

## **Falsework Collapse - Analysis & Case Studies**

腳手架坍塌 -- 分析及事故

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## **Introduction 簡介**

- Falsework is any temporary structure to support a permanent structure while the latter is not self-supporting during construction 一切用以支撐在施工過程中尚不能自我支撐的永久性結構的臨時結構被稱為腳手架。
- Bragg's Committee identified technical reasons and procedural inadequacies were the main causes 布拉格委員會發現技術原因及不適當的程序是主要原因
- Study of bridge collapses revealed that over 50% were falsework related failures 對橋梁坍塌的研究表明50%以上的坍塌是由與腳手架有關的事故造成的
- Causes were inadequate review of falsework design, inadequate control during construction and improper procedures in falsework removal 原因包括對腳手架設計的審查不充分、施工過程中監管不力以及腳手架拆卸的程序不適合

## **Analysis of Falsework Collapses 腳手架坍塌事故分析**

Elliot (1973) described seven collapses occurred within two years in California and he recommended that the contractor is required to have a licensed engineer's check on the design of the falsework. 艾利特(1973)年介紹了兩年內在加州發生的七起坍塌事故，并建議承包商應該有一名注冊工程師負責檢查腳手架的設計

Smith (1976) studied 143 bridge failures since 1877. 史密斯(1976)研究了自1877年以來所發生的143起橋梁坍塌事故

Twenty three of them happened during bridge construction and about 40% of these were due to failure of temporary supports. 其中23起是在施工過程中發生的，另外，約40%事故是由臨時支撐物的失靈而造成的

Hadipriono and Wang analyzed 126 falsework failures in concrete structures. 哈迪普理昂諾和王分析了混凝土結構中的126起脚手架失靈事故

42% of them were related to bridge construction. 其中42%與橋梁建設有關

Falsework collapses during construction stage were summarised and about half of these 85 cases occurred during concrete pouring. 他們總結了施工階段的脚手架坍塌情況，85起事故中，約有一半發生在混凝土澆灌過程中

According to Hadipriono, three types of causes, i.e. the enabling, triggering and procedural causes, were classified. 根據哈迪普理昂諾，原因可分為三類，即強加、觸發及程序性

- The enabling causes are events that contribute to the deficiencies in the design and construction of falsework. 強加原因是指那些造成脚手架設計和搭建失誤的事件
- The triggering causes are usually external events that could initiate a falsework collapse. 觸發原因通常是指一些外部事件，它們可能會造成脚手架坍塌
- Procedural causes are hidden events that produce the enabling and, quite often, the triggering event as well. 程序性原因是指一些隱藏事件，它們會引起強加事故，同時，也常常會引起觸發事故的發生

Most of the enabling and triggering causes stemmed from inadequate procedural methods. Evaluation of these factors is generally only available in more detailed investigation reports. 許多強加和觸發原因是由不合适的程序方法造成的。對這些因素的分析通常只能依賴于詳細的調查報告。

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The most noticeable causes: 最顯而易見的原因

- lack of review of falsework design or construction 缺乏對腳手架設計或搭建的檢查
- unqualified persons to monitor the erection procedures 搭建過程由不合格人員監管
- lack of supervision in monitoring changes during construction 在施工過程中缺乏對監管變化的監督

Hadipriono (1985) further identified external events and deficiencies in both the design and construction were the principal sources of 150 major structural failures. 哈迪普理昂諾(1985)進一步發現，設計和施工過程中的外部事故及失誤是造成150起重大結構失靈的主要原因

He revealed that the enabling events were caused by inadequacy in the institutional and procedural methods such as confusions that occurred at interfaces between contractors, subcontractors, construction managers, design engineers, architects and the client's representatives. Consequently, they resulted in inadequate design review and improper construction monitoring. 他指出強加事故是因制度和程序方法存在不足而造成的，如承包商、分包商、施工經理、設計工程師、建築師和業主代表之間的聯系出現混亂，由此，造成對設計沒有予以充分的審核，以及施工監管不恰當

Many failures were stemmed from inadequate design review procedures 許多事故是由不適當的設計審核規程造成的

多事故是由不適當的設計審核規程造成的

- design calculations subcontracted to a professional were not thoroughly checked 沒有對分包給一名專業人員的設計計算進行全面核對
- detailing of important components, or the design of a complex falsework, was performed without fully verified. 沒有對重要構件的細節，或是複雜腳手架的設計進行充分的檢驗

Another trend spotted was the lack of monitoring during construction phases. Frequently, inspection was performed in superficial ways and proper erection

procedures were not adhered to. 所發現的另一種發展趨勢是在施工過程中缺乏監管。檢查工作通常是敷衍塞責，而且不遵守正確的搭建規程

Also lack of expertise and facilities in performing unconventional construction processes were very common. 另外，在採用非傳統的施工方法時，缺少專門技術和設施的情況司空見慣

Hadipriono suggested that: 哈迪普理昂諾建議

- A need to analyze potential problems occurred in the past. 有必要透過過去所發生的事故來分析潛在的問題
- To avoid confusions among parties involved, improve the procedures during design and construction processes. 為避免各有關方面的混亂，應該完善設計和施工過程的規程
- Adequate risk analysis for structures in services and during construction. 對正在使用及施工過程中的結構所存在的風險應該進行全面分析

## *Mechanisms in controlling falsework activities*

*監管腳手架活動的機制*

1. U.K. – Falsework Coordinator

英國 -- 腳手架協調人

The contractor employs a falsework coordinator who is responsible for the checking of the design and construction of falsework, and coordination with other parties involved in falsework construction.

承包商僱用一名腳手架協調人，負責檢查腳手架的設計及搭建，以及協調與搭建腳手架有關的其他方面的工作

2. Hong Kong – Independent

Checking Engineer

香港 -- 獨立審核工程師

A professional engineer, employed by the contractor, checks the design and construction of falsework. His permit would be required at critical stages of falsework construction. 承包商僱用一名專業工程師，負責檢查腳手架的設計和搭建。在腳手架搭建的關鍵環節，應該得到他的許可

3. Developing countries –

發展中國家

Contractor designs the falsework subject to the Engineer or R.E.'s approval but without responsibility.

承包商經工程師或註冊工程師同意后，設計腳手架，但不負任何責任

## Collapse Prediction

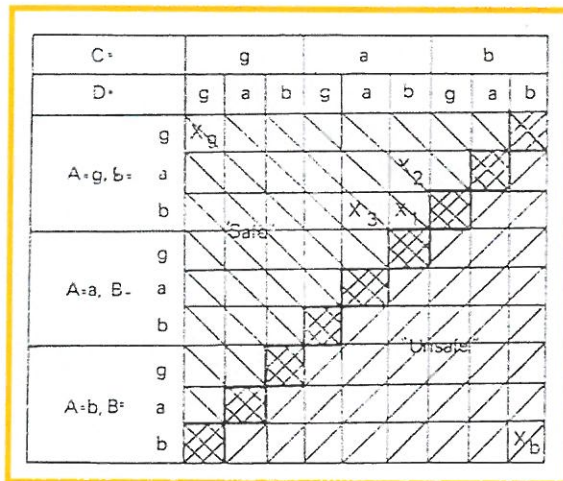
### Methods

坍塌預測方法

In 1973, Pugsley outlined an approach to the problem of assessing the proneness to structural accidents. 1973年，普格斯理介紹了一種分析容易造成結構事故問題的方法

He suggested the following parameters of significance in accident history: 他提出了以下參數，它們在過去事故中均具有重要意義

- new or unusual materials 新型或特別的材料
- new or unusual methods of construction 新的或特別的施工方法
- new or unusual types of structure 新型或特別的結構
- experience and organisation of design and construction team 設計及施工隊伍的經驗及組織
- research and development background 研究與開發背景
- industrial climate 工業氣候
- financial climate and 金融氣候
- political climate. 政治氣候



Blockley (1975) outlined the fuzzy set approach to the problem of predicting the likelihood of a structure failure. 布拉克理(1975)介紹了一套模糊的預測結構事故可能性問題的方法

A failure occurs because there is a major error and/or several smaller errors combined to eliminate the factor of safety. 之所以發生事故，是因為存在一個主要及/或若干個次要的問題，它們共同消除了安全因素

These factors are difficult to quantify but may be measured using fuzzy linguistic variables. 這些因素很難量化，但可利用模糊語言變量予以衡量

Six main categories (parameters) used include: 所用的六個類型(參數)為

- materials 材料
- type of structure 結構種類
- design experience 設計經驗
- time 時間
- construction 施工
- externals 外部因素

Each parameter is assigned the gravity and consequence rating.

The overall effect is then related to a safety index. 每個參數均有其重要性及后果比值。整個結果然后与一個安全指數結合起來

Blockley(1977) classified 24 parameters and assessed for 23 major structural accidents and one existing structure. 布拉克理(1977)曾對24個參數進行了分類及分析，其中23個指數与主結構事故有關，一個与現有結構有關

The accidents are ranked in their order of inevitability. 按照不可避免性，對事故進行排序

Problems such as poor site control, errors of judgement, time and financial pressure were highlighted. 諸如現場管理差、判斷失誤、時間及財務壓力之類問題得到強調

Human errors were predominant in causing the failures and can be prevented by good communications between all parties concerned and by well-defined responsibilities and procedures under the contract.

However, the parameters are assessed in giving an overall score

only. 人為失誤是造成事故的主要原因，然而，倘若各有關方面能很好地溝通，而且在合同中明確職責和規程，這些失誤是可以防止的。所分析的參數只能提供一個總体的分數而已

Melchers (1978) commented on the contents of various failure reports ranging from the formal government inquiry reports to professional magazines. 梅爾切耳斯(1978)對不同事故報告的內容發表了意見，這些報告既有政府的正式調查報告，也有專業雜誌

Non-technical problems such as human errors were not always included in failure reports. 諸如人為失誤的非技術問題通常沒有記載在事故報告中

The following are problems identified from four bridge failures : 下列問題是從四起橋梁事故中找到的

1. Failure to appoint an experienced bridge engineer 沒有委派有經驗的橋梁工程師
2. Negligence in checking the falsework design and failing to submit the falsework drawings. 忽視了腳手架設計的核實工作，而且沒有提交腳手架設計圖
3. The consulting engineers failed to require the contractor to submit details of falsework for approval. 諮詢工程師沒有要求承包商提交腳手架施工詳圖進行審核
4. Routine design work is commonly done by inexperienced engineers. 往往是沒有經驗的工程師進行常規設計

Melchers (1978) suggested a complementary approach on the in-depth study of failed projects, i.e. a pathological approach so that projects would be studied from an organisation as well as a technical viewpoint. 梅爾切耳斯(1978)提出了一個深入研究問題項目的補充方法，即一種病理方法，由此，可從組織和技術的角度對項目進行研究

Yao (1981) explored the gap between the calculated probability of failure (10-6) and Brown's perceived failure rate (10-3) for a certain type of structure. 姚(1981)探討了某一類結構其計算的事故發生可能性(10-6)與布朗感覺的事故發生率(10-3)之間存在的差距

In his example, two subjective factors i.e. the design and construction factors were assessed for their gravity and consequence. The failure probability is found to be of the order of 10-4, which is closer to Brown's perception. 在他的例證中，對兩個主觀因素，即設計和施工因素，進行了分析。結果發現事故發生的可能性在10-4這樣一個範圍內，即更接近於布朗的感覺



Melchers et al (1983) summarised the experience gained from the study of structural failures and satisfactory construction, and commented on the accuracy and completeness of reporting. 通過研究結構事故及令人滿意的施工項目，梅爾切耳斯等(1983)總結出了一些經驗，並對報告的準確性及完整性提出了意見

Most failures can be shown to occur because of gross human errors - the need for a means of assessing the effectiveness in controlling the changes in both the design and construction process on the occurrence of gross human errors. 可以看到，許多事故的發生是因為人為的失誤 -- 因此，應該採取一種手段來分析控制因人為失誤而造成設計和施工過程中的變化的有效性

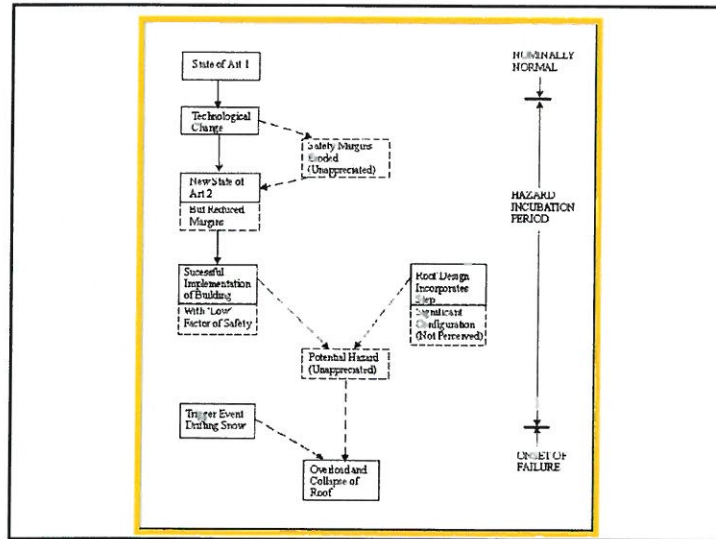
Hadipriono (1985) pointed out human based uncertainties are abundant but are seldom included in the assessment of falsework performance - A method based on fuzzy set concept has been developed. 哈迪普里昂諾(1985)指出，人為的不確定性很多，但在評估腳手架性能時，很少考慮到它們 -- 一種以模糊概念為基礎的方法已建立起來

Reduction of enabling and triggering events can achieve a desired level of overall falsework performance. However, procedural errors are not included. 減少強加和觸發事件能使整個腳手架性能達到預期的水平。但是，程序性的失誤沒有得到考慮

Ellingwood (1987) concluded 10% of failures were traceable to stochastic variability in loads and capacities. The remaining 90% were due to other causes, including design and construction errors, modeling and analysis uncertainties. Independent control stops should be instituted at key decision points in the project, especially where responsibility for project phases changes hands. 艾靈伍德(1987)指出，10%的事故是因荷載能力的隨機變化而引起的。其餘90%是由于其他原因，包括設計和施工失誤、模型及分析的不確定性。應該在項目的關鍵決策環節，尤其是項目需要易手階段，建立獨立監督站

Pidgeon et al (1990) described that Event Sequence Diagram (ESD) provides a powerful means of representing and accessing information about the sequences of events preceding a failure or near-miss incident. 皮建安等(1990)介紹了事故順序圖(ESD)，它是一種在事故發生前或即將發生時，能有效地提供並分析事故發生順序信息的方法

The ESD shows the temporal order and relationship of events leading up to a particular outcome. 順序圖ESD反映的是造成某一具體后果的不同事件間所存在的暫時次序及關係

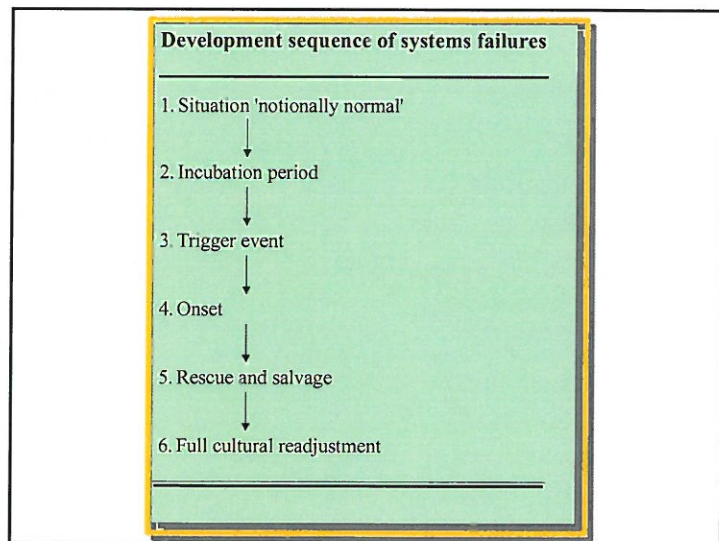


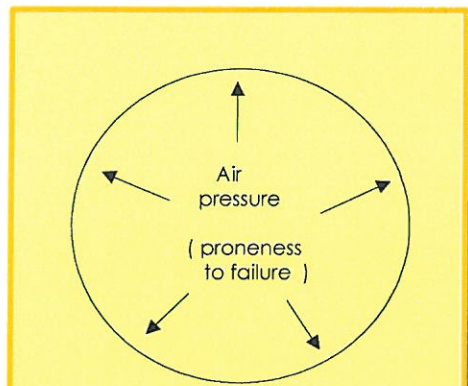
Lucas (1990) stated that we must learn from experience to prevent future crises from occurring. 路卡斯(1990)我們必須吸取教訓，以防止未來危机的發生

The fundamental concept is to find the cause, to derive effective remedies and to prevent future accidents. 基本的思想是找出原因、提出有效解決辦法以及防止未來事故的發生

Turner (1992) identified that large scale accidents have many causes and that their preconditions build up over a period of time. 特納(1992)指出，造成大規模事故的原因有許多，而且它們是日積月累的結果

Crises and disasters developed in a covert and unnoticed fashion during an incubation period. 危机和災難的潛伏期往往是隱蔽，不為人所知的





**Blockley : Balloon Model**

布拉克理：气球模型

Dias and Blockley (1995) argues that engineering students and practising engineers could upgrade their knowledge by learning from case histories of design and construction, and of failure. 戴阿斯和布拉克理(1995)強調，工程學生及實習工程師可以通過學習歷史的設計和施工案例來更新其知識

Reflection on failures will result in improved design and construction. 在事故中反省將有助於設計和施工水平的提高

## Development of a Model for Falsework Collapse Analysis/Prediction

建立腳手架坍塌分析/預測模型

Characteristics of the model to be developed: 需建立模型的特點

1. The key and critical activities of falsework are grouped under the five essential stages and presented by event sequence diagram. 腳手架的關鍵活動要按五個基本階段划分，并用事件順序圖表示出來
2. Different sub-models are derived, e.g. the conventional, independent checking engineer and falsework coordinator system. 要建立不同的次模型，如傳統的獨立檢查工程師及腳手架協調人制度
3. Controls regarding the following common critical activities are included 要對以下常見的關鍵活動進行管理
  - (a) Construction method of the permanent works and risk of falsework collapse. 永久工程的施工方法及腳手架坍塌的風險
  - (b) Changes in falsework design and construction method. 腳手架設計和施工方法的變化
4. The activity or procedure performance will include the effect of personnel's characteristics. 活動或程序的實施應考慮職員特點的作用
5. Communications between parties are shown in the flow diagram include recommendations by researchers on failure analysis. 各方的溝通要反映到流程圖中，應包括研究人員就事故分析情況所提出的建議

### Merits of the model: 模型的優點

1. To show clearly the activities flow for the parties; their roles, responsibilities and involvement. 清楚地反映了各方的活動流程，其職責和參與情況
2. Inadequacy in design is taken into consideration for assessing falsework safety. 在分析腳手架安全時，考慮了設計的不充分性
3. The Balloon model is adopted. At each stage, the activities and procedures are assessed and effects leading to failure are aggregated to indicate the risk. 採用了氣球模型。對每一階段的活動和程序進行了分析，而且總結了導致事故的原因，從而指明了危險之所在
4. For checking any missing activities or inadequacy in procedures. 檢查所有遺漏的活動或規程中存在的不足之處
5. A simple tool to assess the falsework condition. 一種分析腳手架條件的簡便手段

## Procedures

Procedures are categorised under 5 stages:

- Design
- Erection
- Loading
- Taking down
- Anew

(DELTA)

If procedures are properly carried out, the errors will be minimised and the intended factor of safety will not be reduced undesirably and unexpectedly.

## Design stage

- Inadequate falsework design (including the foundation) e.g. under-estimate the loads.
- Inexperienced designer without competent supervision.
- Inadequate checking by a competent engineer.
- Ignore lateral forces due to out of plumb.

## Erection stage

- Use of unsuitable or inferior materials.
- Inadequate falsework construction including foundation, bracing and falsework components.
- Lack of supervision during erection.
- Not in accordance with the drawings.

## Loading Stage

- Improper loading procedures such as concrete placing method different from assumption in design.
- uneven or unexpected load distribution arising from post-tensioning or placing of precast segments.

## Taking Down Stage

Improper dismantling procedures:

- Premature removal of falsework without approval.
- Improper dismantling procedures.
- Lack of competent supervision.

## Anew Stage

Improper or inadequate maintenance of falsework materials and components will result in a lower Factor of Safety (F.O.S.) than assumed in the design.

## Errors at different stages

Load/ error		X1F	X2F	X3F		Failure
	X1	X2	X3			No Failure
	X2	X3				No Failure
	X3		*	*		No Failure
	*	*				
	Design	Erection	Load	Taking down	Anew	

### Case study 1 Minnesota, USA (1990)

- Falsework design was carried out by Contractor's Consultant.
- Under-designed – F.O.S. much reduced.
- No independent checking by the client or Resident Engineer. Documents were submitted for information only.
- Falsework failed when the web of I-beam buckled due to the concrete load.
  
- This was a typical case that the design was inadequate and there was no independent checking.

### Case study 2 Israel (1994)

- Falsework design was under-designed and with wrong assumptions made
- Low and inadequate F.O.S.
- The beam's F.O.S. was reduced to failure

This was a typical case of no checking of falsework design.

### Case study 3 Hong Kong (1996)

- Initially hydraulic jacks were placed at "B Props" in supporting and lowering the post-tensioning beams.
- A change in construction method required fixing of jacks at "A Props" but this had not been independently checked and certified.
- Supports by "A Props" were almost totally removed while the revised construction method statement was still being verified by the Independent Checking Engineer.
- No supervision by Resident Engineer's staff during the loading of the beams onto the props.
- Sketches for falsework erection were inadequate.
- Shifting of I-beams after post-tensioning has led to uneven load distribution on the props.

Triggering causes:

- Remove top part of A Props and transfer load to B Props.

Procedural causes:

- High potential risk in the new construction method – required stringent supervision.
- Inadequate inspection of falsework after post tensioning by ICE, Resident Engineer and Contractor.
- Proceed erection and loading without Resident Engineer's and ICE's inspection and approval.
- Inadequate review / checking / approval of falsework due to a change in construction method.
  
- This was a failure case when the construction method changed and proceeded without approval of the Independent Checking Engineer.

## Conclusions

- Based on the content analysis and event sequence diagram, fifty falsework failure reports have been analysed.
- The principal types of material for failed falsework were tubular steel or metal scaffolding (54%) and steel frames (20%).
- 38% of the failures were in situ concrete construction with post tensioning, which is a typical choice for long span bridge construction.
- 30% of the failures were in situ reinforced construction, mainly for medium and short span bridges.
- Another 22% were for the falsework supporting precast elements followed by post tensioning or steel members.

- Most of the failures (82%) occurred near the end of concrete pouring and placing of precast segments (the falsework would be subject to the full design load). 10 % of failures occurred during dismantling or removal of the falsework.
- Procedural inadequacies:
  - 45% of substantial errors occurred in erection stage
  - 33% occurred in design stage
  - 13% in taking down stage
  - 9% in loading stage.
- A tighter control in procedures during the design and erection stage in preventing falsework failures. Not just an inspection but an assessment of the proneness of falsework to failure.

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