Value of Landslide Investigation to Geotechnical Engineering Practice in Hong Kong

Ingénierie des glissements de terrain à Hong Kong

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ABSTRACT: On average, about 300 landslides were reported to the Geotechnical Engineering Office (GEO) of the Civil Engineering and Development (CEDD) in Hong Kong each year. Over the years, GEO conducted landslide investigations to advance knowledge on slope performance and improve understanding of the causes and mechanisms of landslides. Landslide investigations have become an integral part of the Government's Slope Safety System in Hong Kong. Studies on notable landslides on man-made slopes have led to the use of more robust stabilisation measures for cut slopes, improved rock slope engineering practices, enhanced practices in the monitoring and maintenance of water-carrying services affecting slopes and improvement to drainage detailing. Studies on natural terrain landslides have allowed better understanding on the modes and mechanisms of failure. This also enables advancement in debris mobility assessment which is critical to natural terrain risk management. This paper highlights some key lessons learnt and observations made from selected landslide investigations and how this knowledge helps advance the geotechnical engineering practice in dealing with man-made slopes and natural terrain landslide hazards in Hong Kong.

RÉSUMÉ: En moyenne, environ 300 glissements de terrain sont signalés au Bureau Géotechnique (GEO) chaque année. Au fil des années, les enquêtes de glissements de terrain sont menées par le GEO et jouent un rôle clé dans l'avancement des connaissances sur la stabilité des pentes et la compréhension des causes et des mécanismes de glissements de terrain et sont devenus une partie intégrante du système de sécurisation des pentes à Hong Kong. Les études sur les glissements de terrain sur les pentes anthropiques ont conduit à l'utilisation de mesures plus robustes pour la stabilisation des pentes artificielles, l'amélioration des pratiques d'ingénieurs pour les pentes dans les matériaux rocheux et l'amélioration des pratiques de suivi. Les études sur les glissements de terrains naturels ont permis de mieux comprendre le mode et les mécanismes de défaillance. Cela permet également l'amélioration de l'évaluation des déplacements des boues, ce qui constitue un point essentiel dans la gestion des risques naturels. Ce document met en lumière certains des principaux enseignements tirés des observations faites à partir des enquêtes de glissements de terrain sélectionnés et comment cette connaissance contribue à l'avancement de la pratique de la géotechnique dans le traitement des pentes artificielles et naturelles à Hong Kong.

KEYWORDS : landslides, investigation, geotechnical engineering practice

1. INTRODUCTION

The rapid population growth in Hong Kong since the 1960s and substantial economic expansion has been accompanied by extensive civil engineering and building works, resulting in the formation of a considerable number of man-made slopes and retaining walls over the hilly territory. However, as there was very limited geotechnical control of slope formation in the old days, the stability of many of these slopes is therefore in doubt. Coupled with severe rainstorms and dense hillside development, Hong Kong is prone to landslide risk.

Following a number of landslide disasters in 1970s, the Hong Kong Government established the Geotechnical Control Office in 1977 (renamed as the Geotechnical Engineering Office (GEO) in 1991) to regulate geotechnical engineering works and slope safety in Hong Kong. This paper gives an overall review of the slope engineering practices that have been enhanced as a result of the landslide investigation (LI) findings.

2. GEOTECHNICAL STANDARDS AND PRACTICE

Setting geotechnical standards has been one of the GEO's functions. To date, some 300 guidance documents have been published covering standards of good practice for the investigation, design, construction and maintenance of slopes.

For public development projects, the prevailing Government policy stipulates that all permanent geotechnical works involving slopes and retaining walls as well as related activities, including investigations, designs and construction should be carried out in accordance with the prevailing standards. Details of the geotechnical works are required to be submitted to the GEO for checking. In general, the standards for public development projects are also adopted for private building and civil engineering works in Hong Kong.

3. LANDSLIDE INVESTIGATION

Figure 1: The Kwun Lung Lau Landslide in July 1994

On average, about 300 landslides are reported to the GEO each year. Most of these occurred at man-made slopes affecting buildings, roads or pedestrian walkways. Many landslides which occurred in remote areas or in natural terrain were not reported. Prior to mid-1990s, the GEO conducted LI on few selected cases of technical interest or having significant consequence. The occurrence of a number of fatal landslides in the mid-1990s has highlighted the need to further enhance the landslide risk management strategy in

Hong Kong. Following the Kwun Lung Lau landslide of 23 July 1994 (Figure 1), which killed five people and seriously injured three others (Morgenstern & GEO 2000), the GEO introduced a number of new enhancement initiatives including a systematic LI programme. The scope of landslide investigations includes examination of all reported landslide incidents and in-depth studies of selected landslides to identify the causes of failure and necessary follow-up actions. The objectives of the systematic LI are to identify those slopes in need of early attention, and undertake forensic investigation of landslides that involve coroner inquests, legal actions or financial disputes. Through landslide investigations, the performance of the Government's slope safety system will be reviewed and areas for improvement identified. Landslide investigations help advance the understanding of causes and mechanisms of landslides and enhance slope engineering practices and the reliability of landslide preventive or remedial works.

The annual expenditure of the LI programme is about US$3 million. Based on observations from LI, new guidelines are promulgated to improve the prevailing geotechnical practice. Some salient LI observations and improvements for soil cut slopes, rock slopes, retaining walls, fill slopes and natural hillside are described below.

4. SOIL CUT SLOPES

Soil cut slopes formed or treated prior to 1990s typically involved trimming back to a less steep gradient without the provision of reinforcement or structural support. They are prone to degradation and vulnerable to the presence of local weaknesses in the groundmass. Large scale landslides involving such unsupported cut slopes are not uncommon. Notable examples are the Ching Cheung Road landslide in 1997 (Figure 2) and Shek Kip Mei failure in 1999 (Figure 3). The 1997 Ching Cheung Road landslide involved a failure volume of over 2,000 m^3, resulting in the trapping of a motor car and temporary closure of a major route connecting east and west Kowloon for two months. The Shek Kip Mei failure involved a distressed volume of 6,000 m^3, resulting in permanent evacuation of three housing blocks. Findings from investigation of such failures highlight the vulnerability of unsupported cut slopes to adverse geological features and hydrogeological conditions, which may be difficult to detect. A pragmatic approach of adopting more robust design solutions, such as the use of soil nailing was called for. A soil nailed slope tends to behave as an integral mass and is less sensitive to local adverse conditions as compared with an unsupported cut. The use of soil nailing has been widely adopted for upgrading of slopes in Hong Kong since mid 1990s.

Figure 2: The Ching Cheung Road Landslide in 1997

So far, there are 40 failures among some 7000 slopes installed with soil nails. None of these are major landslides (volume ≥ 50 m^3). This indicates that the use of soil nails is effective in averting large scale failure. These minor failures were mostly involved surface erosion or minor local detachment in the groundmass between soil nail heads. Lessons learnt from investigation of soil-nailed slope failures have led to enhanced understanding of the behaviour of soil-nailed slopes (e.g. the importance of soil-nail head), improved detailing of surface drainage provisions (e.g. provision of intersecting drains for long sloping grounds), and enhanced surface protection details. Advances have also been made in the design of soil nails, as promulgated in the Geoguide 7 (GEO 2008).

Figure 3: Laterally-persistent discontinuity infilled with slickensided kaolin and manganese oxide deposits at the 1999 Shek Kip Mei failure

5. ROCK SLOPES

Major failures (volume ≥ 50 m^3) involving rock slopes are not very common. Most of the landslides were rain-induced and structurally-controlled, involving build-up of cleft water pressure in rock joints. Other contributory factors such as presence of soft infill along discontinuities, slope deterioration, root wedging effect, etc were also noted. These failures highlight the importance of identifying adversely-orientated jointing system which could have implication to the stability of slopes in the design. With respect to minor rock slope failures such as rockfalls, the primary causes were due to presence of local adverse groundwater regimes and/or loose or unstable blocks. Many of the rockfalls were initiated by tree-root actions. Given the scale of the failure and the consequence of the failure in the urbanized setting in Hong Kong, rockfalls are difficult to guard against in design. A pragmatic approach is to provide suitable protective and mitigation measures such as rock mesh netting, rock fall fence and buffer zone where practicable. LI findings are incorporated in the relevant manuals and guidelines to enhance the rock slope engineering practice (GEO 2009).

6. RETAINING WALLS

A few major landslides involving retaining wall failures had occurred in the past, the most notable one being the 1994 Kwun Lung Lau landslide. The landslide involved the a brittle collapse of a 100-year old masonry wall (Morgenstern & GEO 2000) releasing 1000 m^3 of debris causing 5 fatalities. No tell-tale sign was reported prior to the failure. The failure was triggered by saturation of the soil behind the masonry wall as a result of leakage from nearby defective buried water-carrying services. The incident highlighted the importance of regular inspection and maintenance of water-carrying services affecting slopes. Following the incident, a guidance document entitled "Code of Practice on Inspection and Maintenance of Water Carrying Services Affecting Slopes" was issued by the Government, setting out the recommended good practice for regular inspection and maintenance of water-carrying services affecting slopes.

Furthermore, the landslide investigation findings indicated that the failed wall was 10 m high but only about 0.8 m thick. The wall thickness is much less than that indicated in the record available. This incident highlighted the danger of slender masonry walls that are liable to fail in a brittle manner without any prior signs of distress, and the importance of verifying the wall thickness in stability assessment. This lesson learnt was incorporated in the guideline for stability assessment of old masonry walls (GEO 2004a).

7. FILL SLOPES

Following the disastrous failure of a fill slope at Sau Mau Ping in 1976, the Government appointed an Independent Review Panel to review the landslide problem and make recommendations on the design of fill slopes in Hong Kong. The Panel recommended, amongst others, that the minimum treatment of existing loose fill slopes should consist of removing the loose surface soil by excavating to a vertical depth of not less than 3 m and recompacting to an adequate standard, together with the provision of subsurface drainage behind the recompacted fill layer at the toe of the slope. Technical guidance on the treatment of existing loose fill slopes is given in relevant manual and technical circular (GCO 1984, GEO 2004b).

Up to 2012, about 260 loose fill slopes have been upgraded using the recompaction approach by the GEO. Between 1997 and 2012, a total of 18 landslides occurred on recompacted fill slopes. The primary causes of landslides of these incidents are:

(a) Surface flow concentration
(b) Leakage or bursting of water-carrying services
(c) Inadequate subsurface drainage provisions

Discounting washout failures due to concentrated surface water flow or leakage of water-carrying services, landslides on recompacted fill slopes were generally ductile in nature and did not involve sudden and fast-moving debris as in liquefaction failure.

Enhancement measures have been implemented with reference to the lessons learnt from these landslides. For instance, the Code of Practice on Monitoring and Maintenance of Water Carrying Services Affecting Slopes, which was first issued in 1996, has been updated taking into account lessons learnt from landslides triggered by leakage or bursting of water-carrying services (ETWB 2006).

Detailing of slope drainage provisions has also been improved. Areas for improvement include provision of adequate movement joints for surface drainage channels and provision of filter pipes at upstream end of the subsurface drainage blankets behind the recompacted fill etc. The improvement measures were promulgated in the GEO Report Nos. 210 and 225 (Hui et al. 2007, Fugro 2008)

8. NATURAL HILLSIDE

Hong Kong has a land areas of about 1,100 km^2. About 60% is natural terrain, over 30% of which has a slope gradient over 30^o. Natural terrain landslides in Hong Kong are mainly rain-induced. Most of them occurred in remote areas while some affects developments. The GEO has been undertaking technical development works based on the study of natural terrain landslides since the early 1990s.

Based on observed runout distance of landslide debris, a set of simple and suitably conservative guidelines has been developed (Wong 2003) for initial screening purposes to assist planners, land administrators, project managers, etc. to review whether or not a given site is subject to natural terrain landslide hazards. Where a site is shown to be potentially affected by landslide hazards, more refined criteria are then used to examine whether the proposed development meets the 'in-principle objection' criterion (i.e. relocate the proposed development or amend development layout), or the 'alert criteria' (i.e. carry out natural terrain hazard study and appropriate mitigation measures as part of the development).

In June 2008, Hong Kong was hit by a severe rainstorm. The short-duration rainfall intensity had a return period of about 1,000 years. The rainstorm triggered over 2,400 natural terrain landslides mainly on Lantau Island. Some of them affected developed areas and caused significant social disruption such as evacuation of houses and temporary closure of road sections. The GEO carried out systematic studies on some of these landslides. Detailed field mappings and in-depth landslide investigation provided valuable insights into the characteristics of natural terrain landslides.

Comparing the June 2008 landslides with past landslide records revealed that the 2008 landslides seem to 'cluster' around old ones. Up to 92% of the 2008 landslides occurred within 50 m of at least one past landslide, and 80% within two or more past landslides (Wong 2009). Although further work is needed to interpret this phenomenon, this sheds light on the prediction of regions of natural terrain that is more prone to failure and has implications in the determination of natural hillsides that warrant priority for the mitigation of landslide hazards.

Figure 4: Landslide on the hillside behind the Hong Kong University

Detailed landslide investigations on selected June 2008 landslides showed that past failures could have a significant implication to the scale of the landslides. Past failures could lead to extensive colluvial accumulations on hillside, which are susceptible to give rise to a laterally extensive and a much larger scale failure during heavy rainstorm than those in the past (Figure 4) (Maunsell 2009). If the debris of previous failures deposited along the drainage line, it could become 'entrainable', giving rise to a larger scale of a channelized debris flow (CDF) event (Figure 5) (AECOM 2009). In the 2008 rainstorm, significant entrainment was noted in many of the long runout CDFs with entrainment ratio up to 10 or higher (the entrainment ratio is the volume of additional material that has been entrained by a landslide expressed as a proportion of the source volume). The amount of the pre-existing 'entrainable' materials in a drainage line is dynamic and may change significantly after a rainstorm. This highlights the implications of the deposition of debris from past failures on occurrence of some large-scale failures in natural hillsides.

Figure 5: Yu Tung Road channelized debris flow

In general, the June 2008 landslide debris was found to be more mobile when compared with the previous historical natural terrain landslides in Hong Kong (Figure 6). About 20% of the June 2008 landslides have runout distances over 100 m, as compared with about 10% in past landslides that are observed from old aerial photographs.

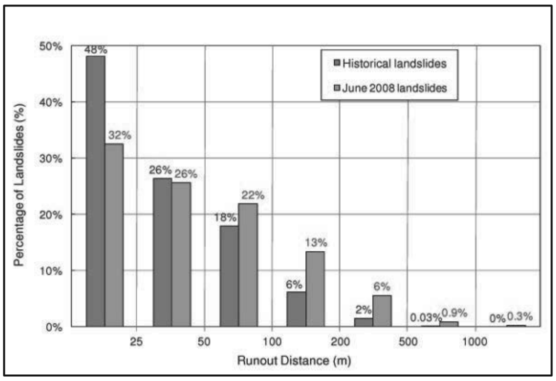

Figure 6: Distribution of landslide runout distance

Detailed studies on selected CDFs revealed that some of the CDFs with long runout generally involved debris with high water content, e.g. the failure near Yu Tung Road (Figure 5). After detaching from the source of failure, the debris mixes with a large amount of water along the drainage line, and results in higher debris mobility. LI revealed that a number of circumstances may lead to such 'watery debris', such as:

(a) debris flows along a major drainage line with a large catchment and a long flow path;
(b) debris flows occurring during heavy rain; and
(c) debris flows along a main drainage line into which many tributaries of drainage lines are feeding.

To facilitate the modeling of debris mobility under such circumstances for natural terrain hazard studies, systematic back analyses were carried out on some selected long runout CDFs that occurred in June 2008 using a 2-D dynamic modelling algorithm, known as 'debris mobility modeller' (2d-DMM) program, as well as 3d-DMM in some cases, to refine the modeling parameters. Improved guidance on debris mobility modeling was promulgated by the GEO (2011).

9. CONCLUSIONS

The landslide investigations have brought insights into the causes, mechanisms and characteristics of landslides. The investigations enhance the understanding of the behaviour of man-made slopes and natural hillside under severe rainstorm and the findings have helped to advance geotechnical engineering practices, and improve standards and design guidelines for enhancing the robustness of slope upgrading and landslide mitigation works.

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