A Contribution to Slope Engineering in Hong Kong - the Engineering Geology Approach
Volume 1: Narrative

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ABSTRACT
Whilst working in Hong Kong from 1993 to 2005, firstly for the Geotechnical Engineering Office of the Hong Kong Government and then for various international consultants, I was involved in a number of important research studies, landslide investigations and construction projects where I was able to make a significant contribution to science, knowledge and practice under the theme of slope engineering. This work was carried out in what I have described as the engineering geology approach which has six interrelated objectives: identification of vulnerable slopes; constraint of slope defect; definition of slope geological and hydrogeological model; geotechnical characterisation; slope design; and design verification – constructability. Six projects are described in this narrative (Volume 1 of the submission) supported by published reports, papers, and research articles which are reproduced in Volumes 2 to 5. The establishment of the Hong Kong Slope Safety System (HKSSS) in Hong Kong in 1977 has developed over the subsequent 28 years into what is considered one of the most sophisticated slope safety systems in the world. The Chai Wan Area Study (Volume 2), the Site Characterisation Study (Volume 3), and the Lai Ping Road investigation (Volume 4) have made positive contributions to the HKSSS through: the development of new slope investigation techniques; the advancement in understanding of the formation of “clay rich seams” and their role in slope instability; and the application of detailed geomorphological mapping of failure scarps in the understanding of slow moving retrogressive landslides. Further work carried out in my role as Resident Geotechnical Engineer for the Foothill Bypass project and Senior Resident Engineer for the Deep Bay Link project contributed to the HKSSS through: developing an understanding of the residual strength of weathered rock in Hong Kong; natural terrain hazard mitigation, in particular a cost benefit approach in scenarios where there is only an economic risk; and in the design and construction of long soil nails in aggressive ground conditions and the use of double corrosion protection systems for long soil nails.
ACKNOWLEDGEMENTS
This submission has been a long time in the making and it has only come about due to the unflinching support of Anna Koor who wanted to move lock, stock and barrel from London into the far flung unknown of Hong Kong back in 1993. This move gave me the opportunity to work on many exciting projects and with Anna’s support I was able to extract the most out of these. It was also Anna who first encouraged me to take the leap into academia and head back to Portsmouth (where we first met) to take up a post at the University, my alma mater in 2005. Ten years later it was Anna once again who cajoled me to first enquire and then attempt to use my experiences in Hong Kong to write my PhD by Publication. She has also been kind enough to read through several drafts of this narrative – what a star!

I also want to thank my colleagues, Andy Gibson and Gareth Swift who kindly reviewed various versions of the narrative and gave continuous encouragement and some excellent constructive comments. Professor Robin Strachan mentored me through the writing process and gave invaluable advice and comments on my final draft. My thanks also go to Philip Benson, Craig Storey, and David Martill for their encouragement through the year.

I also need to send my many thanks to Chris Lam (Chief Geotechnical Engineer in the Planning Division of the GEO) for giving me permission to view Government files and in particular to Keith Roberts and his team, Kenneth Li and Ho Hoi Yan in helping me extract information from the files.
DECLARATION

Whilst registered as a candidate for the above degree, I have not been registered for any other research award. The results and conclusions embodied in this thesis are the work of the named candidate and have not been submitted for any other academic award.

Nicholas Paul Koor

Friday, 15 January 2016
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GEO Information Note 02/2011: Geophysical Techniques for Investigation of Slopes and Retaining Walls

Appendix 4

Volume 2 – appended in CD


Volume 3 – appended in CD

V3.1 Koor N.P. (1999). Site Characterisation Study - Phases 1 and 2. GEO Report No. 71

Volume 4 – appended in CD


Volume 5 – appended in CD

Papers submitted in support of the submission for the award of Doctor of Philosophy by Publication as listed in Table 1 of the Narrative – Volume 1


V5.4 Koor, N. P., Campbell, S. D. G., Sun H. W., and Ho, K. K. S. (2000) Scarp morphology and development associated with a large retrogressive compound landslide at Lai Ping Road – Hong Kong. Urban Geology Conference, University of Hong Kong. (pp 77-88)


1. Introduction

1.1 Background
Complex deeply weathered igneous rocks, steep natural terrain (c.20 to 35°) and high annual rainfall (c.2300mm), combined with intense urbanisation, are the main contributors to slope failures in Hong Kong, see Brand, Premchitt and Philipson (1984), Au (1998), Dai and Lee (2001), Chan (2005) and Cheng (2011) amongst others. A recent example of the meta-stable nature of Hong Kong slopes occurred on 7 June 2008 when an average of 300mm of rain fell over Hong Kong in 12 hours triggering 89 landslides, killing two people and causing significant economic loss (South China Morning Post, 2008, p1).

Two highly destructive landslides in 1972 and 1976, which killed 156 people in total, played a large part in the establishment of the Geotechnical Engineering Office (GEO, formally the Geotechnical Control Office) of the Hong Kong Government in 1977 (CEDD, 2007). GEO’s mandate was to “provide continuity throughout the whole process of investigation, design, construction, monitoring and maintenance of slopes in Hong Kong” (Hong Kong Government, 1977). The GEO is now part of the Civil Engineering and Development Department (CEDD) of the Hong Kong SAR Government. The communication of landslide hazard and risk to the public is orchestrated through the Hong Kong Slope Safety System (HKSSS), which is continually being developed, upgraded and maintained by the GEO (Chan, 2005). This is considered one of the most sophisticated slope safety systems in the world and, as described by Malone (1998) and Chan (2005), has two key aims: to reduce landslide risk and address public attitudes to landslide risk. The continued development of the HKSSS has been responsible for a reduction of risk to life from the failure of old man-made slopes to below 25% of that which existed in 1977 (Cheng, 2011). The mandate of the HKSSS incorporates: safety standards, checking new works, upgrading existing slopes, slope maintenance, promoting public awareness of slope maintenance and safety, squatter¹ clearance on vulnerable slopes, and enhancement of the aesthetics of engineered slopes (Chan, 2005).

¹ Shanty towns erected, by and large, on steep natural terrain in Hong Kong by refugees fleeing persecution during the Chinese Cultural Revolution (1966-1976).
This PhD seeks to demonstrate that the body of work undertaken in Hong Kong\textsuperscript{2} between 1993 and 2005 — by me or in partnership with associate experts — has made a significant contribution to slope engineering in Hong Kong, in terms of science, knowledge, and professional practice and has contributed to the reduction of landslide risk as reported by Cheng (2011). In particular, this narrative will demonstrate that the research projects undertaken whilst working for the GEO - the Chai Wan Area Study (Campbell and Koor, 1996 - Volume 2 of this narrative), the Site Characterisation Study (Koor, 1997 - Volume 3 of this narrative), and the Lai Ping Road landslide investigation (Koor and Campbell, 1998 - Volume 4 of this narrative) – have made a positive and direct impact on: the introduction and development of new slope investigation techniques, the advancement in understanding of the formation of “clay rich seams” and their role in slope stability and; the application of high resolution geomorphological mapping of failure scarps in gaining an understanding of slow moving retrogressive landslides. In addition, my work on debris flow mitigation design (Koor, Hadley and Hart, 2001 and Thorn and Koor, 2002 - Volume 5 of this narrative) for the Foothills Bypass project together with the development of design, installation and design verification protocols for long soil nails in acidic ground (Koor and Cheung, 2005 - Volume 5 of this narrative) developed for the Deep Bay Link project were significant contributors to the development of Hong Kong practice across these two areas of slope engineering.

A summary of my published government reports, journal and conference papers used in support of this narrative can be found in Table 1 together with a contribution statement for jointly authored publications and a list of citations for each, where appropriate.

\subsection{1.2 Engineering Geology Approach}

In order to place my work in a professional and academic framework I have developed the \textit{engineering geology approach} to slope engineering (Figure 1). Six projects or field experiments were carried out within this framework. The evolution of this approach can be divided into three linked subject areas which

\footnotesize

\textsuperscript{2} I was initially employed by the Geotechnical Engineering Office (1993 to 1999) and subsequently worked for major Engineering Consultants until 2005 when I returned to the UK to take up an academic post at the University of Portsmouth.
together form what I would describe as the discipline of Engineering Geology\(^3\). The *engineering geology approach* has, in this narrative, been developed to illustrate how different objectives are “integrated” in slope engineering projects as follows:

1. Geological and geotechnical characterisation – geological and ground model.
2. Geotechnical design – geotechnical model.
3. Construction in the ground – model verification and refinement.

The concept of an “integrated” approach in a slope engineering context for Hong Kong was first published by Franks, Koor and Campbell (1998). This paper describes a methodology which tested the hypothesis that a set of thematic maps derived from a highly detailed desk study combined with regional geological mapping can be used as an effective tool to identify vulnerable slopes (see Section 2.2). This idea of an “integrated” approach has been expanded in this narrative in order to assimilate a number of inter-related project objectives and methodologies developed from the body of work (Table 1) presented here which combine to form the engineering geology approach for slope engineering.

The objectives of the *engineering geology approach* to slope engineering are:

a. Identification of vulnerable slopes
b. Constraint of slope defect
c. Definition of slope geological and hydrogeological model
d. Geotechnical characterisation
e. Slope design
f. Design verification - constructability

In this narrative I use the terms geological model, ground model and geotechnical model as described by Knill (2002) but re-defined here as follows:

**Geological model** – 2, 3 or 4D representation of the geological and hydrogeological conditions at a site based normally on desk study, mapping and ground investigation data.

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\(^3\) Many authors over the years have attempted to define the discipline of engineering geology and what key skills an engineering geologist should have. Pertinent recent references which act as a supplement to this narrative are Morgenstern (2000), Brunsden (2002), Knill (2002), Culshaw (2005), Bock (2006) and Griffiths (2014).
Ground model – application of material parameters to the geological model normally based on laboratory and in situ testing of geological materials - may involve a simplification of the geological model.

Geotechnical model – simplification of the ground model to enable analysis using geotechnical design methods – undertaken using constitutive models for strength, deformation and seepage.

This supporting narrative pulls together the various publications relating to my work in Hong Kong and frames them in a coherent model which, with some simple amendments could be used as a guide for most “ground engineering” projects (see Bock (2006) for a definition of “ground engineering”).

1.3 Pedagogic Contribution

My current position as an educator and academic places me in a unique position. As the programme manager of the longest running undergraduate degree in Engineering Geology and Geotechnics in the UK, I have a continued influence on the quality of engineering geology and geotechnical engineering graduates. I therefore argue that through the transfer of my knowledge and practical experience to my undergraduate students I continue to indirectly influence practice in the UK and overseas (for instance seven former students of mine are currently working in Hong Kong). I have made significant contributions to the degree and therefore the profession through pedagogic developments which are summarised as follows:

- **Introduction of a sandwich year into the degree – this has resulted in:**
  - A significant increase in the number of good quality degrees awarded and in particular 1st Class degrees.
  - Near 100% employability for placement students.
  - Enhanced industrial contacts.
  - Contribution to research with development of Knowledge Transfer Projects.

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4 I joined the University of Portsmouth in 2005 and became programme manager in 2009.
5 Defined as a 2:1 or above by the University of Portsmouth.
6 From an average of 2 per year pre-2009 to 7 per year since 2013.
Research-based final year projects using real data collected by students whilst on placement – this has led to a phase shift in the quality of final year projects and associated student learning.

- **Development of the Industrial Bursary Scheme where industry sponsor** a number of students through the degree pathway and provide the placement year – this has led to:
  - Increased applications meaning that the degree continues to thrive.
  - Relationship development with a number of companies.
  - Increase in the entry requirements from the pre-2009 offer of one science to the 2013-14 offer of two sciences, one of which must be either Physics or Maths.

- **Running a Study Tour to Hong Kong for final year students since 2011. This has many pedagogic, employability and transferable skills attributes such as:**
  - The internationalisation of the degree.
  - Exposure to large engineering projects in complex geological and urban environments.
  - Interaction with professionals in work and social scenarios.
  - Potential for students to obtain work overseas.
  - Make links with Alumni working in Hong Kong.
  - Obtain an understanding of the global nature of the industry and the opportunities that exist outside of the UK and Europe.

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Currently we have nine industry sponsors: Atkins, BAM Nuttal; Fugro; PBA; Keller; SRK; ESG; Geol Soc of London with GEA; and Southern Testing.

Since running the Hong Kong Study Tour eight students have obtained work in Hong Kong with Arup, Leighton, Fugro, Gammon Construction and, Vinci.

I organise an Alumni event whilst in Hong Kong so that the current students can develop networking skills.
Figure 1. The engineering geological approach to slope engineering in Hong Kong – unpublished.
2. Geological and geotechnical characterisation

2.1 Introduction
A fundamental part of any ground engineering project is the accurate characterisation of the ground through the development of a geological model, which allows both prediction and performance to be evaluated. This was eloquently described by Fookes (1997) in the 1st Glossop lecture and has since been integrated into the definition of the discipline of engineering geology by others over proceeding years; see Morgenstern (2000), Knill (2002) and, Bock (2006). The following projects focus on the first four sections of the engineering geology approach to slope engineering (Figure 1) used in the production of the geological and ground model. Each project has a particular scale of slope problem to solve, ranging from regional to site specific. These projects are all related to the development of methods or techniques to improve: data collection, the understanding of geological processes and subsequently, the geological and ground model.

2.2 Objective 1. Identification of vulnerable slopes: Chai Wan Area Study – the kaolin seam model
Two fatal landslides at Fei Tsui Road and Shum Wan Road in 1995 were in part controlled by accumulations of low strength clay within a weathered profile of fine-grained volcanic tuff (Knill, 1996a and b). A report by Strange (1996) into the geological features related to landslides in volcanic rocks in Hong Kong recommended that further field and desk study work was required in the Chai Wan area of Hong Kong, which incorporated the Fei Tsui Road landslide site.

I led and steered this project, being responsible for the overall methodology development, engineering geological assessment and the development of what became known as the “integrated approach” (Franks, Koor and Campbell, 1998). This approach and methodology was replicated in a subsequent study centred on Aberdeen encompassing the area close to the fatal Shum Wan Road landslide (Franks, Campbell and Shum, 1999).

A full description of the aims, objectives, methodology, results and conclusions of the Chai Wan Area Study are described in detail by Campbell and Koor
(1996), which was later published as GEO Report 60 (Campbell and Koor, 1998), see Volume 2.

The methodology developed for the Chai Wan Area Study was an integration of desk study and field mapping data into a set of thematic maps\(^\text{10}\). Through the combination and analysis of the thematic maps, nine slopes in the Chai Wan study area were identified that displayed engineering geological characteristics similar to that of the Fei Tsui Road landslide, and which warranted further investigation (Campbell and Koor, 1998). These nine slopes were added to the Landslide Prevention Measures Programme (LPMP)\(^\text{11}\) thus ensuring that they were investigated. Of these nine slopes, five were subsequently upgraded. Although this study was resource intensive (in man-hours), the approach was successful in identifying potentially problematic slopes which would otherwise have gone undetected. The standard screening process used by GEO for slopes to be added to the LPMP prior to this study was simplistic and consisted solely of: a site inspection accompanied by measurements of slope height and slope angle (Chan, 2005). The use of geological information in this process was limited to referencing the published geological map and any previous investigation. The Chai Wan Study therefore had a major impact on the methodology used to screen slopes as it utilised an integrated engineering geology approach rather than a simple mechanistic one. The integrated engineering geology approach was subsequently extended to a region-wide programme (Franks and Campbell, 1998; Yeung and Shaw, 1999; Liu, Ng, Campbell and Franks., 2000; Parry, Sewell and Franks, 2001; and Law and Li, 2001), which included other rock types including coarse ash crystal tuff and fine and medium grained granite. From these five regional wide studies a further fourteen slopes, which would have otherwise gone undetected, were identified as displaying geological features that warranted further investigation. Of these fourteen features ten government and two private slopes have been upgraded. As described above this study had a direct and significant impact on the HKSSS as assessed by Chan

\(^{10}\) Eight thematic maps were produced: Aerial Photograph Interpretation (API) Map, Geological Map, Cut Slope Map, Seepage Map, Landslide Incident Map, Ground Investigation Map (presence of kaolin), Report Summary Map, Natural Terrain Landslide Inventory (NTLI) Map

\(^{11}\) The Landslide Prevention Measures Programme is a systematic upgrading of sub-standard man-made slopes and retaining structures managed by GEO.
(2005) and made a major contribution to the reduction in risk of failure of man-made slopes in Hong Kong.

In his paper on the characterisation of weathered volcanic rocks in Hong Kong Irfan (1999) reports that feldspar in these rock types decomposes to kaolinite and halloysite through the weathering process. He also notes that concentrations and vein in-fills by these clay minerals are likely to be hydrothermal in origin. Prior to the Chai Wan study, the Irfan (1999) model of kaolinite/halloysite concentration was the generally accepted by the engineering geology and geotechnical engineering community in Hong Kong. However, through careful mapping of weathered profiles in the volcanic tuff in the Chai Wan area of Hong Kong, we (Campbell and Koor, 1998) demonstrated that kaolin minerals appeared to be concentrated at weathering fronts and therefore this “concentration” is likely to be a product of the weathering process rather than hydrothermal. The origin of the kaolin minerals may derive as a product of both hydrothermal alteration and sub-areal chemical weathering of feldspars, but our mapping illustrated that the concentration in veins and seams appeared to be associated with the weathering process. This was a key scientific breakthrough. It led to a complete change in opinion as to the importance of “kaolin rich seams” in rock masses and their influence in slope stability problems. The findings are discussed below in more detail.

Based on the important findings of the Chai Wan Study, I instigated further research by securing Central Government funds (HK$2.4 million ~ £200,000) for a study into “kaolin-rich seams” in weathered rock in Hong Kong (my successful funding proposal is contained in Appendix 1). Although I instigated this project, developed the methodology and commenced sampling and identification of laboratories to carry out clay mineralogy and fabric analysis, I subsequently left GEO and handed the project over to colleagues in the Planning Division of GEO. This study (Campbell and Parry, 2002) confirmed our original ideas that kaolin migrates during weathering as a colloid and in solution, which can result in either broad dissemination of kaolin or concentration either in veins and seams or at weathering fronts (Parry, Campbell and Fletcher, 2000a). Shear and brecciation fabrics are also commonly observed in the kaolin seams suggesting historical movement (Parry, Campbell and Fletcher, 2000b). They propose a geological model for the generation of kaolin rich zones as follows: weathering
penetrates rock mass; kaolin remains in situ or migrates; volumetric changes in rock mass (due to weathering) cause movement which opens discontinuities to enable kaolin deposition; cyclic deposition and movement continues until equilibrium is achieved (fabrics developed).

This major finding was initiated by the Chai Wan project and changed the way that practitioners approached the development of geological models in weathered rock profiles. Because there is now a model for the development of these “kaolin-rich seams”, they can be factored into both the geological model developed at a site and the ground investigation designed to investigate such occurrences. In parallel with the Site Characterisation Study (Koor, 1999), the Chai Wan Study and the work by Parry and Campbell (2002), there was an investigation into the use of bore hole geophysics to help identify these “kaolin-rich seams”, which is reported in Lau and Franks (2000a and 2000b).

Much of this work on the occurrence of “kaolin rich seams” led to the development of the GEO Technical Guidance Note No. 4 (TGN 4) (GEO, 2004) – see Appendix 2. This TGN gives guidelines on recognition of geological features hosting, and associated with, silt-and clay-rich layers affecting the stability of cut slopes in volcanic and granitic rocks. The TGN series are regarded as de facto geotechnical standards and cited in the Hong Kong Buildings Ordinance, therefore directly informing and guiding practice. The Hong Kong Building Authority issues practice notes (PNAP) to authorized persons, registered structural engineers and registered geotechnical engineers from time to time in order to promulgate how the provisions of the Buildings Ordinance and its subsidiary regulations, as well as other administrative and advisory matters in the administration of the Buildings Ordinance, are applied and enforced. Section 5 (c) of the PNAP for Rock Faces (PNAP APP-17) emphasises that, “The survey shall include the identification of any water seepages and weak or relatively impermeable geological zones or structures which may have an adverse effect on the stability of the slope (for example, unfavourably oriented persistent layers of kaolinitic clay in altered or weathered rocks)”. This PNAP was instituted

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12 TGN 4 cites a number of my publications as related documents: Campbell, Koor, Franks and Shum (1997), Campbell and Koor (1998), and Franks, Koor and Campbell (1998) – see Appendix 2.
as a direct consequence of the Fei Tsui Road landslide, the Chai Wan Area Study and TGN4 and demonstrates the direct impact of my work on practice and legislation in Hong Kong.

2.2.1 Summary of main contributions to science, knowledge and practice from the Chai Wan Area Study

- The introduction of an engineering geology approach to the identification of slopes which contain geological features potentially adverse to stability. This is a major contribution to the reduction in risk of failure of man-made slopes in Hong Kong.
- Key early stage contribution to the kaolin seam model developed for weathered rock masses in Hong Kong. This triggered a paradigm shift in the way geological models were developed for slope projects and the techniques used in the physical investigation of slopes.
- Direct impact on Government legislation and standards through the Publication of GEO Technical Guidance Note No. 4 (TGN 4) (2004) and PNAP for Rock Faces (PNAP APP-17).

2.3 Objective 2. Constraint of Slope Defect: Site Characterisation Study – Engineering Geophysics

The report assessing the collapse of a thin masonry wall in Kwun Lung Lau on Hong Kong Island in 1994, which killed five people, recommended that: research is carried out into new geophysical techniques to help assist in the detection of subsurface defects and enhanced moisture zones within existing slopes (GEO, 1994). Investigation of the failure demonstrated that the masonry wall was thinner than that indicated by available records, and that defective water-carrying services behind the wall were the main cause of the failure (GEO, 1994). In 1994 while working in the Planning Division of the GEO, I was assigned the lead role in this research project. Funds of HK$1.5M (~£120,000) were allocated to what was subsequently described as the “Site Characterisation Study”. The main aim of this research project was to determine which modern methods of engineering geophysics could be used to identify defects within existing slopes and, in particular, the thickness of retaining structures similar to the failed masonry wall at Kwun Lung Lau.
The results and conclusions of this research project informed ground engineering practice as to the use of a range of engineering geophysical techniques and their feasibility in the assessment of slopes and retaining walls. I designed, planned and managed this complex project — from the initial development of the brief and methodology; the identification of suitable sites; appointment of geophysical companies (both international and local); supervision on site; design-supervision-interpretation of ground investigation; analysis of the results; and the production of the final report. A Working Group composed of representatives from the geotechnical community in Hong Kong was established to obtain consensus on the form and direction of the study. The Slope Safety Technical Review Board (SSTRB) engaged by the GEO to advise government on slope safety issues was required to report to the Hong Kong Government on the progress and conclusions of this study. The SSTRB comprised four international experts in Engineering Geology and Geotechnical Engineering: Professor Norbert Morgenstern (Chair), Sir John Knill (RIP), Professor Robin Fell and Professor Chuck Lee.

A full account of the aims, objectives, methodology and conclusions of the study is written in detail by Koor (1997), and later published as GEO Report 71 (Koor, 1999), see Volume 3. A summary is provided below.

In 1994, the standard site investigation techniques used to investigate exiting slopes and retaining walls in Hong Kong were: surface strips, trial pits and boreholes for slopes; and probing of weep holes, horizontal core holes and trial pits for retaining walls (Chan, 1996; Koor and Chan, 1998; Li, Woodrow and Chan, 1998). The main limitations regarding these intrusive techniques are that changes in wall geometry or localised geological defects can be missed. Techniques, such as geophysics, which can help interpolate between points of known conditions, are therefore of interest if certain constraints can be overcome. Government guidance on the use of engineering geophysics for the investigation of slopes at the time was limited. Geoguide 2 (Geotechnical Control

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13 Weep hole probing is a simple method which assumes that the weep hole extends to the back of the retaining wall and is therefore a measure of its thickness. Although quick and inexpensive the method has significant disadvantages as follows: weep holes are often blocked (under estimate of wall thickness); weep holes extend into backfill (over estimate of wall thickness); internal erosion around weep holes (over estimate of wall thickness) and; weep holes do not actually extend to back of wall (underestimate of wall thickness).
Office, 1987 p.178), which is the Hong Kong Guide to site investigation, devotes one page to land geophysics and simply describes the main techniques: resistivity, gravity, magnetic and seismic. The Geotechnical Manual for Slopes (Geotechnical Control Office, 1984 p. 37) devotes less than one page of text to geophysics as an investigation tool and focusses on seismic and resistivity methods as being useful, but recognises that cultural noise is a significant problem in an urban environment. Geoguide 1 (GEO, 1993 p. 18), which is the Hong Kong Guide for retaining wall design, simply refers to Geoguide 2 for guidance on the site investigation aspects of retaining wall design. Chan (1996), in his report on old masonry walls in Hong Kong discusses investigation techniques and refers to seismic probing between weep holes as being of possible use but reports that trials were unsuccessful. A comprehensive review of land based engineering geophysics practice in Hong Kong at the time of these trials is given in Koor (1999) in Appendix B of Volume 3 of this narrative.

This project, which consisted of a phased series of trials, was the first systematic research project into the use of a suite of modern engineering geophysical techniques to improve the investigation of retaining walls and slopes undertaken and reported in Hong Kong. Phase 1 comprised an initial screening experiment using techniques that were trialled at four sites. Ground investigation data on the features of these sites already existed. Phase 1 allowed the evaluation of eight different techniques performed by seven local and international geophysics contractors. From the results of Phase 1, the four techniques that showed most promise were taken forward to Phase 2 and tested at four new sites. Phase 2 differed from Phase 1 in that the sites had no previous ground investigation information. Each contractor was tasked with performing a geophysical investigation and making an interpretation to guide further intrusive investigation. Once the intrusive investigation results were available, these were sent to the contractors to enable an integrated interpretation to be made.

14 Phase 1 sites were one cut slope, one masonry rubble retaining wall, one masonry facing to a slope and, one fill slope.
15 Shallow seismic reflection, spectral analysis of surface waves, electrical imaging (EI), self-potential, electromagnetic methods (frequency and time domain electromagnetics), ground penetrating radar (GPR), and thermal imaging. Seismic refraction and sonic methods were trialled in addition to these by one contractor.
16 Ground penetrating radar, electrical imaging, frequency domain electromagnetics and, spectral analysis of surface waves.
17 Phase 2 sites were two masonry walls, one cut slope and one loose fill slope.
For the first time in Hong Kong, these trials demonstrated that geophysics, and in particular ground penetrating radar (GPR) and electrical imaging (EI) had the potential to rapidly identify thin walls (Bishop and Koor, 2000). As wall thickness is probably the most critical factor in a stability assessment, this research certainly made a positive contribution to knowledge and practice. It was also clearly demonstrated that success is dependent on detailed mapping of the feature, the correct use of analytical techniques such as migration and that the geophysicist has a thorough knowledge of the construction techniques and structures of old masonry walls in Hong Kong. Without proper attention to detail, spurious interpretations are possible.

I also successfully argued that with care, geophysics has the potential to determine to a certain extent the integrity of the wall, providing information about different construction methods, zones of elevated moisture and cavities (Bishop and Koor, 2000). Many advances in data acquisition and analysis of engineering geophysical data have been made since the completion of the Site Characterisation Study. Of particular significance, is the development of 3D tomography and the use of electrical resistivity arrays to measure changes in water content in real time. These techniques are of interest from a slope safety perspective. One example of this is the ALERT system being developed by the British Geological Survey to monitor hydrogeological processes through soil structures (Kuras, Pritchard, Meldrum, Chambers, Wilkinson, Ogilvy and Wealthall, 2009 and Wilkinson, Loke, Meldrum, Chambers, Kuras, Gunn and Ogilvy, 2012).

Koor (1999) recommended that GPR and EI techniques warranted further research and trials to further develop: a robust data acquisition methodology, analytical techniques, and Hong Kong expertise in these two geophysical methods. At the time of writing these recommendations have not been taken forward by the GEO.

However, further interest in the use of engineering geophysics for slope studies in Hong Kong has continued. Trials to examine thermal infrared imaging and seismic sympathetic vibration techniques were carried out by Hui and Sun (2005) to identify voids below hard surface coverings of slopes. They adopted the methodology that I developed for the “Site Characterisation Study” and
concluded that a further trial of both these techniques is warranted. Thermal imaging techniques were trialled in the Site Characterisation Study (Koor, 1999) and my conclusions were similar to those of Hui and Sun (2005). Collar, Lai and Hu (2000) describe the use of the gravity method as a reconnaissance tool on steep slopes in Hong Kong. They report successfully mapping average thickness of the regolith on slopes. Electrical resistivity imaging was used by Zhang, Mak, Cheung, Lui and Fang (2005) to try and locate cavities such as soil pipes within slopes in Hong Kong. They report that soil pipes were successfully identified in a granitic slope on Hong Kong Island.

Included in Koor (1999) is advice for each of the trialled techniques on best practice in signal generation and measurement relevant to the specific site constraints that are common in Hong Kong. The major constraints for the generation of clear signals and the measurement of returns being: pervasive cultural noise and vibration; hard surface coverings to most cut slopes; ubiquitous use of reinforced concrete in slope engineering works; and the high density of buried services. It became clear from the trials that unless very careful mapping of manmade artefacts along a particular profile was carried out prior to survey work, anomalous measurements owing to the presence of these artefacts could easily arise and therefore lead to misinterpretation. The diverse readings from each of the test sites was significant — mainly the result of incorrectly assessing cultural artefacts as real anomalies, as well as poor attention to detail on the part of some of the companies undertaking the survey work. Figure 2 is a comparison of a set of GPR interpreted sections made along the same profile taken from Koor (1999) and demonstrate the effect of non-standard data acquisition practice. Traverses a, b and c are interpretations of 500MHz GPR antennae reflections and as can be seen each Contractor has made different interpretations as follows: traverse “a” records a single continuous reflector at two way travel time of about 11ns; traverse “b” records a single continuous reflector at a two way travel time of about 9ns with some major discrete parabolic reflectors at chainages 1-2m, 13m, 16m and 19m at two way travel times of between 3 and 40ns; traverse “c” records discrete generally parabolic reflectors at chainages 3.5m, 6m, 10m, 12m, 15.5m, 20m and 24-26m. The trials demonstrate that due to the non-standard procedures for data collection different practitioners employing the same techniques and equipment
produced very different geophysical raw data and therefore interpretation. These trials involving controlled experiments support an argument that geophysical investigations are potentially highly misleading\textsuperscript{18} unless a standardised data acquisition procedure is developed for Hong Kong. However with very careful application of the correct techniques in the right conditions, geophysics should be a powerful aide to characterising the ground. This finding is reflected in the GEO Information Note 02/2011: Geophysical Techniques for Investigation of Slopes and Retaining Walls (reproduced in Appendix 3 of this narrative). It states that ”The available non-invasive geophysical techniques require specific consideration for routine use in investigation of the stability of slopes and retaining walls in Hong Kong. GEO’s field tests indicated that the results were very sensitive to human factors in data acquisition and interpretation”.

I presented the findings of the study to the SSTRB. They reported on my findings and stated “This Phase 2 study has been well-conceived and conducted by the GEO, whose staff should be commended for it. It is a fair and objective assessment and the Board agrees with the conclusions and recommendations of GEO arising from this study” (Slope Safety Technical Review Board, 1997).

2.3.1 Summary of main contributions to science, knowledge and practice from the Site Characterisation Study

- Definitive advice on the use of engineering geophysics for slope and wall investigations detailed in GEO Report 71. This advice was unavailable prior to the Site Characterisation Study and remains the only engineering geophysics guide for Hong Kong conditions. Some of this advice is reproduced in GEO Information Note 02/2011 – Appendix 3.

- Demonstration that GPR combined with EI techniques can be used to rapidly identify thin masonry walls. This has the potential to have a significant impact on slope safety in Hong Kong if further trials of GPR and EI are conducted.

- With care GPR and EI can provide detail of masonry wall structure and enhanced moisture zones in Hong Kong.

\textsuperscript{18} As the international engineering geology community is aware, there is a historic legacy of the misuse of geophysics which has led to its limited use and has inhibited widespread adoption. Civil Engineers appear to be particularly sceptical of geophysics and to some extent this experiment did support that position.
- Standardised methods of geophysical data acquisition are required to promote good practice and generate repeatable results. Attention to detail is critical for accurate interpretation of results in an urban environment such as Hong Kong.
Figure 3. Example of differences in GPR reflectors interpreted along the same traverse – note that GPR interpretations d and e are using lower frequency antennae and therefore depth of penetration is greater than traverses a, b, c (adapted from Koor, 1999)
2.4 Objective 3: Definition of Slope Geological and Hydrogeological Model - Lai Ping Road Landslide

The Lai Ping Road landslide occurred on 2nd July 1997 during an exceptionally heavy rainstorm (the 24hr rainfall before the first failure was 652mm). The landslide comprised four discrete failures in a cut slope to a road which provided access to a borrow area. The cut slope was located within a southerly facing natural slope composed of fine ash tuff with an average inclination of 26°. The landslide blocked the access road and impacted a covered surface reservoir and a church. I carried out an initial inspection of the landslide with my colleague Dr Campbell (Hong Kong Geological Survey) eight days after the failure. During the inspection I identified a zone of major deformation which showed signs of recent movement extending c.50 m above the crest of the failed cut slope. This deformed zone was defined by a c.4 m high scarp which, it was initially assumed, bounded a deep seated landslide of the order of c.100,000 m³. There was significant concern within GEO that if the deep seated landslide volume was mobilised by further heavy rain, the integrity of the service reservoir and some adjacent residential properties could be compromised. This concern triggered a detailed study by a team in GEO into this slope failure to advance the understanding of large scale, deep seated landslides in Hong Kong. This investigation was progressed in parallel with the ground investigation work required for stabilisation of the slope failure, which was undertaken by Messrs Maunsell (now Aecom). I led the geological and engineering geological investigation of the landslide. This investigation formed the basis for a wider investigation into debris mobility and landslide mechanisms, which were being carried out by GEO at the time (Sun and Campbell, 1998).

A full description of the aims, objectives, methodology and findings of the geological study are described in detail by Koor and Campbell (1998), which was later published as GEO Report 166 (Koor and Campbell, 2005), see Volume 4.

A key aim of the investigation was to attempt to understand the failure mechanism and geological and hydrogeological controls of this complex landslide. In order to achieve this key aim I developed a new Hong Kong engineering geology approach in the investigation of this landslide complex. This new engineering geology approach comprised: high-resolution scarp morphology
mapping to gain insights into the development of the landslide; high-resolution geological mapping of scarps and trial trenches to develop models of failure mechanisms and geological control; forensic analysis of ground investigation data to enable the development of a highly detailed geological, hydrogeological and temporal model for landslide development. The models were simplified into ground and geotechnical models and applied to numerical analysis in order to better understand landslide cause and trigger mechanics (Sun and Campbell, 1998).

For the first time in Hong Kong we applied mobile GIS technology (differential GPS) to fix the main features of the landslide. I was therefore able to map the highly complex scarp morphology with great accuracy (see Map EG502 of Volume 4 of this narrative). Ng, Fung and Shum (2004) describe how mobile GIS technology has subsequently been developed and used in geotechnical fieldwork from these simple beginnings in 1997. Through the identification of major and minor scarp features within the scarp complex we were able to demonstrate the retrogressive and episodic nature of the landslide complex. A time frame for each major movement event could also be postulated by the use of: kinematic indicators on the major scarps (see Plate 36(a) in Volume 4 of this narrative); dendrochronology on disrupted trees adjacent to the main scarps and; detailed aerial photograph interpretation (Koor, Campbell, Sun and Ho, 2000). The 3D morphology of the complex shear zone could also be interpreted from meticulous mapping of 3 m to 6 m deep hand-excavated trial pits (Figure 3) and detailed logging of high quality continuous soil and rock core. The data gathered during the geological and geomorphological mapping of this landslide became the benchmark for future landslide investigations in Hong Kong, see Martin (2000).

From the investigation a model of 15 m saprolite thickness as the control on the development of large landslides in the natural terrain (c. 26° or greater) above cut slopes in Hong Kong volcanic rocks can be postulated (the 15 m isopac of saprolite thickness defined the extent of deformation). These conditions tend to generate shear zones close to “rock-head” as described by Jiao (2000) and as identified by Koor and Campbell (2005). The deflection of shear zones around corestone masses is likely to have prevented the first time slide developing into
a high velocity mobile destructive event\textsuperscript{19} due to rock mass dilation and therefore loss of pore pressure. I interpreted that the deflected shear zones can act as dilation breaks during movement but also as a focus for ground water flow and soil pipe development prior to the next episode of movement.

2.4.1 Summary of main contributions to science, knowledge and practice from the Lai Ping Road landslide investigation

- The engineering geology approach which includes the collection of high resolution geological data, results in a more complete understanding of the geological controls of landslide development.
- Careful mapping of scarp complexes in conjunction with aerial photograph interpretation is necessary to determine the temporal development of a retrogressive landslide.
- Mineralogical analysis of clay infill to discontinuities can help verify the retrogressive nature of these complex landslides\textsuperscript{20}.

\textsuperscript{19} Dilation around corestones was mapped extensively in the trial pits (see Figure 3).

\textsuperscript{20} Precipitation of alternating magnesium oxide and kaolinite within discontinuity sets were evidence of episodes dilation with subsequent infilling.
Figure 3. Example of detailed engineering geology trial pit log made during the Lai Ping Road landslide investigation – note detail of descriptions and style of shear surfaces recorded. Soil and rock descriptions made in accordance with Geocode 1. Adapted from Koor and Campbell (1998).
• Corestones within the saprolite appear to deflect shear zones (vertically and horizontally) causing rock mass dilation with a possible consequential reduction in pore pressure, thus halting a particular movement episode.

• Corestone masses within a saprolite appear to control ground water flow and may focus high rates of flow between them, creating zones of higher than ambient pore pressures. The deflection and concentration of ground water flow may also lead to the development of soil pipes\textsuperscript{21} or subterranean stream systems within the saprolite (see also Hencher, 2000 and Martin, 2000).

• Large landslides (c.100,000 m\textsuperscript{3}) in Hong Kong can be retrogressive and slow moving. They can develop large complex zones of deformation above areas of more intense instability\textsuperscript{22}.

\textbf{2.5 Objective 4: Geotechnical Characterisation – Foothills Bypass}

One of the objectives of the work on kaolin-rich zones (Section 2.2) was to develop an understanding of their operational shear strength. A number of these zones contained kinematic indicators such as slickensides, suggesting that there had been historic movement though these zones (Campbell and Parry, 2002). Whilst working as the Resident Geotechnical Engineer on the Foothills Bypass Project for Scot Wilson (HK) Ltd (now Aecom) (Koor, Hadley and Hart 2001), I investigated a series of relict landslides that would potentially impact on the long term stability of the bypass road embankment. I used the engineering geology approach developed at the Lai Ping Road landslide to identify and investigate these features. These landslides were identified by re-interpretation of the site geology through: aerial photography along the road alignment, geomorphological mapping, and detailed trial pit logging. Figure 4 is an example of the detailed logging used to identify and interpret the failure surfaces within a 6 m deep trial pit. The relict landslides were located in a thinning zone of andesitic rock which had weathered to a fine grained soil with little if any quartz

\textsuperscript{21} Significant numbers of soil pipes were mapped within the landslide scars at Lai Ping Road (see Plates 28 and 29 in Koor and Campbell, 1998 – Volume 4 of this narrative).

\textsuperscript{22} Prior to this study, the areas beyond the obvious failure scarps were not systematically mapped in Hong Kong landslide investigations. This was primarily because it was assumed that failures were brittle, shallow events and that retrogressive failures did not occur. In fact, many of my colleagues were sceptical of our initial findings until they saw photographic evidence of the extensive area of deformation. Although this was not new and had been reported by others in the past (see Irfan, 1992 or Hencher, 2000 for example) it was a timely reminder that such landslides do exist in Hong Kong.
content. Block samples (300x300x300mm) containing the relict shear surfaces were taken from the trial pits and tested in a large shear box (Koor, Parry and Yin, 2000). In collaboration with Professor Yin of Hong Kong Polytechnic University a method was developed to test these large oriented samples. The block samples were carefully trimmed in the laboratory so that they could be placed in a 305mm square Boart Longyear LG-115 shear box. Space between the sample and the box was filled with dental plaster with the gap between the upper and lower sections being in-filled either with weak foam or remoulded soil. The direction of geological movement, as indicated by the slickensides was replicated in the shear box tests. Residual shear strength parameters of $c'_r = 0$ kPa and $\varphi_r = 12$ to $19^\circ$ were measured with the higher values attributed to samples with impersistent shear surfaces. These results compared well with the residual shear strength parameters derived from back analysis of other landslides which occur along the bypass alignment (Taylor and Hadley, 2000).

The results of these tests contributed to the knowledge base surrounding the residual strength of weathered rocks in Hong Kong and have been quoted by a number of researchers (Wen, Duzgoren-Aydin and Aydin, 2004, GEO, 2007, Erginal, Öztürk,Ekinci and Demirci, 2009, Ho, and Lau, 2010, Hencher and Lee, 2010, and Hearn, 2011).

The geotechnical characterisation of the completely decomposed andesite through detailed mapping, logging and geotechnical testing was utilised in the re-engineering of the road embankment at the Foothills Bypass (see Koor, et al. 2001).

2.5.1 Summary of main contributions to science, knowledge and practice from the Foothills Bypass project

- Contribution to the knowledge base of residual shear strength of weathered rocks in Hong Kong.
- Development of large shear box testing of block samples containing shear surfaces.
Figure 4. Detailed trial pit log from the Foothills Bypass Project (unpublished) – block samples taken for large shear box testing identified as BS1, BS2 and BS3.
3 Geotechnical design

3.1 Introduction
As the risk to life due to the failure of man-made slopes has diminished in Hong Kong (Cheng, 2007) attention has now focussed on the hazard and risk associated with natural terrain failures. Natural terrain failures are generally classified in Hong Kong into two types, shallow open hillside failures and channelized debris flows\(^{23}\). Due to the potential for significant loss to life from these types of events, one of the favoured methods of risk reduction is of containment with the use of large rigid debris-resisting barriers. The philosophy of designing large ridged debris-resisting barriers to contain a design debris flow event is now well established in Hong Kong (Lo, 2000 updated by Kwan, 2012). This approach does, however, necessitate the construction of large reinforced retaining structures, which often require significant engineering in the form of piled foundations and anchors to resist the large calculated debris impact forces. Where there is a high risk to life scenario then this approach and the associated high cost is often appropriate (if passive options are not acceptable or possible). However, where the risk is primarily economic then a different approach can and in my opinion should be adopted (Thorn and Koor, 2002). My contribution to the evolution of debris flow mitigation in Hong Kong is presented in the following section and focusses on the Foothills Bypass Project.

3.2 Objective 5: Slope Design: Foothills Bypass
The background to the Foothills Bypass Project is detailed in Koor, Hadley and Hart (2001), which is reproduced in Volume 5 of this narrative. I was the Resident Geotechnical Engineer for this project and responsible for the control of all geotechnical works on site. Significant geotechnical hazards affected this project (Koor, 2007) and as such, my role was broader than that of the traditional Hong Kong resident engineer. Complex geological conditions, unique in Hong Kong, existed at the site. Updating the geological model, as part of the risk management strategy, played a crucial part in the design approach as areas of the site were uncovered (Koor, 2007).

\(^{23}\) Large deep seated landslides in the natural terrain do exist in Hong Kong but they are less common and where identified as being active are generally slow moving and therefore of less concern (see Irfan, 1992, Evans, Huang and King, 1997, Irfan, 1998, Martin, 2000, Hencher and Lee, 2010)
Channelised debris flows from the steep terrain above the proposed route presented one of the significant geological hazards to the long term viability of this project (Koor, 2007). The largest flow, known as the Tsing Shan Debris Flow which occurred in 1990, involving some 10,000 m³ of debris (Chan, Lam and Shum, 1991 and King, 1996), deposited debris across the future proposed road alignment. In partial response to this debris flow hazard, the road was to be formed on an embankment that was designed to act as an earth bund to trap major debris flow events and protect the road. The road embankment was incorporated into the design of an extensive earthworks solution to stabilise positions of historic instability (known as Area 19). The Area 19 earthworks, coupled with the road embankment, were constructed to ensure that an event of up to 10,000 m³ debouching from one of four drainage gullies, would deposit on the slope stabilisation earthworks (which have a gradient of 11°) and be prevented from affecting the road. Hadley, Taylor and Hearn, (1998) describe the methodology adopted for the debris flow risk assessment at the Foothills Bypass. The risk reduction strategy proposed as a result of the hazard assessment was eventually incorporated into the design mitigation for the bypass. This led to the adoption of ridged debris-resisting barriers being proposed in the four gullies above Area 19 and they formed part of the construction contract.

The proposed ridged debris-resisting barriers were not intended to capture a 10,000 m³ debris flow; they were designed to protect the earthworks from small, more frequent 600-800 m³ events that were predicted from the debris flow hazard assessment (see Hadley et al. 1998). It was appreciated that an event as large as 10,000 m³ would overflow any rigid barrier and flow onto the earthworks where it would be contained. A detailed ground investigation conducted during construction established that “rock head” was deeper at the proposed rigid barrier locations than had been anticipated, requiring that piled foundations and rock anchors be introduced rather than the originally assumed rock dowel solution. It was also evident that major temporary works were

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24 Due to the steep terrain extensive access road cuts would be required to transport piling equipment to each of the barrier sites. These cut slopes would need to be properly
needed to construct the barrier foundations and that this would cause significant disruption to the natural terrain and possibly be a trigger for future landslide events. It was accepted that there was a very small risk to life from a Tsing Shan size event occurring and that the major loss would be economic. I therefore proposed to the client, consultant and the GEO to take a different approach in the selection and design of mitigation measures. I recommended that a cost benefit analysis be undertaken in order to make an informed judgment as to the economic benefit of providing the ridged barriers. This assessment indicated that the construction of the barriers was not justified economically and, as a result, they were deleted from the works saving an estimated HK$48M (~£4M). In their place, less visually intrusive and less expensive debris flow deposition basins were constructed in each valley as a prescriptive measure (Thorn and Koor, 2002). This was the first time that such an approach had been reported in Hong Kong.

The debris flow mitigation works for the Foothills Bypass were designed at a time when GEO was becoming sensitised to the hazard presented by natural terrain landslides (Ng, Ho and Roberts, 2014). Protocols and design guides for natural terrain hazard assessment and mitigation were being developed (Lo, 2000 and Ng, Parry, King, Franks and Shaw, 2002). My work was presented at the 2002 conference: “Natural Terrain – A Constraint to Development” organised by the Institution of Mining and Metallurgy – Hong Kong Branch and contributed to the body of work and case histories that helped formulate the development of Government policy in this area of landslide risk reduction.

The main techniques currently employed in natural terrain hazard mitigation works include: ridged reinforced concrete anchored barriers within drainage gullies; soil nails (for open slope failures); and flexible nets for open slope or debris flows but only for small design events (<300 m$^3$) (Chan, 2005). There is a reluctance to use less intrusive measures in drainage gullies that are successfully used elsewhere (see Hungr, Morgan, VanDine and Lister, 1987 and VanDine, 1996 for Canadian practice and a more up-to-date global view in Huebl and Fiebiger, 2005) such as check-dams to collect bed load and debris, deflection remediated once the barrier was complete – in my experience an often poorly completed task carried out at the end of a project when supervision is running down.
barriers and depositional basins (where space permits). As a result of my work on the Foothills Bypass and on the Deep Bay Link project (see below) — where I carried out value engineering and completely redesigned the natural hazard mitigation proposed by Arup — I was later employed as an expert to review several mitigation schemes (after I joined the University of Portsmouth). This enabled me to have a direct influence on the use of softer options for debris flow mitigation and involved direct discussion with the GEO Planning Division about how these types of mitigation measures could be incorporated to reduce design events and how these might win approval within the GEO checking regime. A recent example is the “Review of LPMitP Agreement No CE17/2008 (GE) – Natural Terrain Hazard Mitigation Works, New Territories East and West” carried out for Arup (Hong Kong) (VanDine and Koor (2009) - see Appendix 4). I carried out this review with Doug VanDine, Principal of VanDine Geological Engineering Limited. We recommended a number of innovative solutions which are summarised as follows:

- Use of Tensioned Steel Mesh Fences (TSMF) for some of the drainages with smaller (c. <500 m$^3$) design magnitude debris flows.
- Upstream check dams to reduce the calculated debris flow volume.
- Reduction of drainage gradient upstream of rigid debris flow containment barriers to promote deposition and to increase the potential basin volume.
- Delete baffles in the debris basins as they reduce potential containment volume and can complicate the construction process.
- The maximum velocities of the debris flows used for design impact velocities should be determined at the location of the containment barrier, not necessarily the maximum velocity along the drainage line.

Due to the rigid framework of allowable natural terrain hazard mitigation solutions operating in Hong Kong at the time (Lo, 2000) none of our recommendations were implemented on this project. Even now these simple solutions, which are standard practice in many parts of the world have not yet been adopted in Hong Kong (Roberts pers. com. 26 March 2015 and Millis pers. com. 31 March 2015)
3.2.1. Summary of main contributions to science, knowledge and practice from the Foothills Bypass natural hazard mitigation design

- Contribution to natural terrain landslide mitigation design in Hong Kong through publications and presentations of the work at the Foothills Bypass Project.
- Development of a cost-benefit approach to the selection of natural hazard mitigation where there is a risk of high economic loss but negligible risk of loss to life.
4 Construction in the ground

4.1 Introduction
The constructability of ground elements plays a vital part in the design process and impacts directly on the safe and economic completion of a construction project. The verification of design and the establishment of a construction methodology that takes into account existing geological hazards through field trials is common practice in ground engineering. The *engineering geology approach* plays a fundamental role in the verification process through the refinement of the geological/ground model by monitoring the reaction of the ground during construction and the prediction of ground defects which could affect slope performance. During the construction process, particularly on large civil engineering projects, a flexible contractual approach needs to be adopted so that changes can be made as the geological model is refined. Whilst working as a professional Engineering Geologist I ensured that this strategy was adopted on the sites under my control. The following example demonstrates the positive impact of such a flexible *engineering geology approach*.

4.2 Objective 6: Design Verification and Constructability: Deep Bay Link – Soil Nail Design and Construction
Deep Bay Link is a dual, three-lane trunk road providing a strategic link between the Hong Kong Shenzhen Western Corridor and the existing Yuen Long Highway (Koor and Cheung, 2005). The link traverses a broad low-lying valley and is primarily supported by a reinforced concrete viaduct except where the road passes through the northern extremity of a range of hills in a 40 m deep cut. The hills are composed of a medium to coarse grained granite which has an over print of low grade metamorphism associated with shearing. As a consequence, the granitic rock mass has a weak foliation and contains a number of pervasive shear zones. The foliation and shear zones control the weathering profile which made a predictive ground model difficult to develop.

As the Senior Resident Geotechnical Engineer, I was responsible for the design and construction of all the geotechnical elements associated with the project. The 40 m high cut was originally designed as a soil nailed slope incorporating a bored pile wall at the base. Following a refinement of the geological and
geotechnical model with the integration of new ground investigation and testing data, I instigated a re-design which enabled the deletion of the bore pile wall (saving about HK$80M ~ £7M) but requiring long soil nails (up to 28 m long) supporting cut slopes at angles of up to 60° (Koor and Cheung, 2005).

Due to high soil nail design loads\(^{25}\) the nail reinforcement required the use of either a single 50 mm deformed bar or 36 mm high yield bars (such as Diwidag Bars). Safety concerns over the handling of 12 m long 50 mm bars led to the adoption of the high yield steel bar option. Although not standard practice at the time in Hong Kong, I initiated testing to determine the corrosivity of the ground as this would impact on the protection provided for long and potentially heavily loaded soil nails. There was no guidance in Hong Kong on corrosion protection measures for soil nails in aggressive ground conditions (Shui and Cheung, 2003) and I therefore developed a methodology to help determine the best solution for this site. From test results to determine ground corrosion potential it was considered that the steel needed corrosion protection (Koor and Cheung, 2005). The potential for hydrogen embrittlement of high yield steel elements which have been zinc coated (Arup, 2003) meant that an alternative to standard zinc coating was required. Options such as heat shrunk plastic or epoxy coatings to the bars were considered, but finally a double corrosion system was adopted consisting of a HDPE corrugated full length sheath which surrounds the bar and is filled with grout in lieu of the zinc coating (Koor and Cheung, 2005).

The adoption of a sheath protection system; the unusually long and heavily loaded nails; and the sheared and foliated nature of the granite presented a unique set of construction and design issues. The issues identified were: bore collapse due to the foliated and completely decomposed granite; bore collapse due to intersection with the ground water table; clashes from long nails not being bored within alignment tolerance; grout performance in long nails with double corrosion protection; and installation problems with the double corrosion protection sheath. In order to address these issues I designed a series of validation trials consisting of eight preliminary soil nails up to 30m long being installed at the site. These were all successfully constructed and load tested to

\[^{25}\] Upto 490kN per nail.
two times the design load and exhumed for inspection. On exhumation the quality of the grouting was inspected and nail deviation from the design inclination was measured. Grout was seen to have completely filled the internal and external void around the corrugated sheath with excellent contact between the grout and the surrounding saprolite. Deviation from the design inclination of 10° was measured to be a maximum of 10° over a 30 m length nail. Over 2,000 permanent soil nails with double corrosion protection up to 28 m long were successfully installed at the site following these trials.

The main observations and conclusions obtained from construction, testing and exhumation of the nails were: for long soil nails (>25 m) it is advisable to construct preliminary nails to test both constructability and capacity; grouting the annuli (between ground and sleeve, and sleeve and bar) should be carried out simultaneously to avoid sheath floatation and possible grout leakage from the outer to inner annulus or vice-versa; for long nails it is more efficient to use pressure grouting pumps with larger smooth bore grouting pipes than normal to ensure a continuous grouting process; care should be taken when specifying nail diameters for long nails with double corrosion systems, and designers should allow at least 30 to 40 mm clearance between the sheath and the drillhole wall to allow for installation difficulties; the maximum drillhole deviation of 10° measured for the 30 m nail, affects the horizontal nail capacity by less than 5% and is therefore considered not to be a concern, bearing in mind the conservative design methodologies adopted in Hong Kong; and soil nail deviation does occur during the drilling of the nail hole and care needs to be taken on soil nail spacing to ensure that soil nails do not clash.

This was the first time in Hong Kong that such long nails, incorporating a double corrosion system were used and directly contributed to the development of soil nailing design and construction practice. I presented the methodology for the design and construction of long nails in corrosive ground at the 25th Annual Seminar on Safe and Green Slopes organised by the Hong Kong Institution of Engineers Geotechnical Division in May 2005. The relatively recent Guide to Soil Nail Construction – Geoguide 7 (GEO, 2008) contains advice on trials for buildability using long nails and on corrosion protection testing and systems and directly follows the recommendations set out in Koor and Cheung (2005).
4.2.1. Summary of main contributions to science, knowledge and practice from the Deep Bay Link Project

- Demonstration that soil nails up to 30 m long can be successfully constructed using a double corrosion system.
- Development of a methodology to select corrosion protection for soil nails based on chemical and constructability testing.
- Methodology developed for the construction of preliminary soil nails to test both capacity and constructability especially in aggressive ground conditions which require special corrosion protection measures.
- Direct contribution to soil nail design and practice through The Guide to Soil Nail Construction – Geoguide 7 (GEO, 2008) which contains advice on trials for buildability using long nails and on corrosion protection testing and systems following the recommendations set out in Koor and Cheung (2005).
5. Summary

The main contributions that I have made to science, knowledge and professional practice as supported by my publications are as follows:

5.1 Contribution to science and knowledge

1. The identification of weathering related concentrations of kaolin in rock masses in Hong Kong. This led to weak seam model development for Hong Kong rock masses and a paradigm shift in the way geological models were constructed.

2. Design, analysis and management of trials applied to the use of engineering geophysics to identify slope defects and thin retaining walls.

3. Demonstration that a combination of GPR and EI could be used as a quick and effective measure for the determination of masonry wall thickness and the identification of defects.

4. Demonstration that detailed mapping prior to the use of geophysics is required in urban environments such as Hong Kong if reliable and repeatable results are to be obtained.

5. Corestone complexes in landslides can act as ground water flow concentrators and dilation breaks.

6. Addition to the database of knowledge of the residual shear strength of weathered rocks in Hong Kong.

5.2 Contribution to practice

1. Development of an integrated engineering geology approach using thematic maps for the identification of geological features in existing man made slopes which could result in failure.

2. Development of an engineering geology approach to forensic landslide investigation incorporating geological mapping, detailed geomorphological mapping especially of scarp morphology, detailed trial pit and rotary core logging, and dendrochronology. This enabled a temporal model of the retrogressive nature of the landslide to be developed and the evolution of a realistic well constrained hydrogeological model.

3. The development and promotion of the cost-benefit analysis method for natural hazard mitigation schemes where the risk is only economic.
4. Methodology developed and promoted for the design and safe construction of long soil nails in aggressive ground conditions in Hong Kong.
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Table 1 – Publications: contribution and citation

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# Table 1 – Publications: contribution and citation

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<tr>
<td>Koor N. P., Campbell S. D. G., Sun H. W., and Ho, K. K. S. (2000) Scarp morphology and development associated with a large retrogressive compound landslide at Lai Ping Road – Hong Kong. Urban Geology Conference, University of Hong Kong. (pp</td>
<td>Paper based on the Lai Ping Road landslide investigation which I led with assistance from Dr Diarmid Campbell. Paper focusses on the mapping of the scarps which was carried out jointly by myself and Dr Campbell. Dr Wing Sun and Mr Ken Ho were part of the team</td>
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<td>77-88)</td>
<td>investigation of landslide mobility connected to this study. I co-wrote the paper with Dr Campbell.</td>
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<td>Terrain – A Constraint to Development. Institution of Mining and Metallurgy – Hong Kong Branch. (pp 143-150).</td>
<td>and construction of the alternative to ridged barriers which I designed and supervised construction. I wrote the paper with Mark Thorn who was the engineer for the consultant Scott Wilson (now Aecom).</td>
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Appendix 1

Funding Proposal for Mineralogical and Strength Testing of Clay-rich Weathered Rocks.
Draft Project Brief

Mineralogical and Shear Strength Study of Clay-rich Weathered Rocks

Please find attached the above draft project brief for your comment.

2. The objective of the study is to improve our knowledge of the formation, occurrence and influence of “clay rich saprolites” on slope stability. The study will involve detailed mineralogical and fabric determination and a suite of shear strength testing done in-house at the PWCL and at a local Univeristy.

3. Please send your comments on the attached draft brief to Mr N P Koor (GE/EG3) by 20 February 1998. We will assume that you have no comments if a reply not recieved befor 20 Feb 98.

(H.H.Choy)
Atg Chief Geotechnical Engineer/Planning

Distribution

GGE/D
CGE/SP (Attn: W K Pun)
CGE/M (Attn: J M Shen, SGE/GI and SGE/Lab)
CGE/D
CGE/ME
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CGE/I
CGE/A
CGE/FM
CGE/LI
CGE/W
GCE/M&Q
CGE/SS
SGE/GS (Attn: C J N Fletcher and S D G Campbell)
SGE/EG (Attn: C A M Franks and K C Lau)
Draft Project Brief

Mineralogical and Shear Strength Study of Clay-rich Weathered Rocks

1. Objective

To improve our knowledge of the formation, occurrence and influence of “clay rich saprolites” on slope stability.

2. Need

The two fatal landslides at Fei Tsui Road (Chai Wan) and Shum Wan Road (Aberdeen) in August 1995 were both large; 14,000m$^3$ and 26,000m$^3$ of debris respectively. Both landslides were influenced by localised occurrences of low-strength, clay-rich zones within the weathered rock mass (GEO, 1996a and GEO, 1996b). An in-house pilot study into the distribution of clay-rich weathered rocks in Hong Kong concluded that these features may be widespread especially in certain volcanic rocks (Campbell & Koor, 1996 and Franks et al. 1997). The need for a combined mineralogical and shear strength study was endorsed by the Slope Safety Technical Review Board (SSTRB) in May 1997 (SSTRB, 1997).

At present there is an incomplete understanding of the formation and occurrence of clay-rich zones within weathered profiles of granite and volcanic rocks. The adoption of appropriate geotechnical parameters for slope stability assessments and design in such materials carries a degree of uncertainty. It is essential to understand the processes leading to the formation of such zones and how best to characterise them in terms of shear strength for slope stability assessment. The proposed study will address these points and will complement an ongoing GEO study of which rocks such features are most likely to be encountered in.

3. Proposal

The objective will be achieved by investigating the mineralogy and shear strength characteristics of clay-rich zones within the weathering profiles of a variety of rock types.

The project will be split into four distinct phases; literature review, identification of sampling sites and sampling, mineralogical and shear strength testing and reporting. It is intended to carry out the mineralogical and strength testing using Government, local University and commercial facilities. This will enable expertise from within Hong Kong and overseas to be utilised and allow flexibility within the planning and phasing of the works. This is particularly desirable in the case of the interpretation of the mineralogy which is to some extent subjective. An implementation plan which describes in detail each phase of the project is presented in Annex I and is summarised below.

3.1. Literature Review

Much work has already been carried out in Hong Kong and overseas on the products of subaerial weathering and shear strength parameters of such materials. To assimilate all the information contained within GEO, Hong Kong and published literature a review is required. It is intended that the shear strength literature review is carried out by the local University involved in the shear strength testing and soil modeling.
A literature review of techniques used to determine and interpret clay mineralogy, fabric and texture is also required to understand their reliability and repeatability. It is intended to appoint a consultant with wide experience in this specialist field to carry out this literature review.

3.2. Identification of Sampling Sites and Sampling

It is proposed to sample "clay-rich saprolites" taken from a variety of rock types throughout Hong Kong. Both fine- and coarse-ash tufts will be sampled together with fine- to medium- and coarse-grained granites. Most of the sampling sites will be obtained from Phases 2 & 3 of the on-going project entitled "Engineering Geological Features Related to Landslides in Hong Kong" being carried out by Planning Division. Sites have already been identified for sampling clay-rich fine ash tuff saprolite in Chai Wan, Aberdeen and possibly Tseung Kwan O. The Project Engineer will also liaise with District Divisions, Design Division and the LPM Consultants to select suitable active LPM and other sites for sampling.

A GEO Ground Investigation Term Contractor managed by Materials Division will be used to obtain block samples at each selected site. Some minor investigation works such as chunam stripping and shallow trial pits may be required at certain sites to obtain the most appropriate samples.

3.3. Mineralogical & Strength Testing

It is intended that strength testing be carried out by the PWCL together with the local University undertaking the literature review. A soil model will be developed by the local University. Parallel sets of mineralogical testing will be carried out by two specialist Consultants who have done work of a similar nature.

3.4. Reporting

Factual and interpretative reports will be obtained from the University and the specialist mineralogical consultants on the work carried out. Planning Division will assimilate all the results and prepare a summary Special Projects Report on the study.

4. Background Information

The large fatal landslides at Fei Tsui Road and Shum Wan Road in August 1995 occurred in fine-grained volcanic rocks with surfaces of rupture on, or close to, clay-rich seams. Follow-up studies by the GEO in the Chai Wan and Aberdeen areas (Campbell & Koor, 1996 and Franks et al., 1997) identified other slopes which may contain clay-rich seams, and suggested that the problem was not restricted to the two landslide sites. Investigation of the two fatal landslides showed that these clay-rich seams can have lower strengths than are normally adopted for weathered rocks in Hong Kong.

Basic information on the clay mineralogy is essential to understand how such seams are formed and where they are likely to exist. Knowledge of the structure of the clay minerals is also required for understanding the potential failure mechanisms of large landslides.
controlled by "clay rich zones". Assessment of the behavior and typical shear strength parameters for clay-rich weathered rocks in Hong Kong is critical for ensuring that safe and economic remedial works are carried out on slopes which contain these features.

5. Resources

5.1. Staff

The project will be managed by the Engineering Geology Section of the Planning Division. Mr N P Koor will be the Project Engineer responsible for day-to-day technical and administrative matters with support from Dr C A M Franks and Dr K C Lau when required. Specialist support on the mineralogical aspects of the project will be given by Dr S D G Campbell of the HKGS.

It is anticipated that the Project Engineer will be required to spend approximately 10 man-months spread over the two years of testing to run the project. A further 3 man-months will be required to complete the final report. A further 8 man-months spread over the two years will be required from the three supporting GE's including their contributions to the final report.

TO support will be required during the initial phases of the project, particularly during the site selection and sampling. A total of 6-man months of TO(G) will be required.

It is anticipated that, with the current work load, the professional staff resources need to carry out the project will be available within Planning Division.

5.2. Funding

Funding of $2.4M has been approved in the 1998-99 Capital Account Estimates under Subhead 700, Item No. 532.

6. Programme

An outline programme of tasks for the study is given in Appendix II. The programme commencement date is April 1998 and it is anticipated that all testing will be completed by April 2000. The final summary report will be available by the end of July 2000.

7. Project Reviewers

The suggested reviewers are J.M. Shen, W.K. Pun & C.J.N. Fletcher.

8. Consultation

The project reviewers will be consulted on a regular basis in the form of review meetings. It is suggested that these review meetings are held once every three months for the first year of the project and then once every six months there after.
9. **References**


ANNEX I - IMPLEMENTATION PLAN FOR MINERALOGICAL AND STRENGTH TESTING OF CLAY-RICH WEATHERED ROCKS.

1. Identification of sites which contain clay-rich weathered rocks. It is anticipated that both volcanic and granitic saprolites of different grain sizes (i.e. coarse and fine ash tuff and coarse, medium and fine grained granite) will be sampled although it is likely that the fine grained volcanic tuffs may provide the bulk of the samples. Sites which contain clay rich saprolite zones will primarily be identified through Phases 2 & 3 of the Engineering Geological Features Related to Landslides project being carried out by Planning Division at present. Active LPM sites will also be taken advantage of through liaison with Design Division and the LPM Consultants. Two sites from each rock type would be desirable making ten sites in all. Suitable sites in fine ash tuff in Chai Wan and Aberdeen have already been identified. The site selection will be an ongoing process continuing over the first year of the project.

2. Sampling of clay-rich weathered rocks for subsequent testing. So as not to disturb the clay structure, high quality block samples will be taken of weathered rock containing the clay-rich zones. The samples will be taken from either the slope surface or from within a hand excavated trial pit by the GEO term contractor. Up to five block samples will be taken at each site together with bulk samples for index testing. Three block samples will be used for strength testing, one for mineralogical testing and the remaining sample will be used for detailed material and textural descriptions by GEO. The sampling will be carried out between May 1998 to June 1999.

3. Mineralogical Testing. Determination of clay mineralogy is a highly specialised skill. Because interpretation is involved in the identification of clay minerals, it is proposed to send samples to at least two different overseas laboratories, either commercial or University based. The testing will be carried out between August 1998 to October 1999.

The following specialised mineralogical tests will include; optical microscopy, back scatter scanning electron microscopy and X-ray diffraction. Other tests may be required depending on the outcome of the initial analysis.

4. Shear strength testing. Standard geotechnical index properties will be determined for all the materials collected. Test specimens will be cut from the block samples for strength testing. Strength testing will only commence once the initial results of the clay mineralogical testing are known since this will affect the type of testing specified. The following strength testing is proposed; direct shear to obtain peak and post-peak strengths, ring shear to obtain large strain residual strengths, triaxial stress path tests with mid-plane pore pressure measurements and simple shear tests. It is expected that a certain number of direct, ring shear and stress path tests will be carried out at the PWCL. However, the bulk of the testing will be carried out at a local University. With input from GEO the University will synthesis the test data and produce a soil failure model. The testing and soil modeling will be carried out between May 1998 to April 2000.
# Annex II - Draft Programme for Mineralogical and Shear Strength Study of Clay-rich Weathered Rock

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HEAD 43 - CIVIL ENGINEERING DEPARTMENT
Subhead 700 - General other non-recurrent
New Item - Mineralogical and Strength Testing of Clay-rich Weathered Rocks

2. PREAMBLE

Members are invited to approve a new commitment of $2.4 million for the evaluation of the mineralogical and strength characteristics of clay-rich weathered rocks in Hong Kong.

3. PROBLEM

The relationship between the mineralogy and strength of clay-rich weathered rocks and the role played by such clayey materials in the development of large-scale landslides in Hong Kong is poorly understood. The strength of such materials has not been quantified with sufficient accuracy for reliable and economic slope design in Hong Kong.

4. PROPOSAL

The Director of Civil Engineering proposes to include a new item at an estimated cost of $2.4 million for mineralogical and strength testing of clay-rich weathered rocks. An implementation plan is attached at Annex I.

5. JUSTIFICATION

The two fatal landslides at Fei Tsui Road (Chai Wan) and Shum Wan Road (Aberdeen) in August 1995 were both large, 14,000m$^3$ and 26,000m$^3$ of debris respectively. The volume of both landslides was controlled by low-strength, clay-rich zones within the weathered rock mass. The proposed study will provide an understanding of the fundamental properties of low-strength, clay-rich weathered rocks in Hong Kong and for the first time enable accurate assessments to be made of the potential for large volume landslides in areas which possess similar geological features. An in-house pilot study into the distribution of clay-rich weathered rocks in Hong Kong concluded that these features are not unique but may be widespread especially in certain volcanic rocks.

The need for such a study was endorsed by the Slope Safety Technical Review Board (SSTRB) in May 1997.

At present there is inadequate understanding of how clay-rich zones form during weathering of granite and volcanic rocks and what geotechnical parameters should be applied for slope stability assessments and design in such materials. It is essential to understand how such zones form and how best to deal with them from a landslide prevention perspective. The proposed study
will address these points and will complement an ongoing GEO study of where such features are most likely to be encountered in Hong Kong.

A direct benefit of the study will be increased slope safety in Hong Kong. The consequence of not carrying out this study is that it will not be possible to accurately assess the stability of slopes containing clay-rich zones. An alternative solution is to adopt conservative design parameters but this will lead to very high slope construction costs and inefficient use of land.

6. FINANCIAL IMPLICATIONS

The non-recurrent expenditure with projected annual cash flow is as follows:

**Sampling**

30 Block Samples @ $1000/sample  
20 1m deep trial pits @ $3000/pit  
50m of slope stripping @ $1000/m  

30 000  
60 000  
50 000  
140 000

(Estimate based on current GEO Ground Investigation Term Contract rates)

**Clay Mineralogy of 30 Samples**

Mineralogical testing carried out in one overseas laboratory  
Mineralogical testing carried out in second overseas laboratory  

600 000  
600 000  
1 200 000

(Estimates based on mineralogical testing carried for GEO in 1995/96)

**Shear Strength Testing**

Strength testing of 50 samples at $14 000/sample  

700 000

(Rate is estimated from current costs of standard laboratory strength testing from commercial testing laboratories in Hong Kong, with a 100% increase to allow for precise specimen preparation and more complex testing)

**Sub Total**  

2 040 000

15% Contingency Sum  

306 000

**Total**  

$2 400 000

**Cash Flow Requirements**

April 98 to April 99  

$1.0 million
7. ENVIRONMENTAL IMPLICATIONS

Not relevant.

8. OTHER PROPOSALS CONSIDERED

Two possible option are:

(i) Fund a research project at a local university to carry out the project. This has been considered and rejected due to the lack of relevant expertise in Hong Kong and previous experience of major delays in obtaining reports and results from research institutions.

(ii) Do not carry out the project. Large failures are highly destructive when they occur in urban areas of Hong Kong. It is critical to fully understand the conditions and mechanisms of such failures. Without this knowledge the long term stability of slopes containing clay-rich zones cannot be assessed accurately. This option is therefore rejected from a public safety point of view.

Possible options to reduce costs within the scope of the proposal have also been considered as follows:

(a) Carry out the mineralogical testing in Hong Kong. This option is rejected as there are no known clay mineralogists practising in Hong Kong.

(b) Carry out the strength testing in Hong Kong. Some of strength testing can be carried out at the Public Works Central Laboratory (PWCL) but it is envisaged that the majority will be beyond the present capabilities of the PWCL and will need to be conducted in specialist overseas laboratories.

9. BACKGROUND INFORMATION

The large fatal landslides at Fei Tsui Road and Shum Wan Road in August 1995 occurred in fine-grained volcanic rocks with surfaces of rupture on, or close to, clay-rich seams. Follow-up studies by the GEO in the Chai Wan and Aberdeen areas identified other slopes which may contain clay-rich seams, and suggests that the problem may be more widespread than previously thought. Investigation of the two fatal landslides showed that these clay-rich seams can have lower strengths than are normally adopted for weathered rocks in Hong Kong.

Basic information on the clay mineralogy is essential to understand how such seams are formed and where they are likely to exist. Knowledge of the structure of the clay minerals is essential for understanding the failure mechanisms of large landslides. Determination of typical shear strength parameters for clay-rich weathered rocks in Hong Kong is critical for ensuring
that safe and economic remedial works are carried out to slopes which contain these features.
ANNEX I - IMPLEMENTATION PLAN FOR MINERALOGICAL AND STRENGTH TESTING OF CLAY-RICH WEATHERED ROCKS.

1. **Identification of sites which contain clay-rich weathered rocks.** From a complementary in-house GEO study it is expected that up to six sites in different rock types will be identified. *The proposed start date is August 1997.*

2. **Sampling of clay-rich weathered rocks for subsequent testing.** So as not to disturb the clay structure, high quality block samples will be taken of weathered rock containing the clay-rich zones. The samples will be taken from either the slope surface or from within a hand excavated trial pit by the GEO term contractor. *The sampling will be carried out from April to October 1998.*

3. **Mineralogical Testing.** Determination of clay mineralogy is a highly specialised skill. Because interpretation is involved in the identification of clay minerals, it is proposed to send samples to at least two different overseas laboratories, either commercial or University based. There are no specialist clay mineralogists in Hong Kong. *The testing will be carried out from April 1998 to October 1999.*

The following specialised mineralogical tests will be carried out; optical microscopy, scanning electron microscopy, major element X-ray fluorescence, X-ray diffraction, transmission electron microscopy, thermal analysis and infra-red spectroscopy. Other tests may be required depending on the outcome of the initial analysis.

4. **Shear strength testing** Standard geotechnical index properties will be determined for all the materials collected. About three specimens will be cut from the block samples for strength testing. Strength testing will only commence once the initial results of the clay mineralogical testing are known since this will affect the type of testing specified, e.g. direct shear, simple shear, ring shear or consolidated drained triaxial tests, with pore water measurement. Some testing can be carried out at the Governments Public Works Central Laboratory. More complex strength tests will need to be carried out at a specialist research laboratory. *The testing will be carried out from April 1999 to April 2000.*
Appendix 2

1. SCOPE

1.1 This Technical Guidance Note (TGN) presents guidelines for recognising site conditions indicating the presence of geological features hosting, and associated with, silt- and clay-rich layers (predominantly kaolin), that may have an influence on the stability of cut slopes in volcanic and granitic rocks. This TGN is not intended to cover all geological features that may influence the stability of cut slopes. Dimensions of features provided below are approximate only and should not be used in any absolute sense.

1.2 Any feedback on this TGN should be directed to Chief Geotechnical Engineer/Planning of the GEO.

2. TECHNICAL POLICY

2.1 The technical guidelines promulgated in this TGN were agreed by GEO’s Geotechnical Control Conference (GCC) in April 2001.

3. RELATED DOCUMENTS


[3053][\ced3053\TGN\TGN_4_Iss1A.doc][1.7.2004][CWL]
DEFINITIONS

4.1 **Volcanic rock** is used here to include tuff, tuffite and lava of any composition.

4.2 **Granitic rock** is used here to include granite, granodiorite, syenite and monzonite, and finer-grained intrusive equivalents of all of these.

4.3 **Eutaxitic** is a descriptive term for foliation within pyroclastic rocks resulting in a streaked or banded appearance, and is due to pumice or other material being stretched out whilst still in a hot viscous state, and subsequently preserved by welding.

4.4 **Saprolite** is a term for soil derived from in situ rock weathering that retains evidence of the original rock texture, fabric and structure.

TECHNICAL RECOMMENDATIONS

5.1 In assessing the stability of a cut slope in volcanic or granitic rock, attention should be given to establishing whether any of the following geological features are present, and if so, whether they may adversely affect slope stability:

(i) laterally persistent (e.g. > 4 m) weak silt- and clay-rich layers, within the rock mass, regardless of thickness,

(ii) completely and highly decomposed rock (Grades V and IV) forming planar layers that sit on slightly and moderately decomposed rock (Grades II and III), and which dip directly, or obliquely outwards from slope faces,

(iii) persistent (e.g. > 4 m), planar, steep joint sets and other geological contacts (e.g. dykes, faults etc.) that could form release surfaces.

5.2 The following additional ground conditions are often indicative of the presence of geological features listed in 5.1 and should also be checked:

(i) stratification dipping out of the slope (e.g. as indicated by eutaxitic foliation in some fine ash tuffs),

(ii) zones of continuous seepage, and

(iii) clusters of previous slope failures.

5.3 In site investigation, the following items are recommended to facilitate the identification of geological features that may be adverse to slope stability:

(i) The desk study should establish the history of any past failures (including the
mechanism and type of failure) and continuous seepage, and, where site formation photographs are available, the presence of significant geological features.

(ii) The engineering geological mapping should establish whether the orientation of bedding, bedding-parallel fabrics (e.g. eutaxitic foliation Note (3)) or laterally continuous discontinuities (e.g. sheeting joints) are adversely oriented, and identify any weak silt- and clay-rich layers, especially within adversely-oriented persistent discontinuities or along the weathering front (i.e. the boundary below which rock predominates in a partially weathered rock mass profile). Such adversely oriented weak layers may also occur in local depressions in the weathering front, caused for example by zones of faulting, discontinuities with close spacing, and subvertical eutaxitic foliation. Evidence of previous movement, especially that associated with any weak layers, should be noted, and could include:

(a) slickensiding, particularly within silt and clay-rich layers,

(b) brecciation and shear deformation of silt and clay-rich layers, and

(c) tension cracks and infilled tension cracks, possibly controlled by subvertical joints and particularly where associated with adversely oriented weak layers.

Zones of continuous seepage, especially where associated with silt- and clay-rich layers, should also be mapped.

(iii) During the initial phase of ground investigation, emphasis should be directed to developing a representative geological and hydrogeological model rather than testing. The ground investigation should focus on examining and logging the saprolite profile in detail, with emphasis placed on identifying the presence of adversely-oriented, weak silt- and clay-rich layers, especially in the vicinity of the weathering front, regardless or not whether these layers daylight in the slope under investigation. The ground investigation should also identify any such features within the rock mass where they may influence slope stability.

Suitable techniques for detailed examination of the saprolite profile should include:

(a) full-face mapping and logging of cut slopes, after stripping of surface cover, and adjacent exposures,

(b) excavation and logging of trial pits, and

(c) logging of drillholes.
Suitable techniques for detailed examination of the saprolite profile may also include:

(d) excavation of trenches or adits,

(e) continuous sampling in drillholes using triple tube core barrels with air-foam as the flushing medium, and

(f) downhole geophysical logging Note (4) and other downhole techniques, including borehole televiewer and impression packer.

6. ANNEX


(R K S Chan)
Head, Geotechnical Engineering Office
EXPLANATORY NOTES

(1) Weak silt- and clay-rich layers predominantly comprise white to buff kaolin, but may contain other materials, most notably dark brown manganiferous and iron oxides.

(2) At the Fei Tsui Road landslide site, the rock type was a eutaxitic fine-ash crystal tuff. The investigation of the Fei Tsui Road landslide (GEO, 1996a) highlighted various geological features in this rock type that influence the stability of cut slopes. The recognition of these geological features during site investigation at other cut slopes in similar rock types should raise awareness of the potential for a slope failure in similar circumstances to those pertaining at the Fei Tsui Road site.

(3) Eutaxitic foliation could provide an indication of the orientation of potential bedding plane structures in volcanic rocks.

(4) Technical guidelines on the use of downhole geophysical investigation techniques in the identification of weak layers are given in TGN 3.
GEO Technical Guidance Note No. 4 (TGN 4)

Issue No. 1 Revision: A Date: 1.7.2004 Page 8 of 8
Appendix 3

GEO Information Note 02/2011: Geophysical Techniques for Investigation of Slopes and Retaining Walls.
Geophysical Techniques for Investigation of Slopes and Retaining Walls

Key Message: The GEO has completed a study on the use of geophysical techniques in ground investigation for assessment of the stability of slopes and retaining walls in Hong Kong. Two techniques, the Gamma Density and Spectral Gamma Ray methods, are found to be useful. They are now included in CEDD’s ground investigation term contracts to facilitate their use.

Introduction

The GEO has completed a study on the use of geophysical techniques in ground investigation, to assist in identification of geological features that may affect the stability of slopes and retaining walls in Hong Kong.

Geophysical Surveys

Geophysical surveys measure the response of signals, such as vibration or electricity, passing through the ground. By interpreting the results of the surveys, physical properties of the ground, such as density, electrical conductivity, magnetic susceptibility and elasticity, can be estimated.

Techniques used in geophysical surveys can be classified into two main categories:

(a) invasive techniques, which require excavation or drilling at the site for carrying out geophysical surveys, and

(b) non-invasive techniques, which do not require any excavation or drilling at the site.

In GEO’s study, field tests were carried out with the use of seven non-invasive and eight invasive geophysical techniques.

Invasive Techniques

GEO’s study concluded that the Gamma Density and Spectral Gamma Ray methods are useful as supplementary ground investigation techniques, to help identify weak layers in the ground. The techniques are now included in CEDD’s ground investigation term contracts to facilitate their use, particularly in landslide and slope studies under the Landslip Prevention and Mitigation Programme.

Further information on the Gamma Density and Spectral Gamma Ray methods is given in Appendix A.

Non-invasive Techniques

The available non-invasive geophysical techniques require specific consideration for routine use in investigation of the stability of slopes and retaining walls in Hong Kong. GEO’s field tests indicated that the results were very sensitive to human factors in data...
acquisition and interpretation. Also, the capability of the techniques in measuring ground properties relevant to assessment of slope and retaining wall stability, such as zones of seepage, location of corestones, areas of loose fill and thickness of retaining wall, was limited.

Prepared by Planning Division
Geotechnical Engineering Office
Civil Engineering and Development Department
September 2011
Appendix A

1. **Gamma Density Method**

1.1 The principle of the Gamma Density method is to irradiate the target material with medium-high energy collimated gamma rays and to measure their attenuation between the tool source and the detectors. The attenuation is a function of the electron density of the target material, which in turn is closely related to its mass density.

1.2 Based on the relative density contrast between target materials, the technique can be used, within a drillhole, to identify weak layers in the ground. Such weak layers include clay-rich layers, weathered seams and disturbed zones that are of comparatively low mass density. The method is most suitable for use in uncased or plastic-cased drillholes and where the relative density contrast between the target (weak layers) and adjacent materials is high. Caution needs to be exercised in interpreting the data as the absence of a strong signature does not necessarily confirm the absence of weak layers in the ground.

2. **Spectral Gamma Ray Method**

2.1 The Spectral Gamma Ray method is based on the principle that decomposition of potassium-bearing minerals leads to a progressive loss of potassium ions (K). Naturally occurring potassium contains radiogenic K. Thus the amount of radiogenic K present in the material is related to the degree of decomposition of potassium-bearing minerals in the parent rock and hence the degree of weathering of the rock mass. The Spectral Gamma Ray method produces a log of the potassium count rate along the drillhole.

2.2 The location along the drillhole where the count rate shows a significant reduction compared to the adjacent materials can be interpreted as a more weathered, weak layer. Interpretation of the data is dependent on the origin of the target material, which may significantly affect the potassium count rate.
Appendix 4

Review Memo

To: Mark Wallace, ARUP HK  
c.c. Stuart Millis, Dom Sum.  
From: Doug VanDine and Nick Koor  
Date: July 17, 2009


- Area A – Fei Ngo Shan
- Area E – Hong Lok Yuen
- Area G – Sham Tseng San Tsuen
- Area H – Wu Uk

1. INTRODUCTION
At your request we have briefly reviewed the mitigative options for the above noted areas.

The review consisted of:
- reviewing the final Natural Terrain Hazard Assessment reports (dated June 2009) for the four areas
- reviewing the corresponding draft Option Assessment reports (dated June 2009) for the four areas
- visiting portions of each of the four areas with Stuart Millis
- office meetings with Mark Wallace, Stuart Millis and Dom Sum.

In addition, accompanied by Stuart Millis and Dom Sum, we briefly met with Sam Ng and Keith Roberts of the GEO Planning Division to discuss our review.

The review was carried out over 2½ days, July 15 to July 17, 2009.

This review memo summaries our observations and suggestions.

2. GENERAL OBSERVATIONS AND SUGGESTIONS
2.1. The mitigative design for each drainage and open hillslope should be site specific, taking into account local topographic, geomorphic and geologic conditions, and the elements at risk. We believe that it is important that the design is reviewed and modified as appropriate, during construction, to ensure that the works are properly integrated with the surrounding topography etc. This will require well qualified site supervision during construction, with the scope for amendment built into the works contract.

2.2. Designs for debris flow containment barriers (rigid or flexible) should consider normal and storm water discharges in the absence of any debris flows, retention of design magnitude debris flows, training of normal and storm water discharges, immediately after debris flow events, back into the existing drainage downstream of the barrier. Debris must be removed from behind a barrier after a debris flow event.
2.3. Tensioned Steel Mesh Fences (TSMF) should be considered for flexible debris flow containment barriers for some of the drainages with smaller (c. <500 m$^3$) design magnitude debris flows. TSMFs may be relatively cost effective and also have the advantage of being relatively unobtrusive in the natural environment.

2.4. On some drainages, the calculated design magnitude debris flow can be reduced by an easily estimated amount by constructing appropriately and strategically located and designed upstream check dams. Using such check dams would also reduce the potential debris flow magnitude from co- incidental debris flows on multiple tributaries of a particular drainage.

Check dams are designed and constructed to collect bedload and debris, that is not removed after it has accumulated, and therefore check dams are relatively low maintenance. They can be constructed of reinforced concrete, steel and/or grouted rock. They should be keyed into the banks and bed of the drainage, and have accompanying scour protection downstream. They must be designed to train normal and storm water discharges in the existing drainage. To avoid failure from a debris flow, before they are filled by natural bed load, they can be artificially backfilled.

2.5. Where a rigid debris flow containment barrier is located on a steeper gradient (within the debris flow transportation zone), it is suggested that the drainage gradient, upstream of the barrier be reduced, both to promote deposition and to increase the potential basin volume. Where bedrock is not located at the upstream end of debris basin, a small check dam should be constructed to prevent upstream erosion of the nick point. It may be possible to tie in the construction of the rigid barrier with the upstream check dam base.

2.6. We feel that the use of baffles is generally not required (in addition to debris flow containment barriers) in the drainages identified in the study areas. The debris basins themselves should dissipate the energy. In addition, baffles reduce the potential containment volume and can sometimes complicate the construction process.

2.7. The maximum velocities of the debris flows used for design impact velocities should be determined at the location of the containment barrier, not necessarily the maximum velocity along the drainage. We feel that velocities, in the order of 20 to 25 m/sec, are unreasonably high.

2.8. The following are some areas of applied research that would be useful for this project and all such projects in Hong Kong SAR in the future:
   - a TSMF could be installed as a flexible debris flow containment barrier on a test drainage to study its effectiveness
   - a series of impact load cells could be installed at various locations on the face of a rigid barrier to study debris flow impact pressures
   - the results of computer calculated back analyses, and superelevation field measurements made after debris flow events, could be used to estimate appropriate maximum debris flow velocities. It would useful to create a data base of debris flow velocities for Hong Kong SAR.

2.9. It may be appropriate to educate the GEO District Engineers responsible for checking the mitigation proposals in the field of debris flows and debris flow mitigation in the natural environment.
3. SPECIFIC OBSERVATIONS AND SUGGESTIONS

3.1. Area A – Fei Ngo Shan

We visited this area in the morning of July 15, 2009. We hiked up the drainage in Segment A1 from the location of the proposed barrier, to above the 2008 debris slide. We inspected the lower portion of the southern half of Segment A2.

Segment A1
In the area of the 2008 debris slide, we suggest that cutting back all remaining backscarsps and bioengineering be used to reduce the possibility of future instability and minimize erosion of the area.

We noted an accumulation of relatively large boulders on a gentle gradient reach of the drainage, at the downstream end of the 2008 debris slide. We suggest that this is a good location for a check dam. Such a check dam, and possibly another check dam further upstream on the same drainage, would reduce the design magnitude debris flow.

We agree with location of the debris flow containment barrier as proposed in Option A, if the “Licensed Land” can be removed, otherwise the barrier should be located upstream of the Licensed Land. We feel the baffles are not required. Both a rigid and a flexible barrier should be considered, and the left side (looking downstream) of the barrier should be tied into the very large boulder just upstream. The 500 m$^3$ design magnitude debris flow could be reduced if the above discussed check dam(s) is/are constructed. The design impact velocity should be obtained from the computer calculated back analyses of the 2008 debris slides in the area.

Segment A2
We feel that Option A, a TSMF, without the baffles, is appropriate for the estimated 200 m$^3$ open hill slope failure. There are several loose boulders near the west end of the proposed TSMF. We suggest that these loose boulders be scaled and removed, in a controlled manner, before installation of the TSMF.

3.2. Area E – Hong Lok Yuen

We visited this area in the morning of July 15, 2009. We inspected portions of drainages in Segments E3 and E4, and inspected the lower portion of Segment E2. We viewed Segment E1 from various vantage points from the other three segments.

Segment E1
We feel that Option B, soil nailing the lower, steeper portion of this segment is appropriate as it is contiguous with the cut slope below.

Segment E2
We feel that Option A, a TSMF along the lower portion of this segment is more appropriate. However, if soil nailing equipment is used for soil nailing in Segment E1, it may be more appropriate to carry out soil nailing of a smaller, but steeper portion of Segment E2.
Segments E3 and E4
We feel that Option A, a debris flow containment barrier near the lower portion of the drainages and TSMFs along the lower portion of the open hill slopes is appropriate without baffles. Both rigid and flexible debris flow containment barriers should be considered. We feel the proposed debris impact velocities, 25 and 16 m/sec, respectively, are too high and should be re-examined.

3.3. Area G – Sham Tseng

We visited Sham Tseng in the afternoon of July 15, 2009. As the site is composed of nine Segments (G1 – G9) we only had time to inspect the lower reaches of one drainage line in Segment G3 plus the existing rigid barrier at the toe of Segment G5. It was difficult to get an overall impression of the area as there is no easily accessible vantage point from which to view the hill slope.

3.3.1. Site Observations – Segment G3

A suspended water pipe is located at the mouth of drainage line DL.2 (probably a continuation from a pipe shown on the topographic map further west). Any barrier will need to be located above this pipe to protect it from any impact. Further up the channel just before it splits into drainage lines DL2.1 and DL2.2, the channel is in rock making this an ideal area for a rigid barrier. This location would make construction easier as the structure could be keyed and dowelled into the rock rather than using mini-piles and soil nail anchors as is the norm.

3.3.2. Site Observations – Rigid Barrier Segment G5

This is a massive structure which will cope with the design events calculated for this segment. General observations were:

- Baffles did not seem to be necessary and took-up valuable storage space.
- Barrier on the eastern flank of the gully was not keyed into the valley side leaving it vulnerable to uncontrolled surface water flow.
- Storage volume is well in excess of 4,000m³ and therefore has spare capacity.

3.3.3. Suggestions for consideration for each Segment – Chanelised Debris Flows

Segment G1/G2
Combine the flexible barrier at the heads of the channels from Option B (G2) to drainage line DL1.2 with the rigid barrier of Option A. The rigid barrier may need to be moved up-hill above a water pipe if this is found to be still in use. The baffles should be deleted and the barrier size reduced to take into account the reduced design event due to the flexible barriers at the head of each of the channels. To deal with the potential of multiple events it is suggested that a series of check dams are located along drainage lines DL1.1a and DL1.1b. The inclusion of these check dams would also reduce the design event and hence the size of the rigid barrier down stream.

Three existing iron grillage barriers are noted on the Engineering Geology maps in drainage line DL1.2 – these should be inspected and removed if considered to be in poor condition and therefore could add to any entrained volume.

Segment G3
As noted above in Section 3.3.1. the proposed rigid barrier in Option A needs to be moved up slope above the pipe line to a position just below the confluence of drainage lines DL2.1 and DL2.2. The channel is in rock here making construction much simpler. To deal with the potential of multiple events it is suggested that a series of check dams are located along drainage lines DL2.1 and DL2.2. The inclusion of these check dams would reduce the design event and hence the size of the rigid barrier down stream. There may be the option of replacing the rigid barrier with a flexible barrier if the design event can be reduced to c. < 500 m³.

Segment G4
We suggest that Option C is appropriate here for drainage line DL3 but with the deletion of the baffles up stream of the rigid barrier.

For drainage line DL4.1 we suggest that deflector in Option A is suggested.

Segment G5
The current mitigation measure of an over sized rigid barrier is considered adequate and no further work is required. It may however be prudent to extend the eastern wing wall so that it is keyed into the valley sides.

Segments G6 to G8
We suggest that Option B for each of these segments is suggested.

Segment G9
We suggest that Option A is appropriate with the deletion of the baffles up stream of the proposed rigid barrier.

Segments G1 to G9
It would be useful to plot each of the above suggested design options onto one drawing. This will enable an integrated maintenance access plan to be developed especially for the TSMFs at the heads of the drainage lines and the check dams.

3.3.4. Suggestions for consideration for each Segment – Open Hillside Failures & Rock Fall Hazards

A combination of soil nails and flexible tensioned steel mesh fences is proposed to mitigate these two hazards. We suggest that soil nails are appropriate in Segments 5 east, 6 and 7, and that flexible fences are appropriate in Segments 1 to 4, 5 west and 8 and 9.

3.4. Area H – Wu Uk, Tai Lam Chung

We visited the site in the afternoon on July 15, 2009. This is very small site and we could therefore inspect both Segments H1 and H1a.
Segment H1
Here an over steepened shotcrete slope about 2m high exists above an existing cut slope at the toe of eastern part of Segment H1. The natural terrain slopes quite gently above the man-made features at about 20 to 25°. The slope is well vegetated in the lower reaches, a shallow landslide is visible above the over steeped slope. It is suggested that the soil nail mitigation Option A is appropriate and this is extended to the man made features at the slope toe.

Segment H1a
Segment H1 is separated from H1a by a lobate protrusion in the natural terrain. At the base of this segment is a large flat area at the top of a small cut slope. A small ephemeral stream has been identified on the Engineering Geology mapping sheet which has two relict scars associated with general up slope erosion. It is suggested that the flat area at the base of the slope will act as a deposition area for any small 100 m³ events that occur in this segment. To avoid debris being washed down into the village a small wall about 1 m high is suggested to constrain any washout or remobilisation.

We thank you for the opportunity to assist you with this assignment. Should you have any questions with respect to this review memo, don’t hesitate to contact the undersigned.

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