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Case Study of Ji-Lou Landslide Triggered by Typhoon Morakot

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ABSTRACT

Typhoon Morakot brought tremendous rainfall to southern Taiwan. It caused many villages and towns to be flooded in low-lying areas as well as numerous landslides and debris flows in mountainous areas. Therefore, the disaster resulted in severe casualties and property damage. This paper presents a case study of Ji-Lou landslide triggered by Typhoon Morakot. A series of hydrogeological investigations, in-site tests, and laboratory experiments were carried out to establish the hydrogeological conceptual model of Ji-Lou landslide. Coupled analysis of rainfall, infiltration, seepage, slope stability, and slope deformation was used to estimate the slope stability of Ji-Lou landslide during Typhoon Morakot. For the active landslide analysis, a two-dimensional numerical program, GeoStudio, was employed to perform the modeling practice. The results show the F.S. of Ji-Lou landslide reduced from 1.57 to 0.97 during Typhoon Morakot. In addition, the results of coupled analysis demonstrated good agreement between the predicted results and the data from field monitoring of the typhoon event. Further, it is expected the landslide initiation, enlargement, and reactivation can be more confidently predicted through using the aforementioned physics-based models.

KEY WORDS: Landslide; Typhoon Morakot; Ji-Lou landslide.

INTRODUCTION

Taiwan is an active mountain belt created by the oblique collision between the northern Luzon arc and the Asian continental margin. The inherent complexities of geological nature create numerous discontinuities through rock masses and relatively steep hillside on the island. In recent years, the increase in the frequency and intensity of extreme natural events due to global warming or climate change brought significant landslide and debris flow hazards. The Chi-Chi Earthquake and the following several typhoon events such as Toraji, Minduli, and Airi in particular triggered hazards including landslides, debris flows, and floods which caused significant property damage and inflicted heavy casualties. In 2009, a comprehensive survey was conducted on landslides caused by Typhoon Morakot in southern Taiwan. Typhoon Morakot caused many villages and towns to be flooded in low-lying areas as well as numerous landslides and debris flows in mountainous areas. Therefore, the disaster resulted in severe casualties and property damage.

The causes of landslides in these slopes are attributed to a number of factors. As is well known, rainfall is one of the most significant triggering factors for landslide occurrence (Ng and Shi, 1998). In general, the rainfall infiltration could result in changing the suction and the moisture of soil, raising the unit weight of soil, and reducing the shear strength of soil in the colluvium of landslide. The stability of landslide is closely related to the groundwater pressure in response to rainfall infiltration, the geological and topographical conditions, and the physical and mechanical parameters. To assess the potential susceptibility to landslide, an effective modeling of rainfall-induced landslide is essential (Jiao *et al.*, 2005; Tsaparas *et al.*, 2002).

Taking Ji-Lou landslide as an example, the paper presents the modeling of rainfall-induced landslide using a numerical approach coupled with infiltration, seepage, slope stability, and slope deformation. The establishment of model was based on the in-situ investigations, including geological drilling, surface geological investigation, geophysical investigation, and borehole explorations. The material strength and hydraulic properties of model were given both by the field and laboratory tests. In addition, the monitoring data of landslide were collected and used to compare with the modeling results. It is expected that these results can be a reference to the further slope stability assessment under a given predicted rainfall.

CASE BACKGROUND

Ji-Lou tribe, located at Gaoping river watershed in the southern Taiwan, is an active landslide due to typhoon events. Coordinates for the case study site are 224221, 2515673 (TWD97). The site was selected as the results of previous reports and geological survey. Fig. 1(a) shows the panorama view of Ji-Lou tribe before Typhoon Morakot. On August 8, 2009, Typhoon Morakot brought significant rainfall causing landslide at the down slope of the Ji-Lou tribe which shown as Fig. 1(b).

Ji-Lou tribe has abundant rainfall due to the surrounding densely wooded mountains. According to the Central Weather Bureau, the annual precipitation at the Ji-Lou tribe averages 2,894 millimeters, the highest monthly value is in June with 615 millimeters, and the lowest value is in January with 23 millimeters. Approximately 86.6% of annual rainfall occurs May to September, leaving just a small percent of rainfall the rest of the year. This concentrated rainfall in the summer is significant because it produces conditions for slope failure, particularly in June to August when peak rainfall occurs.

In case study, the paper defined the Ji-Lou study area which shown as Fig. 2. The topography of the site is generally high in the west, sloping downward at approximately 25 degrees toward the east with a range in elevation between 900-1,100 m. The river is part of the Ailiaobei river, which is a tributary in the Gaoping river watershed. The Ji-Lou study area is located at the source of the Ailiaobei tributary. According to the geologic map (1/50,000) by Central Geological Survey (Sinotech Engineering Consultants, Inc., 2009) (Fig. 2), Ji-Lou study area belongs to Chaochou formation. The lithology of Chaochou formation is slate intercalated with thin beds of meta-sandstone and the slaty cleavage is well developed.

(a) Before the Typhoon Morakot disaster

(b) After the Typhoon Morakot disaster

Fig. 1 Panorama view of Ji-Lou study area and landslide photo triggered by Typhoon Morakot.

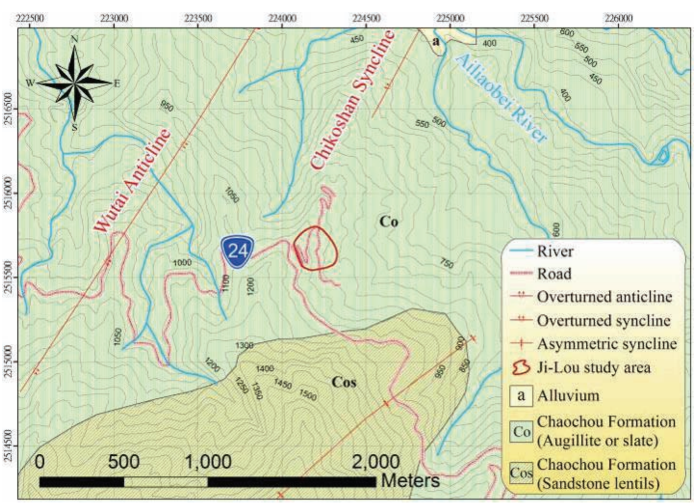


Fig. 2 Regional geological map of Ji-Lou study area. (Sinotech Engineering Consultants, Inc., 2009)

HYDROGEOLOGIC INVESTIGATION

For improving understanding of landslide behaviors, the study finds out the hydrogeological properties of Ji-Lou study area using several investigation methods. The investigation methods including geological drilling, surface geological investigation, double-ring infiltration test, geophysical prospecting methods (resistivity image profiling method, RIP; borehole televiewer; borehole logging; double packer test), pressure plate test, and laboratory tests.

Table 1 shows the purpose and applications of above investigation methods. For the site characterization, borehole drilling and downhole testings including borehole televiewer, borehole logging, and double packer system to the study of hydraulic properties of fractured rocks were conducted for the hydrogeological investigation of active landslides. The double-ring infiltration test and laboratory tests were also made to obtain the mechanical parameters. Fig. 3 shows the results of investigation methods of Table 1 provide topography, geology, and hydrogeological property for establishing the conceptual model of Ji-Lou study area.

Table 1. Purpose and applications of hydrogeological investigation.

Method	Purpose and applications
Geological drilling	1. Geological structure and mapping; 2. Hydrogeological properties of numerical analysis; 3. Potential slip surface of landslide.
Surface geological investigation	1. Topographic and geologic features.
Double-ring infiltration test	1. Infiltration rate of colluvium; 2. Hydrogeological properties of numerical analysis.
Resistivity image profiling method	1. Potential slip surface of landslide; 2. Aquifer characteristic and geological features.
Borehole televiewer and logging	1. Borehole image and geological features; 2. Strikes and dips of geologic features; 3. Collection and interpretation of core samples.
Double packer test	1. Hydraulic conductivity of rock mass; 2. Aquifer characteristic of landslide.
Pressure plate test	1. Soil-water characteristic curve of colluvium; 2. Hydrogeological properties of numerical analysis.
Laboratory test	1. Hydrogeological properties of numerical analysis.

IN-SITU MONITORING SYSTEM

Monitoring system

The monitoring system set up in the Ji-Lou study area included: one set of rain gauges (FR-02), one surface extensometer (FE-02), two observation wells (FH-21 and FH-25), two multi-layer observation wells at varying depths (FH-27 and FH-29), 15 surface observation points (TFA-01~TFA-15), and three inclinometers (FH-21, FH-23 and FH-25). The investigation simultaneously recorded rainfall, groundwater levels, strain, and deformation of the unsaturated soil matrix at Ji-Lou study area. The layout and design of monitoring system at Ji-Lou study area is shown in Fig. 4.

Monitoring results

(A) Precipitation

Fig. 5(a) shows the precipitation data of Ji-Lou study area. According to Fig. 5(a), we know that the precipitation amount of 1,840 mm was recorded during the monitoring period of June 19, 2009 to October 9, 2009, at the Ji-Lou study area. Rainfall in the area during Typhoon Morakot was recorded as 1,216 mm. The greatest daily rainfall was on August 8, 2009, with 580 mm.

(B) Groundwater table

The groundwater level at the Ji-Lou study area was monitored using observation wells. Figs. 5(b)~5(c) show the trend of the groundwater level of Ji-Lou study area (FH-21 and FH-25). The results show that the groundwater level rises with the amount of precipitation and is significantly impacted by events such as heavy rains associated with typhoons. For example, the groundwater level of FH-21 is raising over 26 m (from GL-45.10 m to GL-18.76 m).

(C) Surface and ground movement

The monitoring system for the surface and ground movement at the Ji-Lou study area included the surface observation points, surface extensometer and inclinometers. The findings are as follows. The locations of surface observation points are shown in Fig. 4(b). Measurements were taken before and after Typhoon Morakot. Observations found that after Typhoon Morakot the displacement of each point was significant, with displacement ranging between 1.33~107.59 cm. Furthermore, TFA-01, TFA-03, TFA-04, and TFA-05 were destroyed after Typhoon Morakot.

This shows that the Ji-Lou study area has large-scale slide. The surface extensometers shown in Fig. 5(d), were arranged according to an anticipated event such as Typhoon Morakot. Surface displacement at the top of the slope was found to be about 2.3 cm. Ground movement measurements were also taken prior to the typhoon event. Monitoring results surrounding Typhoon Morakot indicate that the Ji-Lou study area has experienced a large-scale landslide.

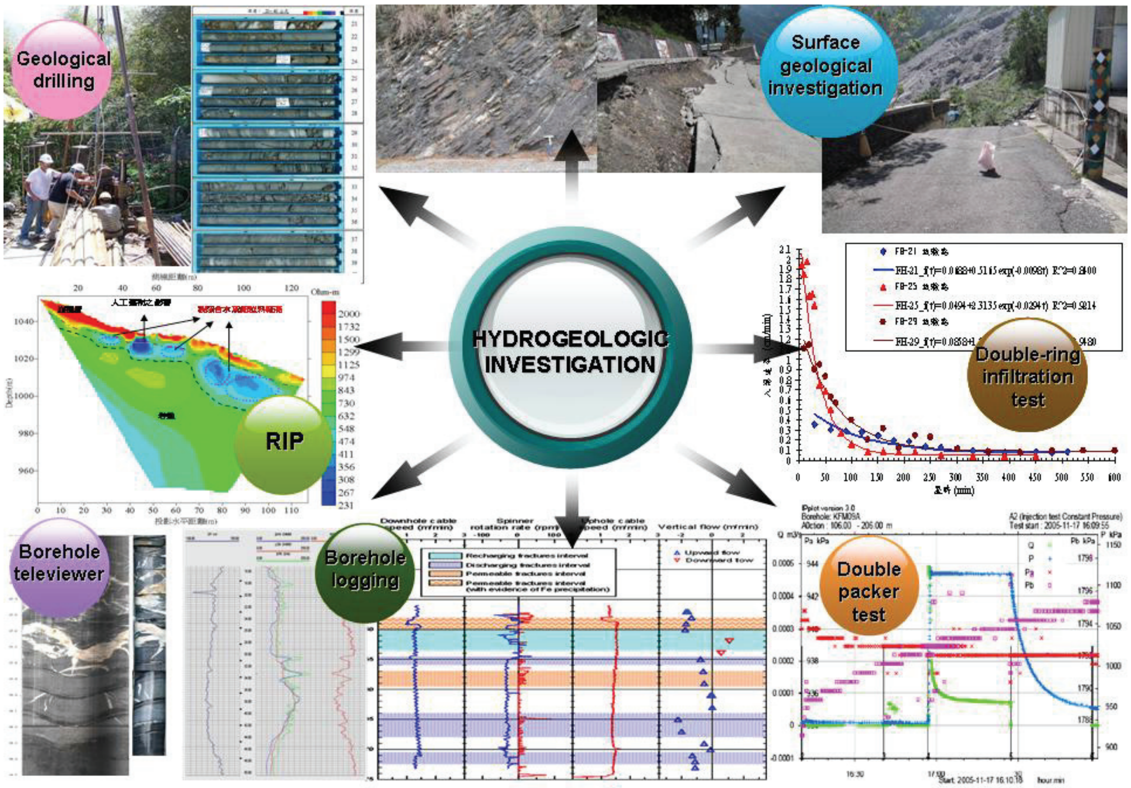
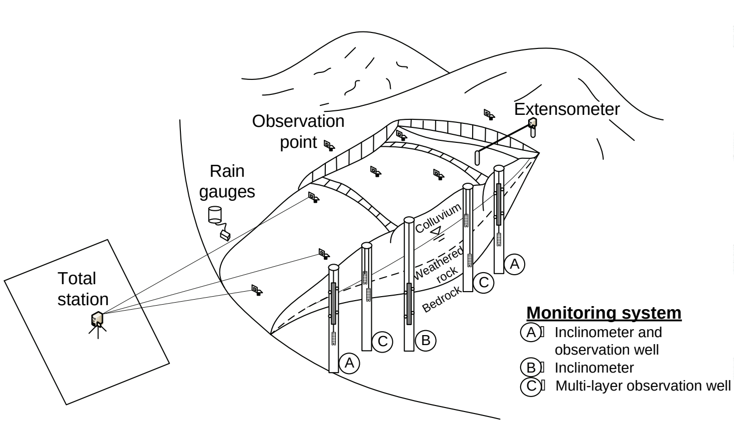
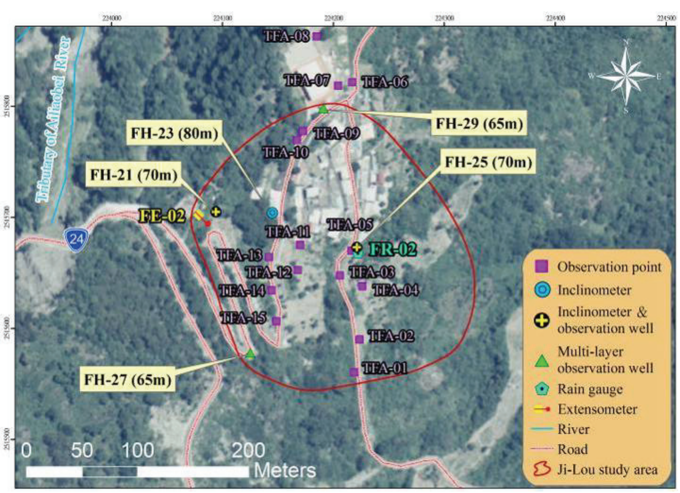


Fig. 3　Results of hydrogeological investigation.



(a) Layout and design of monitoring system



(b) Layout of monitoring system of Ji-Lou study area (taken on 2009)

Fig. 4　Layout and design of monitoring system at Ji-Lou study area.

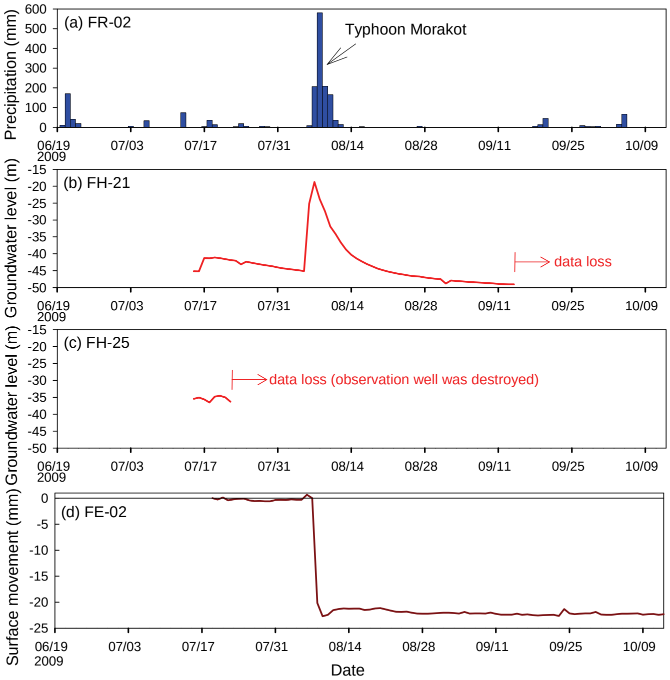


Fig. 5 Monitoring results of Ji-Lou study area.

ANALYTICAL PROCESS

The analytical process of this paper shows as Fig. 6. The analytical procedure for the Ji-Lou study area included: incorporating new data into the hydrogeologic conceptual model. The data was collected through fieldwork (Table 1). To improve understanding of active landslide triggering mechanisms especially focused on the rainfall induced landslide, modeling and analysis using two-dimensional unsaturated numerical programs, GeoStudio, was made.

GeoStudio can be used to model both saturated and unsaturated flows under steady-state and transient conditions. The SEEP/W module of GeoStudio was used to simulate the pore-water pressure changes that were measured in the field. Flux sections were used to determine the infiltration rate in the modelled slope. The steady-state seepage analysis was based on steady state seepage flow rates and normal groundwater levels. The transient state seepage analysis used the rainfall hygrograph to determine the initial boundary of the infiltration, and simulate the variation in water table level at each time.

The SLOPE/W module of GeoStudio was used to quantify how the change in pore-water pressures affected the factor of safety of the slope. The SIGMA/W module of GeoStudio was used to simulate the ground deformation. Seepage flow and groundwater level of each time step is all provided by the above SEEP/W simulation result.

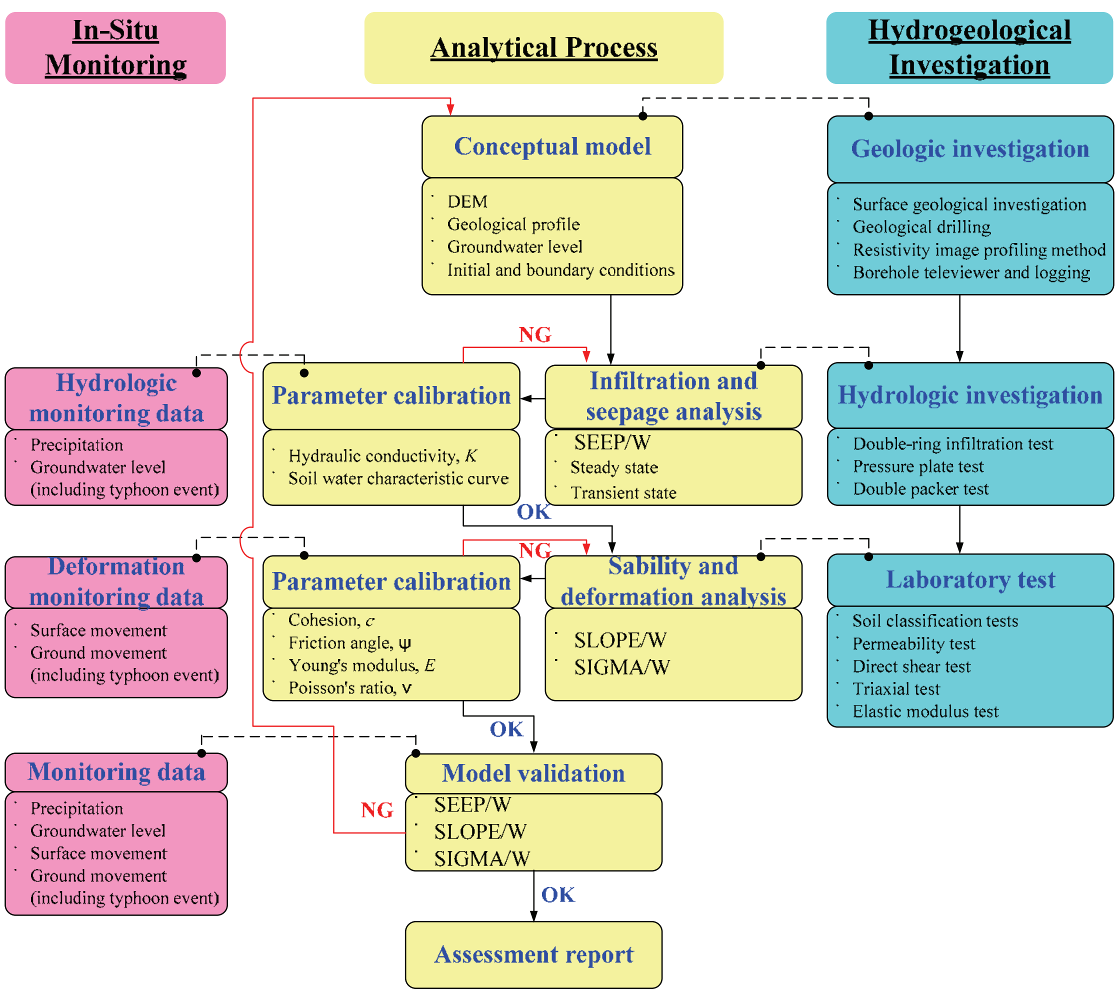


Fig. 6 Flow chart of rainfall-induced landslides hazard assessment.

ANALYSIS RESULTS AND DISCUSSION

Hydrogeologic conceptual model

The numerical geological model of the stuay area was established by the 5 m × 5 m DEM. This analysis profile starts from the top of the crest line and passes through boreholes FH-21, FH-23 and FH-25, and then down to the bottom of the trench. The hydrogeologic unit of this site can be divided into the colluvium layer and the bedrock layer. Morphometric and geotechnical analyses were carried out for Ji-Lou study area through a series of in-situ and laboratory tests, the results of which were used as input for the modeling process.

The boundary conditions of the hydrogeologic conceptual model are shown in Fig. 7. To analyze the infiltration and seepage flow, the left side boundary (SA) was set as a constant head boundary equal to the water table of the toe creek trench. The right side boundary (RB) was set as a constant because a crest line had already been established. The lower boundary (AB) was set as a no-flux boundary. The surface of the slope (RS) was then set as a rainfall-infiltration boundary. The steady state seepage flow refers to the average annual rainfall. The transient state seepage analysis was then set as the amount of precipitation. When the deformation analyzed was performed, the left and right sides were set at zero displacement in the horizontal direction, while in the bottom boundary both the horizontal and vertical displacements were zero.

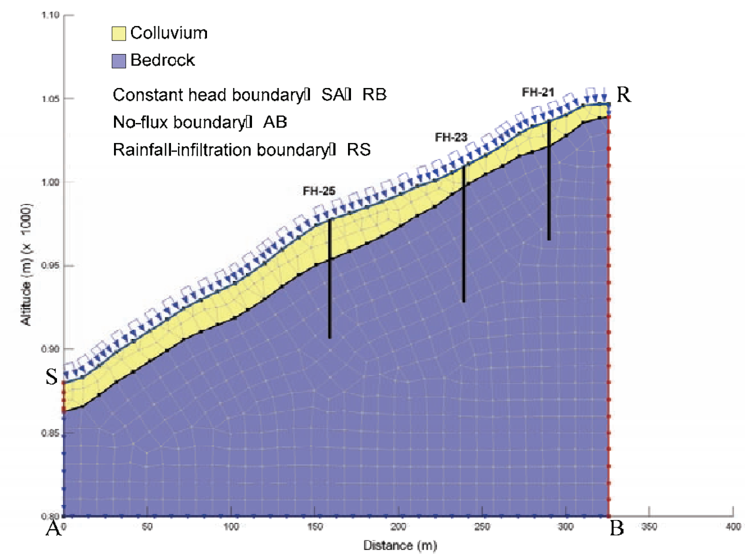


Fig. 7 Hydrogeologic conceptual model and boundary conditions of Ji-Lou study area.

Infiltration and seepage analysis

The reference values of parameters were obtained from the series of investigations which shown as Table 1, and then further verified by the in-situ monitoring data observed from July 16, 2009 to August 24, 2009. This study first calibrated the hydraulic parameters by comparing data without measured rainfall to the typical groundwater level for steady state seepage flow analysis. Then the fluctuating groundwater levels experienced during rainfall events (including Typhoon Morakot) were used in the transient seepage analysis to identify the accuracy of all hydraulic parameters. Using the above-mentioned procedure, hydraulic parameters (Table 2) and groundwater level characteristic for this site were determined, and the follow-up stability and displacement analysis were conducted. The results of the steady state and transient state analyses are described as follows.

Table 2. Hydrogeological parameters of Ji-Lou study area.

	Colluvium	Bedrock
Hydraulic conductivity, K_s (m/sec)	1.39×10^{-4}	1.00×10^{-6}
Volumetric water content, w (%)	39	9
Unit weight, γ_t (kN/m^3)	18.0	25.9
Cohesion, C (kPa)	42	300
Friction angle, ψ (deg)	36	37
Young's modulus, E (kPa)	6.0×10^4	2.5×10^6
Poisson's ratio, ν	0.24	0.14

Note: K_s was obtained from permeability test and double packer test; w was obtained from pressure plate test; γ_t was obtained from soil classification tests; C and ψ were obtained from direct shear test and triaxial test; E and ν were was obtained from elastic modulus test.

The steady state seepage flow analysis aimed to align with the observed normal water level of well No. FH-21 and FH-25. Monitoring data prior to Typhoon Morakot, indicated the normal groundwater level in FH-21 and FH-25 to be between GL-41~45 m and GL-34~36 m respectively. Through steady state seepage flow analysis, it is known from the seepage flow vector that the seepage velocity along the interface between the colluvium layer and the bedrock layer is more rapid.

The transient state seepage analysis was initiated from the above steady state analysis with normal groundwater levels, and set the slope surface as the rainfall infiltration boundary to lead to the situation of groundwater level variation and water seepage flow in the rainfall conditions. The rainfall infiltration period used for the analysis was from July 16 to August 24, 2009. This period included Typhoon Morakot. The rainfall hydrograph is shown in Fig. 8(a).

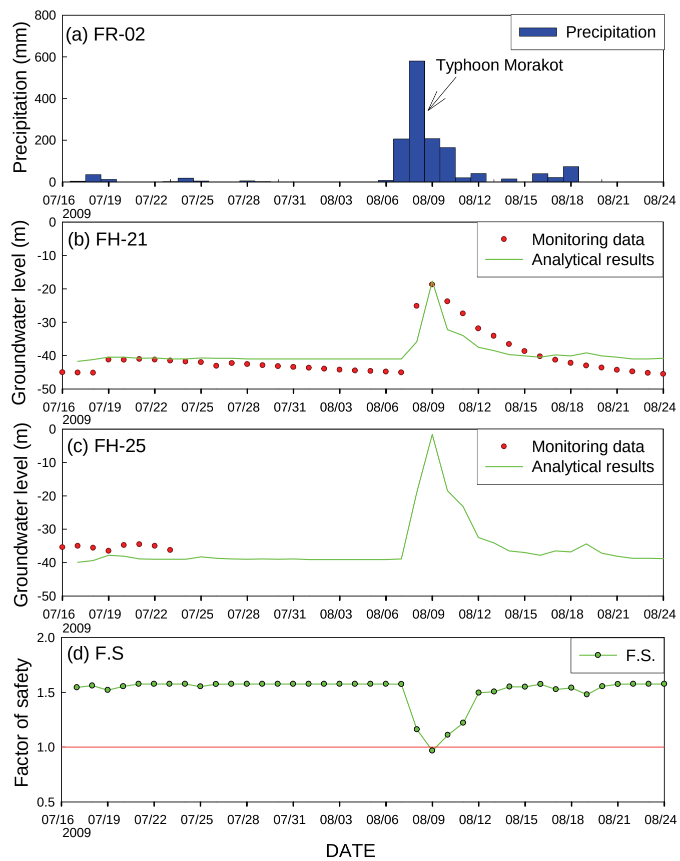


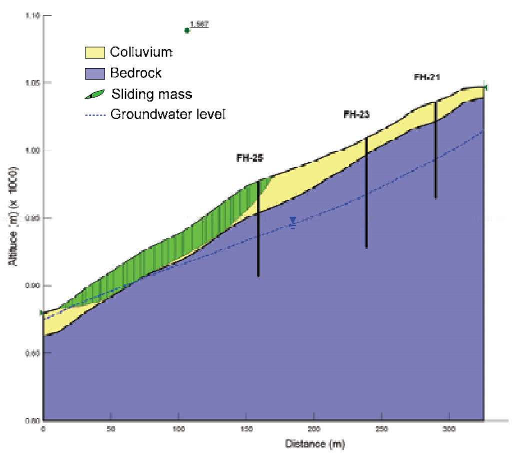
Fig. 8 Analysis results of rainfall-induced Ji-Lou study area hazard assessment.

In Fig. 8(b) and 8(c), the dotted medium red line indicates the record for the groundwater level of the observation well FH-21 and FH-25 respectively. The analytical results shown by the green solid line follow the groundwater level variation trend for the period of Typhoon Morakot. For example, Fig. 8(b) shows the groundwater level from GL-41 m rise to GL-18.8 m during the period of Typhoon Morakot. The results of coupled analysis demonstrated good agreement between the predicted results and the data from field monitoring of the typhoon event.

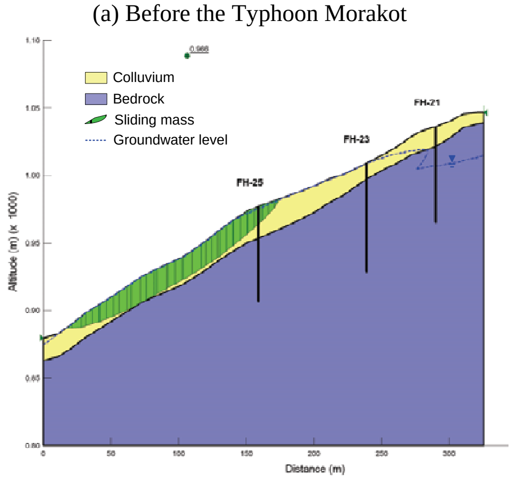
Stability and deformation analysis

For this study an autosearch method was adapted for the Ji-Lou study area, and the limit equilibrium (Morgenstern-Price) method was used to assess risk in the area. Fig. 9(a) is the result of the risk assessment for the Ji-Lou study area before Typhoon Morakot. It shows that the section of land with the greatest potential for failure was located on the down slope and passed through the boundary of the colluvium and bedrock layers. The F.S. of 1.57 indicates that the Ji-Lou study area should be considered stable under normal circumstances.

The F.S. variation for the period of Typhoon Morakot is shown in Fig. 8(d), and indicates that the typhoon caused the groundwater level to rise because of rainfall, which decreased the F.S. of Ji-Lou study area. When rainfall ceased the groundwater level returned to normal and the risk of slope instability decreased.



(a) Before the Typhoon Morakot



(b) After the Typhoon Morakot disaster

Fig. 9 Slope stability analysis results of Ji-Lou study area.

During Typhoon Morakot, potential risk in the Ji-Lou study area began to increase on August 7, and by August 9 the F.S. was at it's most threatening point of 0.97. According to above results, the down slope of Ji-Lou study area must be failure. The slope failure occurred at the colluvium and bedrock layers, as shown in Fig. 9(b). This result is consistent with the field investigation obtained after Typhoon Morakot. (Fig. 10)

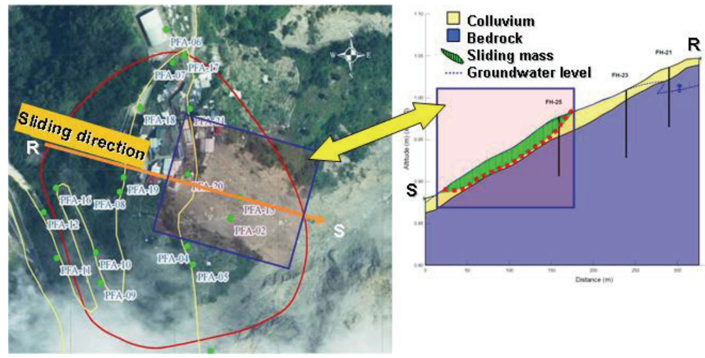
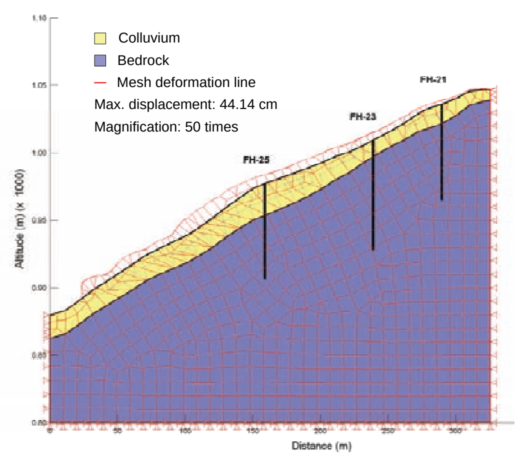
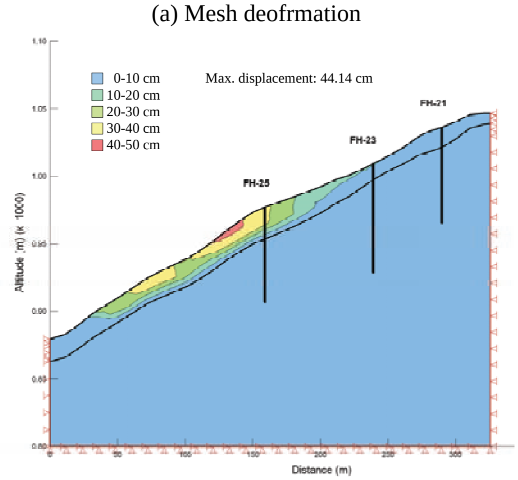


Fig. 10 The result of stability analysis compares with field condition.

Fig. 11 shows the results of deformation at the Ji-Lou study area during Typhoon Morakot. The position with the most sliding potential was at the down slope (including FH-25) to the slope toe. The sliding mass was consistent with the stability analysis (Fig. 9(b)). General speaking, the Ji-Lou study area had significant deformation during Typhoon Morakot. The greatest displacement was over 44 cm.



(a) Mesh deofrmation



(b) Displacement contour

Fig. 11 Slope deformation analysis results of Ji-Lou study area.

CONCLUSIONS AND SUGGESTIONS

The Typhoon Morakot brought a huge tragedy to southern Taiwan due to torrential rainfall. Many river basins and roads were destroyed, property was damaged and lives were lost due to slope failure. This research was conducted in an effort to assess the risk of such events and develop strategies to prevent so much misfortune from happening in the future. The preliminary conclusions and observations are as follows:

1. The destruction primarily included: road and stream bank collapse and large slope failures and debris flows. The main cause for disaster was heavy rainfall that led to infiltration, seepage flow and variation of ground water table levels, which resulted in softening of the soil layers making the shallow topsoil and colluviums slide. This slide brought a great deal of rock detritus, thus destroying houses and roads.
2. During the period of Typhoon Morakot, most of the observation points in the Ji-Lou study area had significant displacement. The measured displacement was about 1.33~107.59 cm. Furthermore, TFA-01, TFA-03, TFA-04, and TFA-05 were destroyed after Typhoon Morakot.
3. With steady state seepage flow analysis, the seepage flow vectors can identify that the subsoil water seepage velocity is quicker in the interface of colluvium layers and bedrock layers. Additionally, through the use of transient state seepage analysis, the analytical model can simulate the trend of groundwater level variation in the period of Typhoon Morakot.
4. The results already show that the model analysis can simulate normal groundwater levels before and during Typhoon Morakot. Furthermore, it can evaluate slope stability and deformation. The results of coupled analysis demonstrated good agreement between the predicted results and the data from field monitoring of the typhoon event.
5. According to the F.S. variation around the time of Typhoon Morakot, it shows that the F.S. of Ji-Lou landslide reduced from 1.57 to 0.97 during Typhoon Morakot. This result is consistent with the field investigation obtained after Typhoon Morakot.
6. The result of the displacement at the Ji-Lou study area during Typhoon Morakot shows that The position with the most sliding potential was at the down slope (including FH-25) to the slope toe.

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