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CASE STUDIES ON THE SLIDING BEHAVIORS OF THE TSAO-LING DIP-SLOPE LANDSLIDES INDUCED BY EARTHQUAKES

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ABSTRACT: From 1862 to 1999, four catastrophic landslides were recorded of the Tsao-Ling dip-slope, involving mass movement with multi-million cubic meters of material. Through analysis of the historical events, the earthquake appeared to be the most significant triggering factor. The Newmark's method was adopted and modified to take into account the vertical acceleration for simulating the sliding behaviors of the debris mass. The results of analysis appeared to be satisfactory for the Chi-Chi event in 1999, and provided insight for the 1862 and 1941 events.

Key Words: Tsao-Ling landslide, Newmark's method, critical condition, sliding simulation

INTRODUCTION

During the Chi-Chi earthquake in 1999, a large scale dip-slope landslide occurred in the Tsao-Ling area of Yun-Lin County, which was known as the Tsao-Ling landslide shown in Fig. 1. From 1862 to 1999, four catastrophic landslides of the Tsao-Ling dip-slope were recorded, which involved mass movement of multi-million cubic meters of material. The historical records suggested that the debris slid pass the Ching-Shui River channel, and landed over the other side of the river since the 1862 event. The slope angle of the dip-slope is quite mild, and results of back analysis indicated that the slope would remain stable under static condition. Such results could explain the reason why three out of the four historical landslides were induced by earthquakes. However, in each of the landslide, the sliding mass travelled a long distance and appeared to cross the Ching-Shui River channel. The geological formations of the Tsao-Ling dip-slope are composed of Sandstone over Sandstone/Shale interlayer. Although the shearing strength of the shale degrades significantly with increasing strain after reaching peak strength, it is still not sufficient to explain the large distance of mass movement passing the river channel.

In this research, case studies of historical events of the Tsao-Ling landslides induced by earthquakes were performed using Newmark's method. The degradation of the shearing strength of material and the vertical ground acceleration were taken into account.

Fig.1 The landslide scarps and debris mass on top of the old landslide dam. (by J.J. Hung)

LOCATION AND GEOLOGICAL FORMATION OF THE DIP SLOPE

The location of the dip-slope landslide was situated at 120°40’24” east longitude, 23°34’44” north latitude in the Tsao-Ling Village, Kou-Kern Township, of Yun-Lin County in the foothill region of Central Taiwan as shown in Fig. 2. The dip angles of the remained slope ranged from 12 to 14 degree and the strike of the slope was N35°W dipping into south direction. The landslide area is located on the west side of the Tsao-Ling anticline, and the landslide slope oriented NNE–SSE with low angle submergence into Ching-Shui River valley as shown in Fig. 3. The site geological formation is composed of Tawo sandstone (Pliocene epoch), Chinshui shale and Cholan formation (Pliocene to Pleistocene epoch) from the bottom to the top and the orientation of all strata is N20°W ~ N40°W and dipping into the direction of 14° SW, which is approximately the same as the strike and dipping direction of the slope (Central Geological Survey, 2000). The Chingshui River passes through the toe of dip slope and cuts into the toe of slope, which causes the bedding planes to daylight. Two sets of orthogonal open joint (N25°E ~ N 40°E/SW, N48°W ~ N88°W / N) are observed on the remaining dip slope. Surface water can thus infiltrate into deeper formation and soften the rock. Observing the profiles of previous landslide history (Figures 7, 9, and 10), the dip-slope sliding could have occurred in the Cholan formation, at the interface of Cholan formation and Chinshui shale, and in the Chinshui shale. The Cholan formation is mainly composed of thick layer of weakly cemented sandstone which is highly porous and permeable, and with thin interlayer of siltstone and mudstone. While the Chingshui shale is a weak material with low permeability, and easily softened by submergence of water.

LANDSLIDE HISTORY OF TSAO-LING

Catastrophic dip-slope landslides in Tsao-Ling occurred in 1862, 1941, 1942, 1979, and 1999. Debris of the landslides dammed up the Ching-Shui River, and breaching of the landslide dam of the previous events took place in 1898, 1951, and 1979, respectively. A summary of the dip-plane landslide events of the Tsao-Ling area is listed in Table 1 (Kawada, 1943; Chang, 1951; Hsu, 1951; Hsu and Leung, 1977; Hung, 1980, 1999; Hung, et al., 1994, 2002; Chang and Lee, 1989; Lee, et al., 1993, 1994; NCREE, NAPHM, and Taiwan Geotechnical Society, 1999; Lin et al., 2000b; Yeng, 2000). Three major landslide events prior to the landslide triggered by the Chi-Chi earthquake are briefly reviewed in the follows.

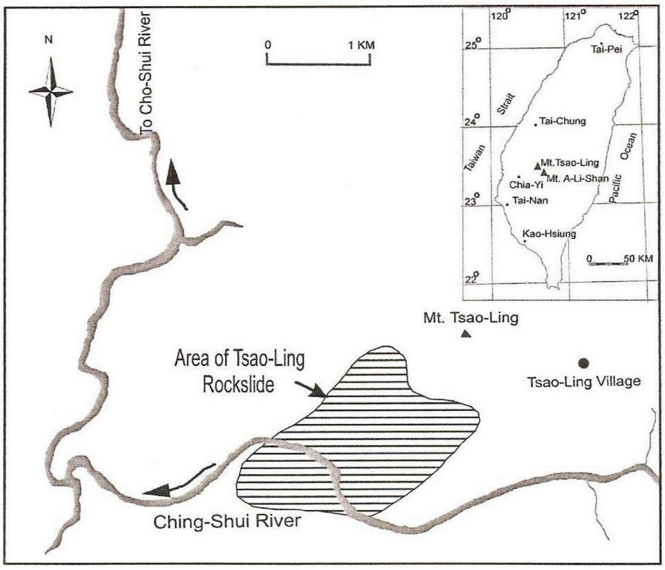

Fig. 2 Location of the Tsao-Ling landslide (Hung, et al. 2002)

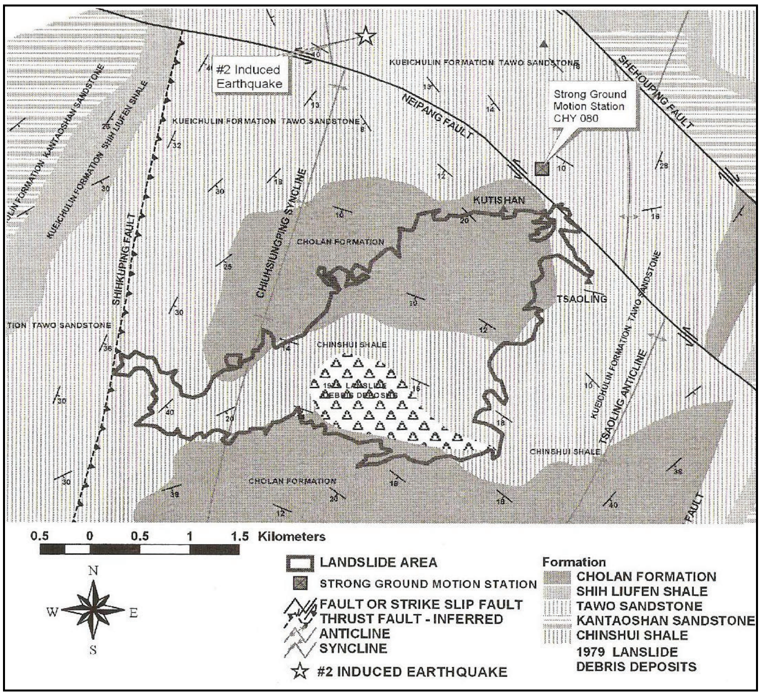

Fig. 3 The geological map of Tsao-Ling landslide area (modified from the geological map of the Central Geological Survey, 2000)

Landslide event in1862

The first reported event of dip-slope landslide and subsequent formation of a landslide dam occurred on June 6th, 1862, and was caused by an earthquake with magnitude between 6 and 7. Breaching of the landslide dam occurred later in 1898 (Taipei Observatory, 1942).

Landslide events in1941 and 1942

On December 17th, 1941, a rockslide was induced by the Chia-Yi earthquake with a magnitude of 7.1, which involved a mass movement of more than 100-million cubic meters and formed the southwest flank of Tsao-Ling as shown in Fig. 4 (Kawada, 1943). On August 10th, 1942, heavy rain caused another rockslide on the remaining slope, and more than 150 million cubic meters of the rock mass slid down the dip slope, and the Ching-Shui River was dammed with debris. The profiles of 1941 and 1942 rockslide events were reconstructed as shown in Fig. 5. Following five days rainfall with cumulative precipitation of 776 mm, the landslide dam with height of 140m to 200m and width of 4800m at base was overtopped on May 18th, 1951, and 120 million cubic meters of water was released causing severe flood in the downstream area and losses of lies and properties.

Table 1 Summary of the landslide events in the Tsao-Ling area (revised from Wu, et al., 2001)

Landslide event	Date	Time	Triggering Factor	Debris Volume, (m^3)	Dam capacity, (m^3)	Blocked length, (m)
(1)	1862.06.06	-	**Earthquake**		-	-
(2)	1941.12.17	04:17 am	**Earthquake**	$150x10^6$	$120x10^6$	2,000
	1942.08.10	12:00 pm	Rainfall	$200x10^6$		
	1942.08.10	12:10 pm	Rainfall			
(3)	1979.08.15	04:00 am	Rainfall	$5x10^6$	$40x10^6$	2,000
(4)	1999.09.21	01:47 am	**Earthquake**	$120x10^6$	$46x10^6$	4,815

Fig. 4 Landslide in Tsao-Ling area caused by the Chia-Yi earthquake, 1941 (Kawada, 1943)

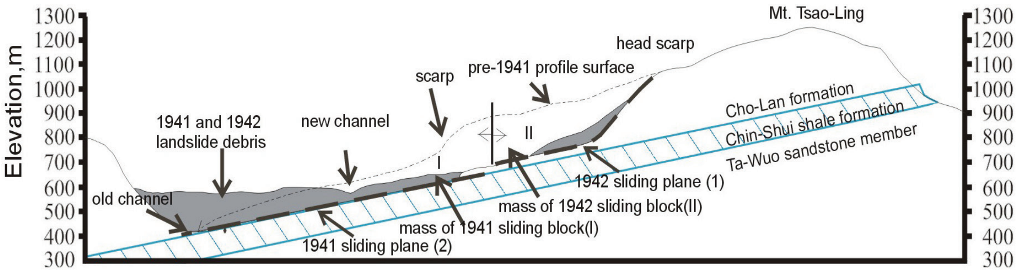

Fig. 5 Reconstructed ground profile of 1941 Tsao-Ling landslide event. (Lee, et al., 1993)

Landslide event in1979

On August 15th, 1979, heavy rainfall caused failure of the lower part of remaining slope since the previous event with debris volume of 5 million cubic meters. The sliding mass collided with the remaining landslide dam and the Ching-Shui River was once again dammed. Following 2 days of rainfall with cumulative precipitation of 624 mm, the landslide dam with a height of 90 meters was overtopped on August 24th, 1979. Two bridges downstream were destroyed, and the Tung-Tou community in the Chu-Shan Township was flooded. The reconstructed profile of the 1979 rockslide event is shown in Fig. 6 and the lower part of the 1979 sliding plane was in Chinshui shale formation.

Landslide event in1999, Chi-Chi earthquake

On September 21st, 1999, the Chi-Chi earthquake struck Central Taiwan, causing a large scale dip-slope landslide in the Tsao-Ling area as shown in Fig. 1. The landslide was located at a distance of 35 km to the south of epicenter and 6.6 km to the southern tip of Che-Lung-Pu fault. The topography and prfile of the landslide area are as shown in Fig. 7, which ranged from elevation of 400m to 1234m above sea level. The average width of the landslide was approximately 3800m, and the length was 2800m, covering an area of 440 hectare. The large-scale dip-slope landslide in Tsao-Ling involved movement of rock mass of 120 million cubic meters. Among those, only 25-million cubic meters of the sliding mass dropped into the valley of the Ching-Shui River at the toe of the slope. The remaining sliding mass of about 100 million cubic meters slid passing the Ching-Shui River, and landed on the remains of old landslide dam. Residents and their houses sitting on the sliding mass near the crest of the slope flew with the sliding mass and landed on top of the landslide dam through a horizontal distance of 3100 m away and 800m downward, and a total of 32 people were killed and 7 survived after the “sliding-landing” process. The vegetation on a few hill-slopes downstream of the landslide dam was stripped, most likely by the air-blast released from the impact of the sliding mass. The Ching-Shui River was dammed by the large amount of debris and the dammed-up lake held a total of 45 million cubic meters of water. The emergency spillway was constructed through the plugged section of Ching-Shui River valley. Overflow of the impounded water commenced on December 22nd, 1999, without causing damage to the dam.

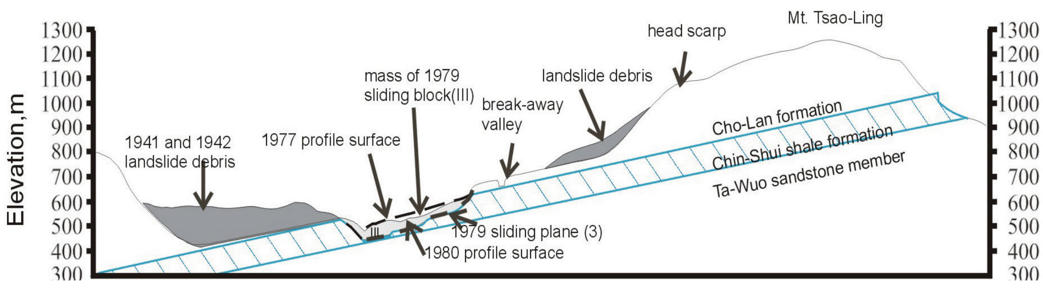

Fig. 6 Reconstructed ground profile of 1979 Tsao-Ling landslide event. (Lee, et al., 1993)

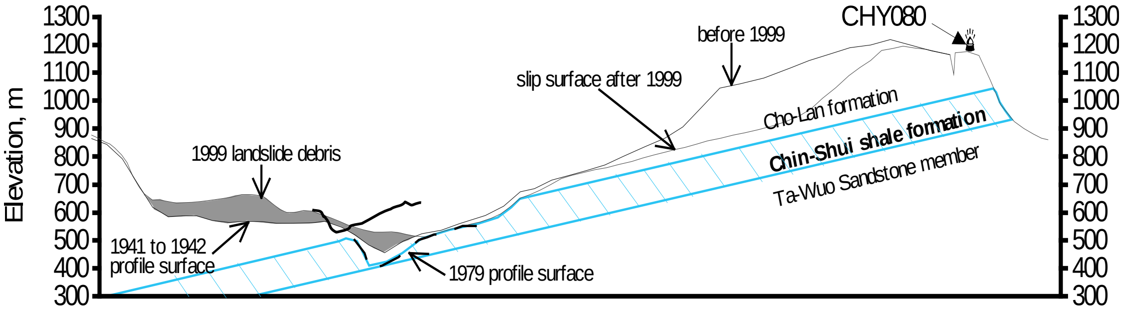

Fig. 7 The slope profile and sliding surface of the Tsao-Ling landslide caused by the Chi-Chi Earthquake, 1999. (Chen et al., 2004)

From the previous discussions, three out of the four landslide events were triggered by the earthquakes. The 1979 event occurred on the lower part of remaining slope since the previous events in 1942 and 1941. Thus the events in 1942 and 1979 can be considered as failure of the residual slope of the landslide caused by the Chia-Yi Earthquake in 1941. Back analysis performed on all three events result in factor of safety as large as 4 under static condition due to the mild slope angle. Therefore, it is suggested that earthquake is the major triggering factor of the landslide events of the Tsao-Ling dip-slope.

CRITICAL CONDITIONS FROM NEWMARK'S ANALYSIS

In order to study the sliding behavior of landslide mass and to evaluate the possibility of sliding mass travelling pass the river channel, simulation of landslide was performed using Newmark's method. It is proposed that when ground acceleration exceeds a critical value, the slope starts sliding and yields a permanent displacement. The yielding horizontal acceleration is derived using the limit equilibrium method, in which the factor of safety equals 1. In the case where earthquake acceleration exceeds yielding acceleration, the slope sliding starts with increasing velocity and displacement. The velocity and displacement can be obtained by integration of acceleration history exceeding critical acceleration.

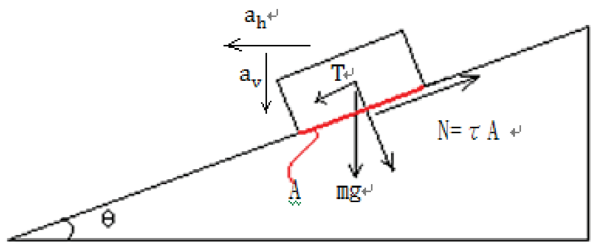

Fig. 8 The sliding block model considering the vertical acceleration and horizontal acceleration

Noted that in the derivation of critical acceleration proposed by Newmark (1963) took into account the horizontal acceleration acting on the slope only. However, when the slope locates near the epicenter and/or fault zone of the earthquake, it is often subjected to high vertical acceleration, which has a significant effect on the stability of slope. In order to take into account the vertical acceleration, the derivation of the critical condition can be developed using the procedures illustrated using the sliding block model as an example in Fig.8. In Fig. 8, the block with mass m is resting on the slope with an angle of θ, and the block is subjected to a horizontal acceleration of $a_h=k_h\times g$, and a vertical acceleration of $a_v=k_v\times g$, where g is the acceleration of gravity. By assuming the driving force down-slope, T, and the resisting force, N, derived from the soil strength, τ, are in equilibrium, the correlation between the coefficient of horizontal acceleration, k_h, and coefficient of vertical acceleration k_v can be derived as:

$$k_v = \frac{\lfloor c_p A + mg(\tan\phi_p \cos\theta - \sin\theta) \rfloor - k_h mg(\cos\theta + \sin\theta \tan\phi_p)}{mg(\sin\theta - \cos\theta \tan\phi_p)} \tag{1}$$

where A is the contact area between the block and the slope surface, c_p and ϕ_p are the peak shear strength parameters of the soil. Eq. (1) defines the critical condition of the sliding block in Fig. 8, when the vertical acceleration becomes larger than the vertical acceleration computed for a given horizontal acceleration, the block will start sliding. By assigning different values of horizontal acceleration in Eq. (1), the corresponding critical vertical acceleration can be computed. Thus, a critical line defining the initiation of the sliding can be plotted as vertical acceleration, a_v, versus the horizontal acceleration, a_h, at the critical state as shown in Fig. 9. The vertical ground acceleration has a significant effect on the critical condition as the critical horizontal acceleration decreases rapidly with increasing vertical acceleration. For a slope with given material properties and sliding surface, the corresponding critical line can be constructed. By tracing the time records of the ground acceleration in vertical and horizontal directions versus the critical line, the initiation of sliding can be determined as the acceleration records exceed the critical line as shown in Fig. 9. The part of the acceleration records exceeding the critical line can be integrated to provide the sliding velocity time correlation and the permanent displacements in both the vertical and horizontal directions.

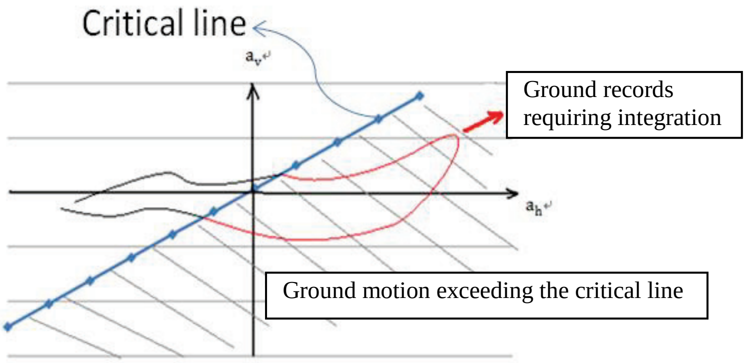

Fig. 9 Illustration of the critical line and tracing of ground motion record, the ground record in the cross-line area indicating ground motion exceeding the critical line.

MATERIAL PROPERTIES AND GROUND MOTION

Material properties of both the intact rock and debris material were reported by many researchers (Hung et al., 1981, 1982, Lee, et al., 1993, Chen, 2000, Lin et al., 2000c, Yeng, 2000). The laboratory testing results including unit weight and both peak and residual strength parameters are summarized in Table 2 for Cholan formation and Chinshui shale. The residual friction angle of the Chinshui shale (13°) is about the same as the inclination angle of the bedding plane (ranging from about 12° to 14°). The testing results of Cholan formation shown in Table 2 were obtained from specimens with higher shale contents.

For both formations, material strength reduced significantly from peak values to residual when subjected to submergence. Based on field investigation before Chi-Chi earthquake, it was found that the calcium carbonate cementation of the Cholan formation has been dissolved by percolating water, and the process led to increased permeability and reduced strength of the sandstone (Hung, et. al., 1982). The water permeated into the sandstone or entered through the open joints easily, and perched near the contact face of the Cholan formation and Chinshui shale and softened the rocks. The Cholan formation is a shallow marginal sea deposition formation, with seashell fossils, which also provided the sources of calcium carbonate. In field investigation, it was found that the water seeped down-slope along the interface of the two formations and out from the lower right corner of the cliff The weathering process of the rock material proceeds rather rapidly as observed in the field. Based on the slake durability test conducted by Lee, et al. (1993) on Cholan formation material, the durability index of the first cycle was 46.2 % and that of second cycle was 4.8%, and the rock was classified as very low durability according to Gamble (1971). It indicated that the weathering process would precede rapidly accompanying material strength degradation.

Table 2. Material properties of Chinshui shale and Cholan formation.

Item	Chinshui Shale	Cholan Formation	Reference Source
Total unit weight γ_t (kN/m^3)	25.8	24.5	Lee,2001
Peak friction angle, ϕ_p (^{o})	36.8	38.5	Lee,2001
Peak cohesion, c_p (kPa)	664	980	Lee,2001
Residual friction angle, ϕ_r (^{o})	13.4	18.9	Lee,2001
Residual cohesion, c_r (kPa)	0	0	Lee,2001
Submerged friction angle (^{o}) @ w=2%	19	-	Yeng,2000
Submerged friction angle (^{o}) @ w=4%	14	-	Yeng,2000
Friction angle (^{o}) (long-term submergence)	2.8	-	Yeng,2000
Cohesion (kPa) (long-term submergence)	0	-	Yeng,2000

The ground motion at the Tsao-Ling landslide caused by the Chi-Chi earthquake could be determined using records of the free field strong motion stations installed by the Central Weather Bureau (http:// http://www.cwb.gov.tw/V5e/seismic/chichi.htm). The strong ground motion records of station CHY080 of the Central Weather Bureau located just north to the crest of Tsao-Ling as shown in Fig. 7 can be used to represent the ground motion at the landslide site. The peak horizontal ground accelerations were 841.5 gal in North-South direction and 792.4 gal in East-West direction, and the peak vertical ground acceleration was 715.8 gal, respectively. In order to consider properly the effects of ground motion on the dip slope sliding, the horizontal ground motion records in both N-S and E-W directions were combined and resolved into the component in dip direction of the slope, with the positive acceleration indicating ground motion outward of slope. The transformed horizontal ground acceleration in the dip-slope direction is with a peak acceleration of 646.6 gal. The peak ground acceleration resolved into the dip direction is lower than those in N-S and E-W directions, and the acting duration is about 41.95 seconds with acceleration larger than 50gal. The seismic parameters representing ground motion characteristics are listed in Table 3.

Table 3 Ground motion characteristics of station CHY080 of Chi-Chi earthquake

Parameter \ Direction	Vertical (Z)	Horizontal (N-S)	Horizontal (E-W)	Horizontal (Dip direction)
Peak ground acceleration (gal)	715.8	841.5	792.4	646.4
Bracketed duration, sec (as A_c > ±50gal)	12.94	33.72	41.95	41.95

The ground motions of the 1862 and1941 earthquakes were estimated based on the descriptions in documents, degradation law and estimated seismicity. The Chia-Yi Earthquake in 1941 had a magnitude of 7.1 and focal depth of 10km, the estimated seismicity is about 6, which corresponded to a ground acceleration ranging 250 t0 400 gal, and the earthquake in 1862 had about the same seismicity as the Chia-Yi Earthquake. Due to lack of ground motion records, the evaluation will be conducted in a manner to verify the possible condition for initiation of the mass sliding.

LANDSLIDE SIMULATION AND PERMANENT DISPLACEMENT

To perform the landslide simulation using Newmark's method, the slope profile was taken as along the dip direction of the slope with the location of sliding surface as shown in Fig. 7. The material properties used in the analysis included the peak shearing strength parameters, c_p and ϕ_p, the unit weight of the material as shown in Table 2, and the slope angle θ was approximately 12°. In addition, as the sliding of the slope initiated, the shearing strength on the sliding surface would have undergone a gradual reduction until reaching the residual strength of the material. In order to take into account the strength reduction as the shearing displacement increases, the critical line defined in Eq. (1) were computed using peak strength and gradually reduced by 20% of strength for each line until reaching residual strength to establish multiple critical lines shown in Fig. 10 for the Chi-Chi Earthquake event. The ground motion record was also plotted in Fig. 10, in which the ground motion record touched the critical line with peak strength at the ground motion record of 38.6 sec, and the sliding initiated. As the sliding occurred, the shear strain would accumulate which caused the shear strength to reduce. It was assumed that the shearing strength would reduce to the residual as soon as the ground motion record exceeded the critical line, and the exceeding ground record starts from 38.6 sec to 73.2 sec. and was integrated. The horizontal displacement obtained was about 457.25m, and vertical displacement was 12.47m. However, to use the peak strength for determining the initiation of sliding would be more conservative, for the laboratory test tends to use intact specimen compared to the field condition where rock material might be jointed and weathered. If the residual strength is used for critical lines, then the integrated horizontal displacement would be 493.8m, which is significantly larger than in the peak strength condition. Although the vertical displacement thus determined in not as significant due to the acceleration of gravity, however, the vertical acceleration affected the critical lines and critical state significantly. As observed in Fig. 10, the critical horizontal acceleration reduced significantly even with small amount of increase in vertical acceleration. With the computed displacement, the sliding mass would be deposited in the river channel as shown in Fig.11, which might suggest that other factor such as air-cushion could play a role in lifting the sliding mass across the river channel.

Simulations of the 1862 and 1941 events were conducted in a similar way using the profile shown in Fig. 5. The sliding body of the 1862 event was estimated from the profile shown in Fig.5. The critical lines were developed for both events, and it was found that for a horizontal ground acceleration of 0.3 g, the shear strength would be reduced to below 50% of peak strength in order to have sliding initiated for the 1941 event, and 40% of peak strength for the 1862 event. In both cases, the reductions of material strength are reasonable as discussed previously. Due to lacking ground motion records for the two events, the displacement of sliding mass cannot be computed, however, the sliding distances of the debris mass appeared to be much smaller than the Chi-Chi event. The simulation using the critical lines derived from the Newmark's method appeared to provide satisfactory results, and the effects of vertical acceleration could be taken into consideration using the procedures developed in this research.

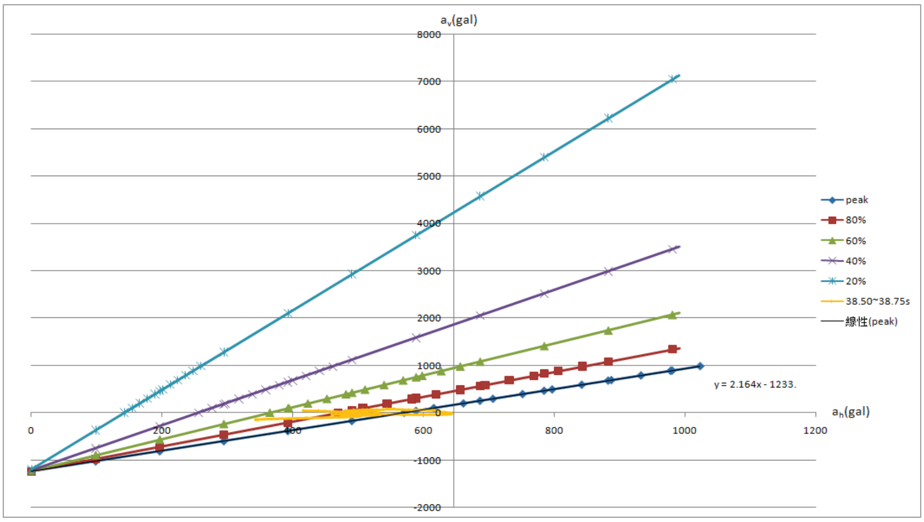

Fig. 10 Ground motion record versus critical lines for different degradation of shearing strength

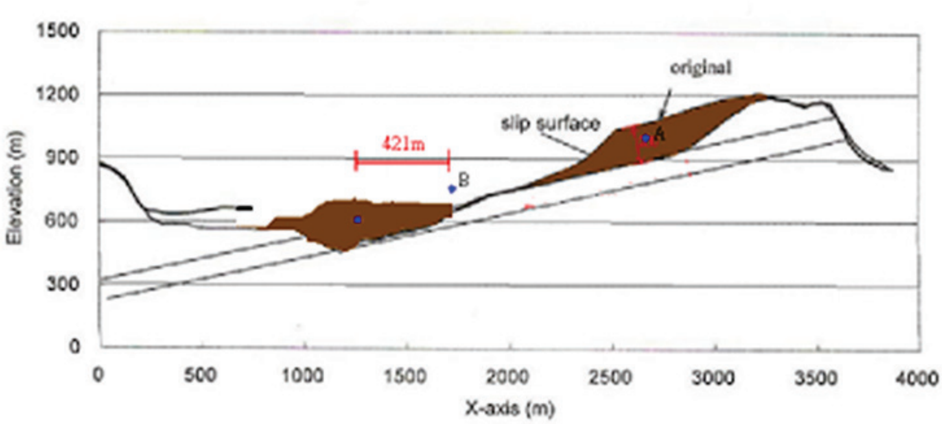

Fig. 11 Final position of the sliding mass simulated using critical line

CONCLUSIONS

In this paper, the case history, geological and geomorphologic properties, and possible causes of the Tsao-Ling landslide are presented. Observing the previous landslide history, the landslides were most likely triggered by the excessive ground motion caused by earthquakes despite the rather mild slope angle compared to the weakened strength of the sandstone/shale formation. In all three landslide cases triggered by the earthquakes, the landslide bodies appeared to slide pass the river channel and landed the other side of the Ching-Shui River to form the debris dam. The Newmark's method was adopted and modified to provide a critical line which took into account the effect of vertical ground acceleration. The resulting critical lines suggested that the critical horizontal acceleration reduced significantly even with small amount of increase in vertical acceleration.

Based on the analysis results of the three events, the simulations using the proposed critical line derived from Newmark's method provide satisfactory results, and the effects of vertical acceleration could be taken into consideration reasonably. The resulting sliding displacement appeared to be reasonable for the Chi-Chi event in 1999. However, the computed displacement was not large enough for the sliding mass to travel pass the river channel, which might suggest that other factor such as air-cushion could play a role in lifting the sliding mass across the river channel. Although lacking ground motion records, the results of simulation provided insight for the 1862 and 1941 events.

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