Systemic Causes for failure of geotechnical works around the world

Despite the absence of definitive statistics, most experts would agree that the incidence of geotechnical disasters has increased over the last 20 years. This is not just an issue for major international projects which catch the press headlines. There is strong evidence to suggest that whilst geotechnical processes themselves are becoming better controlled and more reliable, failures of small and medium scale geotechnical works continue to arise with embarrassing frequency.

A number of studies have been carried out to determine the main causes of this situation and there is emerging broad agreement in the conclusions drawn from these. Here, the author seeks to bring together this body of work to develop recommendations for action to reverse the current trend.

Some earlier studies of failure of geotechnical works

Bea (2006) reviewed about 600 well documented cases, over a 20 year span, where things went wrong on civil engineering projects. This underlined the dominant influence of what are referred to as "people factors". It is concluded that in about 80 % of the cases, failure was due to human, organizational and knowledge uncertainties, as opposed to engineering issues.

Sowers (1993) reviewed more than 500 cases of foundation failure and showed that 88 % of them were caused by human factors. The remainder (12 %) was due to lack of technology.

Van Tol et al (2009) published similar conclusions based on the analyses of some fifty excavation pits in the Netherlands that had suffered failure to a lesser or greater extent. It was concluded that about 60% of the failures were due to incorrect application of existing knowledge and that 88% of the failures in their study could have been avoided if proper risk management had been carried out prior to commencing works.

O'Rourke, in his 2009 Rankin Lecture (to be published) and, again in his John Mitchell Memorial Lecture (2010), reviewed geohazards in relation to large geographically distributed systems. The geohazards he has considered are Earthquakes, Tsunamis, Severe storms, Floods, Droughts and Volcanoes. He noted that the fate of energy, water, sewage, communication and transport systems is inextricably linked with the fate of the ground itself. He goes on to show, by reference to a number of 20th and 21st century natural disasters in the United States, that large geographically distributed systems rarely have sufficient redundancy planned within in them to be able to remain serviceable once particular components are cut out by a geo hazard.

The broad picture from all these studies is consistent. Very few failures occur through the lack of fundamental knowledge. Some do occur due to misapplication of existing knowledge. Many of these could be avoided by more robust organisation of the control and management of construction works. From minor projects through to major natural events, better risk engineering and management should avoid relatively modest errors or emissions developing into major disasters.

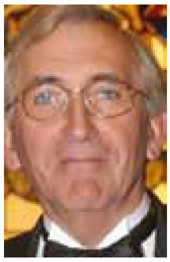
Case histories reviewed

A number of case histories are reviewed here to try to distinguish the main risk drivers that must receive attention if a reduction in geotechnical failures is to be achieved.

Earthquakes in San Francisco

The Great San Francisco Earthquake of 1906 caused enormous devastation. The Bay Area of the city, where houses were founded on man-made fill, suffered major damage due to liquefaction both in the fills and in underlying sediments. O'Rourke (to be published) describes how breakages in the fire main system, caused by the earthquake, led to a complete collapse of the fire fighting system in the city to the extent the significant areas of the city, which had not been seriously damaged by ground shaking, had to be abandoned to burn.

San Francisco was again hit by the 1989 Loma Prieta Earthquake.



David E Sherwood
FREng, CEng, FICE, BSc, Director-Bachy Soletanche

Figure 1. 1989 damage in the Maria District, San Francisco.

Figure 2. Typical damage in Bay Area, San Francisco (1906)

Figure 3. The Cypress Freeway after the 1989 earthquake

Major buildings that had been designed to modern seismic codes survived largely unscathed and as designed. The Marina district, a shallow bay filled in with demolition waste after the 1906 earthquake, suffered some of the worst damage in the 1989 earthquake. (see Figure 1). Open plan timber framed homes in the Bay Area also faired particularly badly. But the water and gas systems were, by 1989, robust enough to avoid a 1906 type disaster.

In strong contrast to tall buildings, major elements of the freeway system that had been constructed in mid 20th century did not comply with modern codes with disastrous consequences. Figure 3 shows the double deck Cypress overpass in Oakland where both inadequate moment joints between the cross beams and the supporting columns and inadequate shear reinforcement within the columns themselves are evident after the earthquake.

Clearly, some lessons had been learned but were only selectively applied. There was no technology deficit here: simply a failure to apply past experience generally in what is recognised as a very challenging environment.

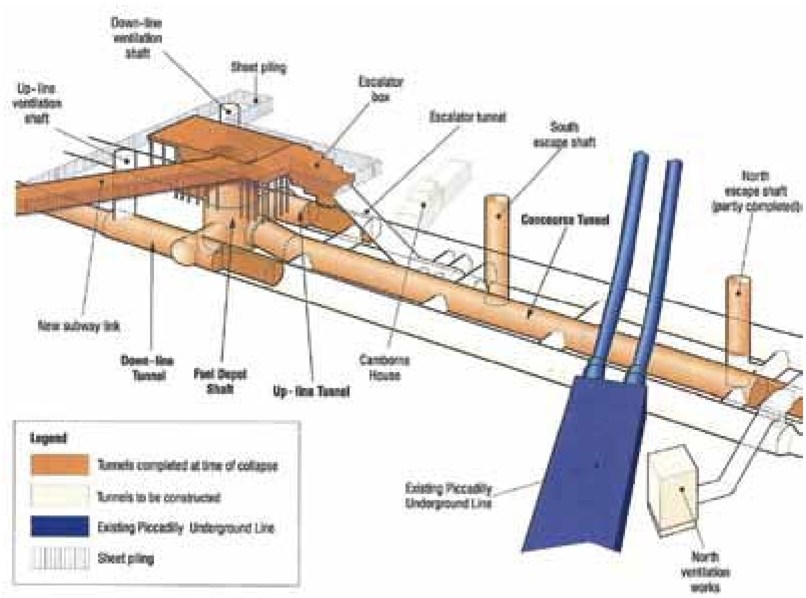


Figure 4. London Heahtrow Central Area Tunnelling Works, 1994

Figure 5. The Capri shaft after collapse, São Paulo Metro, 2007.

Recent Tsunamis in the Indian Ocean

Since the Indian Ocean tsunami in 2004 caused by the Sumatra-Andaman earthquake, warning systems have been reinforced throughout the world's oceans. However, in October 2010, a significant tsunami occurred off the western Sumatran coast leading to again to substantial loss of life, particularly on North Pagai Island, where no advance warning was received.

This throws into stark relief the challenge of matching technology and systems with the reality of life in under developed regions.

Haiti and Chile Earthquakes in 2010

Codes and standards remain a majorissue throughout the under developed world. This is graphically illustrated by contrasting the loss of life and infrastructure between the magnitude 7.0 earthquake that hit Haiti in January 2010 which led to more than 220,000 deaths and the Maule, Chile, magnitude 8.8 event a month later, with fewer than 500 deaths reported. Chile has a very well developed seismic code which is universally enforced whilst Haiti has none. This remains the situation in many regions of the world, particularly in under developed countries where traditional buildings are almost universal.

A wide ranging investigation into this failure highlighted many „short cuts" that had been taken to simplify and expedite the works

Tunnelling at London Heathrow Central Area, 1994

A project for the tunnelling works, shown in Figure 4, was let on a design and build basis where the contractor was responsible both for the design of the primary support and self certification of the works. The client's consultants were responsible for the design of the secondary (permanent) support and for the overall monitoring of the works and the surrounding area.

A collapse started within one of the running tunnels that rapidly progressively collapsed way back to the main Fuel Depot shaft, leading to loss of a large part of the works, huge settlements around the central area of the airport and disruption of the airport that lasted for several years whilst the situation was being recovered. The collapse started in the NATM lining at a narrow closure strip in its invert, where neither the lining thickness nor the quality of shotcrete was properly controlled.

A wide ranging investigation into this failure highlighted many "short cuts" that had been taken to simplify and expedite the works and a combination of all these was probably the main cause of the failure. Most damning were the fact that signs of the impending failure were obvious in the monitoring data for more than a week before the collapse but the data were not been analysed in real time and the absence of independent peer review of the contractor's work.

A wide ranging investigation into this failure highlighted many "short cuts" that had been taken to simplify and expedite the works and a combination of all these was probably the main cause of the failure. Most damning were the fact that signs of the impending failure were obvious in the monitoring data for more than a week before the collapse but the data were not been analysed in real time and the absence of independent peer review of the contractor's work.

São Paulo, Brazil 2007

In January 2007 a major failure occurred during construction of a metro tunnel in São Paulo. The problem started with failure of the roof of a tunnel being constructed by the NATM method and, as at Heathrow above, this rapidly propagated back to the shaft leading to enormous material damage to the construction site and facilities, neighbouring population and public infrastructure (see Figure 5).

In broad terms, one could interchange the list of causation with that from Heathrow 13 years earlier. Absolutely none of the lessons had been learned despite the similarity of the works. A report on the accident indicates poor or erroneous application of knowledge rather than a gap in the knowledge base itself. There were major organisational systemic issues in poor communications, lack of peer review, lack of back analysis to confirm design, ignorance of risk etc. that should not occur on a major project anywhere in the world today.

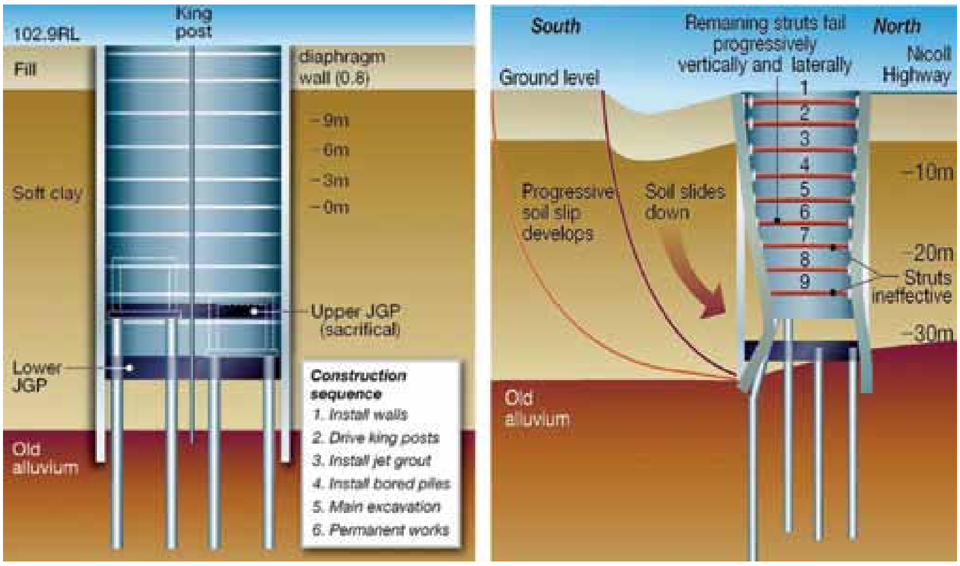


Figure 6. Cross Section and likely mode of failure, Nicoll Highway

Cut and Cover at Nicoll Highway, Singapore, 2004

A cut and cover tunnel was being constructed within braced diaphragm walls adjacent to Nicoll Highway in Singapore. When the excavation reached about 30m deep in April 2004 there was a catastrophic failure of the ground support system. A cross section of the cut and cover at the critical section is shown in Figure 6 also with an interpretation of the mode of failure.

The failure resulted in the complete destruction of a large part of the cut and cover box with wide ranging collateral damage to the adjacent Nicoll Highway and other surrounding assets and structures. (see Figure 7). The project had been let on a design and build, lump sum bas is at a time when the Singapore market was particularly competitive.

It seems that the drive for production may often cloud good judgement

A committee of inquiry set up by the Singapore Government concluded that the collapse was rooted in over optimistic design of the diaphragm walls and under design of the strut-waler connections.

It also appears that the monitoring and review regimes were not effective and the back analysis process was not rigorous enough to pick up the design errors. The back analyses carried out were more targeted on justifying why wall displacements were substantially larger than originally predicted rather than really questioning why they were as they were. But even when the revised predictions were again exceeded, no significant alarm bells seem to have rung.

It is probable, then, that a main driver behind the whole problem was a relentless search for economies in a very competitive contractual situation. As with São Paulo Metro some 3 years later and Heathrow 10 years earlier, what remains inexplicable is why construction was continued despite monitoring data showing clearly that deflections were very much greater than anticipated in the design. It seems that the drive for production may often cloud good judgement.

Short Caisson Piles in the late 1990s in Hong Kong

In the late 1990's a spate of piling problems arose in Hong Kong driven by the commercial pressures evident in a situation where subcontractors were forced to take unrealistic risk allocations in lump sum contacts and by the pressure from project managers to maintain programmes at all costs.

At the Yuen Chau Kok Public Housing Scheme in the Shatin Area,

Figure 7. Failed Cut & Cover tunnel excavation and Nicoll Highway

Figure 8. The tower blocks and models of their piled foundations.

two high rise buildings were constructed, each of which was founded on 18no 2.3m diameter caisson piles that were designed to be founded in solid granite. The piles were intended to be belled to 2.8m diameter at their base. Before the towers were fully completed, significant differential settlements developed. An investigation revealed that out of a total of 36 no piles, 21no were shorter than they were stated to have been by between 2m to 15m, 11no further piles were founded only in soft mud, a residue from the supporting fluid used in the piles during construction and only 4no piles were actually founded in granite as prescribed by the contract. The results of the investigation are shown in a model in Figure 8. The lighter coloured pile sections did not exist.

The piles were specified to be fully cased and excavated by hammer grab. However, during the works the method was changed to augering and chiselling with a powerful rotary piling machine using "supermud" as opposed to casing to support the pile walls. Whilst the report does not criticise this change of method, it is critical about the fact that the change of method was not approved. In fact the results suggest that the site team were neither trained nor experienced in this more modern method of piling and the procedures followed in cleaning and constructing piles were not appropriate. The piling contractor, faced with a challenging contract financially, resorted to corrupt practices and falsified records, presumably in the vain hope that nothing would go wrong.

Building Collapse, Shanghai, 2009

A 13 story luxury apartment building in Shanghai collapsed by toppling over, completely intact. (see Figure 9). On the right below, the pile the pile foundations can be seen snapped and broken off.

Figure 9. Toppled apartment building, Shanghai, 2009.

It was one of a group of eleven identical buildings in the development.

Apparently the construction company was in the process of excavating a 4.6m deep underground car park on one side of the building and piled the arisings in a spoil heap up to 10m high on the other side of the building. There was heavy rain in the days before the collapse and this may have been a contributing factor. The presumed failure mechanism is shown in Figure 10.

The official line initially was that contractor was rushing to finish the work under pressure from the developers and was entirely responsible. In April 2010, however it was reported that the two corrupt property developers responsible for the collapse had been imprisoned for life for embezzlement, corruption and negligence. Apparently, the contractor's personnel who were initially arrested have been released without charge.

Recommendations for action

An analysis of the case histories reviewed above confirms again that the major causes of failure are due to human and organisational factors rather than lack of appropriate technology. What needs to be done at different levels in the

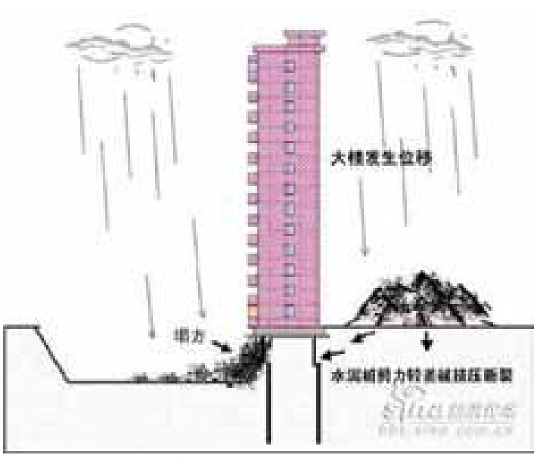


Figure 10. Likely failure mechanism. Shanghai Apartment Building.

Refferences

- BEA, R. (2006). Reliability and Human Factors in Geotechnical Engineering. Journal of Geotechnical and Geoenvironmental Engineering, May 2006, pp. 631-643.
- O'ROURKE, T. D. (2010). BGA 2009 Rankin Lecture (to be published)
- O'ROURKE, T. D. (2010). John Mitchell Memorial Lecture. Geotechnical Practices in Urban Regeneration. DFI/EFFC 11th International Conference on Geotechnical Challenges in Urban Regeneration, London, May 2010.
- SOWERS, G.F. (1993). Human Factors in Civil and Geotechnical Engineering Failures. Journal of Geotechnical Engineering. 119 (2), pp. 238-256.
- VAN TOL, A. F., KHORF, M. and VAN STAVEREN, M. (2009). The Education of Geotechnical Engineers Should Incorpote Risk Management.
  Proceedings of the 17th International Conference on Soil Mechanics and Geotechnical Engineering, Alexandria, Egypt. p 2741 - 2744. M. Hamza et al. (Eds.) © 2009 IOS Press

construction industry to reduce failures are summarised below.

At individual professional level

Education and training programmes for geotechnical engineers should

- include risk management.
- develop awareness of limits of competence and experience,
- inculcate the need for peer review.
- inculcate honesty and responsibility particularly in respect of self-certification systems.

At project organisation level

- Project managers need to achieve a better balance between the drive to get things done and respect for engineering and to accept peer review.
- Contractors and project organisations need to develop a culture which encourages continuous learning.
- Project organisations must be structured to include professionals who are capable of identifying site change that affect design and the culture of independent peer review.
- Project organisations must include risk management as an integral part of project management.
- Clients should promote forms of contract that ensure an environment where parties are encouraged to work together as a team.
- Clients need to be realistic in the allocation of responsibility for individual risks. A good principle is to allocate each individual risk to the party in the contract best suited to managing and bearing it.

At the construction industry level

- Procurement of construction works needs to move forward to a best value for money basis taking due account of how risk has been allocated between the stakeholders.
- The pre-qualification procedures for contractors need to be revised to ensure that competence is well matched to the challenges of the project.
- There needs to be industry wide action to set out clear requirements for academic and training programmes in relation to risk management, professional integrity and ethics.
- There needs to be sustained action to stamp out corruption at all levels.

At national and international level

- Professional advisors to public utilities and governments should always alert their clients to the risks caused by fragile distributed systems in coping with foreseeable natural events.
- Professional institutions should highlight to authorities and governments the need for improved codes and standards, particularly in relation to flooding and seismic events.

Läs mer på Internet
www.x

Författarens e-post
david.sherwood@bacsol.co.uk