Geotechnical construction risk management at the Foothills Bypass Project – Hong Kong

Nicholas P Koor
School of Earth and Environmental Sciences - University of Portsmouth

Abstract: The Foothills Bypass is a dual 2-lane highway on the western side of Tuen Mun in the New Territories of Hong Kong. The road is constructed on 1.7 km of embankment along the foothills of Tsing Shan and on viaduct at its northern end where it links with a grade separated interchange. The stabilisation of a large area of existing instability (Area 19) formed a major and integral part of the works. Stabilisation included, staged excavation, deep trench drain installation, and filling works. Geological hazards that represented a risk to construction and long term performance of the project were; high pore pressures; low strength relict shear zones ($\varphi'_r = 9^\circ$); and collapse features. These geotechnical risks were managed by ensuring that the appropriate staff were engaged on site in combination with effective communication between site staff, the design team and the contractor. A key risk management tool was the continuous development of the conceptual ground model through all stages of the project.

1 BACKGROUND

1.1 Scope

The management of geotechnical risk and the benefits that a proper risk management framework can bring to a project are unquestioned by most ground engineering professionals (geologists, engineering geologists and geotechnical engineers). Geotechnical risk management frameworks embedded in the over-all project risk management strategy and the use of geotechnical risk registers during a Civil or Building Engineering project are seen as positive moves in the construction industry. These bring benefit to the construction team in terms of reduced design and construction risk, and to the Client in an overall reduction in financial risk.

This paper describes; the geological hazards identified at the Foothills Bypass project; the construction and long term risks associated with these hazards; and the geotechnical risk management strategy adopted during the construction process to mitigate and manage these risks. Key to the risk management strategy was the continuous refinement of the conceptual ground model by an experienced site team. A brief case history which demonstrates this important risk management tool is also presented in this paper.

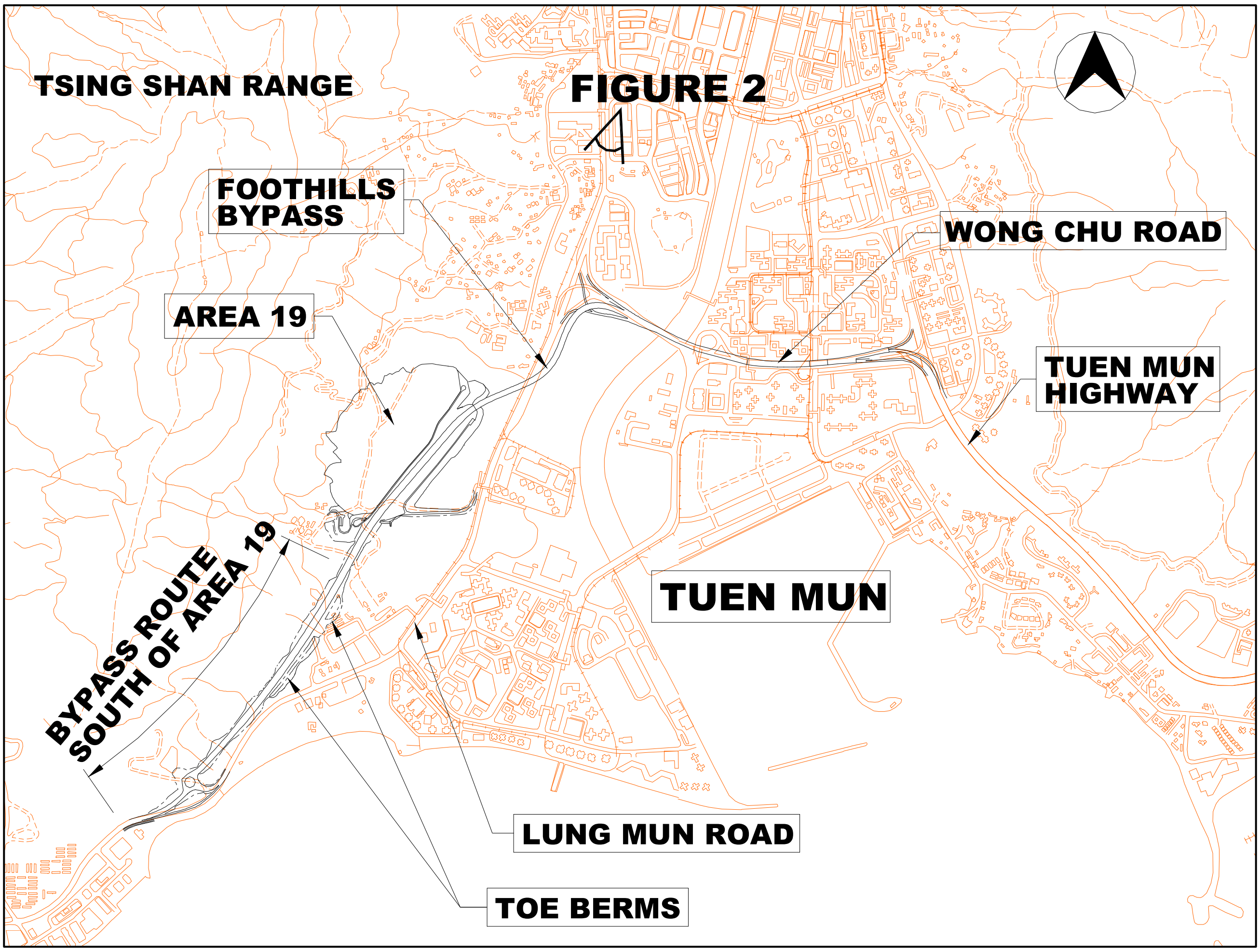

Fig. 1. Foothills Bypass & Wong Chu Road layout with connection to Tuen Mun Highway

1.2 The project

The Foothills Bypass (now Lung Fu Road) is a 2.6 km long, dual 2-lane highway connecting Tuen Mun West (near Butterfly Beach) to the Tuen Mun Highway via Wong Chu Road (Figure 1). The road is constructed on 1.7 km of embankment along the foothills of Tsing Shan and 0.9 km on viaduct, which takes it over Lung Mun Road to connect into Wong Chu Road and the Tuen Mun Highway. Associated with the bypass construction was the stabilisation of a large area of relict instability (600 m by 300 m) located within Tuen Mun Area 19, up-slope of the proposed bypass. Scott Wilson Ltd. was commissioned in 1995 by the Territory Development Department (now the Civil Engineering and Development Department) of the Hong Kong SAR Government to investigate, design and supervise the construction of the Foothills Bypass. Construction commenced in October 1998 and was substantially complete in October 2001. The Main Contractor for the project was Gammon Construction Ltd. and the total construction cost for the road embankment and slope stabilisation works was in the order of HK$400M (US$50M).

Area 19 has had a long history of instability; geological (Langford *et al.* 1986); and recent due to borrowing activity in 1977 (Hunt 1982; Taylor & Hadley 2000). The instability triggered in 1977 was active through the 1980s and 1990s causing ongoing maintenance and stability issues for various Government Departments and effectively sterilising the land at the toe of the slope. The design and construction of the bypass incorporating the stabilisation of Area 19 is described by Koor *et al.* (2001) and Thorn and Koor (2002). During the design process significant geological hazards were identified which if not properly managed, could have resulted in potential loss of life during construction, disruption to the construction process, dramatically increased construction costs and, increased long term maintenance costs.

1.3 Conceptual Ground Model

Fundamental to any geotechnical risk management strategy is the identification of all possible design and construction geohazards. This relies on experienced ground engineering professionals working as a team to initially identify as many of the hazards as possible and then to translate these into potential risks to the project. To ensure that all the major hazard elements are identified, a well constrained conceptual ground model as described by Fookes (1997) must be constructed. For the conceptual ground model to be a useful tool throughout the design life of the project it must evolve as more ground is exposed, especially during construction. This ensures that appropriate design and construction solutions can be applied to problems as they arise using the best model available. The model should be used throughout the design life of the project to aid the interpretation of any ground related defects and updated as these are investigated and remediated. This evolution of the geological model during all phases of the project, especially during construction when more ground information is exposed than at any other time, proved an invaluable tool in managing geotechnical risk for the Foothills Bypass project.

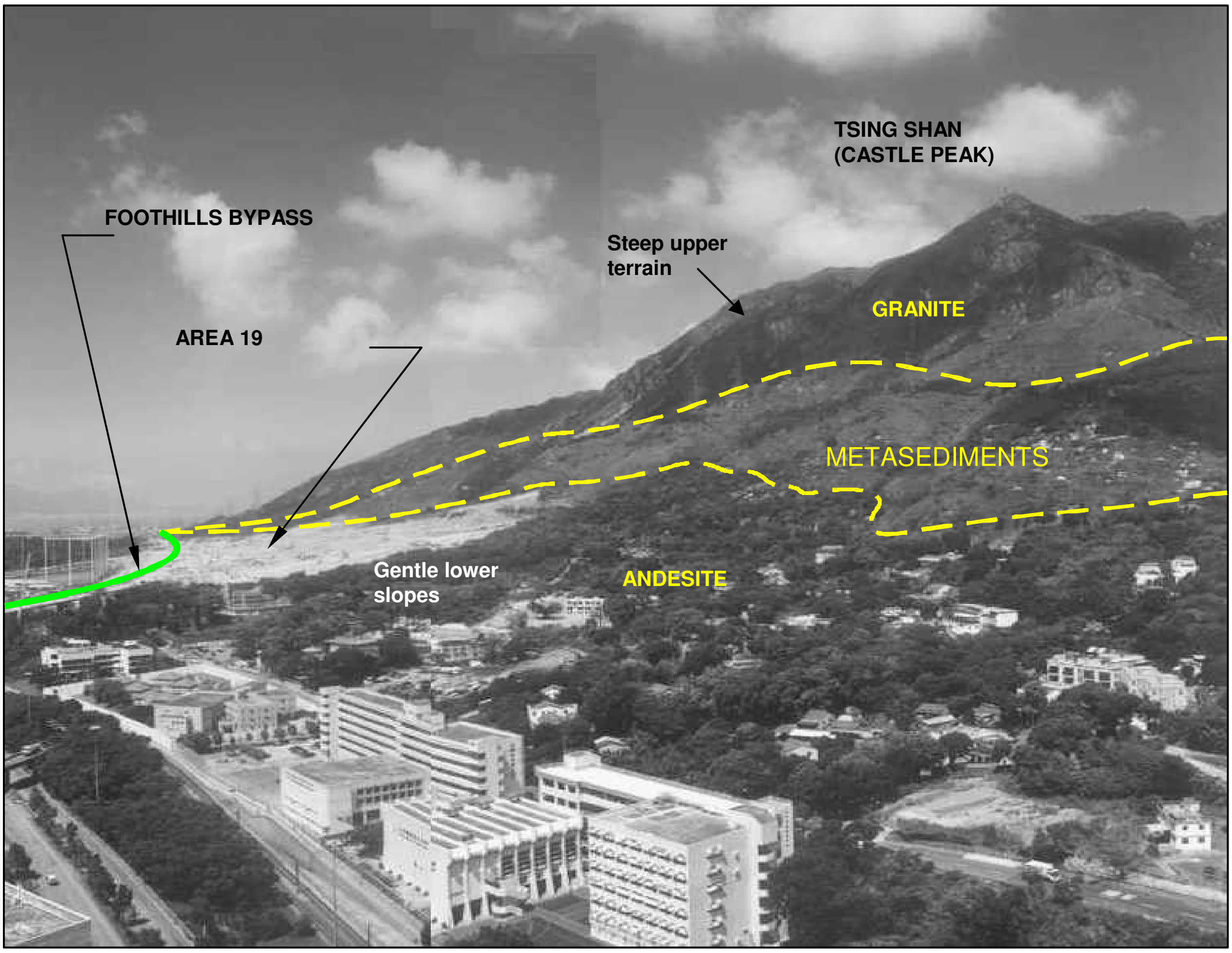

Fig. 2. Geomorphology and general geology of the foothills of Tsing Shan

The geology of the Tsing Shan range is varied and this is reflected in its geomorphology (Figure 2). The upper very steep slopes of Tsing Shan, which consist of megacrystic fine to medium grained granites, dominate the surrounding landscape. Down slope, the granite gives way to a distinct set of rounded spurs and associated less steep slopes underlain by metasedimentary strata of the Tuen Mun Formation, which comprise siltstones, quartzites, tuffites and conglomerates.

Downhill, and marked by another change in gradient, is the subdued and gently sloping terrain of the footslopes, which are underlain by volcanics also of the Tuen Mun Formation. The volcanic rocks consist primarily of andesitic lava's. The andesite weathers to a firm to stiff becoming very stiff greenish grey slightly clayey silt with closely spaced relict joints. The joint surfaces, frequently polished/slickensided as a result of previous movement and often manganese-coated, are generally discontinuous. In addition to the joints, continuous (c. 10s of metres), low angle, through-going, shear surfaces are present in the uppermost few metres of the weathered andesite in Area 19 (Figure 3). These were noted during investigations in the early 1980s (Hunt, 1982) and during the more recent stabilisation works. These shear surfaces are smooth undulating and often highly polished and striated and are interpreted as being the surfaces of rupture of both recent and relict landslides. The presence of such discontinuities within the soil mass has a significant effect on its overall behaviour, particularly the mass strength.

Large areas of the gentler lower slopes are covered by large tracts of Quaternary colluvium containing a high proportion of granite clasts (Figure 3). Both older, weathered and locally cemented colluvium and a younger looser colluvium are identifiable. These materials appear to have found their way onto the foot-slopes by both debris flow and less intense transportation processes such as hill creep. A hazard assessment conducted in 1996 identified that large-scale debris flows emanating from Castle Peak could be anticipated during the design life of the road and these would probably traverse the proposed route (SWK, 1996; Hadley *et al.* 1998).

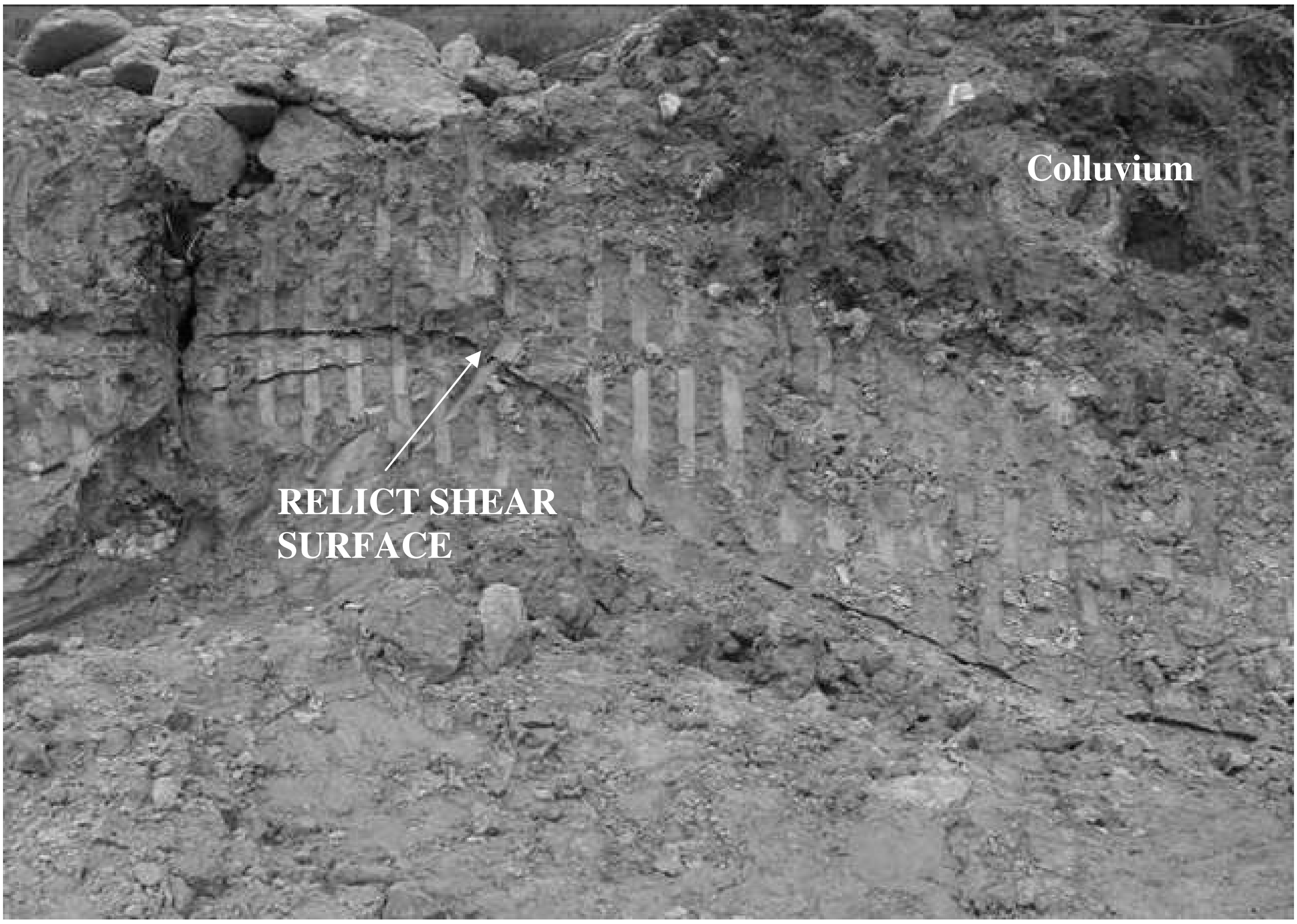

Fig. 3. Relict shear surface in completely decomposed andesite exposed during Area 19 stabilisation works in 1998

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, are observed within either the colluvium or the underlying volcanics. The responses that do occur tend to be over a period of three to seven days or longer. Perched groundwater conditions often develop within the colluvium, particularly during the wet season. Vertical ground water flow is generally from the colluvium into the decomposed volcanics below. Artesian conditions, frequently encountered within the footslopes of mountain ranges, were not been observed although several spring or seepage lines in Area 19 and further south were encountered during construction but these were related to topographic controls rather than artesian conditions.

The Foothills Bypass is founded generally on colluvium overlying partially weathered andesite along most of the route apart from the southern end where it is founded directly onto partially weathered granite.

A geological model based on that proposed by Langford *et al.* (1986) explains the origins of the instability in Area 19 and is consistent with observations made during construction. The model postulates that during the Quaternary Period, rapid erosion by down-cutting streams through the colluvium and completely decomposed andesite resulted in landsliding with the surfaces of rupture being mainly within the partially weathered andesite. The relict surfaces of rupture are very weak and are believed to be at or close to residual strength which has been measured as low as $\varphi_r' = 9°$ (Taylor & Hadley 2000; Koor *et al.* 2000). It is believed that it is these very weak relict surfaces of rupture that were reactivated during the borrowing activity in 1977. It was considered likely at the design stage that such failure planes were present throughout the partially weathered andesite up to its contact with the meta-sediments.

1.4 Construction in Area 19

The bypass was constructed on a fill embankment up to 20 m high, which forms a toe weight to Area 19 with filling up-slope at an angle of 11°. Sub-surface drainage in the form of 6 m deep counter-fort drains at 12 m centres were incorporated together with extensive surface drainage measures (Figure 4). To monitor the long term performance of the slope stabilisation measures, a comprehensive network of geotechnical instrumentation was installed and linked to an automatic system which allows real time movement; pore pressure and rain fall monitoring.

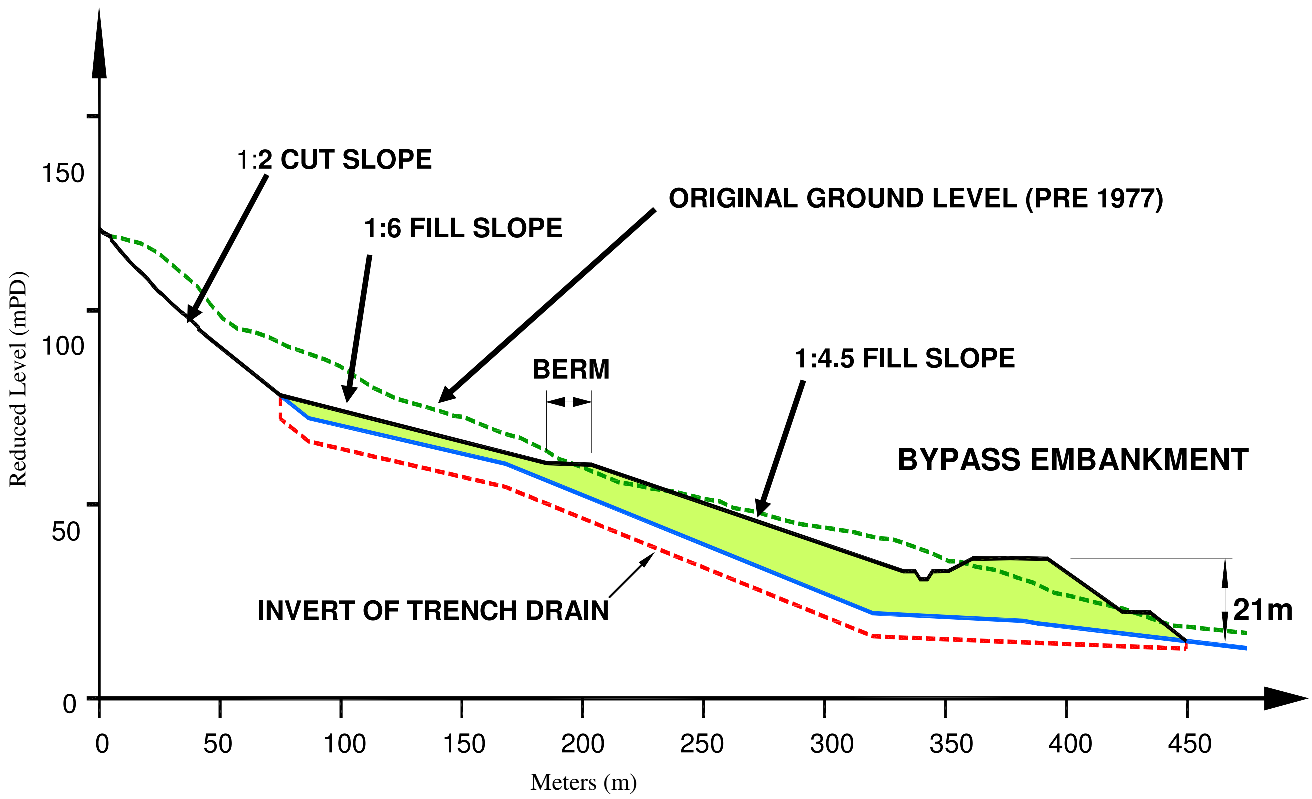

Fig.4. Typical section through the stabilisation works in Area 19

The landslide stabilisation works in Area 19 involved the removal of about 0.2 million m^3 of soil from the slope; construction of 17 km of 6 m deep trench drains (Figure 4); and the compaction of 1.8 million m^3 of fill to form the embankment toe weight. The cost of these stabilisation works were approximately HK$140M (US$17.5M). Critical to the success of the slope stabilisation and to avoid large-scale slope movements in Area 19 was the sequencing of the drainage and earthworks (Figure 5).

2 GEOTECHNICAL HAZARD AND RISK MANAGEMENT FOR THE FOOTHILLS BYPASS PROJECT

2.1 Risk management in Hong Kong

It was not until the publication of the Environmental, Transport and Works Bureau Technical Circular (Works) (ETWBTCW) No 6/2005 – Implementation of Systematic Risk Management in Public Works Project’s in 2005 that risk management strategies became common practice in Hong Kong for Public Works Projects. However, the fundamental premise of reducing risk by the adoption of best practice in investigation and design, good communication and an integrated team approach (Clayton 2001), is the basis of any good geotechnical design and practice. This framework is embedded in the work practices of major Consultants and Contractors in Hong Kong, which, together with appropriate Quality Management Systems, ensures that geotechnical risks are minimised even without a formal risk management strategy. So, although a formalised geotechnical risk management strategy was not in-place for the Foothills Bypass project, the risks were effectively managed through sound engineering practice.

2.2. Main Geotechnical Risks

The main geotechnical hazards and their consequences identified at the detailed design stage are listed in Table 1.

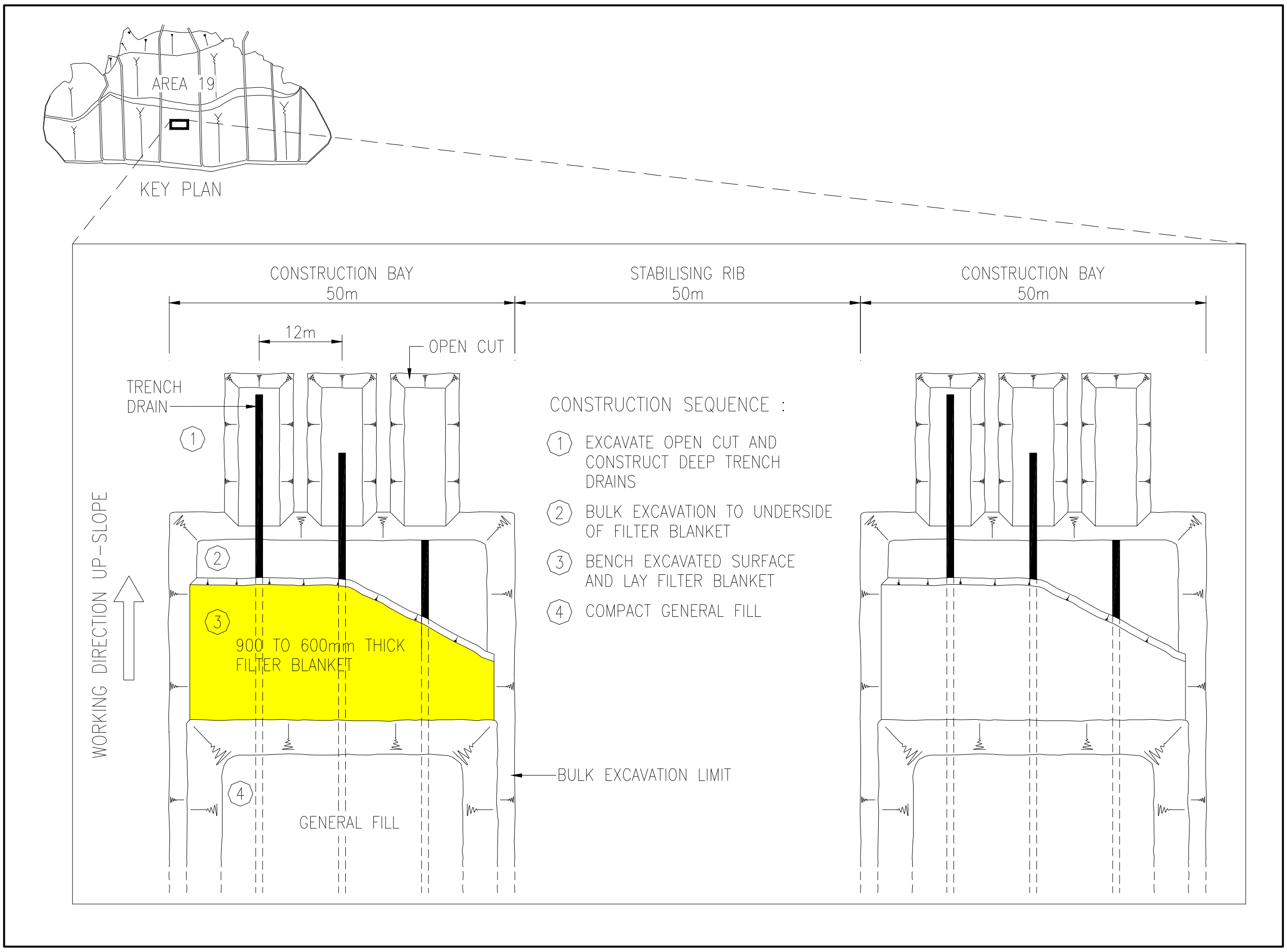

Fig. 5. Construction sequence in Area 19 to prevent large scale instability during bulk excavation, trench drain installation and filling works.

The major hazards to the permanent works posed by; weak relict shear surfaces within the completely decomposed andesite in Area 19; high pore pressures in Area 19 and; long run-out debris flows, were identified and taken into account at the detailed design stage. They are described in detail by Hadley *et al*. (1997), Taylor and Hadley (2000) and Thorn and Koor (2002).

2.3 Geotechnical risk management during construction

At an early stage in the project it was identified by both the Consultant and the Client that given the geological and geotechnical complexity at the site the key personnel representing the Consultant and Contractor must be full time on site to ensure that the geotechnical risks were properly managed. Therefore a full time Resident Geotechnical Engineer (RGE) responsible for the supervision of all the geotechnical works for the project was provided by the Consultant. The Contractor was also required, through the Contract, to provide a full time Geotechnical Engineer to work closely with the RGE. Due to the complex geology at the site, the RGE selected was an experienced Engineering Geologist. This appointment was seen as critical to the success of the project.

Geological hazards that could not be properly constrained during the detailed design stage included:

(a) The presence of relict shear surfaces in the completely decomposed andesite south of Area 19

(b) The presence of collapse features within the completely decomposed andesite

Geotechnical hazards which had to be managed during construction included:

(i) Large scale instability triggered during construction in Area 19

(ii) Collapse of deep trench drains

Table 1. Major geotechnical hazards identified for the Foothills Bypass project

Major Hazard	Event	Consequence
Relict weak shear surfaces within completely decomposed andesite in Area 19 and further south	1. Area 19 earthworks and embankment instability	1. Potential loss of life and long term maintenance issues.
	2. Large scale instability triggered during construction	2. Potential loss of life and major construction disruption – land issues if failure extends beyond site limits
	3. Deep trench drain collapse during construction	3. Potential loss of life - construction disruption
High ground water levels in Area 19 and further south	1. Pore pressures higher than design values in Area 19 triggering movement	1.Increased maintenance cost
	2. Seepage lines not identified during construction	2. Internal erosion of earthworks leading to embankment collapse – potential loss of life - maintenance costs
	3. Flooding of excavations especially deep trench drains	3. Deep trench drain collapse – potential loss of life – construction disruption
Long run-out debris flows and floods	1. Debris flow damage to Area 19 earthworks	1. Blocking of drainage and erosion of earthworks leading to slope failures – increased maintenance costs.
	2. Debris flow impacts road embankment	2. Flow overrides embankment impacting traffic – possible loss of life
Collapse features - completely decomposed andesite	1. Undermining of road embankment leading to collapse (sudden or slow moving)	1. Road collapse – potential loss of life and maintenance costs

To manage these hazards and the associated risks to the project, certain management and technical constraints were incorporated into the construction stage of the project as detailed in Table 2. This sets out the risk management strategy for the geotechnical elements of the work.

3 CASE HISTORY – EMBANKMENT STABILITY SOUTH OF AREA 19

Extensive confirmatory ground investigation, not possible at the design stage, enabled constant refining, and updating of the geological model used to develop the geotechnical solution for the bypass works. Trial trenching to the south of Area 19 (Figure 6) combined with geomorphological mapping and re-interpretation of aerial photographs established that areas of instability and relict landslides existed along the embankment route. These relict landslides occur within the completely decomposed andesite and appear to be of a similar form to those described in Area 19. Block samples of completely decomposed andesite containing shear surfaces were tested in a large shear box and measured field strengths of $c'=0$ kPa and $\varphi'= 12$ to 19°, which are within the same range as determined for Area 19 (Taylor & Hadley 2000) and close to the mass strength parameters used in the slope stabilisation permanent works design.

Following this work, the geological model derived for the route south of Area 19 was modified to take into account the findings of the confirmatory investigation and embankment stability was then re-assessed. The weak shear surfaces within the andesite resulted in embankment toe stability having less than the required factor of safety and therefore embankment redesign was required. To ensure that the progress of the contractor was not compromised, a "bolt-on" solution of toe berms, designed to increase toe stability, was adopted along the down-slope side of the embankment (Figure 1). Due to space restrictions and the existing topography at one critical section, ground improvement in the form of grout columns (66 columns of 750 mm diameter, 12 m long and at 2 m centres) constructed using the continuous-flight-auger technique, were required together with a rock fill toe berm. The grout columns enhance the shear strength of the completely decomposed andesite and disrupt the continuity of any continuous weak shear surfaces.

Table 2. Management of major hazards for the Foothills Bypass project

Major Hazard	Management of Risk	Outcome
Relict weak shear surfaces within completely decomposed andesite south of Area 19	1. Construction phase site investigation comprising; re-interpretation of aerial photographs; geomorphological mapping after initial site clearance; focussed ground investigation consisting of deep trial trenches; and laboratory testing of large block samples.	1. Identification of relict shear surfaces associated with landslides within the completely decomposed andesite in the embankment foundation. Shear surfaces had strengths as low as $c' = 0$ kN/m^2 and $\varphi' = 12°$.
	2. Refinement of geological and geotechnical model. Analysis of embankment stability with the inclusion of low strength shear surfaces.	2. Where the colluvium was less than 5m thick the factor of safety against basal embankment failure was less than the required 1.4.
	3. Redesign of embankment to take into account low strength foundation and to minimise the disruption to the construction process.	3. "Bolt-on" solution of toe berms designed to increase embankment toe stability. At one critical section, ground improvement required together with a rock fill toe berm.
Large scale instability in Area 19 triggered during construction possibly extending beyond site limits	1. Detailed construction method statement developed by Contractor for Area 19 construction with close collaboration with RGE. Excavation fronts limited to 50 m wide bays (Figure 5) to allow trench drain construction and filling from the toe up.	1. Methodology ensured that; unloading at the toe of the slope was minimised; support removed only over a relatively short width thus limiting the size of any incipient ground movement into the excavation; deep trench drain construction in advance of the bulk excavation had a stabilising effect by actively reducing pore pressures in the slope and reinforcing the ground ahead of bulk excavation.
	2. Ground movement and real time ground water monitoring by contractor incorporated into the construction methodology.	2. Only small-scale containable slope movements were triggered during the excavation and trench drain construction stages. Ground water monitoring indicated substantial lowering of pore pressures within the andesite and colluvium achieved.
	3. Detailed mapping carried out by RGE during construction in Area 19, with the results fed back into the geological model.	3. Mapping confirmed original geological and geotechnical model for Area 19 was correct. No design amendments required for Area 19 stabilisation works.
Deep trench drain collapse during construction in Area 19	1. Detailed construction method statement developed by Contractor for trench drain construction with close collaboration with RGE. Trench box system adopted.	1. Trench boxes used to support sides to allow access for sub-soil drain installation and drainage filter compaction. No reportable injuries made.
	2. Ground movement and groundwater monitoring in association with over-all construction in Area 19	2. Localised movement into supported trench – movement initiated along sub-vertical relict joint sets in the completely decomposed andesite.
Collapse features - completely decomposed andesite	1. Construction phase re-interpretation of aerial photographs and detailed geomorphological mapping after initial site clearance.	1. No evidence of closed circular depressions found during mapping. These depressions could be interpreted as backfilled ponds used for cultivation – still a possible hazard but road embankment design utilised a geotextile mat to span soft spots .

4 CONCLUDING REMARKS

The Foothills Bypass project was geotechnically challenging. A key to the successful completion of the project was a comprehensive risk mitigation strategy. The key elements of this strategy were:

- Suitably qualified staff resident on site throughout the construction period to supervise the geotechnical elements of the project.
- Positive communication between the design and construction team with frequent site visits made by senior members of the design team.

- Close and co-operative working relationship between the Consultants' and Contractors' geotechnical teams to ensure properly designed and detailed method statements and temporary works.
- Continuous refinement of the conceptual ground model throughout the construction phase of the project.

This last point proved to be an invaluable tool during the design and construction phases of the project in mitigating geotechnical risk. Slope deformation and ground water monitoring in Area 19 after construction was complete, was fed back into the ground model which is effectively maintained and updated through periodic Engineers maintenance inspections.

The role of the Geotechnical Engineering Office (GEO) of the Hong Kong SAR should not be underestimated in the process of geotechnical risk management and reduction in Hong Kong. The ETWBTCW No.29/2002 - Geotechnical Control for Slopes and Retaining Walls sets out the policy and procedures on geotechnical control for man-made slopes and retaining walls in Government projects undertaken by Works Departments or their Consultants. The details of all permanent geotechnical works for man-made slopes

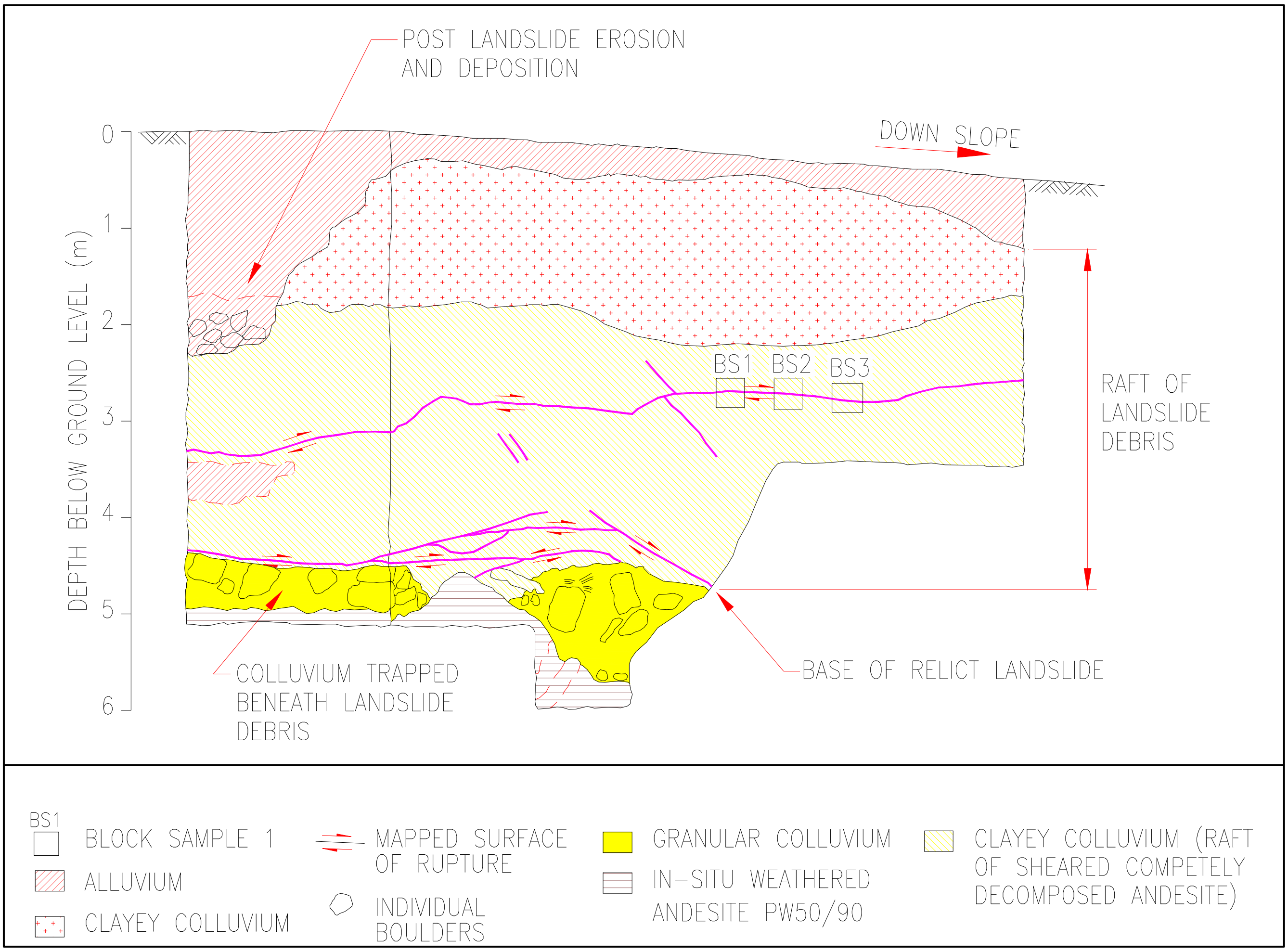

Fig. 6. Trial trench log south of Area 19 – sheared raft of completely decomposed andesite landslide debris overlying granular colluvium

and retaining walls are required to be submitted to GEO for checking at the; project planning stage; detailed design stage; construction stage and; at project completion. This process ensures that geological and geotechnical advice and reviews are made by highly experienced professionals through the investigation, design and construction stages of any project. As such the GEO become an important member of the risk management process, although the design responsibility and therefore the design risk is firmly and quite rightly the Consultants responsibility. It is the opinion of the author that this process represents an excellent tool for ensuring that major geological hazards are not missed and that design strategies are fit to cope with these risks because of highly complex ground conditions in Hong Kong, and often accelerated design and construction process (super fast-track projects) becoming more and more common. The GEO has similar roles in; the geotechnical control of tunnels (ETWBTCW No. 15/2005) and foundation designs in areas underlain by cavernous marble (ETWBTCW No. 04/2004).

ACKNOWLEDGEMENTS

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

REFERENCES

Clayton, C.R.I. (2001). *Managing Geotechnical Risk.* Thomas Telford Ltd. London.

Fookes, P.G. (1997) *Geology for Engineers: the Geological Model, Prediction and Performance.* The First Glossop Lecture, QJEG, 30, pp 293-424.

Hadley, D. Hearn, G.J. and Taylor, G.R. (1998). Debris Flow Assessments for the Foothills Bypass, Hong Kong. Slope Engineering in Hong Kong. Proc. of the Annual Seminar on Slope Engineering in Hong Kong, HKIE.

Hunt, T. (1982). Slope failures in colluvium overlying weak residual soils in Hong Kong. *Proceedings of the ASCE Speciallity Conference on Engineering and Construction in Tropical and Residual Soils, Honolulu,* pp 443-462.

Langford, R.L., Arthurton, R.S. & Lai, K.W. (1986). Geological Survey and Ground Investigations in Tuen Mun New Town, Hong Kong. *The Role of Geology in Urban Development. Geological Society of Hong Kong.* Bulletin No 3, pp 199-208.

Koor N. P., Parry S. and Yin J. H. (2000). The shear strength of infilled and slickensided discontinuities of some Hong Kong saprolites. Engineering Geology HK 2000. Institution of Mining and Metallurgy – Hong Kong Branch. pp 187 – 192.

Koor N. P., Hadley D. & Hart J. R. (2001). Foothills Bypass, Hong Kong – Design to Construction. Geotechnical Engineering Meeting Society's Needs. The 14th Southeast Asian Geotechnical Conference. pp 813 – 818.

Scott Wilson Kirkpatrick (1996). Foothills Bypass Tuen Mun Road / Wong Chu Road Interchange and Other Road Junction Improvement Works – Final Geotechnical Appraisal Report.

Taylor, G.R. & Hadley, D. (2000). Stabilisation of a Large Landslide in Tuen Mun, Hong Kong. *Landslides in research, theory and practice.* Ed. by Bromhead, E. Dixon, N. and Ibsen, M-L. Proceedings of the 8th International Symposium on Landslides, Cardiff, vol. 3 pp1454-1460.

Thorn M. & Koor N. P. (2002). Debris flow mitigation works, Foothills Bypass, Tuen Mun. Natural Terrain – A Constraint to Development. Institution of Mining and Metallurgy – Hong Kong Branch. pp 143-150.