The study of rainfall induced sliding of a fill slope in Shenzhen, China

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Abstract: Due to over 200 millimetres of heavy rainfall on 19 August 2005 and over 300 millimetres of heavy rainfall on 20 August 2005 in Shenzhen, a fill slope was found to be sliding with an approximate volume of 150,000 cubic metres of material involved. A lot of cracks were produced during the two days. The accumulated horizontal deformation along the whole fill slope was up to 500 mm.

Soon after the heavy rainfall, an intense monitoring scheme including piezometers and inclinometers was carried out in the fill slope. On September 23 2005, Typhoon Damrey brought over 100 millimetres of heavy rainfall to Shenzhen, which caused the fill slope to further slide with another horizontal deformation of about 30 mm.

Based on the field monitoring results, the possible sliding mechanism for the fill slope is discussed, the preventive method for the fill slope is also proposed and finally a more intense monitoring scheme including tensimeters and moisture probes is suggested.

Résumé: En raison de fortes précipitations de plus de 200 mm d'eau le 19 Août 2005 et de plus de 300 mm le 20 Août 2005 a Shenzen, une pente de 150 000 mètre cube a glissé. De nombreuses fissures se sont formées pendant ces 2 jours. La déformation horizontale accumulée le long de la pente était de 500mm.

Peu de temps après la précipitation, un intensif system de se surveillance comprenant des piézomètres et des inclinomètres fut mis an place sur la pente. Le 23 Septembre 2005, le Typhon Damrey déversa 100 mm de précipitations sur Shenzen, ce qui accentua le même glissement de terrain avec une déformation horizontale de 30 mm.

Basée sur les mesures sur site, le mécanisme de glissement de la pente est abordé, la méthode préventive pour la pente est également présentée et finalement un système d'échantillonnage plus intense comprenant des tensiomètres et des capteurs d'humidité est conseillé.

Keywords: case studies, deformation, geological hazards, monitoring, slope stability, landslides

INTRODUCTION

On 19 and 20 August 2005, during the heavy rainfall, an around 200-m long and 45-m high fill slope in Shenzhen, China, was found to be sliding. If it failed, it would block the sole access to the largest landfill in Shenzhen, which would severely influence the normal life of the citizens there. In case the landslide would occur, the sole access to the landfill was temporarily closed during the heavy rainfall.

Immediately followed the incident, a detailed investigation was carried out to study the causes of the sliding fill slope. At the meantime, an emergency and permanent remedial works for the sliding fill slope were being designed. The study included a comprehensive ground investigation, a detailed analysis of rainfall records and a plane translational slip analysis.

This paper presents part of the outcomes of the study. The possible sliding mechanism of the fill slope is discussed and the preventive method for the remedial works is also proposed.

LITERATURE REVIEW

Rainfall-induced failure of loose fill slopes poses significant geotechnical threats to Hong Kong (Sun 1998). The loss of human lives, damage to properties and chaos and disruption caused by disastrous fill slopes have been severe for years in Hong Kong (Lumb 1975). Each year hundreds of landslides, occur during the rainy season. Many of these are the results of post-war urban development in Hong Kong that involved a concentration of construction of cut and fill slopes for infrastructures and building sites (knill *et al*. 1977).

On 18 June 1972, after three days of heavy rainfall, the most disastrous landslide in Hong Kong's history occurred. By noon on that day, a rainfall intensity of around 100 mm/hour was recorded and roads nearby were flooded up to 30 cm. At around 1:10 pm, part of the 40 m high fill embankment behind the Sau Mau Ping housing estate suddenly collapsed and inundated a single-storey dwelling in the estate, which killed 71 people and injured 60 people (Hong Kong Government 1972). On 25 August 1976, another disastrous landslide occurred in a fill slope within the above same estate, in which 18 people were killed (Geotechnical Engineering Office 1977).

Around twenty-five years ago, Shenzhen, a border's away from Hong Kong, is just a small town with a population of only 30,000 in China. After designated as a Special Economic Zone, Shenzhen developed extremely fast into a modern city with a population of over 12 million. In order to accommodate such an increasing population, the use of steeply sloping sites with extensive cut and fill for building/infrastructure development is inevitable. As a result, more and more landslides would occur there.

On 18 September 2002, under the influence of heavy rainfall, a fill slope of Yang Bao Di Mountain near Meilin Inspection Port, Shenzhen suddenly failed. The scar of the landslide moved about 140 m from the toe of the fill slope and buried a lot of squatter's temporarily built houses. The scar volume was estimated to be about 25,000 cubic metres. The failure caused 4 fatalities, one missing and 31 injured (Yang *et al*. 2003).

SITE CONDITIONS AND GROUND INVESTIGATION

The site of the fill slope is located in Lohu District, Shenzhen, which was formed by end-tipping during the construction of the landfill. The sliding fill slope has a length of around 200 m and a height of around 45 m. The absolute elevations at the crest, on the berm and at the toe of the fill slope are 159.5 m, 140.5 m and 115.0 m, respectively. At the toe of the fill slope, there is a 10-m high masonry retaining wall. Away from the retaining wall is the sole access for the waste vehicles to enter the landfill. The down slope has a slope angle of 25-30º with the surface heavily vegetated and the upper slope has a slope angle of 40-45º with the surface protected by concrete grillages. There is a berm in the middle of the fill slope and the width of the berm is 10-40 m. There is another access to the landfill at the crest of the fill slope, however, this access has not been completed yet.

The fill slope was formed in 1993. It was reported that part of masonry retaining wall once failed in 2000 due to heavy rainfall. The failed retaining wall was repaired and stabilized later. However, no documents could be found about the above failure.

Soon after the sliding fill slope was reported to Land Department of Shenzhen, which is responsible for geohazard prevention there, some senior geotechnical experts were invited to visit the site during heavy rainfall. In case landslide occurred, some emergency works were suggested, including: (1) The berm shall be protected with waterproof canvas to prevent further rainfall infiltration; (2) The sole access to the landfill shall be temporarily closed to prevent the possible damage to waste vehicles and (3) The masonry retaining wall shall be protected at the toe with loaded sandbag.

Once the rainfall stopped on 21 August 2005, ground investigation within the possible boundary of sliding (Figure 1) was carried out at the fill slope site. The final factual report of ground investigation was completed in October 2005. Ground investigation works include topographical survey, drillholes, trial pits, geophysical exploration, insitu testing, laboratory testing and field monitoring of groundwater and horizontal deformation. A total of 53 drillholes were formed at the fill slope site.

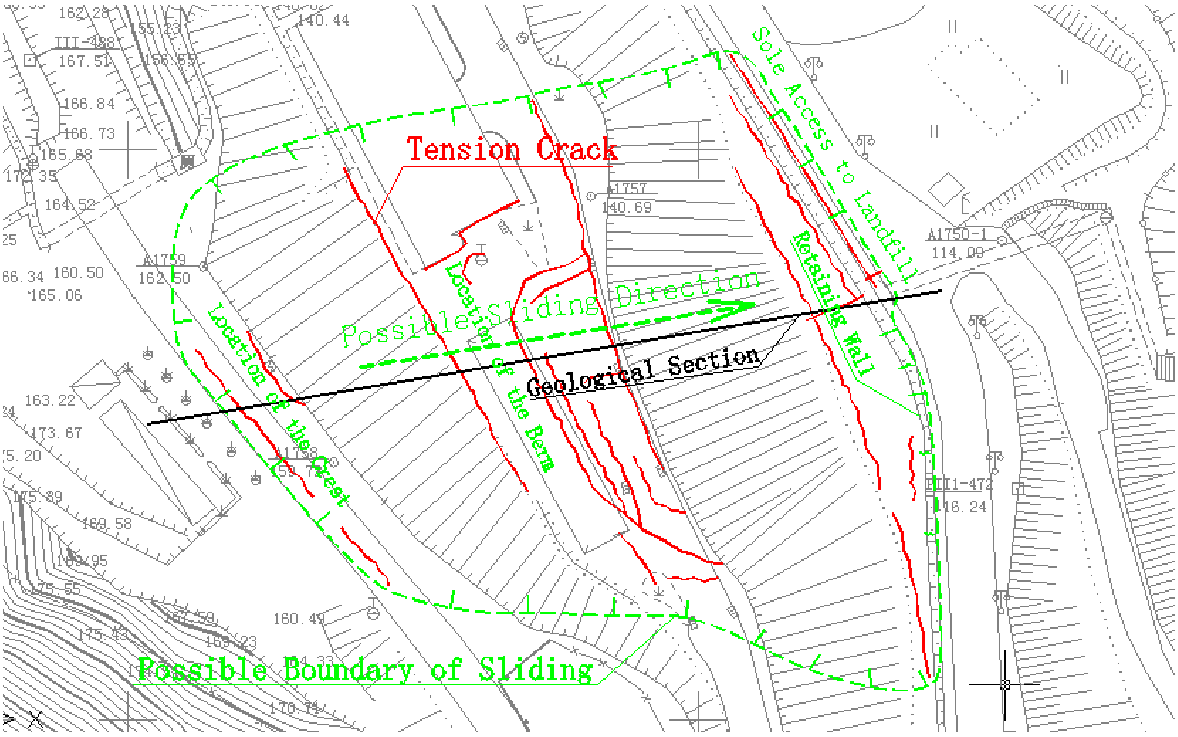

Figure 1. Plan of possible sliding boundary of the fill slope

The geology of the fill slope, as revealed by the ground investigation, consists of mainly fill, which is underlain by highly decomposed sandstone (Figure 2). The fill is mainly made of highly decomposed sandstone with some silty clay in some locations. The maximum depth of the fill slope is up to 17 m.

Standard penetration tests (SPT) were carried out in some of the boreholes. The SPT tests show that the *N* value varied from an average of five blows for fill to over fifty flows for decomposed sandstone. Laboratory tests were carried out on the disturbed soil samples obtained during the site investigation. The laboratory program to characterize the soil properties included tests for the following: (1) Bulk density, (2) Dry density, (3) Specific gravity, (4) Atterberg limits. Detailed results of the testing program including both the field and laboratory tests are summarized in Table 1.

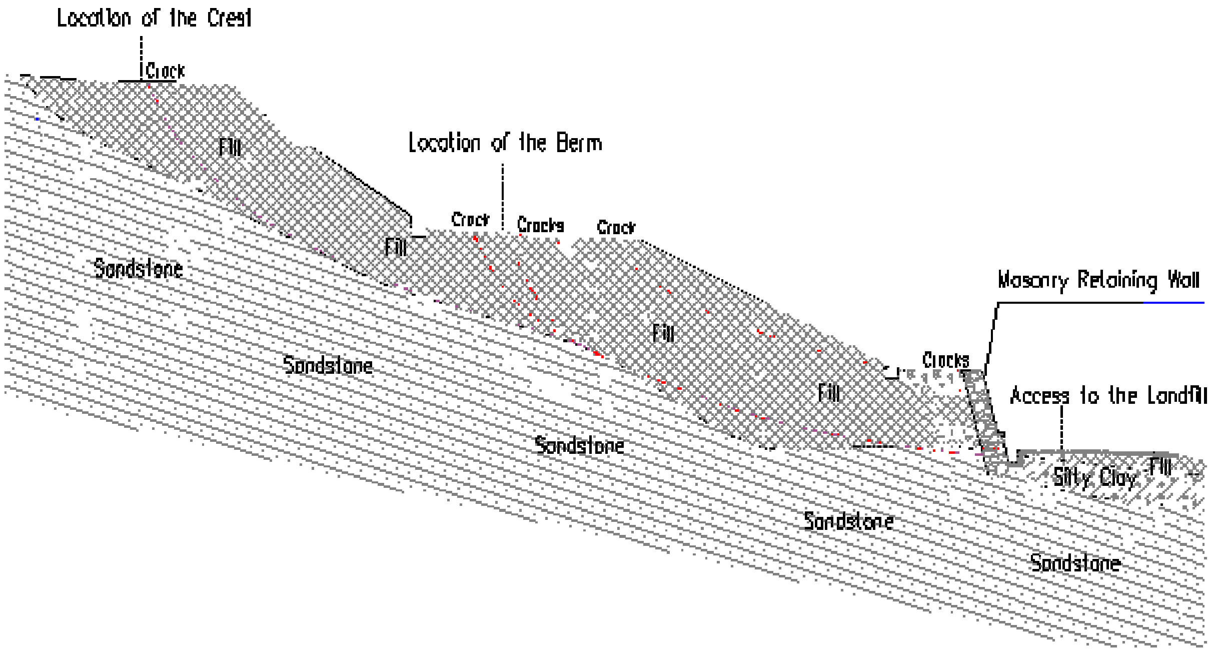

Figure 2. Typical geological section of the sliding fill slope

Table 1. Soil properties of the fill

Bulk density (Mg/m^3)	1.81~2.01
Dry density (Mg/m^3)	14.8~16.2
Specific gravity	2.72~2.75
Void ratio	0.603~0. 879
Natural water content (%)	14.2~26.1
Liquidity index	0.006~0.193
Plasticity index (%)	13~19
SPT value (No. of Blows)	3~7

During the incidence of the fill slope, cracks were not only developed in the masonry retaining wall (Figure 3 and Figure 4), but were also developed in the fill slope (Figure 5 to Figure 6). There are three main obvious cracks at the back of the masonry retaining wall, six main obvious cracks on the berm of the fill slope and two main obvious cracks at the crest of the fill slope (Figure 1). Based on the possible boundary of the sliding fill slope, the scar volume is estimated to 150,000 cubic metres. Most of the cracks are tension cracks. The cracks at the back of the masonry retaining wall are open with voids open up to 200 mm, these at the crest of the fill slope up to 100 mm (Figure 5) and these on the berm of the fill slope up to 500 mm (Figure 6). Furthermore, the soil under the pavement on the berm of the fill slope settled up to 500 mm (Figure 7).

Figure 3. Crack on the top of the masonry retaining wall

Figure 4. Vertical crack along the surface of the masonry retaining wall

Figure 5. Crack at the crest of the fill slope showing horizontal displacement up to 100 mm

Figure 6. Crack on the berm of the fill slope showing horizontal displacement up to 500 mm

Figure 7. Soil under the pavement on the berm of the fill slope settled up to 500 mm

Figure 8. Groundwater flowing out of the weepholes of the masonry retaining wall

Figure 9. Groundwater flowing out of the cracks of the masonry retaining wall

Figure 10. Drainage channel at the left crest of the fill slope was seriously damaged and blocked

The groundwater level monitored during the later ground investigation at the crest of the fill slope was around 17m below the ground surface (142.5 m mPD), that on the berm of the fill slope 13 m below the ground surface (127.5 m mPD) and that near the toe of the fill slope (or at the back of the masonry slope) 11m below the ground surface (119.0 m mPD). However, photos taken soon after the heavy rainfall shows that the groundwater at the back of the masonry retaining wall was extremely high, just less than 2 m below the ground surface (Figure 8 and Figure 9). The rise of the groundwater level in the fill slope was estimated to be about 10 m during the two-day's heavy rainfall. As part of the drainage channels of the fill slope are connected with drainage channels of other catchments in the landfill site, if the drainage channel of the fill slope was damaged or blocked (Figure 10), more surface water would infiltrate into the fill slope during the heavy rainfall, which would cause the groundwater in the fill slope to rise unexpectedly high. Another possibility for the high rise of groundwater level of the fill slope may be due to the blockage of some weepholes of the masonry retaining wall.

ANALYSIS OF RAINFALL RECORDS

The climate in Shenzhen is sub-tropical and monsoonal, with mild, dry winters and hot, humid summers. Furthermore, heavy rainfall is very common in Shenzhen and is usually associated with slow-moving troughs of low pressure and tropical cyclones. The daily rainfalls recorded by Shenzhen Observatory Bureau in August and September 2005 are shown in Figures 11 and 12, respectively. From Figure 11, we know that the rainfall on 19 August 2005 is 243 mm and the rainfall on 20 August 2005 is 303 mm, although the rainfall on the preceding day of 19 August 2005 was not particularly high. From Figure 12, we know that the rainfall on 25 September 2005 is 130 mm, which was brought by Typhoon Damrey.

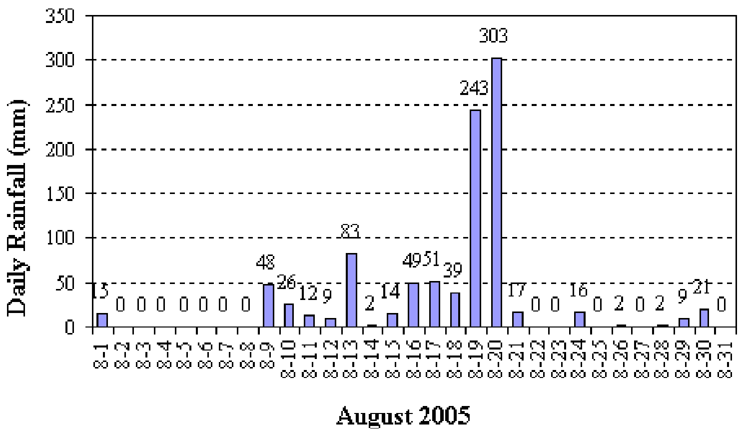

Figure 11. Daily rainfall in August 2005

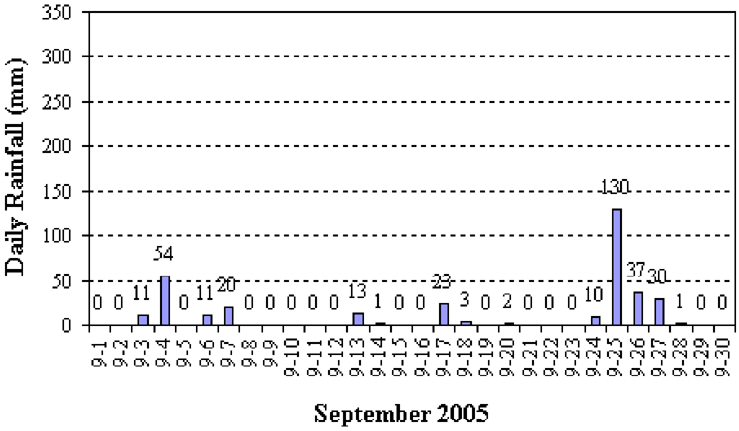

Figure 12. Daily rainfall in September 2005

FIELD MONITORING

Piezometers were installed in 9 drillholes, with 3 at the crest, 3 on the berm and 3 near the toe of the fill slope (or at the back of the masonry retaining wall), respectively. The monitoring of groundwater levels was carried out by using a dipmeter and started on 13 September 2005. The groundwater levels at the crest, on the berm and near the toe generally decreased slightly (less than 1 m) from on 13 September 2005 to on 12 October 2005. On 25 September 2005, due to the 130 mm rainfall brought by Typhoon Damrey, the groundwater levels at the crest and near the toe increased slightly (less than 0.5 m), however, the groundwater level on the berm increased 2.5 m.

Inclinometers were installed in 6 drillholes, with 2 at the crest, 2 on the berm and 2 near the toe of the fill slope (or at the back of the masonry retaining wall), respectively. The monitoring of horizontal displacement was carried out by using portable torpedo and started also on 13 September 2005. No measurable subsurface ground displacements at the crest and near the berm were detected after the inclinometer readings began on 13 September 2005 and up to on 12 October 2005, at which time some emergency stabilisation works were adopted. However, some 30 mm of horizontal displacement was recorded from inclinometers installed on the berm.

A 2.5 m rise of groundwater level and a 30 mm increase of horizontal deformation on the berm during the rainfall brought by Typhoon Damrey may be due to the many cracks on the berm.

ANALYSIS OF A PLANE TRANSLATIONAL SLIP

It is assumed that the potential failure surface is parallel to the surface of the slope and is at a depth that is small compared with the length of the slope. The slope can then be considered as being of infinite length. The slope is inclined at angle β to the horizontal. The water table is taken to be parallel to the slope. When the effective cohesion c'=0 and the slope is fully saturated i.e. the water table coincides with the surface of the slope, the factor of safety for the fill slope can be expressed in the following formula (Craig 1997)

$$F=(\gamma'/\gamma_{sat})(\tan\phi'/\tan\beta)$$

where F is the factor of safety, γ' is the buoyant unit weight, γ_{sat} is the saturated unit weight, β is the slope angle and ϕ' is the effective internal frictional angle.

Suppose γ' is 9.1 kN/m^3, γ_{sat} is 19.1 kN/m^3, ϕ' is 37º and β is 25º, then F will be 0.78, which shows that a shallow failure of the fill slope would occur if the fill slope is fully saturated.

CAUSES OF THE SLIDING

Based about the above study, there are a number of factors causing the sliding of the fill slope.

- In a slope, the gravity (sliding) forces are related to the angle of the slope. The soil strength (anti-sliding forces) is dependent of soil types, its degree of compaction or density, and whether the soil is wet or dry.
- For a loose fill slope such as decomposed sandstone soil, the critical angle would be in the order of 33 degrees, when compacted properly, this critical angle would increase to at least 37 degrees. For a unsaturated fill slope, if suction is considered, the fill slope can stand at a slope greater than 37 degrees. That is why the upper slope of the fill slope can stand at a slope of up to 45 degrees.
- From the analysis of a plane translational slip, even though the fill slope has a slope angle of 25 degrees, if it is fully saturated, a shallow failure, as a consequence of rainfall infiltration, would occur. Therefore, it is

postulated that the down slope of the fill slope was saturated or at least partially saturated during the heavy rainfall on 19 and 20 August 2005.

- As the fill slope is formed by end-tipping, its permeability would be greater, therefore, its infiltration capacity would also be greater, which would finally increase the groundwater level. There is evidence that the groundwater level at the back of the masonry retaining wall was extremely high (Figure 8). Therefore, there is a possibility of a deep-seated zone of large deformation close to the base of the fill, triggered by a significant rise of groundwater level followed the rainstorms on 19 and 20 August 2005.
- Another reason why the groundwater level at the back of the masonry wall is extremely high may be due to the blockage of the weepholes of the masonry retaining wall. Furthermore, it is postulated that the masonry retaining wall is under-designed without considering the rise of the groundwater level and a possible sliding of the fill slope along the sloping surface of highly decomposed sandstone.
- The permanent remedial works would be anti-sliding piles to prevent a possible deep-seated slope failure. For a shallow failure, soil nailing plus grillage is recommended, which has been proved effective by Li, J. (2003).

CONCLUSIONS AND FURTHER STUDY

From the study of rainfall-induced sliding of a fill slope in Shenzhen, the following conclusions can be made:

- The first reason for the sliding of the fill slope is the loose state of the fill.
- The second reason for the sliding of the fill slope is the loss of suction and the high rise of groundwater level due to the rainstorms on 19 and 20 August 2005.
- The third reason for the sliding of the fill slope is the under-designed masonry retaining wall.
- Remedial works shall be adopted before the coming of the next raining season in case the fill slope would finally fail.

Based on the study of rainfall-induced sliding of a fill slope in Shenzhen, the following recommendations for further study are suggested:

- To judge whether a liquefaction failure would occur in the fill slope, insitu density test using sand replacement technique and standard compaction test is recommended.
- To estimate the depth of wetting front, insitu permeability test using Guelph permeameter is recommended.
- To illustrate the contribution of suction to the fill slope, tensiometers and moisture probes is recommended to be installed.
- To more accurately calculate the slope stability of the fill slope, triaxial test for remolded fill sample under different compaction states is recommended.
- Seepage analysis and deep-seated slope stability analysis considering the masonry retaining wall is recommended.
- Automatic monitoring of groundwater level, horizontal displacement, soil suction and moisture content is highly recommended.

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