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Relationship between rainfall characteristics and slope stability – case study of Taipingshan landslide in Taiwan

Rapport entre les caractéristiques de précipitation et la stabilité de pente - étude de cas du glissement de terrain de Taipingshan à Taiwan

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ABSTRACT: Taipingshan landslide was triggered by Typhoon Saola in 2012. According to extensometer and precipitation data, Taipingshan landslide began when the accumulated rainfall reached 1,255 mm, and the sliding speed exceeded 2 mm/h. When the accumulated rainfall reached 1,694 mm, the sliding speed exceeded 30 mm/h, and the extensometer was severed. This study used a two-dimensional infiltration- seepage-stability coupled hydrogeologic model to input rainfall conditions to discuss the relationship between rainfall characteristics and slope stability. The rainfall conditions used in this study are as follows: (1) Rainfall patterns, including uniform, advanced, central, and delayed; (2) rainfall durations, including 24, 48, 72, and 96 hours. This study uses the aforementioned actual typhoon event to verify the research results. The contribution of this study is to clarify the relationship between rainfall characteristics and slope stability through actual typhoon events, and provide the rainfall characteristics recommended for subsequent slope monitoring and early warning analysis to obtain appropriate early warning indicators.

RÉSUMÉ: En 2012, le typhon Soala a provoqué le glissement de terrain de Tapingshan. Selon les données de l'extensomètre et des précipitations, le terrain de Taipingshan a commencé à glisser lorsque les précipitations cumulées ont atteint 1,255 mm et que la vitesse de glissement dépassait 2 mm/h. Lorsque les précipitations cumulées ont atteint 1,694 mm, la vitesse de glissement était supérieure à 30mm/h et l'extensomètre s'est rompue. Cette étude a utilisé une stabilité bidimensionnel infiltration-suintement couplée d'un modèle hydrogéologique pour l'apport des conditions de précipitations afin de discuter le rapport entre la stabilité des pentes and les caractéristiques de précipitation. Les conditions de précipitation utilisées dans cette étude sont les suivant: (1) le régime des précipitations, notamment uniformes, avancés, centraux et différés; (2) les durées de précipitations, y compris 24, 48,72 et 96 heures. Cette étude utilise le typhon susmentionné pour vérifier les résultats de la recherche. La contribution de cette étude est de clarifier le rapport entre les caractéristiques de précipitation et la stabilité de pente en utilisant les évènements actuels de typhon et d'apporter des caractéristiques de précipitation recommandée pour le contrôle ultérieur des pentes et l'analyse d'alerte précoce pour obtenir des indicateur d'alerte rapide appropries.

Keywords: rainfall pattern, rainfall duration, slope stability, Taipingshan landslide

1 INTRODUCTION

Landslide activity can be attributed to a number of factors, however, rainfall has long been recognized as one of the most significant triggering factors (Ng and Shi, 1998). In order to effectively avoid or reduce rainfall-induced slope disaster, appropriate slope analysis models and early warning assessments are necessary. One of the key issues to affect the slope stability is rainfall condition.

This paper presents a case study of the Taipingshan landslide, which was triggered by Typhoon Saola in 2012 (Chung et al., 2017). This study used a two-dimensional infiltration-seepage-stability coupled hydrogeologic model to input rainfall conditions to discuss the relationship between rainfall characteristics and slope stability. The rainfall conditions used in this study are as follows: (1) Rainfall patterns, including uniform, advanced, central, and delayed; (2) rainfall durations, including 24, 48, 72, and 96 hours. This study uses the aforementioned actual typhoon event to verify the research results.

2 TAIPINGSHAN LANDSLIDE INDUCED BY TYPHOON SAOLA

2.1 Background

Taipingshan villa is one of the most famous scenic locations within the Taipingshan National Forest Recreation Area in northern Taiwan. It is located between Datong and Nanou Townships in Yilan County at coordinates 304396, 2709656 (TWD97). The villa sits on top of an active landslide which has been triggered by past typhoon events. (Figure 1)

According to a 1/50,000 geologic map (Central Geological Survey), Taipingshan villa is located in the Lushan Formation. The Lushan Formation consists largely of black to dark gray argillite, slate, and phyllite with occasional interbeds of dark gray compact sandstone and disseminated marly nodules. The slaty cleavage is well developed. The topography of the site is generally high in the northwest, sloping downward at approximately 17-20 degrees toward southeast with a range in elevation between 1,800-2,000 m.

Before 2012, landslide activity associated with Typhoon Haitan in July, 2005 was the most severe to have ever occurred at Taipingshan villa. Since then and between 2008 and 2013, the Forestry Bureau has committed large funding to repair resulting unstable slopes and damage to infrastructure. However, because of fragile and sensitive geology, during storms, high soil erosion rates, infrastructure damage, and landslides still often occur at the Taipingshan villa. Structures within the Taipingshan villa show evidence of displacement and damage that has occurred over a long period of time (Sinotech Engineering Consultants, Inc., 2010).

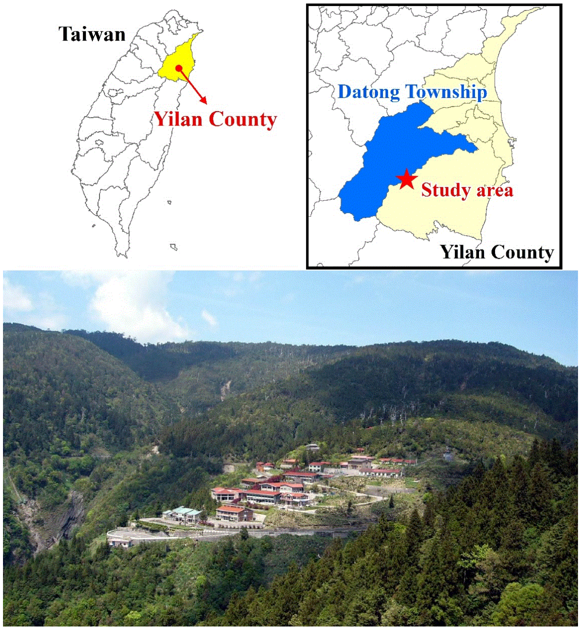

Figure 1. Location and panorama view of Taipingshan villa

2.2 Disaster Investigation

In 2012, Typhoon Saola delivered tremendous rainfall; total accumulated rainfall exceeded 1,800 mm (rainfall duration in 89 hours).

Taipingshan villa suffered severe damage as shown in Figure 2. Several parts of the railway, trail and buildings within the area were destroyed and Taipingshan villa was forced to close. The majority of landslide activity occurred in the western portion of the villa including the History Exhibition Hall, Songluo Meeting House, Bongbong Train Station, and Taiwan Cypress House. The landslide activity can be broken down into three sliding masses: A, B, and C. Features and damage associated with the sliding masses include: A main scarp near the Taiwan Cypress House (Photo 1 and Photo 2), cracking of retaining walls beside the Songluo Meeting House (Photo 3), subsidence and cracking of the railway (Photo 4 and Photo 5). As of summer 2015, the structures and facility damages that resulted from Typhoon Saola had yet to be restored.

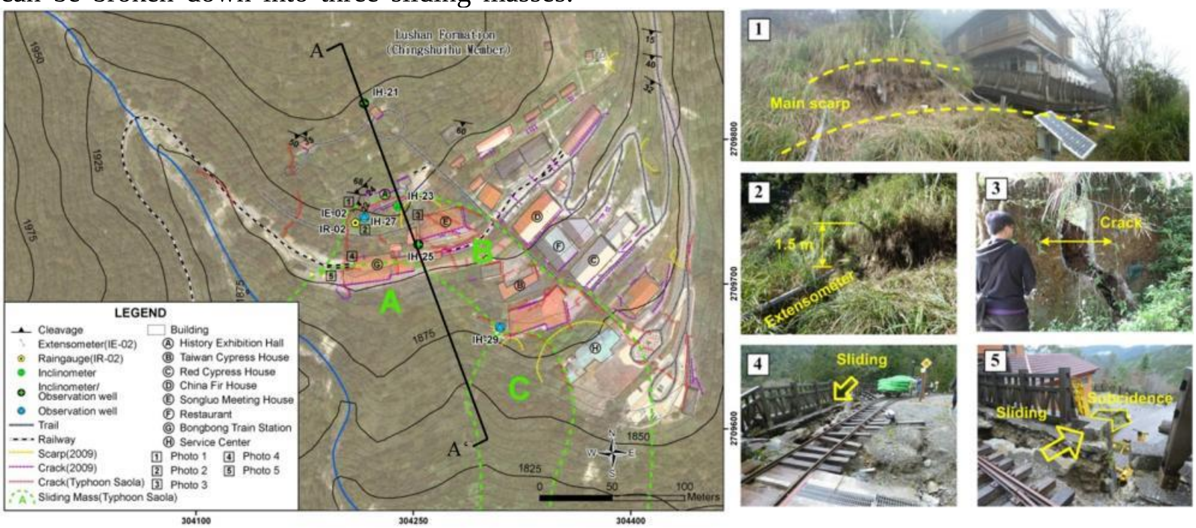

Figure 2. Investigation results of Taipingshan landslide induced by Typhoon Saola

According to extensometer and precipitation data (Figure 3), Taipingshan landslide began when the accumulated rainfall reached 1,255 mm (8/1 22:00), and the sliding speed exceeded 2 mm/h. Therefore, the rainfall threshold can be defined as 1,255 mm by Typhoon Saola. When the accumulated rainfall reached 1,694 mm (8/2 5:00), the sliding speed exceeded 30 mm/h, and the extensometer was severed. It shows that the sliding mass of Taipingshan landslide was separated during rapidly sliding period.

Landslide activity at Taipingshan villa may be divided into three sliding masses. The sliding mechanism may be rainfall infiltration and lateral recharge from surface and sub-surface drainage of the upper slopes, which causes groundwater levels to rise and interact with the interface between the weathered rock and colluvium. The resultant reduced shear strength along the interface causes sliding of mass A and retrogressive failure in mass B and C, as shown in Figure 4.

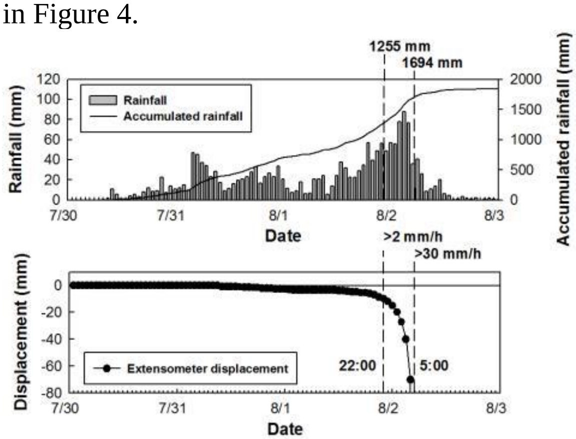

Figure 3. Relationship between displacement and rainfall during Typhoon Saola

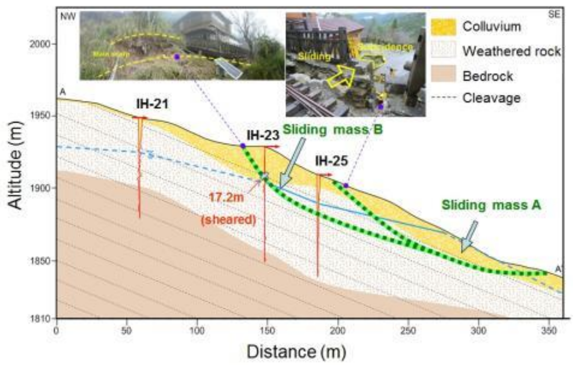

Figure 4. Sliding mass triggered by Typhoon Saola

3 ANALYSIS MODEL

The Geostudio limit equilibrium method module of the software SLOPE/W by GEO-SLOPE International Ltd. was used for stability analysis. Since much of the modelled slope is unsaturated, the factor of safety (F.S.) computed by SLOPE/W was based on a Mohr-Coulomb modified equation suggested by Fredlund et al. (1978). Changes in pore-water pressures and the subsequent effect on the F.S. of the slope were quantified. Transient analysis results of the SEEP/W module of pore-water pressure conditions at various points along the slope were input into the SLOPE/W module, allowing highly irregular saturated/unsaturated conditions or transient pore-water pressure conditions to be included in the stability analysis. This in turn permitted the prediction of changes in stability with time.

3.1 Hydrogeologic Conceptual Model

The geological model was established using a 5m×5m Digital Elevation Model (DEM) of Taipingshan villa. The profile analyzed from the DEM is indicated by the line AA' shown in Figure 2. The boundary conditions of the hydrogeologic conceptual model are shown in Figure 5. To analyze infiltration and seepage flow, the left side boundary (RA) was set as a constant because a crest line had already been established. The right side boundary (SB) was set as a constant head boundary equal to the water table at the toe of the slope and adjacent drainage. 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.

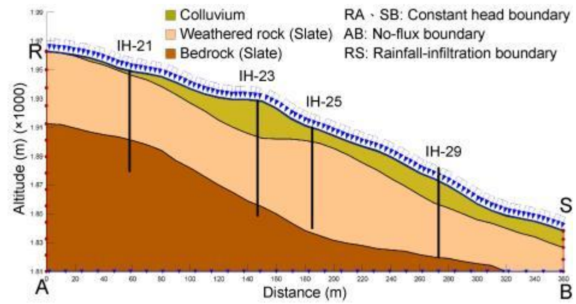

Figure 5. Hydrogeologic conceptual model of the Taipingshan villa

3.2 Rainfall Conditions

The rainfall characteristics of Typhoon Saola are as follows: 1) The total accumulated rainfall is 1839.3 mm; 2) the rainfall duration is 89 hours; 3) the rainfall pattern is similar to the central type. (Figure 3)

In the case study, the rainfall conditions used are as follows: 1) Rainfall patterns, including uniform, advanced, central, and delayed (Ng et al. 2001; de Lima and Singh, 2002), shown in Figure 6; 2) rainfall durations, including 24, 48, 72, and 96 hours.

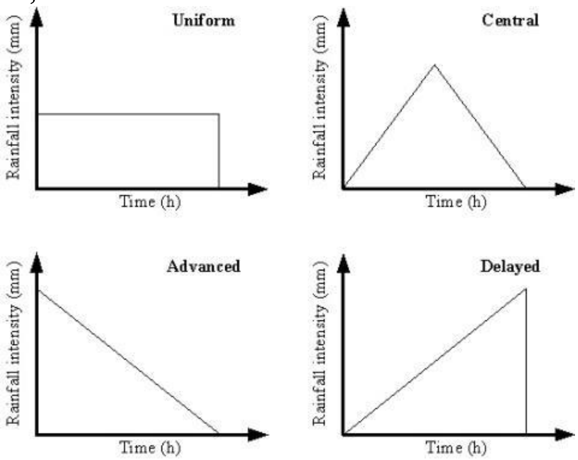

Figure 6. Four rainfall patterns

4 ANALYSIS RESULTS

4.1 Back Analysis

According to Figure 3, Taipingshan landslide began to slide when the accumulated rainfall reached 1,255 mm. It is assumed that F.S. is equal to 1.0 at this time.

Through back analysis, the change of F.S. during Typhoon Saola are shown in Figure 7 and Figure 8 (Legend ID: TPS-SL-SL). Figure 7 shows that the F.S. at the 63rd hour is less than 1.0. Figure 8 shows that the accumulated rainfall is 1255 mm at the 63rd hr. After above analysis, the hydrogeologic parameters of the Taipingshan villa shown as Table 1.

Table 1. Hydrogeologic parameters of the Taipingshan villa

	Colluvium	Weathered rock	Bedrock
Hydraulic conductivity (m/sec)	9.2×10^{-6}	5.1×10^{-6}	5.0×10^{-7}
Unit weight (kN/m^3)	18.5	26.8	27.1
Cohesion (kPa)	24	550	2050
Friction angle (deg)	28.4	30.35	26.11

4.2 Rainfall Pattern

In order to understand the effect of rainfall pattern on stability, the rainfall conditions used are as follows: 1) Total accumulated rainfall is 1839.3 mm (Typhoon Saola); 2) rainfall duration is 89 hours (Typhoon Saola); 3) four rainfall patterns (Figure 6). The analysis results are shown in Figure 7 and Figure 8. The rainfall threshold and time step are listed in Table 2.

Table 2. Analysis results under various rainfall patterns

ID	Rainfall duration	Rainfall pattern	Time Step	Rainfall threshold
TPS-SL-SL	89	Saola	63	1,255
TPS-SL-U	89	Uniform	60	1,240
TPS-SL-A	89	Advanced	37	1,206
TPS-SL-C	89	Central	53	1,234
TPS-SL-D	89	Delayed	73	1,240

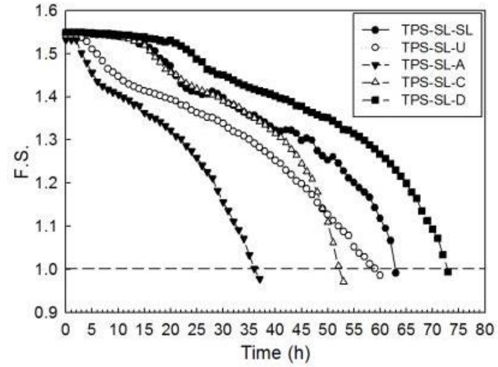

Figure 7. Change of calculated F.S. with time under various rainfall patterns

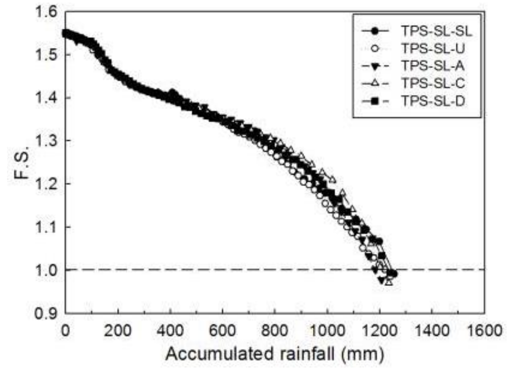

Figure 8. Change of calculated F.S. with accumulated rainfall under various rainfall patterns

Analysis results show the following:

1. In terms of the time step of reaching the rainfall threshold, advanced type is the fastest, followed by central type, uniform type, and delayed type; wherein the time step of uniform type is closest to the Typhoon Saola.
2. In terms of the rainfall threshold, the various rainfall patterns are quite close to the Typhoon Saola, and the difference is less than 4%.

4.3 Rainfall Duration

In order to understand the effect of rainfall duration on stability, the following rainfall conditions were used as follows: 1) Total accumulated rainfall is 1839.3 mm (Typhoon Saola); 2) four rainfall durations, including 24, 48, 72, and 96 hours; 3) four rainfall patterns (Figure 6). The analysis results are shown in Figure 9 and Figure 10. The rainfall threshold and time step are listed in Table 3.

Table 3. Analysis results under various rainfall durations

ID	Rainfall duration	Rainfall pattern	Time Step	Rainfall threshold
TPS-24-U	24	Uniform	18	1,379
TPS-24-A	24	Advanced	14	1,502
TPS-24-C	24	Central	18	1,592
TPS-24-D	24	Delayed	22	1,551
TPS-48-U	48	Uniform	32	1,226
TPS-48-A	48	Advanced	21	1,248
TPS-48-C	48	Central	29	1,257
TPS-48-D	48	Delayed	40	1,283
TPS-72-U	72	Uniform	47	1,201
TPS-72-A	72	Advanced	30	1,207
TPS-72-C	72	Central	43	1,239
TPS-72-D	72	Delayed	59	1,239
TPS-96-U	96	Uniform	67	1,284
TPS-96-A	96	Advanced	40	1,209
TPS-96-C	96	Central	57	1,229
TPS-96-D	96	Delayed	80	1,280

Analysis results show the following:

1. As in Section 4.2, advanced type is the fastest, followed by central type, uniform type, and delayed type.
2. The shorter the rainfall duration, the faster the F.S. decreases, because the rainfall intensity exceeds the infiltration potential, resulting in less actual infiltration.
3. The longer the rainfall duration, the closer the rainfall threshold will be to the Typhoon Saola. However, it is possible to obtain unconservative results in 96 hours. Therefore, it is better to use a rainfall duration of 72 hours.

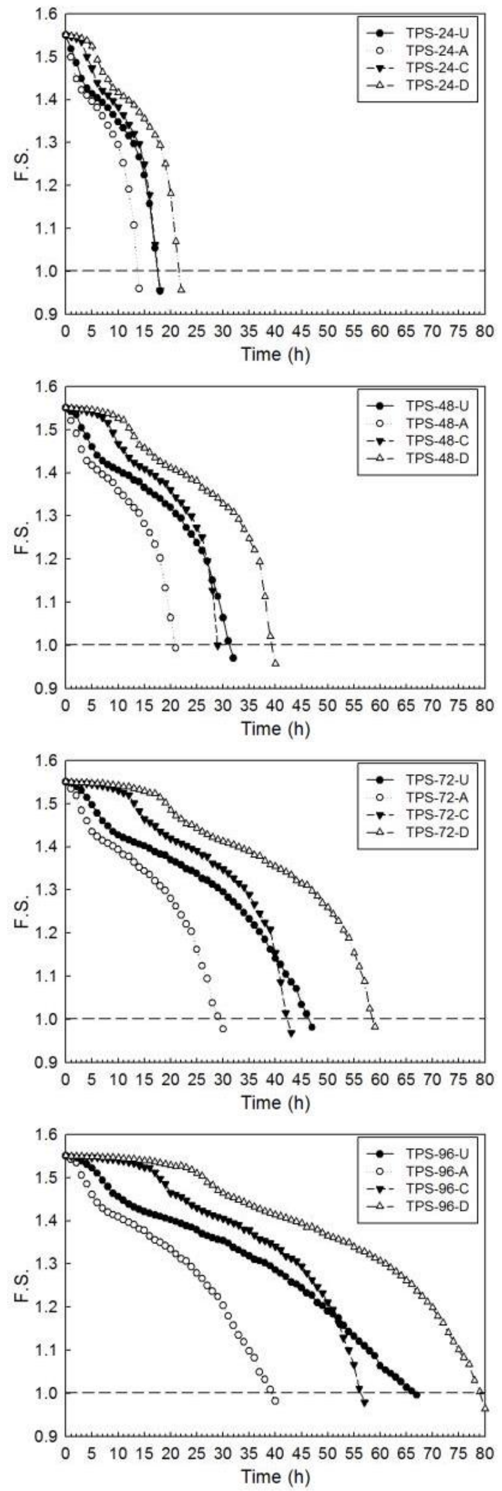

Figure 9. Change of calculated F.S. with time under various rainfall durations

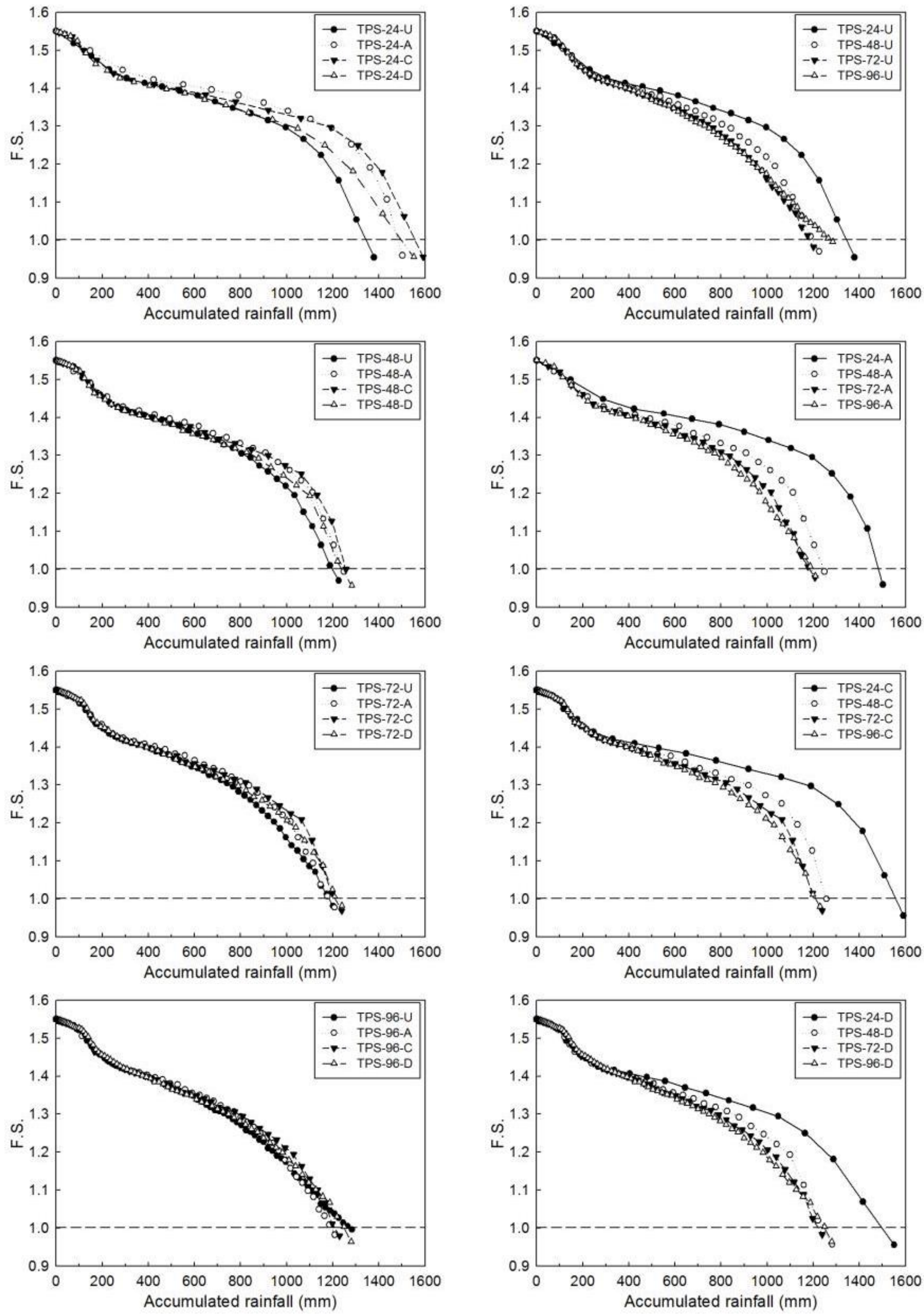

Figure 10. Change of calculated F.S. with accumulated rainfall under various rainfall durations

5 CONCLUSIONS

Based on the above described research, the following conclusions and recommendations can be derived:

1. The contribution of this study is to clarify the relationship between rainfall characteristics and slope stability through actual typhoon events, and provide the rainfall characteristics recommended for subsequent slope monitoring and early warning analysis to obtain appropriate early warning indicators.
2. The rainfall pattern affects the time to reach the rainfall threshold, advanced type is the fastest, followed by central type, uniform type, and delayed type.
3. Rainfall duration will affect the degree of F.S. decline. The shorter the rainfall duration, the faster the F.S. decreases, because the rainfall intensity exceeds the infiltration potential, resulting in less actual infiltration.
4. Due to its simplicity and practicability, the empirical rainfall threshold for landslide occurrence is commonly used, but it seems not to clearly analyze the actual physical processes of the landslide, and seems not to take the rainfall infiltration into consideration. It is recommended to consider the factor of rainfall infiltration when assessing the rainfall threshold and early warning time.
5. To predict the critical rainfall threshold and warning time, it is recommended that the total rainfall be determined by the rainfall frequency analysis results, and the specific return period rainfall can be used. The rainfall duration can be 72 hours, and the rainfall pattern can be uniform or central type.

6 ACKNOWLEDGEMENTS

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