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MONITORING AND NUMERICAL ANALYSIS FOR TYPHOON MORAKOT INDUCED LANDSLIDE IN CAU-PIN AREA

Jeng Ching-Jiang[1] Tan Chih-Hao[2] Chung Ming-Chien[2] Lee Jiin-Fa[3] Li-Yuan Fei[3]

ABSTRACT

This paper presents the monitoring data for rainfall induced landslides associated with Typhoon Morakot in the Kao-Pin area, and examines the accuracy of hydrogeologic numerical simulation analyses for the infiltration, seepage, groundwater variation, pore water pressure change and displacement of the land. The observed data areas are located along the Chishan River and Laonong river watershed in Kaohsiung County. The main routes included are Route 20, Route 27, Route 27 A and county road No. 128 and No. 130. Types of disasters experienced from the torrential rainfall include: landslides along roadways and river banks, and several large-scale rock falls and debris flows. The case study presented refers to the project on the landslide site of Baolong near local road No. 128, which was conducted by Sinotech Engineering Consultants Inc., and commissioned by Central Geological Survey, MOEA. For the numerical analysis, the program GeoStudio^{TM} was used, and SEEP / W, SLOPE / W and SIGMA / W modules were utilized. An integrated field investigation and test results, as well as on-site monitoring data were used and comparisons were made. The results show that the model of analysis accurately simulates water levels that occurred during Typhoon Morakot and may be useful for predicting slope stability and deformation.

Keywords: Typhoon Morakot、Rainfall、Landslide、Seepage

1.INTRODUCTION

In 2009, a comprehensive survey was conducted on landslides caused by Typhoon Morakot in southern Taiwan. The landslides were primarily shallow failure triggered by heavy rainfall. Typical conditions that contribute to these types of landslides are surface slopes comprised of colluvium or weathered topsoil which are infiltrated by rainfall causing a variation in suction and resulting in an increased water table elevation thus reducing shear strength of the overlying load. The outcome when triggered by a variable such as heavy rainfall is displacement or sliding of the slope. The multitudes of factors that contribute to slope failure make it a complex system. Previous studies have primarily calculated changes in water table elevation while overlooking the impact of rainfall infiltration from the surface. Thus, researchers have not been in a position to predict and plan response strategies for events such as typhoons and the heavy rains that ensue.

This paper presents a portion of the reconnaissance report of the slope failure associated with Typhoon Morakot in Kaohsiung and Pingtung in 2009. The case study took into account rainfall, seepage, displacement and stability analysis, and the results were compared with the monitoring data to validate the reliability. It is expected that these results can be a reference to the further slope stability assessment under a given predicted rainfall.

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[1] Associate Professor, Huafan University, Taipei County, Taiwan
[2] PH.D., Sinotech Engineering Consultants, Inc., Taipei, Taiwan
[3] Section chief, Central Geological Survey, MOEA

2. SLOPE FAILURE IN KAOHSIUNG AND PINGTUNG

2.1 Observed Area

Torrential rains brought by Typhoon Morakot, caused landslides and debris flows that destroyed many roads and bridges in the watershed along the Chishan and Laonong rivers, as shown in Fig. 1. The main roads in this area include Route 20, Route 27, Route 27 A and county road No. 128 and No. 130.

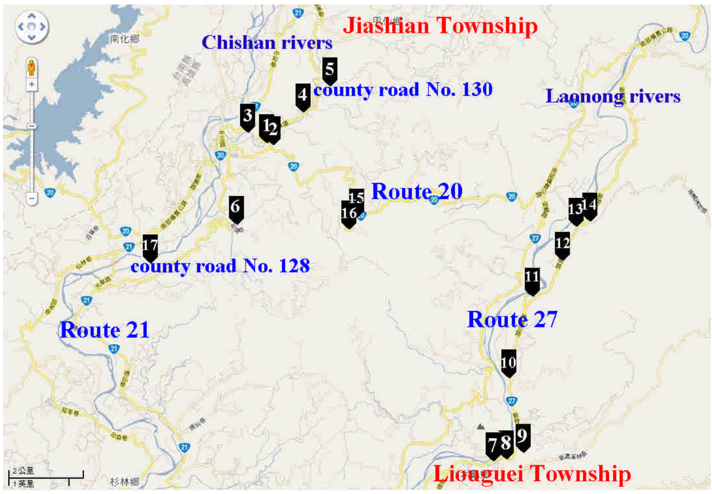

Fig.1 Location map of landslide exploration routes

2.2 Impact of Landslide

On August 8, 2009, Typhoon Morakot brought significant rainfall causing landslides that destroyed major access roads along the Chishan River and Laonong River watershed in Kaohsiung County. Further destruction from landslides in the area included: (1) Shinkai village: 32 people were buried alive by the debris flow, the main bridges of the access road to Liou Guei and Laonong collapsed. (2) Shinfa village: 13 to 15 residential buildings were buried and six people died. (3)A Religion Park (Rainbow Mountain) in Shinkai was buried by debris flow. (4) Lio-Jing bridge on Route 27: the bridge and two buildings were buried by debris flow. (5) Chao-Nan village on Route 27: 10 buildings were buried by debris flow. (6) Baolai hot springs in Taoyuan Village: significant scouring occurred along the banks of the river, 10 people and several buildings were buried by debris, many landslides occurred along Laonong River causing dammed lakes. (7) The government office building of Taoyuan Village was buried by debris. Further destruction within the case study area can be seen in Table 1 and photos No. 1-16. The location of the case study area is shown in Fig. 1.


No.1


No.2


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Fig.2 Landslide hazard investigation Photos in Kaohsiung and Pingtung area

Table 1 List of landslide hazard investigation in Kaohsiung-Pingtung area

Number	River and road location	Coordinate(E)	Coordinate(N)	Disaster type
1	Chishan River, Jia Xian county road No.130, Above Lung Feng Temple	209070	2553609	Road side retaining wall Damage
2	Chishan River, Jia Xian county road No.130, Under Lung Feng Temple	209143	2553535	Soil collapse and retaining wall lateral movement
3	Chishan River, Yu Kuang River, Tsz En Bridge	208611	2553769	River bank collapse and riverbed silt up
4	Chishan River, Yu Kuang River, No.3 Bridge	210035	2554425	River bank collapse and riverbed silt up
5	Chishan River, Yu Kuang River intersection with Peng Ping Keng	210735	2555086	Debris flow caused by landslides
6	Chishan River, Di Shuei Bridge, county road No.128	208047	2551122	Debris flow caused by landslides
7	Laonong River, Liou Guei Route 27, Bang Fu Chi Bridge	214856	2545023	Debris flow and river bank erosion
8	Laonong Rive, Route 27, Taiwan Power Company Water Inlet	215408	2545216	River road landslides
9	Laonong Rive, Route 27, Miao Chung Temple	215917	2545504	Behind temple landslides
10	Laonong Rive, Route 28, Shin Fa Road	215509	2547000	Debris flow and river road landslide
11	Laonong Rive, Route 29, Shin-Bau Bridge	216180	2549411	Debris flow triggered bridge broken
12	Laonong Rive, county road No.113, Tsai Hung Mountain Buddhist Garden	216336	2550459	Slope landslide and debris accumulation
13	Laonong Rive, Route 27; Shin Fa village:32	217202	2551044	Debris flow destroyed houses
14	Laonong Rive, Route 27; Bu-Lao River, Shin Kai Bridge	217574	2551478	Debris flow triggered landslide and destroyed house
15	Laonong Rive, Route 20	211456	2551644	Roads slope sliding
16	Laonong Rive, Route 20, Nei Liao Bridge	211235	2551329	Roads slope sliding and broken bridge

2.3 Destruction and Preliminary Evaluation

Table 1 provides a summary of the destruction within the observed area. The majority of damage to the area was the result of landslides near roads and riverbanks, and debris flows as indicated in No. 5 through No. 14. A preliminary evaluation relates the destruction to torrential rains which led to infiltration, seepage, rise in groundwater levels and ultimately slope failure causing roads and buildings at the toe of the slope to be buried.

3. CASE STUDY ON NUMERICAL ANALYSIS

3.1 Location and Condition of the Site

The case study site is located in the Typhoon Morakot disaster area on a slope in Baolung, merely 3 km from Jia Xian, the town that experienced the most severe damage in 2009 (No. 17 shown in Fig. 1). Coordinates for the case study site are 205985, 2550480. This site was selected as a result of previous slope failures. On June 14 and 15, 2005, heavy rains associated with a southwest air current, caused landslides to occur. During those landslides, the entire hillside collapsed and roads leading into and out of the area were destroyed. As a result of that event, a monitoring system to collect data for analysis of unsaturated soil slope stability was already in place prior to Typhoon Morakot.

3.2 The topography hydrology and geology

The topography of the site is generally high in the Northwest, sloping downward at approximately 20 degrees toward the Southeast with a range in elevation between 300-450m. The river is part of the Chi-San stream, which is the largest tributary in the Gao Pingxi basin. The Baolung investigation area is located at the source of the Chi-San tributary. According to the geologic map (1/50,000) by Central Geological Survey (Song et al., 2000) (Fig. 3), the strike and dip of the rock layer for the Baolung investigation area is N40 º E 21 º N, and consists of thin interbedded layers of shale and siltstone.

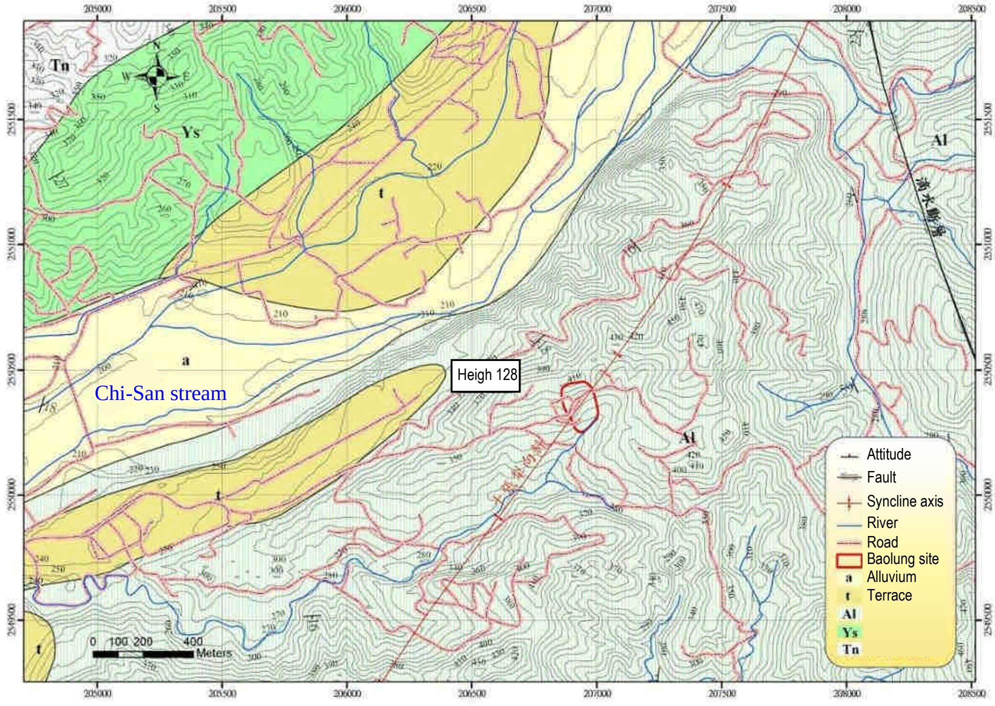

Fig.3 Geologic map of exploration area (Chiahsien)

The Baolung case study site has abundant rainfall due to the surrounding densely wooded mountains. According to the Central Weather Bureau, the annual precipitation at the Baolung investigation area averages 2,575 millimeters, the highest monthly value is in July with 623 millimeters, and the lowest value is in December with 15 millimeters. Approximately 88.8% 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 July and August when peak rainfall occurs. Evidence of this includes the devastating landslides caused by Typhoon Kaemi in July 2006 and Typhoon Kalmaegi in July 2008.

3.3 The Site Monitoring Data

A. The monitoring system

The monitoring system set up in the Baolung investigation area included: one set of rain gauges (FR-01), one surface extensometer (FE-01), two full-depth water level observation wells (TFB-01~ TFBs-15s), two observation wells at varying depths (FH-07 and FH-09), 15 surface observation points (F 01~ F15s), three inclinometers (FH-01, FH-03 and FH-05), and two locations with soil tensilmeters (FF-01 and FF-02 add up to 6 tensilmeters). The investigation simultaneously recorded rainfall, groundwater levels, strain, deformation and suction of the unsaturated soil matrix at Baolung. The monitoring system plan is shown in Figure 4.

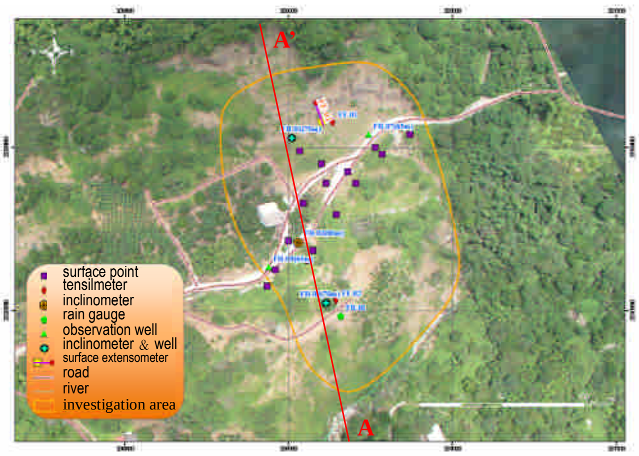

Fig.4 The monitoring system set up in Baolung investigation area

B. Monitoring results

(A) Measured precipitation

A rainfall amount of 2,329 mm was recorded during the monitoring period of July 20, 2009 to October 12, 2009, at the Baolung investigation area. Rainfall in the area during Typhoon Morakot was recorded as 1,828 mm. The greatest daily rainfall was on August 8, 2009, with 947 mm.

(B)Water table monitoring

The water table level at the Baolung site was monitored using observation wells. The results show that the water table rises with the amount of precipitation and is significantly impacted by events such as heavy rains associated with typhoons. Additionally, observation wells of various depth show that the Baolung site has confined ground water; its water table in normal and in typhoon condition is always higher than the shallow layer of water table.

(C) Surface and ground movement

The monitoring system for the surface and ground movement at the Baolung site included the surface observation points, and surface extensometers and inclinometers. The findings are as follows.

The locations of surface observation points are shown in Fig. 4. Measurements were taken before and after Typhoon Morakot. Observations found that after Typhoon Morakot the displacement of each point was not significant, with only a slight displacement ranging between 0.22~1.34 cm. This shows that the Baolung site has only partial creep, and evidence of a large-scale deep slide is lacking.

The surface extensometers shown in Fig. 4, were arranged according to an anticipated event such as Typhoon Morakot. Surface displacement at the top of the slope was found to be about 2.2 cm. Ground movement measurements were also taken prior to the typhoon event. Monitoring results surrounding Typhoon Morakot indicate that the Baolung investigation area has not experienced a large-scale deep landslide.

(D) Monitoring matrix suction of the shallow unsaturated soil

The monitoring plan of the matrix suction of the unsaturated shallow soil is shown in figure 4. The monitoring results indicate: (1) matrix suction decreases with rainfall; (2) matrix suction slowly increases after rainfall has ceased; (3) matrix suction descends with the exaltation of water content, and is reacted from the deepest (3.0 m) first, then moves to the shallow layer (2.0 m and 1.0 m). This trend is contrary to typical rain seepage and occurs most likely because of the permeability of the surface soil and the small geographical area at the site that causes a slower speed of rain seepage. While the water table approach to the ground surface and lift to raise notable with the rain.

3.4 Analytical model and parameters

The GeoStudio program was used in conjunction with the hydrological and geological data collected to create a model that would aid in the prediction of future landslides based on environmental conditions.

A. Analytical process

The analytical procedure for the Baolung investigation area included: incorporating new data into the hydrogeologic concept model. The data was collected through fieldwork (drilling, surveys and testing) and then simulations were conducted with the SEEP/W, SLOPE/W and SIGMA/W models in GeoStudioTM programs. The model SEEP/W is a simulation involving rain infiltration and seepage flow. The steady-state seepage analysis and transient state seepage analysis were both conducted. The steady-state seepage analysis was based on steady state seepage flow rates and normal water table 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. SLOPE/W and SIGMA/W analytical models were used to simulate the stability and deformation of the ground. Seepage flow and water table of each time step is all provided by the above SEEP/W simulation result.

B. The hydrogeologic concept model

The numerical geological model of the investigation 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-01, FH-03 and FH-05, and then down to the bottom of the trench. The geologic unit of this site can be divided into the colluvium layer, weathered rock layer and the base rock layer.

The boundary conditions of the hydrologic concept model are shown in Fig. 5. To analyze the infiltration and seepage flow, the left side boundary was set as a constant head boundary equal to the water level of the toe creek trench. The right side boundary was set as a constant because a crest line had already been established. The lower boundary was set as a no runoff boundary. The surface of the slope 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.

3.5 Analysis results and discussion

A. The rain infiltration and seepage analysis result

The reference values of hydrologic parameters were obtained from the field infiltration test, pressure plate test, plug hydraulic test and laboratory permeability test, and then further verified by the field hydrology monitoring data observed from July 20, 2009 to September 18, 2009. This study first calibrated the hydraulic parameters by comparing data without measured rainfall to the typical water level for steady state seepage flow analysis. Then the fluctuating water 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 and water table 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.

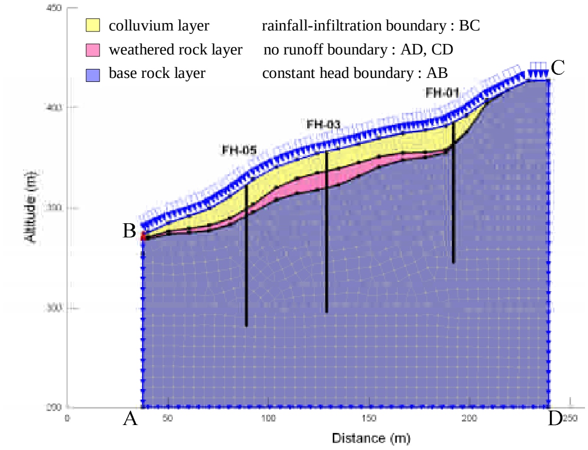

Fig.5 The hydrology geology concept model of Baolung investigation area

The steady state seepage flow analysis aimed to align with the observed normal water level of well No. FH-01 and FH-05. Monitoring data prior to Typhoon Morakot, indicated the normal water level in FH-01 and FH-05 to be between GL-21~23 m and GL-14~15 m respectively. Through steady state seepage flow analysis it was determined that the water table at the top of the slope at well No. FH-01 is distributed under the base rock layer. While in well FH-01 to the toe of the slope the water is under the weathered rock layer. In addition, it is known from the seepage flow vector that the seepage velocity along the interface between the colluvium layer and the weathered rock layer is more rapid.

The transient state seepage analysis was initiated from the above steady state analysis with normal water table levels, and set the slope surface as the rainfall infiltration boundary to lead to the situation of water level variation and water seepage flow in the rainfall conditions. The rainfall infiltration period used for the analysis was from July 20 to September 18, 2009. This period included Typhoon Morakot. The rainfall hydrograph is show in Fig. 6(a).

In Fig. 6(b) the dotted medium red line indicates the record for the water level of the observation well FH-01. The analytical results shown by the green solid line follow the water level variation trend for the period of Typhoon Morakot. However, the water level significantly descends to GL-42 m after the typhoon, and such water level dissipation eludes the analysis at this time. Figure 6(c) the medium red dotted line shows the water level at observation well FH-05 for the period of Typhoon Morakot. The concurrence of the analytical data (green solid line) shows that it can imitate the water level variation trend and the range of the water level for the period of Typhoon Morakot.

B. The steady state analysis results

All the hydrogeologic parameters were determined from the laboratory tests. For this study an auto-search method was adapted for the Baolung investigation area, and the limit equilibrium (Morgenstern-Price) method was used to assess risk in the area. Figure 7(a) is the result of the risk assessment for the Baolung investigation 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 weathered rock layers. The safety factor of 1.485 indicates that the Baolung investigation area should be considered stable under normal circumstances.

The safety factor variation for the period of Typhoon Morakot is shown in Fig. 6(d), and indicates that the typhoon caused the water table to rise because of rainfall, which decreased the safety factor. When rainfall ceased the water table level returned to normal and the risk of slope instability decreased.

During Typhoon Morakot, potential risk in the Baolung investigation area began to increase on August 8, and by August 10 the safety factor was at it’s most threatening point of 1.125. This low safety factor was possibly the result of partial slope failure, small-scale failures in the area, or slip near the toe of the slope. The slope failure occurred at the colluvium and weathered rock layers, as shown in Fig. 7(b). This result is consistent with the field investigation obtained after Typhoon Morakot. The field investigation found that the Baolung investigation area had a small-scale collapse at the slope toe. This event was also verified by data from section 3.3 in the content (c) of the surface and ground momvement monitoring.

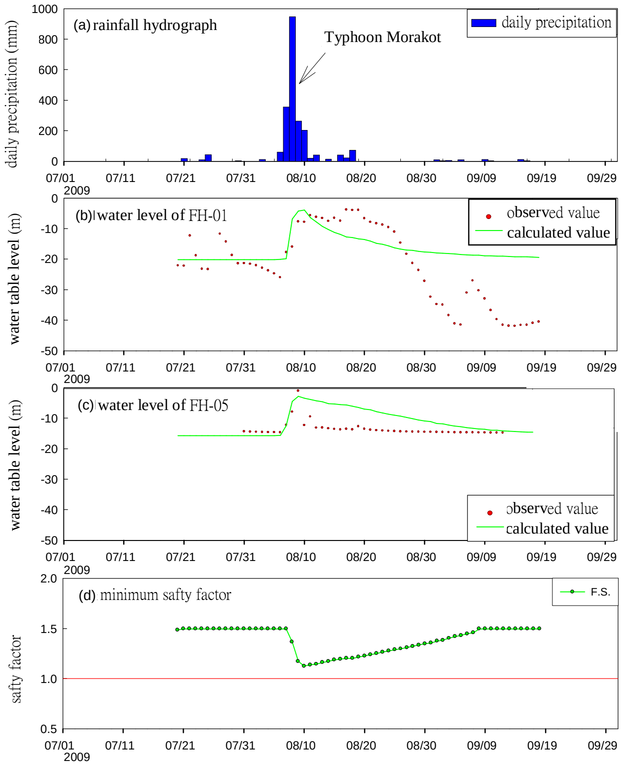

Fig.6 Two-dimensional slope stability analysis results of the Baolung investigation area vs. infiltration

C. The displacement analysis result

Figure 8 shows the results of displacement at the Baolung investigation area during Typhoon Morakot. The position with the most sliding potential was at the lower slope (hole FH-05) to the slope toe. The sliding block was consistent with the stability analysis (Fig. 7(b)). General speaking, the Baolung investigation area had no notable displacement during Typhoon Morakot. The greatest displacement found was approximately 6.3 cm.

This study examined the displacement analysis result through the inclinometers and observing deformation in the Baolung investigation area. Although this area showed slight displacement during Typhoon Morakot, the observed displacement at holes No. FH-01, FH-03 and FH-05 indicate it was not significant (lie among the 3~8 mm). The strain indicated in the numerical analysis, shows the ground surface displacement on each hole ranged between 8~32 mm. The best trend occurred at No. FH-03. At holes No.FH-01 and FH-05, the simulation results were greater than the monitoring data, showing the analysis results to be conservative.

4 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.

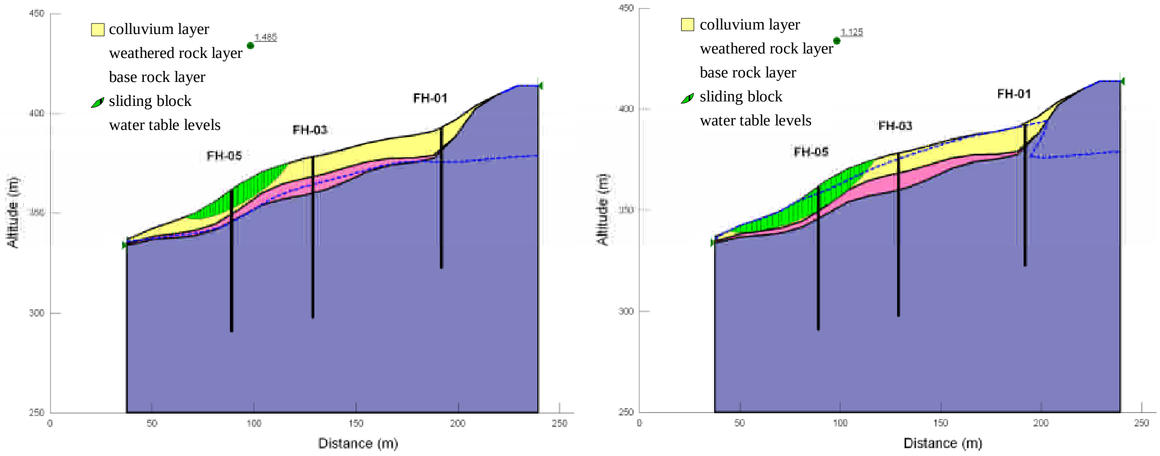

Fig.7 Result of safety factor of Baolung investigation area before the Typhoon Morakot.

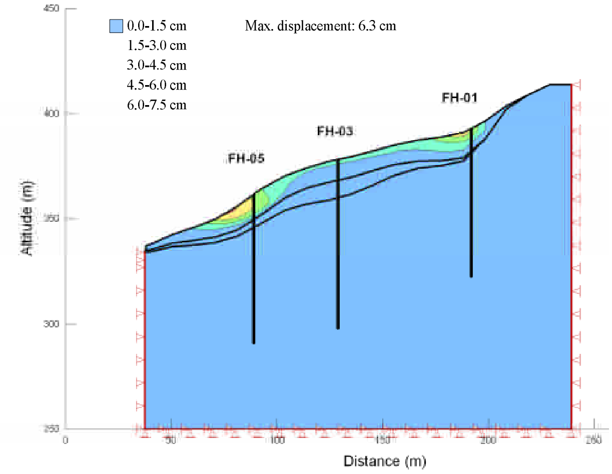

Fig.8 The deformation of the assessment results in Baolung investigation area

Consequently, this study reviewed the field exploration of the disaster, as well as the discussion on the intact monitoring and analysis results from the Central Geological Survey, MOEA entrusted to the Sinotech Engineering Consultants, Inc. This information was crucial to understanding the problem of the rainfall induced shallow slope failure. The observed areas included the Chishan river and Laonong river watershed in Kaohsiung County, the main routes included are Route 20, Route 27, Route 27 A and county road No. 128 and No. 130. 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 Baolung investigation area had not shown obvious displacement. The measured displacement was about 0.22~1.34 cm. This indicates the Baolung investigation area only has a slight creep in some areas, with no evidence of large-scale deep slides.

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 weathered rock layers. Additionally, through the use of transient state seepage analysis, the analytical model can simulate the trend of ground water level variation in the period of Typhoon Morakot.

4.Inspite monitoring for less than a year, the results already show that the model analysis can simulate normal water table levels before and during. Furthermore, it can evaluate slope stability and displacement. However, the water level dissipation after a typhoon needs more follow-up monitoring data to increase its accuracy.

5.According to the safety factor variation around the time of Typhoon Morakot, it shows that during the typhoon period at the Baolung investigation area the safety factor started to decreases reducing on August 8, reaching its lowest level on untill August 10th with a factor of 1.125. This low safety factor was possibly the result of partial slope failure, small-scale failures in the area, or slip near the toe of the slope. The slope failure occurred at the colluvium and weathered rock layers, shown as Fig. 9(b). This result is consistent with the field investigation obtained after Typhoon Morakot. The field investigation found that the Baolung investigation area had a small-scale collapse at the slope toe.

6.The result of the displacement at the Baolung investigation area during Typhoon Morakot shows that the position with the most potential for sliding is at the lower slope (hole FH-05) to the slope toe. General speaking, the Baolung investigation area had no notable displacement during Typhoon Morakot. The greatest displacement found was approximately 6.3 cm.

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