Full-Scale Field Monitoring of a Rainfall-Induced Sliding Slope in Hainan, China

Étude en vraie grandeur d'un talus glissant soumis à des précipitations à Hainan en Chine

Li A.G., Qiu J.J., Mo J.F., Gao W.
Shenzhen Geotechnical Investigation & Surveying Institute Co. Ltd., Shenzhen, China

Tham L.G., Yan R.W.M.
Department of Civil Engineering, The University of Hong Kong, Hong Kong, China

ABSTRACT: This paper investigates the mechanism of rainfall-induced sliding slope through a study based on a full-scale field monitoring conducted in a sliding slope in Shimei Bay, Wanning City, Hainan, China, where some premium hotels and residential buildings are being built along a natural hillside slope. Due to the heavy rainfall in October, 2011, it was found that the hillside slope was sliding during the heavy rainfall. A number of instruments, including soil moisture probes, tensiometers, open standpipes and piezometers, inclinometers, and a rain gauge were installed in the slope. Field monitoring of the sliding slope was conducted during one dry and one wet seasons before the stabilization of the sliding slope. The paper mainly introduced the instrumentation system of field monitoring of the sliding slope. It also introduced the preliminary analysis of the variations of rainfall intensity, soil moisture content, matric suction, ground water level, slope deformation during the dry season of 2011 and the wet season of 2012 before the stabilization of the sliding slope.

RÉSUMÉ : Cet article étudie le rôle des précipitations sur une pente glissante via une étude basée sur un suivi sur le terrain à grande échelle, menée dans une pente glissante dans Shimei Bay, ville de Wanning, Hainan, en Chine, où certains hôtels de luxe et des bâtiments résidentiels sont en cours de construction, le long d'une la pente naturelle. En raison des fortes pluies en Octobre 2011, il a été constaté que la pente (colline) glissait pendant les fortes pluies. Un certain nombre d'instruments, y compris les sondes d'humidité, tensiomètres, bornes-fontaines, des piézomètres ouverts, inclinomètres, et une jauge de pluie ont été installés dans la pente. Le contrôle du glissement a été effectué pendant une saison sèche et une saison humide, avant la stabilisation de la pente. Cet article présente le système d'instrumentation mise en place sur le site. On présente également dans cet article l'analyse préliminaire sur des variations de l'intensité des précipitations, l'humidité du sol, succion matricielle, le niveau de la nappe phréatique et la déformation de la pente pendant la saison sèche de 2011 et la saison des pluies de 2012, avant la mise en place des renforcements du site.

KEYWORDS: field-monitoring ; sliding slope ; rainfall-induced ; strumentation.

1 INTRODUCTION

Rainfall-induced landslides are common in the tropical areas in China, especially in Southen China. Each year hundreds of landslides, occur during the rainy season. Many of these landslides have caused heavy damage and numerous fatalities. The majority of these landslides are associated with heavy rainfall. Hence, rainfall-induced slope failure becomes one of the most common types of landslides in Hong Kong (Lumb, 1962a, 1962b, 1975; Brand, et al. 1984; Au, 1998; Franks, 1999, Dai, et al. 1999, 2001; Li , et al. 2002, 2003, 2005a, 2005b, 2006).

Due to the new policy that China aims to build the southern island of Hainan into a top international tourism destination by 2020, the Hainan local government promises to boost development not only by expanding oil and gas exploration, offering more duty free services, developing logistics, reducing pollution, but also by improving transportation networks and infrastructure. Thus, more premium hotels, resorts, family-run hotels and residential buildings are being built along the east coast of the island.

In area of our study site, a lot of landslides were reported. A total of 4 landslides were recognized within the site. Site investigation was also carried out, which found that there was even a big landslide with a scar volume of 500000 m^3 just one kilometer away from the site. There was even a heavy debris flow, which almost damaged the newly built east fast train for Haikou to Sanya, which is just 5 kilometers away. As little research work was carried out in Hainan for the landslides, there are even few documents for the landslides, only occasionally in the local newspapers.

In order to investigate the mechanism of rainfall-induced slope failure, a study is being carried out based on a full-scale field monitoring conducted in a sliding slope in Shimei Bay, Wanning City, Hainan, China, where some premium hotels and residential buildings are being built along a natural hillside slope.

Due to the heavy rainfall in October, 2011, it was found that the hillside slope was sliding during the heavy rainfall. The sliding slope was a gentle hillside, which was cut to accommodate a temporary road construction, and consisted mainly of residual soil, CDG and HDG. To characterize the soil properties of the sliding slope, a detailed site investigation was carried out prior to the instrumentation.

A number of instruments, including soil moisture probes, tensiometers, open standpipes and piezometers, inclinometers, and a rain gauge were installed in the slope. Site investigation included borehole drilling, soil sampling, field and laboratory tests was carried out. Field monitoring of the sliding slope was conducted during one dry and one wet seasons before the stabilization of the sliding slope. The pre-stabilized slope was monitored during the dry season of 2011 and the wet season of 2012. The stabilization of the sliding slope started before the end of the wet season in 2012.

Anti-sliding piles plus pre-stressed anchors were designed to stabilize the sliding slope. Other instruments including load cells and strain gauges were suggested to be installed in the anchors and piles during the stabilization of the sliding slope. It was suggested that the post-stabilized slope should also be monitored for another dry season of 2012 and another wet season of 2013.

The paper mainly introduced the instrumentation system of fielding monitoring of the sliding slope. It also introduced the preliminary analysis of the variations of rainfall intensity, soil moisture content, matric suction, ground water level, slope deformation during the dry season of 2011 and the wet season of 2012 before the stabilization of the sliding slope.

2 SITE CONDITIONS

The site is a natural hillside terrain covered by a lot of vegetation. The section was originally a gentle slope and then it was cut to accommodate the footpath for the main road. Ground investigation work was carried out during instrument installation. The site ground as revealed by the ground investigation is mainly residual soil, completely decomposed granite (CDG) and highly decomposed granite (HDG), which are underlain by moderately decomposed granite (MDG) and slightly decomposed granite (SDG).

Laboratory tests were carried out on the soil samples obtained at the sliding slope during the site investigation. The soil, as revealed by site investigation, is completely decomposed medium-grained granite and can be classified as a very weak to weak, light brown to brown, silty/clayey sand. The laboratory program to characterize the soil properties included: (1) Bulk density, (2) Dry density, (3) Specific gravity, (4) Atterberg limits and (5) Particle size distribution.

Part of the laboratory tests results are summarized in Table 1.

Table 1. Soil properties for the sliding slope.

Bulk density (Mg/m3)	*1.76~1.93*
Dry density (Mg/m3)	1.44~1.54
Specific gravity	2.627~2.655
Void ratio	0.7314~0.8443
Porosity	0.42~0.46
Liquid limit (%)	31.5~44.3
Plasticity index (%)	12~23

3 INSTRUMENTATION SYSTEM

The instruments included soil moisture probes to measure volumetric water content, tensiometers to measure matric suction (negative pore water pressure), open standpipes and piezometers to measure ground water level and positive pore water pressure, inclinometers to measure the lateral ground movements, and a rain gauge to measure rainfall intensity.

The philosophy for instrumentation design was as follows: The moisture probes and tensiometers were installed in the shallow depth to monitor volumetric water content and matric suction in the unsaturated zone of the soil. The open standpipes and piezometers were installed in both the shallow depth and greater depth to monitor both perched and deep ground water or positive pore pressure in the saturated zone of the soil. The inclinometers were installed in the soil to monitor horizontal deformation of the sliding slope. The rain gauge was installed to monitor the specific rainfall intensity of the monitored sliding slope. Figure 1 shows instrumentation layout plan.

A total of six moisture probes were used to measure volumetric water contents inside different parts of the sliding slope (Figure 1). Three moisture probes were installed in borehole M1 (M1-1 (1m), M1-2 (2m) and M1-3 (3m)) at depths of 1 m, 2 m and 3 m, respectively, at the toe of the slope. The other three moisture probes were installed in boreholes M3 (M3-1 (1m), M3-2 (2m) and M3-3 (3m)) at depths of 1 m, 2 m and 3 m, respectively, near the crest of the slope. A total of six tensiometers were used to measure matric suction at different locations of the sliding slope (Figure 1). Three of them were installed in boreholes T1 (T1-1 (1m), T1-2 (2m) and T1-3 (3m)) at depths of 1 m, 2 m, 3 m and 4 m, respectively at the toe of the sliding slope. The other three were installed in boreholes T3 (T3-1 (1m), T3-2 (2m) and T3-3 (3m)) at depths of 1 m, 2 m, 3 m and 4 m, respectively, near the crest of the sliding slope. A total of three open standpipes were used to measure ground water levels at different locations of the sliding slope (Figure 1). A total of three vibrating wire piezometers (P1, P2 and P3) were used to measure positive pore water pressures at different locations of the sliding slope (Figure 1). A total of three inclinometer tubes (IN1, IN2 and IN3) were used to measure the lateral ground movements at different locations of the sliding slope (Figure 1). One 0.5 mm "tipping bucket" rain gauge with internal logger was used to monitor the rainfall intensity of the monitored slope site automatically (Figure 1).

Ground water levels in the open standpipes were monitored manually with the help of a dipmeter. An automatic data acquisition system was set up for the sliding slope to monitor moisture content, matric suction, positive pore water pressure and horizontal deformation continuously. The automatic data acquisition system consists of sensors, cables, data loggers and power supplies. An instrumentation hut was constructed at the top of the sliding slope to house the data loggers and power supplies. The data loggers were configured to collect data at 15/30-min intervals and the data were transmitted to both the office in the site and the office in Shenzhen instantly via wireless data transition system.

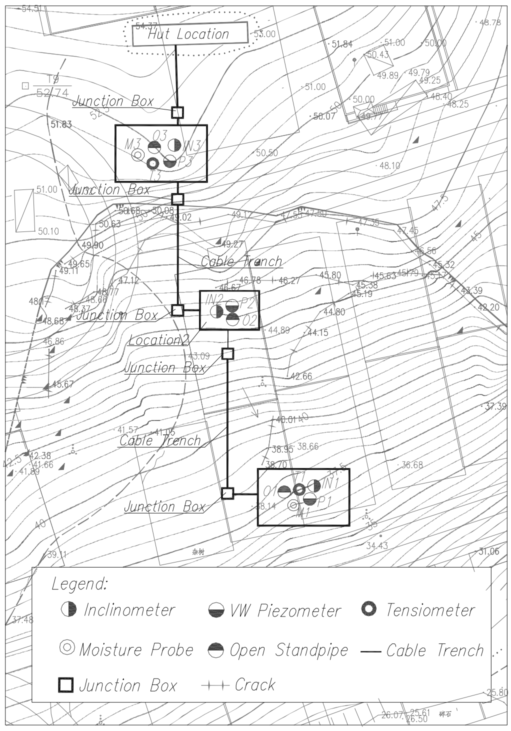

Figure 1. Boreholes and instrumentation layout plan.

4 PRELIMINARY MONITORING RESULTS

4.1 *Moisture Probes and Tensiometers*

Figures 2 and 3 show the variations of the volumetric water content and the matric suction of Borehole M3 at the crest of the sliding slope from November 2011 to June 2012. By examining the volumetric water content and the matric suction records and their comparison with daily rainfall in borehole M3 at the crest of the sliding slope during the above period (Figures 2 and 3), the following observations can be made:

(1) The volumetric water content increased due to rainfall infiltration in the wet season and decreased due to evaporation in the dry season. The matric suction decreased due to rainfall infiltration in the wet season and increased due to evaporation in the dry season.

(2) The volumetric water content at different depths was not uniform. Generally, the volumetric water content at a shallow depth was lower than that at greater depths during the dry season, while the volumetric water content at a shallow depth was higher than that at greater depths during the wet season. The matric suction at different depths was not uniform too. Generally, the matric suction at a shallow depth was higher than that at greater depths during the dry season, while the matric suction at a shallow depth was lower than that at greater depths during the wet season.

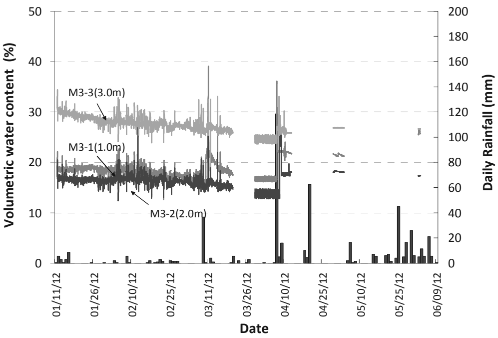

Figure 2. Variations of volumetric water content and daily rainfall from November 2011 to June 2012 in borehole M3 at the crest of the sliding slope.

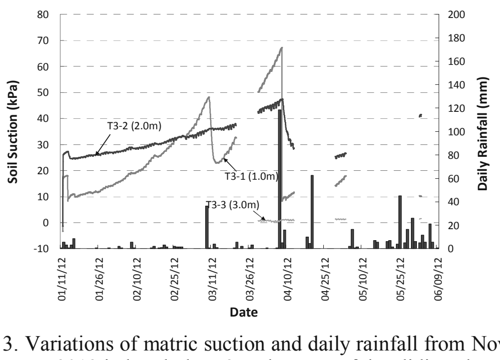

Figure 3. Variations of matric suction and daily rainfall from November 2011 to June 2012 in borehole M3 at the crest of the sliding slope.

4.2 *Open Standpipes and Piezometers*

The monitoring of the three open standpipes was carried out by using a dipmeter. The monitoring of the open standpipes was to check the monitoring data of nearby installed piezometers. Figure 4 shows the variations of the ground water levels in Borehole P1 at the toe of the sliding slope from November 2011 to June 2012. By examining the ground water level records and comparing them with the daily rainfall data during the above period, the following observations can be made:

(1) The pore water pressure at P1-A was higher than that at P1-B. It probably implies that there was a perched water level in the sliding slope and the permeability of the residual soil is higher than that of CDG.

(2) The groundwater level deceased around 6.0 m at both P1-A and P1-B.

(3) The rise of the groundwater level was sensitive to rainfall, and it was more sensitive at shallow depth. Furthermore, there was a time lag for monitoring the highest ground water level due to rainfall.

(4) The highest groundwater levels monitored in November, 2011 was probably due to the heavy rainfall during the wet season in 2011, which caused the landslide.

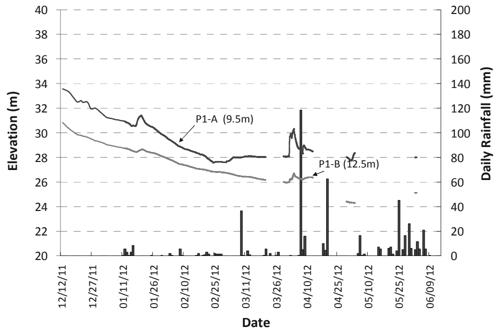

Figure 4. Variations of ground water level and daily rainfall from November 2011 to June 2012 in borehole P1 at the toe of the sliding slope

4.3 *Inclinometers*

Figure 5 shows the monitored horizontal displacements from November 2011 to June 2012 in borehole IN1 at the toe of the sliding slope. By examining the monitored horizontal displacements during the above period, the following observations can be made:

(1) The maximum horizontal displacement from June 2011 to July 2012 in borehole IN1 at the toe of the sliding slope was about 10.0 mm (Figure 25).

(2) The monitored sliding slope was sliding slowly. It is believed that with rainfall infiltration, the matric suction in soils at shallow depth partially disappeared, which decreased the stability of this sliding soil slope.

(3) The decease of groundwater level was up to 6.0 m during the dry season, however, the increase of groundwater level due to the heavy rainfall on April 7 was less than 1.0 m, therefore, the maximum horizontal displacement was insignificant.

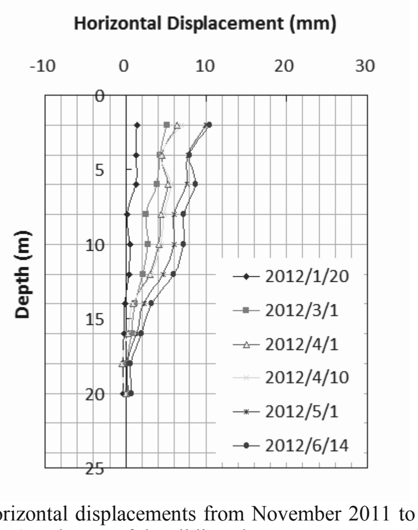

Figure 5. Horizontal displacements from November 2011 to June 2012 in borehole IN1 at the toe of the sliding slope

5 THE FAILURE OF THE MONITORING SLIDING SLOPE

As the client started the stabilization of the sliding slope using man-dug piles and anchors, it was found that it was very difficult to protect the monitored system. Therefore, automatic monitoring system for the sliding slope has to be given up. Instead, the sliding slope was being monitored manually during the stabilization of the sliding slope.

There are several rows of piles needed to be constructed during the stabilization and furthermore, there are a lot of excavations before the stabilization. Though many warning letters had been issued to the Contractor by the Consultant, before the completion of the stabilization works, due to a heavy rainfall on November 4, part of the sliding slope had completely collapsed, which caused the fifth landslide for the site.

The investigation of the fifth landslides was carried out later. It was found that the main reason for the landslide was the improper excavation. Some of the excavation has an angle of 45 ° to 50°. As the Contractor believed that the wet season would end and there would be no heavy rainfall in November 2012 just as in November 2011, improper excavation was carried out for the sliding slope.

Another very important reason for the failure of the improper excavated sliding slope may be due to the significant increase of the volumetric water content and the dramatic decrease of the matric suction of the sliding slope. It may be proved that negative pore-water pressure (or matric suction) plays a crucial role in the stability of unsaturated soil slope. With rainfall infiltration, the matric suction in soils at shallow depth would partially or completely disappear. Consequently, a slope failure may occur.

It is a pity that the automatic monitored system has to be abandoned due to the construction.

Figure 5. Failure of the sliding slope during a heavy rainfall on November 4, 2012.

6 CONCLUSIONS

From the study of the field monitoring of a monitoring sliding slope in Hainan, China and the failure of the sliding slope at last, the following conclusions can be made:

(1) The volumetric water content increased in the wet season and decreased in the dry season. Correspondingly, the matric suction decreased in the wet season and increased in the dry season.

(2) The variations of the volumetric water content and matric suction with time at different depths were different. Maximum variations often occurred near the ground surface. The large variations of volumetric water content and matric suction during rainy season at shallow depth may explain the reason why so many slope failures occurred in this region during heavy rainstorms.

(3) The ground water level generally rose during the wet season and fell during the dry season. The rise of the ground water level occurred during heavy rainfall or long after the rainfall. The ground water level also decreased temporarily after the heavy rainfall.

(4) As the volumetric water content increased during the rainfall, the monitored slope was sliding slowly, though insignificantly. Furthermore, the monitored horizontal displacement during the monitored period was not significant, which is probably due to insignificant rise of the groundwater level in the sliding slope.

(5) It is believed that the main reason for the failure of the sliding slope was the improper excavation. It could also be due to the loss of the matric suction, which plays a crucial role in the stability of unsaturated soil slope.

7 ACKNOWLEDGEMENTS

The authors would like to thank China Resources Hainan Shimei Bay Tourism & Development Co., Ltd. for their providence of the site and especially their kind assistance during the installation of the instruments and the monitoring of the sliding slope in the field.

8 REFERENCES

Lumb, P. (1962a). General nature of the soils of Hong Kong, Proc. Symp. Hong Kong Soils. Hong Kong, 19-32.

Lumb, P. (1962b). Effect of rainstorms on slope stability, Proc. Symp. Hong Kong Soils. Hong Kong, 73-87.

Lumb, P. (1975). Slope failures in Hong Kong. Q. J. Engng Geol. 8, 31-65.

Brand, E.W., Premchitt, J. & Phillipson, H.B. (1984). Relationship between rainfall and landslides. Proceedings of the fourth International Symposium on Landslides. Canada, 1, 377-384.

Au, S.W.C. (1998). Rain-induced slope instability in Hong Kong. Engineering Geology. 51, 1-36.

Franks, C.A.M. (1999). Characteristics of some rainfall-induced landslides on natural slopes, Lantau Island, Hong Kong. Quarterly Journal of Engineering Geology. 32 247-259.

Dai, F.C., Lee, C.F., Wang, S.J., & Feng, Y.Y. (1999). Stress-strain behavior of a loosely compacted volcanic-derived soil and its significance to rainfall-induced fill slope failures. Engineering Geology 53, 359-370.

Dai, F.C. & Lee, C.F. (2001). Frequency-volume relation and prediction of rainfall-induced landslides. Engineering Geology 59, No. 3-4, 253-266.

Li, A.G., Yue, Z.Q., Tham, L.G., Lee, C.F. & Law, K.T. (2002). Rainfall Infiltration at an Instrumented Cut Slope. 55th Canadian Geotechnical Conference, October 20-23, 2002, Ontario, Canada, 1159-1167.

Li, A.G., Yue, Z.Q., Tham, L.G., Lee, C.F. & Law, K.T. (2003). Design and Installation of a Comprehensive Instrumentation System for a Slope in Hong Kong. Chinese Journal of Rock Mechanics and Engineering, 22 No. 5, 790-796. (In Chinese)

Li, A.G., Yue, Z.Q., Tham, L.G., Lee, C.F. & Law, K.T. (2005a). Field Monitored Variations of Soil Moisture and Matric Suction in a Saprolite Slope. Canadian Geotechnical Journal. 42 13-26.

Li, A.G., Tham, L.G., Yue, Z.Q., Lee, C.F. & Law, K.T. (2005b). Field Soil-Water Characteristics of Completely Decomposed Granite. Journal of Geotechnical and Geoenvironmental Engineering. 131 No.9 1176-1180.

Li, A.G., Xiong, J.A., Nan, L. and Qiu, J. J. (2006). The Study of Rainfall-Induced Sliding of a Fill Slope in Shenzhen, China, The 10th IAEG Congress, 6-10 September 2006, Nottingham, United Kingdom.