Coupled Stability Analyses of Rainfall Induced Landslide: A Case Study in Taiwan Piedmont Area

Hung-Chieh Lo[1], Shih-Meng Hsu[2], Su-Yun Chi[3], Cheng-Yu Ku[4]

[1]Research Engineer, Geotechnical engineering Research Center, Sinotech Engineering Consultants, Inc., Basement No. 7, Lane 26, Yat-Sen Road, Taipei City 110, Taiwan; jaylo@sinotech.org.tw

[2]Senior Research Engineer & Director of hydrogeology research group, Geotechnical engineering Research Center, Sinotech Engineering Consultants, Inc., Basement No. 7, Lane 26, Yat-Sen Road, Taipei City 110, Taiwan; shihmeng@sinotech.org.tw

[3]Manager, Geotechnical Engineering Research Center, Sinotech Engineering Consultants, Inc., Basement No. 7, Lane 26, Yat-Sen Road, Taipei 110, Taiwan; sychi@sinotech.org.tw

[4]Assisstant Professor, Department of Harbor and River Engineering, National Taiwan Ocean University, No. 2, Beining Road, Keelung City 202, Taiwan; chkst26@mail.ntou.edu.tw

ABSTRACT: This study presents a 2D time-dependent infiltration-seepage-stability coupled hydrogeological model to simulate the seepage and slope stability of an active landslide site in northern Taiwan. The conceptual model and corresponding hydraulic and mechanical parameters applied in the model were based on a series of in-situ investigations and laboratory experimental results. A seepage analysis was conducted, and the model was calibrated and verified from the field monitoring data in order to minimize the difference between the computed pore pressures and the observed piezometric levels. A stability analysis coupled with the results of seepage analysis was performed to determine the slip potential of the landslide site under the rainfall brought up by two typhoon events. Various designed rainfall with different patterns, intensity and accumulated amount was then introduced to the model. The relationship between different rainfall characteristics and stability of the landslide site was identified and provided a good indication for the risk management under various rainfall conditions.

1. INTRODUCTION AND OBJECTIVES

Taiwan is an island located in an active collision zone between the Eurasian Plate and the Pacific Plate. In recent years, due to the abnormal climate change, typhoon events with high rainfall intensity frequently occurred during the summer and usually triggered severe damages such as landslides in piedmont areas. To better understand such an issue, using a numerical model to simulate rainfall infiltration and slope stability is fairly suitable. By integrating infiltration-seepage-stability to achieve a coupled time-dependent analysis, the factor of safety of the slope can be computed under various rainfall conditions and pore pressure distributions. Several studies performed coupled analysis to simulate some actual landslide problems in these years (Gasmo et al., 2000; Rahardjo et al., 2001;Blatz et al., 2004;Casagli et al. 2006;Cascini et al., 2006;Calvello et al., 2008). In this study, a hydrogeological conceptual model was established to simulate seepage and slope stability at an active landslide site in northern Taiwan. Realization of the conceptual model and corresponding hydraulic and mechanical parameters applied in the model were based on a series of in-situ investigations and laboratory experimental results. The hydraulic parameters applied in the model were calibrated based on in-situ observed rainfall and piezometric levels. The precipitation data observed from two typhoon events, which took place in September of 2008, were used to verify the model. The stability analysis coupled with the result of seepage analysis was subsequently conducted to determine the slip potential of the slope during two typhoon events. Finally, various designed rainfall with different patterns, intensity and amount were introduced to the model, and the relationship between rainfall characteristics and the slope stability of the landslide site was established.

2. HYDROGEOLOGICAL INVESTIGATION OF THE LANDSLIDE SITE

The landslide site is located near the middle stream of the Da-Han River in northern Taiwan (Figure 1). In order to establish a precise hydrogeological conceptual model, four boreholes were drilled, and a series of investigation approaches including light detecting and raging (LIDAR), ground resistivity image profiling (RIP), and borehole image scanning were conducted at the landslide site. According to the results, the elevation of the landslide site was identified (28 degree in slope angle), and the strata were divided into three layers, including colluvial cover, weathered bedrock, and bedrock. The in-situ double-ring infiltration test and packer isolated test were employed to obtain the hydraulic conductivity of three layers. The laboratory tests, such as physical properties test, pressure plate test, direct shear test, and triaxial test were conducted to acquire physical and mechanical parameters for each layer. Furthermore, the rain gage and piezometers were installed on the landslide site, and the observed data were collected to calibrate and verify the model.

3. MODELING OF SEEPAGE AND SLOPE STABILITY

An engineering tool GeoStudio, developed by the University of Calgary, was adopted to simulate seepage and slope stability of the landslide site in this study.

3.1. Seepage Analysis

A finite element analysis module SEEP/W was used to simulate the rainfall infiltration and groundwater flow in this study. Based on Darcy's law, the governing equation is given as:

$$\frac{\partial}{\partial x}\left(Kx\,\frac{\partial H}{\partial x}\right)+\frac{\partial}{\partial y}\left(Ky\,\frac{\partial H}{\partial y}\right)+Q=\frac{\partial\theta}{\partial t} \qquad (1)$$

where H=total head; K_x=hydraulic conductivity in horizontal direction; K_y=hydraulic conductivity in vertical direction; Q=applied boundary flux; θ =volumetric water content; and t=time. For the hydraulic boundary conditions applied in the model, the fixed head was on the right and left while the zero flux was on the bottom. The observed rainfall data was applied as the recharge flux on slope surface. Both steady-state and transient analysis were performed. In transient analysis, the daily time step was applied. The transient hydraulic characteristics, such as flow field, distribution of pressure head and water content can be computed in SEEP/W. The 2D hydrogeological model of the landslide site was shown in Figure 1.

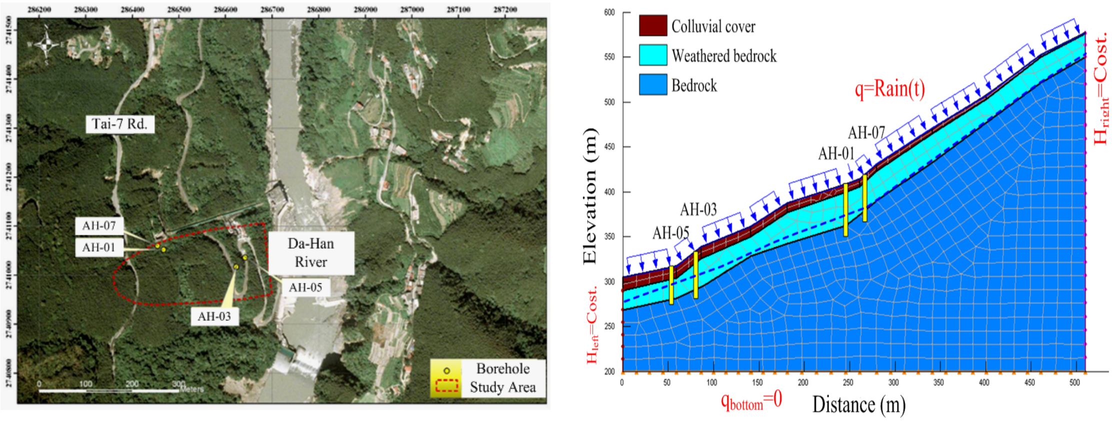


Fig. 1 The aerial photo of the landslide site (left); and the 2D hydrogeological conceptual model (right)

3.2. Calibration and Verification

In order to minimize the divergences between the computed results and real scenario, the calibration and verification of the model are crucial tasks. In this study, three borehole piezometric data observed from December 1, 2007 to August 1, 2008 were adopted to calibrate the hydraulic parameters. The calibrated results indicated that the average errors between simulated and observed groundwater levels of three boreholes are ranging from 1.82 to 2.28% as shown in Table 1. By comparing calibrated groundwater level with observed one, a similar trend in groundwater level movement was found as shown in Figure 2. Because the groundwater is mainly located in the fractured weathered bedrock, most rainfall may flow downward to the hillside through the fractures and hardly remained in the layer. Therefore, both groundwater levels showed small oscillation. Although a well calibration is achieved, the computed groundwater level is slightly higher than the observed groundwater level, namely, the numerical model still possessed some deviations and difficult to fully represent the complexity of real hydrogeological conditions. The calibrated parameters applied in the model were summarized in Table 2.

The rainfall data collected from Sinlerku and Jangmi typhoons, which occurred on September 11, 2008 and September 26, 2008, respectively, were introduced to the model to compute the pore water pressure during two typhoon events. The computed groundwater level was then compared with the observed piezometric level. The corresponding trends were found as shown in Figure 3. The average errors between simulated and observed groundwater levels are ranging from 1.50 to 2.58% for Sinlerku typhoon, and from 0.76 to 0.94% for Jangmi typhoon. It verified that the model is able to represent the real situation.

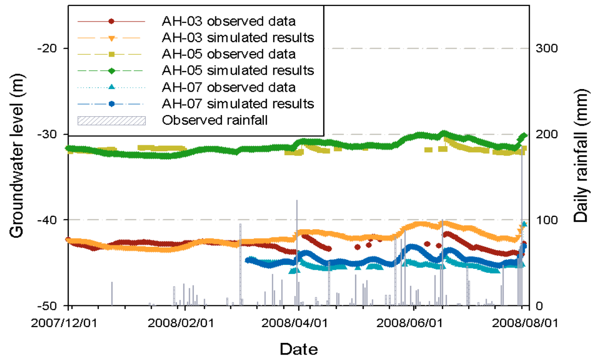


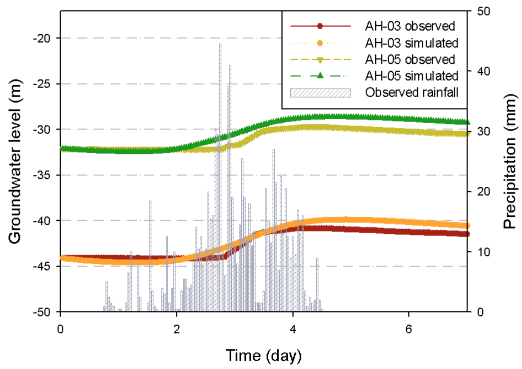
Fig. 2 Comparison of calibrated and observed groundwater level

Table 1. The error between calibrated and observed groundwater level

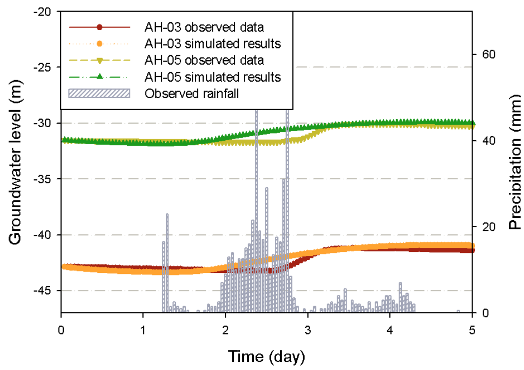
Error (%) \ Borehole No.	AH-03	AH-05	AH-07
Maximum error	7.40	5.71	3.70
Minimum error	0.08	0.05	0.01
Average error	2.02	2.28	1.82
Standard deviation	1.61	1.33	1.19

Table 2. The calibrated hydraulic parameters and applied mechanical parameters

Parameter \ Layer	Colluvial cover	Weathered bedrock	Bedrock
Hydraulic conductivity, K (m/sec)	1.63×10^{-5}	7.94×10^{-5}	7.75×10^{-8}
Volumetric water content, ω (%)	23	22	20
Hydraulic conductivity anisotropy ratio, Kr	1	0.5	1
Unit weight, γ_t (kN/m^3)	16	22	26
Cohesion, c (kPa)	10	80	500
Friction angel, ϕ (deg)	29	32	42



(a) Sinlerku Typhoon Event

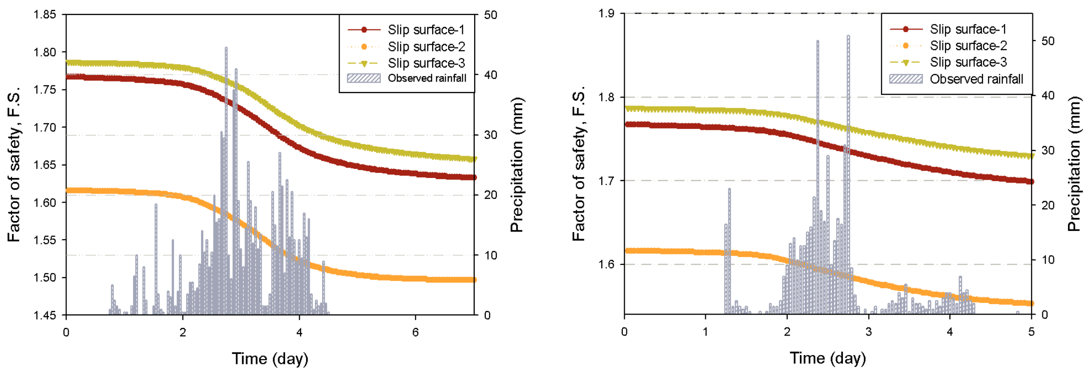


(b) Jangmi Typhoon Event

Fig. 3 The verified results for two typhoon events

3.3. Slope stability analysis

A limit equilibrium method module SLOPE/W was used for the stability analysis. Three slip surfaces, located in the interface between weathered bedrock and bedrock, were recognized and specified to the model based on in-situ investigations including rock core drilling, ground resistivity profiling and borehole image scanning. Considering the unsaturated soil status, the factor of safety computed by SLOPE/W is based on Mohr-Coulomb modified equation suggested by Fredlund (1978). The computed factor of safety during Sinlerku and Jangmi typhoons was shown in Figure 4. Both trends demonstrated that the factor of safety decreased as the rainfall persisted. A more obvious drop in factor of safety, around 7.2~10.1%, was found in Sinlerku typhoon event. Because the Jangmi typhoon had shorter rainfall duration and smaller rainfall amount, the factor of safety only decreased by 3.2~3.9%. Most results showed the factors of safety are greater than 1.5 at last stage, which implied the landslide site is stable under such rainfall condition. The mechanical parameters applied in SLOPE/W were shown in Table 2.



(a) Sinlerku typhoon (b) Jangmi typhoon

Fig. 4 The computed factor of safety during two typhoon events

4. THE RELATIONSHIP BETWEEN THE RAINFALL CHARACTERISTICS AND SLOPE STABILITY

In order to understand the stability of the landslide site under different rainfall characteristics, three types of deigned rainfall conditions, with different patterns, intensity and accumulated amount, were introduced to the model to conduct the coupled stability analysis. In this study, the amount of designed rainfall (824 mm) applied in the model was based on the frequency analysis from the precipitation observed in a rainfall station near the landslide site. The factor of safety was computed and can be used to establish the relationship between the rainfall characteristics and slope stability.

4.1. Rainfall Pattern and Slope Stability

Five rainfall patterns, including advanced, delayed, central, doubled and uniform, were designed and applied in the model (Figure 5). The results of the stability analysis were shown in Figure 6. At the initial stage, about the first 10 hours, the factor of safety for all rainfall patterns had similar and relatively small decline. As time elapsed, the factor of safety for delayed and uniform rainfall patterns declined at an accelerated speed while the factor of safety for other three patterns had a relatively constant decline. At the end of time step, 48 hours later, the factor of safety for central, doubled, and uniform rainfall patterns decreased by 4.5%, 4.6%, and 7.2%, respectively. The factor of safety for the advanced rainfall pattern had the smallest drop of 4.1% while that for the delayed rainfall pattern had the greatest drop of 9.9%. It can be concluded that the delayed rainfall pattern threatens the slope stability the most among all the rainfall patterns.

4.2. Rainfall Intensity and Slope Stability

The slope stability under different rainfall intensity was also examined. The results were shown in Figure 7. The factor of safety decreased by 6.8~7.8% when the rainfall intensity at the levels from 11.4 mm/hr to 22.9 mm/hr. However, as the rainfall intensity increases to more than 22.9mm/hr, apparent declines in factor of safety were displayed. Most noticeably, the factor of safety dropped by 16.4% when the rainfall intensity reached to 68.7 mm/hr. Looking at the rainfall intensity at 68.7 mm/hr, 45.7 mm/hr, 22.9 mm/hr and 11.4 mm/hr after 10 hours, the corresponding decreases in factor of safety were 14%, 5.5%, 0.9% and 0.2%, respectively. It demonstrated that the slope stability depends on the degree of rainfall intensity.

The relationship between the rainfall intensity and factor of safety was shown in Figure 9. The factor of safety significantly dropped in a linear trend when the rainfall intensity increased from 22.9 to 54.9 mm/hr. However, the pace of decline eased significantly after the rainfall intensity reached to 68.7 mm/hr. It revealed that a threshold of rainfall intensity on the slope stability existed. Since the hydraulic conductivity of the colluvial cover is 1.63×10^{-5} m/sec (58.68 mm/hr), the rainfall may not fully infiltrate to the layer while the intensity greater than this value. Therefore, it can be concluded that the slope stability closely related to the degree of infiltration that the layer possesses under various rainfall intensities.

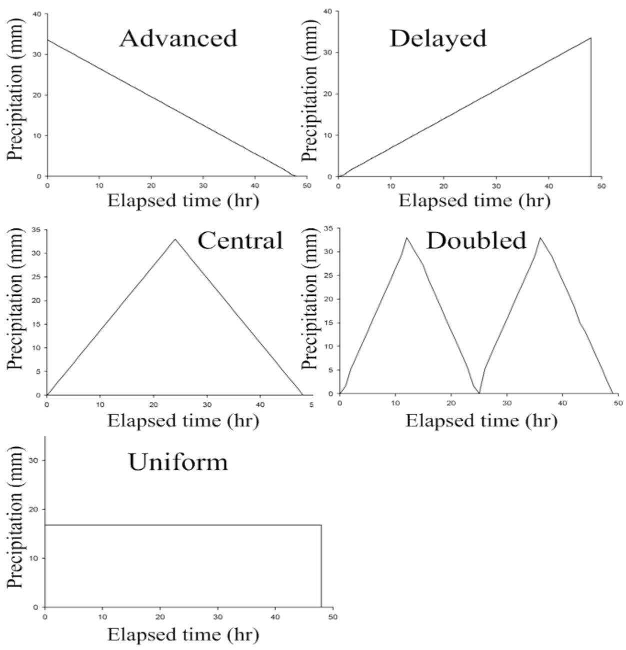


Fig. 5 Types of rainfall patterns

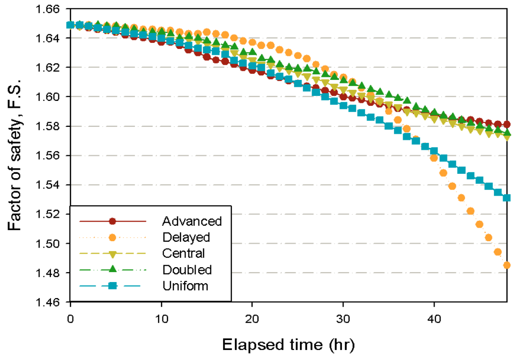


Fig. 6 The computed factor of safety on various rainfall patterns

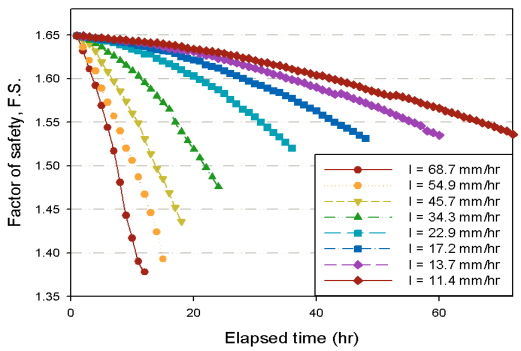


Fig. 7 The computed factor of safety on various rainfall intensity

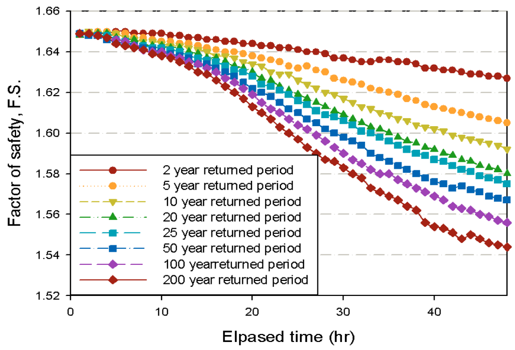


Fig. 8 The computed factor of safety on various rainfall amount

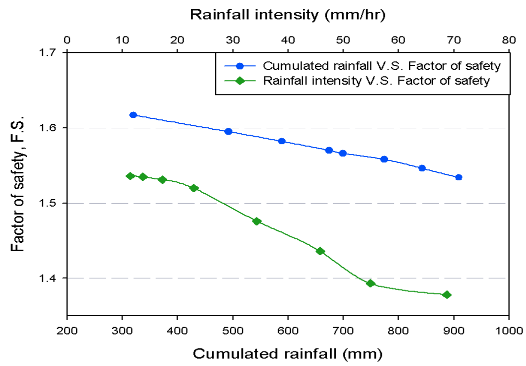


Fig. 9 The relationship between rainfall conditions and factor of safety

4.3. Cumulative Rainfall and Slope Stability

The influence of the cumulative rainfall on the slope stability is finally discussed. The factor of safety under different cumulative rainfall was shown in Figure 8, in which various rainfall amounts applied in the analysis were obtained from rainfall frequency analysis with 48-hour duration. It is apparent that the degree of decline in the factor of safety increased as the rainfall amount increased. The decrease in factor of safety for rainfall amount of 320mm, 674mm and 909mm is 1.3%, 4.2% and 6.4%, respectively. Figure 9 represented the relationship between the rainfall amount and the factor of safety. It also showed that the slope stability slightly decreased as the rainfall amount increased. As the above section described, the groundwater at the landslide site is mainly located in the fractured weathered bedrock. Most rainfall may flow downward to the hillside through the fractures and difficult to remain in the pore space. Therefore, the groundwater may not easy to rise. Under such circumstance, the factor of safety would not apparently descend.

CONCLUSIONS

This paper used the numerical model to determine the stability of an active landslide site under different rainfall conditions. In order to obtain practical results, the hydraulic parameters in seepage analysis were calibrated according to in-situ long term observed data. Two typhoon events were used to verify the model. The results indicated that the model is capable of simulating the real situation. The coupled stability analysis was then conducted to compute the factor of safety during the typhoon events. The results revealed that the landslide site is stable under the rainfall conditions for two typhoon events.

The relationships between rainfall characteristics and slope stability were also discussed. In terms of the rainfall pattern, the delayed rainfall pattern is the type that threatens the slope stability the most. Besides, the simulation revealed that the factor of safety decreased as the rainfall intensity increased. Furthermore, the analysis indicated that the rainfall amount only slightly affect the slope stability. It is due to the higher hydraulic conductivity of the weathered bedrock that engendered the difficulty in accumulating pore water pressure in the layer under different accumulated rainfall amount.

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