UHK Urban Geology 1 Day Conference

Scarp Morphology and Development Associated with a Large Retrogressive Compound Landslide at Lai Ping Road — Hong Kong

N P Koor[1] S D G Campbell, H W Sun & K K H Ho
Geotechnical Engineering Office, Civil Engineering Department, Hong Kong SAR
[1]Present Address, Scott Wilson (Hong Kong) Ltd. Metro Plaza, Kwai Fung, Hong Kong

Abstract

This paper briefly describes morphology and interpretations of scarps associated with a large, slow moving, retrogressive, compound landslide that affected a cut slope at Lai Ping Road, near Sha Tin, in the northeast of Hong Kong. The cut slope failed after intense rainfall on 2 July 1997, and five landslides occurred, with a combined volume of 4000 m^3. The relatively mobile debris impacted with a covered service reservoir but no major damage resulted. Surface ground deformation extends 50 m into the quasi-natural terrain above the cut slope. This is bounded by a main scarp, up to 4 m high, which indicates the presence of a failed mass whose volume is estimated to be up to 100,000 m^3. Surface mapping has revealed numerous scarps and tension cracks, within the confines of the main scarp. These scarps are of differing ages and structural morphotypes, including horsts, grabens, *en echelon* arrays and duplexes. The scarps and tension cracks were influenced in their development by the relict joint structure, depth of weathering and hydrogeology of the slope. It is concluded that the slope has had a lengthy history of spasmodic, deep seated deformation dating back to the initial formation of the cut slope in 1978.

Introduction

On 2 July 1997, a landslide occurred on a roadside cut slope on Lai Ping Road, Kau To Shan, Sha Tin (Figure 1), in the northeast of Hong Kong. The landslide comprised several discrete failures with a combined volume of approximately 4000 m^3. These occurred along a 135 m-long section of the cut slope and completely blocked Lai Ping Road (Figure 1). There were no casualties and damage was limited. However, during an initial site investigation, a major backscarp, extending up to 50 m above the cut slope, was identified in densely vegetated quasi-natural terrain. This indicated the presence of a much larger volume, deep-seated landslide, the identification of which led the Geotechnical Engineering Office (GEO) to instigate a comprehensive investigation to study the mechanism(s) and cause(s) of the failure. The investigation comprised:

- detailed desk study including documentary search and rainfall record analysis,
- geomorphological and geological mapping (scale 1:200) of the landslide site and its environs,
- photogrammetric analysis of aerial photographs,
- comprehensive ground investigation,
- seepage and stability analyses and finite difference modeling, and
- diagnosis of the probable causes of failure.

This paper concentrates on the morphology, and interpretation of the scarps associated with the landslide, and considers their geological controls. Other aspects of the landslide are described elsewhere (Koor and Campbell, 1998; Sun and Campbell, 1998).

Scarp Morphology

A series of scarps are present on the quasi-natural slope above the cut slope, and in landslide scars 1 to 5 (Figure 1) which developed mainly within the cut slope. The scarps are interpreted as surfaces of rupture, with vertical, and varying degrees of lateral, movement. There are, in addition, open tension cracks, with no significant differential vertical displacement.

A detailed map of the scarp morphology is shown in Figure 2. The scarps were mapped, prior to a comprehensive topographic survey of the landslide site, with reference to a series of base stations established by a Global Positioning Satellite (GPS) system, accurate to within 0.5 m. Further known points were then added using tape and compass surveying between the GPS base stations. This enabled a relatively accurate base map of the scarps to be compiled rapidly, despite the relatively thick vegetation cover.

The main scarp of the system, marking the apparent up-slope limit of the deformation, extends to a maximum elevation of +156.6 mPD. This is some 24.8 m above, and 56 m beyond (in plan view), the highest point of any of landslide scars 1 to 5 (Figure 2). The scarps are typically steep (>70°). They have differential vertical offsets of up to 3.8 m (Plate 1) and horizontal extensions of up to 4.2 m. Most scarps dip directly or obliquely down-slope, consistent with the down-slope mass movement. However, a few scars dip up-slope. Some of these are the down-slope margins of extensional grabens. Others may reflect locally generated compression, i.e. heave, within the moving mass, or minor toppling failure. Individual scarps extend laterally for up to 100 m and in plan (Figure 2), the array of scarps displays a wide range of forms. They vary from curvilinear to rectilinear segments, and include:

(i) bifurcations,
(ii) conjugate shear sets,
(iii) left- and right-stepping *en echelon* arrays,
(iv) S- and Z-shaped inflections,
(v) duplexes, and
(vi) other complex movement transfer zones.

Segments nearer the cut slope are generally shorter (typically <8 m long) than those further up-slope, and close to, or forming part of the main scarp. Only one linear segment, which forms part of the main scarp on the northeast side of the landslide, is greater than 15 m in strike length. The scarps nearer the cut slope are generally considered to be older features than those further up-slope, and most were not activated during the recent slope movements. Their comparatively short strike lengths partly reflect their truncation by younger scarps of different orientation.

There is a relatively regular spacing of the scarps. First order scarps, that can be traced laterally for several tens of metres, are typically about 15 m apart, whereas second order features, that can be traced laterally for up to about 20 m are approximately 7 to 8 m apart. The regular spacing of the first and second order scarps may be controlled either by the spacing of major joints within the rock mass and the saprolite, or by the thickness of the soil mass.

The morphology of the main and minor scarps, and particularly the presence of the steep main scarp, grabens and possible local compressional features, suggests that the large area of deformation can be classified as a compound slide. Compound slides are characterised (Hutchinson, 1988) by markedly non-circular slip surfaces formed by a combination of a steep, curved or planar rearward part and a flatter sole. They generally reflect the presence of heterogeneity beneath a slope, often a weak layer or a boundary between weathered and unweathered material.

Geological influences on scarp development

Relict Joints

Locally, the scarps follow relict joint surfaces but generally, no such structural control can be observed at ground level. However, deeper-seated structural control of the orientation of the scarps can be inferred if the dip directions of linear segments of the scarps and those of the dominant joint sets are compared.

The main joints sets observed within the scarps and landslide scars 1 to 5 have dip and dip directions of 49°/198° and 86°/098°. Minor joint sets dip towards 28°/001° and 75°/207°. Therefore, all but the northerly-dipping minor joint set accord well with orientations of main and minor scarps. Only the southeasterly dipping scarps can not be matched to any observed joint set.

The main joints, are generally medium to closely spaced, and are often smooth or slickensided, undulose, and very narrow to tight. They are commonly coated or infilled with manganiferous deposits, limonite, and white or buff kaolin. Locally, and most notably in landslide scar 5 with respect to southwesterly-dipping joints, kaolin-coated joints have acted as basal surfaces of rupture. Also, within landslide scar 4, subvertical northerly-striking joints have acted as lateral release surfaces.

A sheeting joint set, dipping at a low angle parallel to the original natural terrain slope surface (c. 26°) has not been identified. This, coupled with the relatively thick nature of the saprolite at the landslide site (see below), suggests the natural slope had been comparatively stable for some considerable time prior to formation of the cut slope, and that erosion rates had been very slow.

Lithology

The main lithology on the site is a grey to bluish grey, sparsely lapilli-bearing coarse ash crystal tuff, varying to a lapilli ash and locally ash-lapilli tuff. This is consistent with the regional geology shown on the published map of the area (GCO, 1986) which indicates that the tuff is of Jurassic age, despite the fact that it was not assigned to any formation. The tuff exhibits a discontinuous compactional fabric and preferred alignment of lithic clasts and crystals. These indicate a weak stratification that typically dips to the north-northeast, into the hillside, at angles of between 25 and 40°. Although some scarps have a similar strike to the stratification, the stratification appears not to influence their development.

Aphyric and quartzphyric variably flow-banded rhyolite dykes, up to 4 m wide, can be traced laterally for up to 20 m (Figures 1 and 2). They occupy several orientations including: steeply dipping (74 to 88°) to the southeast or south-southeast; steeply dipping (62°) to the south-southwest; and moderately inclined (30-45°) to the north-northeast. The similarity between the orientations of the two steeply dipping dyke sets and some scarps suggests that the dykes may locally control scarp development. However, there is little evidence of this in the exposed scarps.

Saprolite thickness

Extensive ground investigation has established that the saprolite thickness across the landslide site is typically 15 to 24 m thick (Koor and Campbell, 1998) but is markedly thinner on the western side of the site (Figure 2). The ground investigation has also provided evidence of rupture relatively close to, the interface between saprolite and rock. Hence, the total volume of the landslide can be estimated as approximately 100,000 m^3.

Cruden (1991) proposed a method for determining the depth of surfaces of rupture of non-circular, translational landslides in clay, based on the width of grabens at surface. For the landslides he studied, a simple ratio of 1.1 times the graben width correlates well with the known depth to the surface of rupture. The observed distance between first order scarps (c.15 m) at Lai Ping Road may therefore be a function of the depth to the surface of rupture. Using Cruden's multiplier of 1.1, a surface of rupture would be predicted at about 16.5 m depth, which is consistent with observations of rupture close to the base of the saprolite.

Hydrogeology

Major seepage was observed in landslide scars 1 to 5 and ground investigation provided further evidence of groundwater depths.

Soil pipes (0.02 to 1.5 m wide and up to 0.5 m high, Plate 2) are developed at several locations within the mainscarp of landslide scar 5. Persistent groundwater flow was noted from several of these pipes after heavy rain (Plate 3). Site photographs indicate that two of the largest pipes have been present, and actively seeping, for at least 18 years. The soil pipes occur most notably towards the base of colluvium, of which there are two units, with a maximum total thickness of 4 m, exposed in the main scarp of landslide scar 5. Significant thicknesses of colluvium (c. >1 m) are largely restricted to landslide scar 5 (Figure 1) and the area above it, extending to and beyond the main scarp. Soil pipes have also been observed in mazier samples, especially where taken close to the base of the saprolite where rupture has also been intepreted.

The rhyolitic dykes may act as natural dams to ground water flow downslope, causing elevated pore water pressures. Despite their similar orientations to some of the scarps, the discontinuous nature of the dykes suggests any damming effect is likely to be of local significance only.

An intense seepage point was observed above a prominent zone of altered tuff and rhyolite in landslide scar 4 (Figure 1). The altered zone dips north-northeast at about 25 to 40°, into the hillside and subparallel to stratification within the tuff. The zone is characterised by deep red/reddish pink iron staining, common relict joints with white to buff kaolin infills up to 30 mm thick, and some dark brown manganiferous deposits. Hence, it may act as a natural dam to groundwater flow downslope, locally elevating pore water pressures. However the discontinuous nature of the zone suggests that the damming effect is again likely to be minimal and it does not appear to influence scarp development .

Rock Mass Weathering, Decomposition grades and Strength

The rock mass weathering has influenced the mode of failure of the cut slope, and hence the form of the scarps of landslide scars 1-5.

The fresh or slightly decomposed (grades I and II) tuff is extremely strong to very strong and when moderately decomposed (grade III), is strong to moderately strong. Joints are often coated with manganiferous and limonitic deposits and sometimes white and buff kaolin, notably in landslide scar 5.

The highly decomposed tuff (HDT, grade IV) is weak to very weak, and the completely decomposed tuff (CDT, grade V) composed of clayey sandy silt, is extremely weak. Joints are extensively coated with manganiferous deposits and limonite, up to 10 mm thick in HDT and 20 mm thick in CDT. Thin infills of white or buff kaolin (1-2 mm thick) are common in the HDT,and are up to 20 mm thick in relict joints in the CDT. The kaolin infills comprise 50 to 82% halloysite occurring as fibrous overgrowths on books of kaolinite which make up the remaining clay mineral (Merriman *et al.*, 1998). Residual soil (grade VI), exposed mainly in landslide scars 1 and 2 and in the left hand flank of the main scarp (Figure 2) is generally a soft, or soft to firm, clayey sandy silt, but may grade into a silty clay in places. In the left hand flank of the main scarp, the residual soil is firm, or firm to stiff.

Where HDT, CDT and residual soil are predominant, as in PW0/30 zones exposed in the scarps of landslide scars 1, 2, 3 and 4A, composite translational slides and gully erosion are typical. However, where rock content was higher, and discontinuities affected the mass strength, as in landslide scar 4, planar rock and soil slides occurred (landslide scars 4A and 5).

Scarp Evolution

Site observations clearly indicate movement predating the recent phase of failure, on and after, the 2nd July 1997. The scarps formed recently lack vegetation and contrast markedly with older vegetated scarps. In some instances, the uppermost parts of some scarps have a coating of vegetation (moss, ferns etc.), whereas the lower parts, formed during the most recent activity, are bare. The interface between the vegetated and non-vegetated portions of the scarps is typically abrupt. This indicates recent reactivation of a pre-existing scarp (Plate 3). Occasionally, it was possible to measure slickensides related to both recent and older phases of movement on the same scarp (Plate 5). However, the older scarps had generally been eroded to the extent that slickensides were poorly preserved or absent.

Using a combination of evidence derived from detailed site observations, photogrammetry and aerial photograph interpretation, it has been possible to establish a history of landslide evolution since the formation of the cut slope in 1978 (figures 3-5).

Conclusions

The detailed surface mapping made a significant contribution to the investigation of the landslide in that it;

- defined the limit of deformation,
- demonstrated that much of the deformation preceded 2 July 1997,
- classified the landslide type as compound, implying that the location of the surface of rupture may be controlled by the depth of weathering,
- indicated that the surface of rupture may be located at about 16m below ground level, and
- revealed that the orientation of the main scarp was influenced by the main joint orientations.

References

Cruden, D.N. (1991). Observation of graben geometry in landslides. Slope stability engineering. Thomas Telford, London, pp. 33-35.

Koor, N.P. & Campbell, S.D.G. (1998). Geological Characterisation of the Lai Ping Road Landslide. Geological Report No. GR3/98, Geotechnical Engineering Office, Hong Kong, 178 p. + 5 drawings.

Geotechnical Control Office (1986). Shatin: Solid and Superficial Geology, Sheet 7. Hong Kong Geological Survey, Map Series HGM 20, Geotechnical Control Office, Hong Kong.

Hutchinson, J.N. (1988). General Report: Morphology and geotechnical parameters of landslides in relation to geology and hydrogeology. Proceedings of the Fifth International Symposium on Landslides, 10-15 July 1998, Lausanne, pp3-35.

Merriman, R.J. Kemp, S.J. Hards, V.L. and Murphy, H.A. (1998). A mineralogical and microtextral study of the Lai Ping Road Landslip, Hong Kong. British Geological Survey Technical Report, Mineralogy and Petrology Series. Report No. WG/98/25C. 9 plates, pp 11.

Sun, H.W. & Campbell, S.D.G. (1998). The Lai Ping Road Landslide of 2 July 1997. Landslide Investigation Report No. LIR27/98, Geotechnical Engineeering Office, Hong Kong, 138p. + 2 drawings.