a short time although the mounting and removing of the torque and thrust transducers are time consuming and need special effort at the present. A battery is used to supply with small amount of power required for the device and the notebook computer. The transducers are always calibrated in the departmental laboratory. The DPM can be used on many existing hydraulic drilling machines.

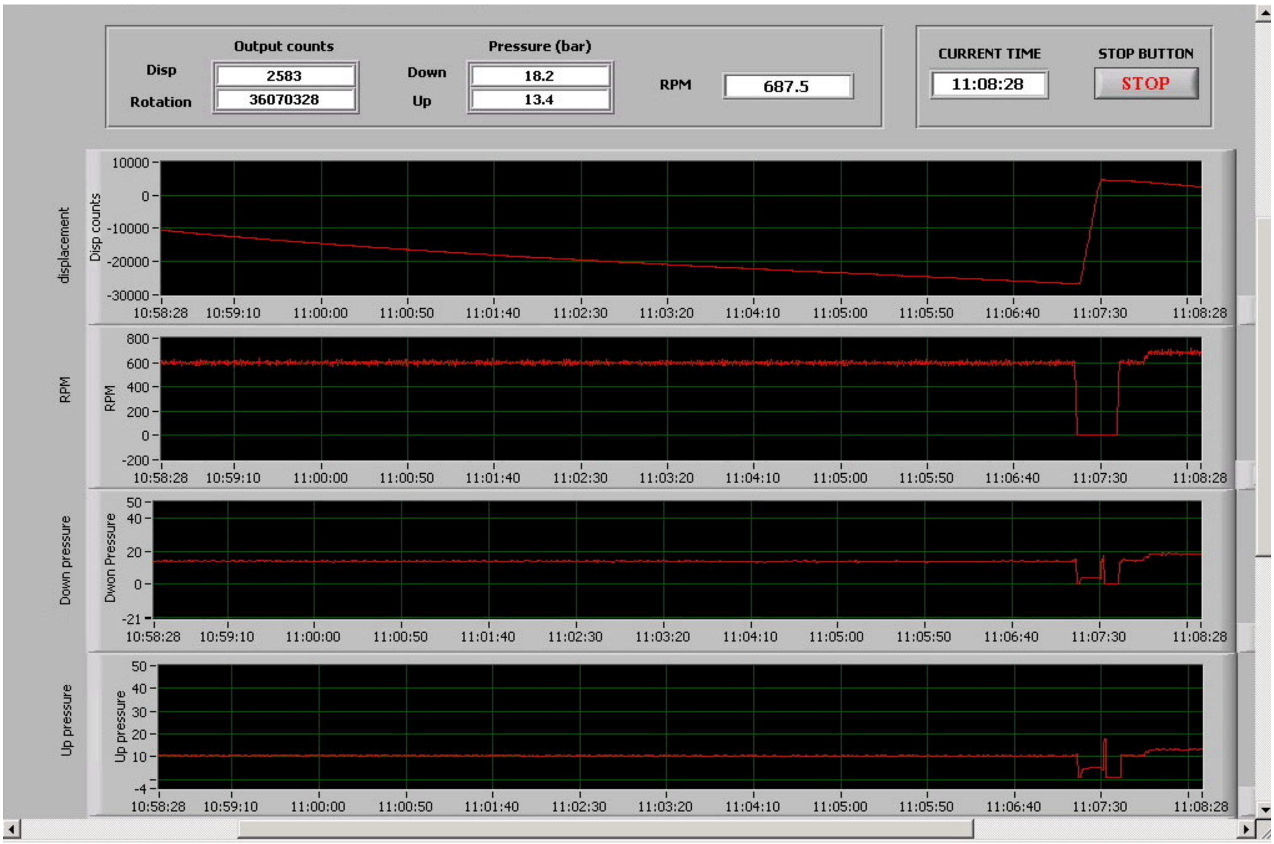

Figure 3. Real time monitoring of four drilling parameters on notebook screen at field

CASE EXAMPLE

In this section, a case study is given to show some monitoring results using the DPM at ground investigation site in Hong Kong, as shown in Figure 1. Figure 3 shows the real time monitoring of the change of the drilling parameters on the notebook screen at the field. The casings were used for the drilling without sampling. The flushing medium was water. The drill bit type was the flush-jointed HW with outer diameter 115 mm and inner diameter 101 mm (GEO, 1987; BSI, 1981).

Figures 4 to 7 show the monitored results of the variations of four drilling parameters from 10:51:57 am to 11:48:11 am. The sampling frequency was 2 Hz. The four drilling parameters are the vertical position of the drill chuck, the rotation speed of the drill rod, the downward pressure for the downward movement of the drill chuck and the upward pressure for the upward movement of the drill chuck.

From Figure 4, it can be observed that the drill chuck was moving downward, upward or stopped with time. In particular, the drill chuck could move upward during the three main drilling periods from 11:09:36 to 11:16:48, from 11:16:18 to 11:24:00, and from 11:24:00 to 11:31:12.

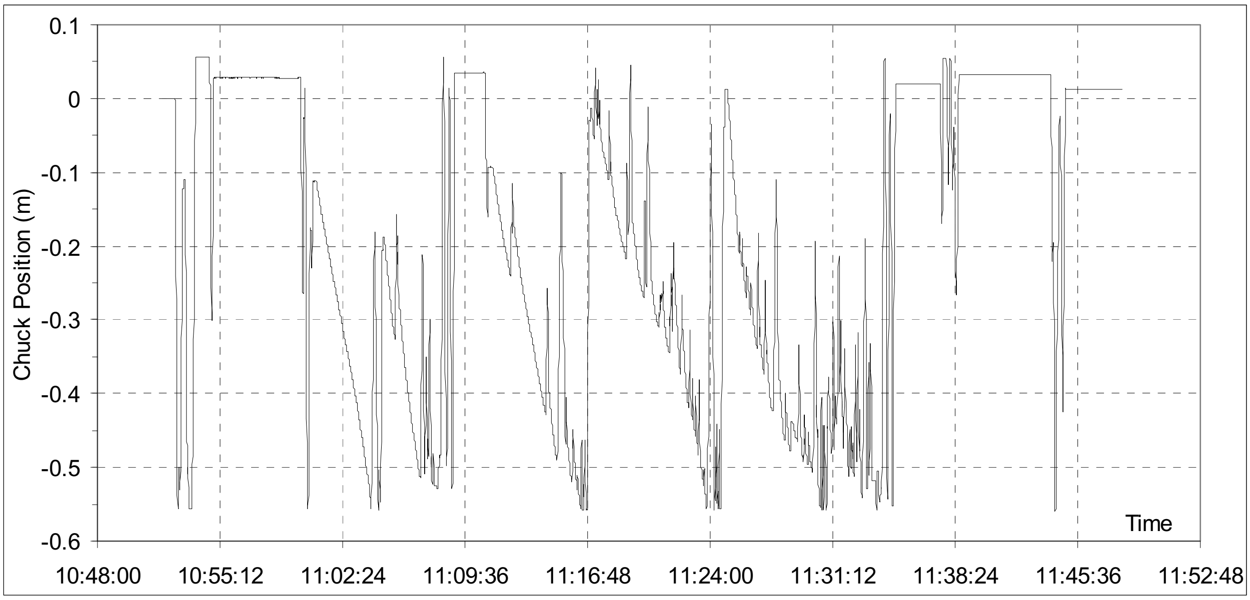

Figure 4. Full process of the downward or upward movement of the drill chuck with respect to a fix point in real time for the drilling of a vertical drillhole with the hydraulic rotary drilling machine in Figure 1

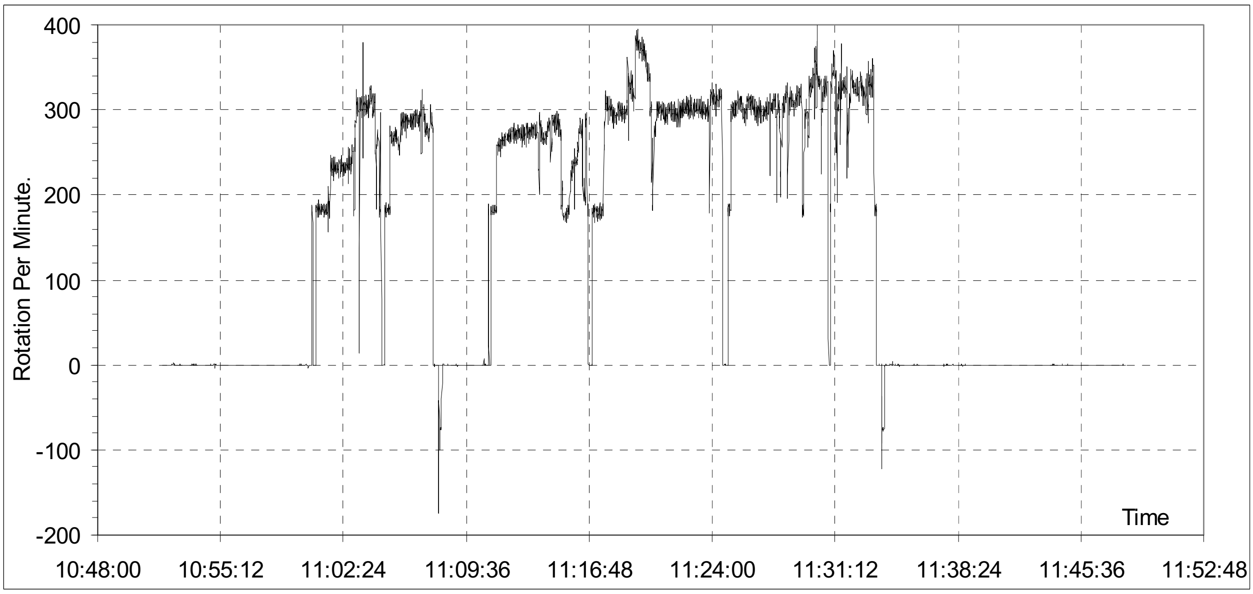

Figure 5. Full process of the forward and reverse rotation speed of the drill rod with respect to its centre in real time for the drilling of a vertical drillhole with the hydraulic rotary drilling machine in Figure 1

From Figure 5, it can be observed that during the main drilling periods, the rod rotational speed was about 200 to 300 round per minute and could reach 400 round per minute. In particular, the rod rotational speed was negative for two periods of time from 11:07:59 to 11:08:11 and from 11:33:55 to 11:34:04, which shows that the drill rod was rotating reversely for disconnecting the rod coupling two times.

From Figures 6 and 7, it can be observed that the downward and upward pressures of the oil had many sharp and high increases. The time period for each sharp increase was short. The reason for this sharp increases in the oil pressures need to be further examined. After each sharp increase, the oil pressure became normal and gradually and smoothly reduced to a minimum value.

Using the data analysis method developed in Yue et al. (2004a), the advancement of the drill bit depth with respect to the new drilling time can be obtained from the original DPM data as shown in Figures 4 to 7. The result for the drill bit depth versus the new drilling time is shown in Figure 8. The net drilling time is defined as the actual time used for the drill bit advancement into the ground.

From the curve in Figure 8, it can be observed that the total drilling depth was 2.164 m within a net drilling time 12 minutes and 46 seconds. Moreover, the curve of the drill bit depth versus the net drilling time comprises eight linear zones from Zone 1 to Zone 8. The average drilling rate for each zone can be obtained using the least square method. They are shown in Figure 8. The values of the eight zones vary from 0.1222 to 0.3037 m/minute. The overall average drilling rate is 0.1656 m/minute. The zoning results can be further used to examining the soil material properties along the drillhole. From the drillhole log, the soil was described as medium dense, light yellow and light grey, slightly silty fine to coarse SAND (alluvium).

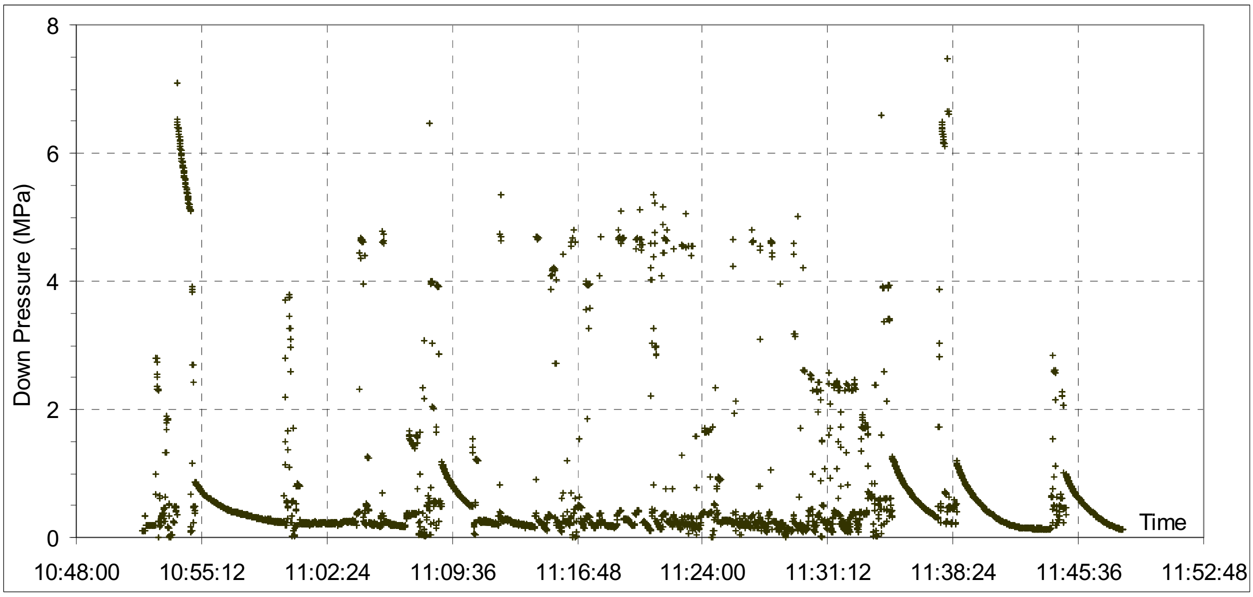

Figure 6. Full process of the oil pressure for pushing the downward movement of the drill chuck and rod in real time for the drilling of a vertical drillhole with the hydraulic rotary drilling machine in Figure 1

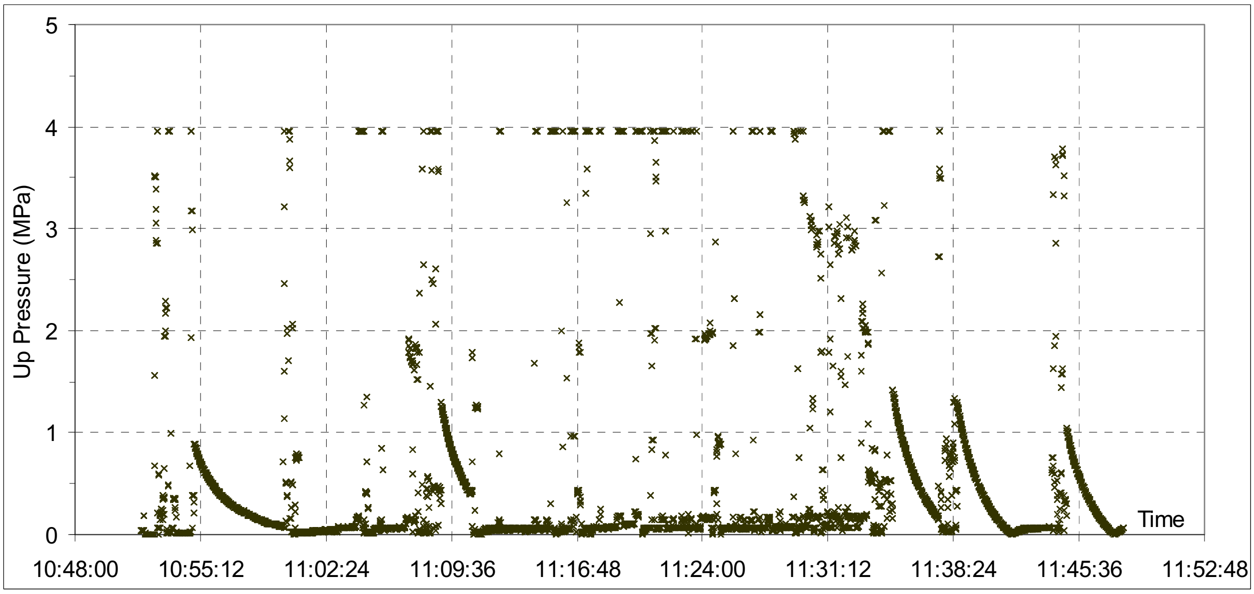

Figure 7. Full process of the oil pressure for pulling the upward movement of the drill chuck and rod in real time for the drilling of a vertical drillhole with the hydraulic rotary drilling machine in Figure 1

Furthermore, from Figures 4 to 7, it can be observed that the time used for the drilling of 2.164 m was from 10:51:57 am to 11:48:11 am. Therefore, the total time used for the drilling was 56 minutes and 14 seconds. Consequently, the net drilling time was about 22.7% of the total drilling time. In other words, the 77.3% of the total drilling time was used for other operations to assist the bit advancement into new ground along the drillhole. These operations included adding new drill rods (casings in this case), tightening or un-tightening casing couplers, as well as moving up or down chuck head with actual drilling into new ground.

The result in Figure 8 can be further used to calculate the instant drilling rate for the drilling period of each half-second. The instant drilling rate with respect to the drilling bet depth is shown in Figure 9. From Figure 9, it is evident that the instant drilling rate varies significantly within very short drill bit advancement depth. This result may have shown that the instant drilling rate has high random variations and may be not useful in ground characterization.

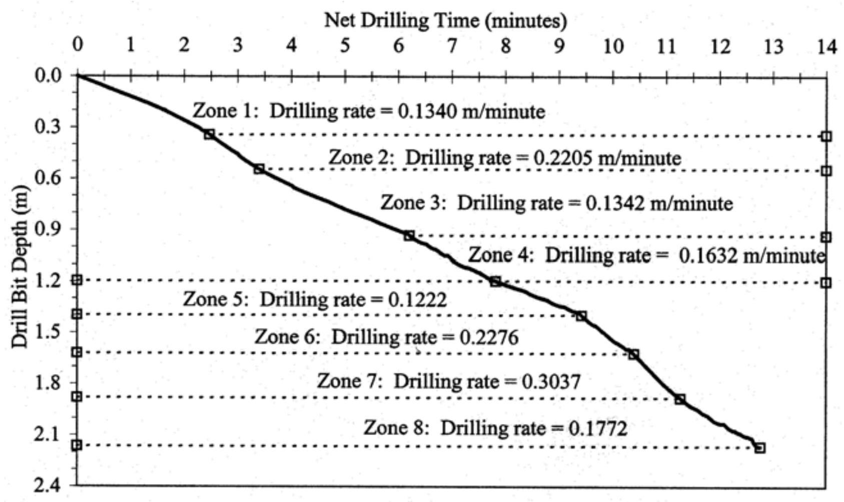

Figure 8. Drill bit advancement with the net drilling time and associated average drilling rates for eight linear zones for drilling a vertical hole of 2.164 m deep in alluvium with the hydraulic rotary drilling machine in Figure 1

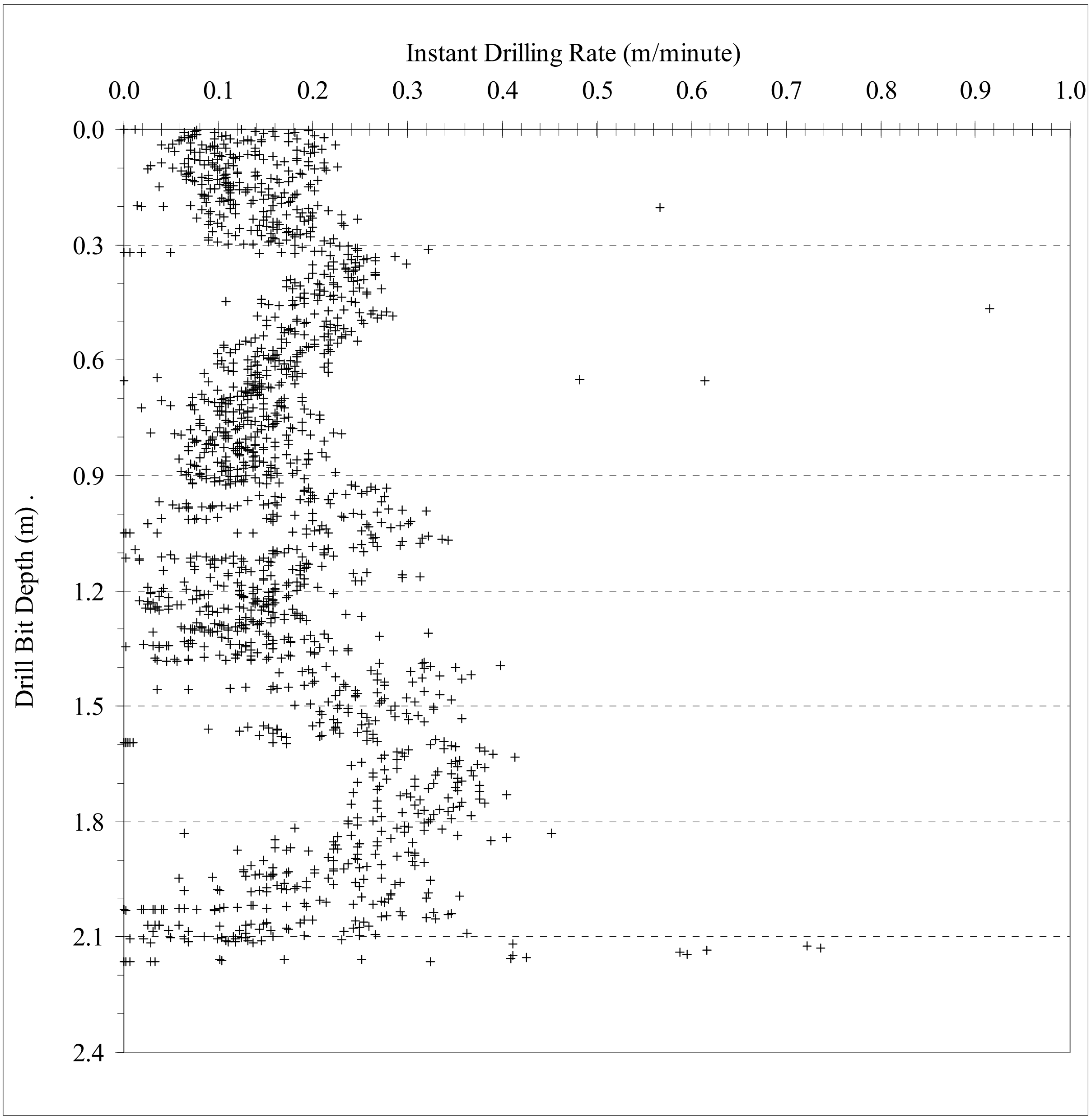

Figure 9. Variation of the instant drilling rate with the corresponding drill bit depth calculated from the drill bit depth versus the net drilling time curve in Figure 8

CONCLUSIONS

Conventional drillhole ground exploration normally reports the encountered materials, the percentage of sample recoveries, the drillhole tests and sampling along the drillhole depth. It also reports the drilling date, location, operators, flush medium, drillhole orientation, drilling machine type, and bit type. The automatic monitoring of the full drilling process associated with the hydraulic drilling machine can offer additional information and factual data about the operations of the drilling machine and the ground soil and rock conditions. These additional information and factual data can be a wealth for geotechnical engineers to make further examination of the drilling operation and ground characterizations for quality control and geotechnical design. These additional information and factual data have not been utilized in geotechnical engineering. The case example given above has shown that the full drilling process monitoring during routine drilling for ground investigation can be achieved. The DPM device is efficient and reliable for automatic and continuous monitoring and recording of the drilling process associated with a hydraulic rotary drilling machine. From the comparison with the conventional manual borehole logging, it has been demonstrated that the DPM results can enlarge geotechnical knowledge and improve engineering practice. Besides, it may be difficult to use the instant drilling rate to zoning ground profiles.

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