Force-based and Displacement-based Back Analysis of Shear Strengths: Case of Tsaoling Landslide

JIAN-HONG WU and CHUN-HWA CHEN
Department of Civil Engineering,
National Cheng Kung University
Address No. 1, University Road, Tainan 701
TAIWAN
jhwu@mail.ncku.edu.tw http://www.civil.ncku.edu.tw/

Abstract: - Tsaoling landslide is a notorious gigantic landslide triggered by the Chi-Chi Earthquake at Taiwan in 1999. The landslide provided a valuable case study to review the available methodologies in analyzing seismic induced landslides. In this study, the force-based back analysis method is applied to investigate the shear strengths of the Tsaoling landslide. Additionally, the calculation results are compared with the ones analyzed by displacement-based analysis. The analysis results confirm that the conventional force-based analysis method, which introduces the maximum horizontal seismic acceleration to the seismic analysis, overestimates the shear strengths. An appropriate factor to "discount" the acceleration or the defining slope safety factor is required in the force-based analysis to obtain accurate shear strengths. On the other hand, the displacement-based analysis, such as Newmark sliding model, provides an alternative way to pursue accurate shear strengths if a seismic-slope failure regression formula is also available. Additionally, the GPS data of ground displacement in a large earthquake are crucial for baseline correction to guarantee the correctness of the seismic data.

Key-Words: - Tsaoling Landslide, Chi-Chi earthquake, force-based, displacement-based, back analysis, shear strength.

1 Introduction

The Chi-Chi Earthquake attacked Taiwan and cased the death of more than 2000 people on September 21, 1999. The epicenter of the earthquake was located at a small town, Chi-Chi, in the central Taiwan (Fig. 1). The magnitude was M_L=7.3, as measured by the Central Weather Bureau (CWB, Taiwan), or M_S=7.7, as measured by the U.S. Geological Survey. Additionally, different from the Great Hanshin Earthquake happened at the metropolis of Osaka and Kobe, Japan in 1995, the Chi-Chi Earthquake is a violent earthquake occurred in the mountainous areas. Thus, roughly 26,000 earthquake-induced slope failures have been identified over an area of 375,000 ha by aerial-photo interpretations [1].

Among the seismic slope failures, Tsaoling landslide is one of the gigantic rock avalanches triggered by the earthquake and is located at the southeast of the epicenter of the Chi-Chi earthquake as shown in Fig. 1. The area of deposit was 3.4 km^2. The volume of the debris was estimated to be 125 million m^3, which is the largest landslide in the Chi-Chi Earthquake [2].

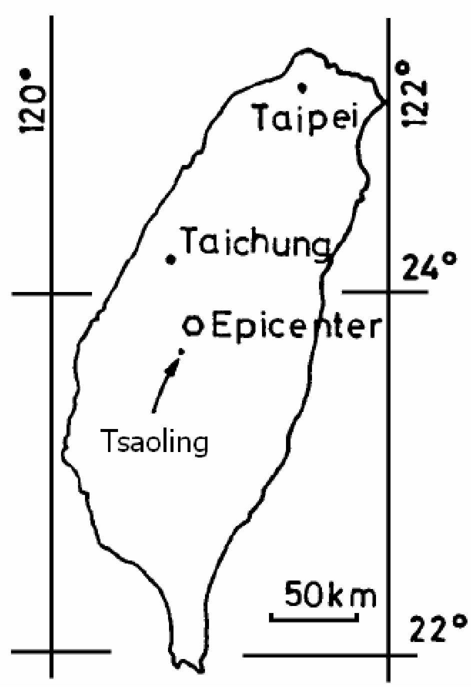


Fig. 1 Location of the Tsaoling landslide

Despite of the large sliding volume, the Chi-Chi Earthquake did not trigger Tsaoling landslide for its first time. Chigira et al. [3] used the data from Lee [2] and Huang et al. [4] to generate Table 1, which demonstrates the landslide history at Tsaoling. Four huge landslide records were available before the Chi-Chi Earthquake, and the first record can be traced back to 1862. Additionally, the records indicate that the earthquake and rainfall are the primary triggering forces to induce Tsaoling landslides. The study of Chigira et al. [3] shows that these landslides, including the one caused by the 1999 earthquake, have essentially not been reactivated old slides, but were sequential new ones that developed upslope, retrogressively.

Table 1 Landslide History at Tsaoling Area

Time	Trigger	Remarks
June 6, 1862	Unknown	
December 17, 1941	Earthquake	Slide volume: 100– 150 million m^3. Landslide dam (70–200 m high). Several scarps formed, of which the highest was at an elevation of 950 m.
August 10, 1942	Rain	Slide volume: 150– 200 million m^3. Landslide dam (170 m high) formed, which failed on May 18, 1951, killing 147 people.
August 15, 1979	Rain	Slide volume: 5 million m^3. Landslide dam formed, which was overtopped on August 24. Scarp of Chinshui shale was made, and the rock mass downslope of this scarp slid.
September 21, 1999	Chi-Chi Earthquake	Slide volume: 125 m^3. Landslide dam was made.

Therefore, slope stability analysis, monitoring, and clarifying the failure mechanism of Tsaoling landslide are essential questions for the authority to safeguard the local residents or determine the constraint area. So far, the force-based and displacement-based slope analysis methods are usually conducted forward analysis in estimating the stability of a slope under the impact of an earthquake. Since the in-situ slope failure performs a full scale test, and the geometry of sliding block can be measured, these analysis methods are expected to be used to back calculate the shear strengths of the sliding surface for the countermeasure design. However, the case study or comparisons between force-based and displacement-based methods under the seismic activity are rare. The Tsaoling landslide provides a valuable case study to answer the question of “Is it possible to apply available methods to accurately back-calculate the shear strengths of a rock avalanche for the further analysis or countermeasure design?”

2 Force-based slope analysis

The ground movement is an essential parameter in seismic analysis. In the very beginning, earthquake scientists attempted to monitor the time-dependent ground displacement during an earthquake to realize the seismic activity. However, the ground may move several meters during a large earthquake. Developing an apparatus to record the seismic movement is difficult. Thus, recording the seismic accelerations using free-field accelerograph is an alternative method to obtain ground seismic behavior since the seismic acceleration can be mathematically integrated to velocity and be double integrated to displacement.

Additionally, using seismic acceleration provides a simple approach to involve seismic impact to the slope analysis since acceleration can be easily converted to the seismic force acting on a specified object based on the following classic Newton’s second law of motion:

$$F = m \cdot a \tag{1}$$

where, F indicates the seismic force. m is the mass of the object. a is the seismic acceleration.

A pseudo-static analysis can be carried out by the limit equilibrium method by considering the dynamic loading occurrence with a time constant force which is proportional to the mass of unstable block of rock, according to the seismic coefficient. When analyzing a dynamic slope stability problem, STABL 6 employs the pseudo-static method and is classified as a force-based slope analysis program. The seismic coefficient is generally assumed as the recorded peak ground accelerations [5].

3 Displacement-based slope analysis

On the other hand, Newmark [6] proposed the displacement-based slope analysis method to evaluate the stability of a slope under an earthquake. A rigorous Newmark analysis is conducted by double integrating the parts of a specific strong-motion record that exceed the critical acceleration.

Additionally, several simplified empirical formulas for estimating Newmark displacements (D_N) have been regressed to avoid the computational complexity and difficulties of selecting an appropriate earthquake time-history associated with a conventional Newmark analysis or analyze the stability of the slope without neighboring accelerograph stations. Thus, we can back calculate the shear strengths of the Tsaoling landslide if the Newmark displacement calculated from the Newmark sliding model can be compared with the one obtained from the regress model.

3.1 Newmark Sliding Model

The Newmark sliding model with considering the influences of the accelerations normal to the sliding surface is conducted in this study. Fig. 2 illustrates a simplified free-body diagram of the model [7]. Only gravitational and seismic accelerations generate the external forces acting on the block. The resultant forces normal and tangential to the sliding surface under an earthquake can be formulated by Eqs. (2) and (3), respectively.

Resultant forces normal to the slope, N:

$$N = mg \cdot \cos\theta, \tag{2}$$

Downhill driving forces parallel to the slope, T:

$$T = m \cdot (g \cdot \sin\theta + a_d), \tag{3}$$

where, m is the mass of the sliding block, g is gravitational acceleration, θ is the slope dip angle, and a_d indicates seismic acceleration tangential to the slope.

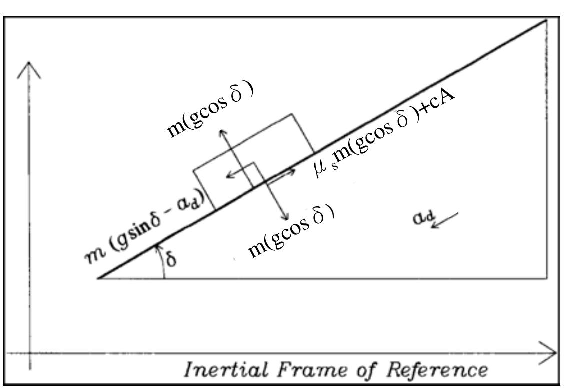


Fig. 2 Free-body diagram of the Newmark sliding model with concerning the normal accelerations

Acceleration a_d is derived in terms of a_N (north acceleration), a_E (east acceleration) and a_V (vertical acceleration) using Eq. (4):

$$a_d = a_E \cos\theta \cos\delta - a_N \cos\theta \sin\delta - a_V \sin\theta, \tag{4}$$

where, δ is the angle of strike from north.

Assume,

$$S = (T - N \cdot \tan\phi - cA) / m, \tag{5}$$

where, S is the down-dip sliding acceleration, A is the sliding surface area, and c and ø are cohesion and angle of friction of the sliding surface.

The safety factor is given by FS=(Ntanø +cA)/T. When FS<1, S in Eq. (4) is >0 [6]. Then, block motion is initiated. Block displacement is cumulated by double integration of the down-dip sliding acceleration when S>0.

3.2 Empirical Formula

In this study, the Eq. (6) regress the data of the earthquakes and slope failures at Taiwan and is adopted to calculate D_N in the horizontal direction[8]:

$$\log(D_N) = -5.645 + 0.943 M_L - 0.017R + \log[(1-q)^{1.87}(q)^{-1.392}] + 0.411p \tag{6}$$

where, M_L is the Richter's magnitude of an earthquake. R indicates the focal distance. $q = A_c/A_m$, with A_c is the critical acceleration, and A_m shows the maximum ground acceleration due to the earthquake. p is a coefficient which depends on the probability of exceedance. For probability 50%, the value of p is 0.

4 Geological Outline of Tsaoling

Figure 3 illustrates the geological outline near Tsaoling landslide. The investigated slope is located at the western foothill area of Taiwan. The Dajianshan Fault is located at the west of the Tsaoling and is the boundary of the west foothill area in the east and the hills and the plains in the west. In addition, the fault extents northward and connects the Chelungpu fault, which caused the Chi-Chi Earthquake.

The Tsaoling landslide slope is a dip-slope failure and is located at the east wing of the Jioucyongping Syncline. The Cingshuei River cuts through the toe of the slope and was blocked to form a huge reservoir by the slid blocks as shown in Fig. 4. The parent rocks of the Tsaoling landslide slope consist of Choulan Formation at the upper part, and the Chinshui Shale at the lower part. The formations

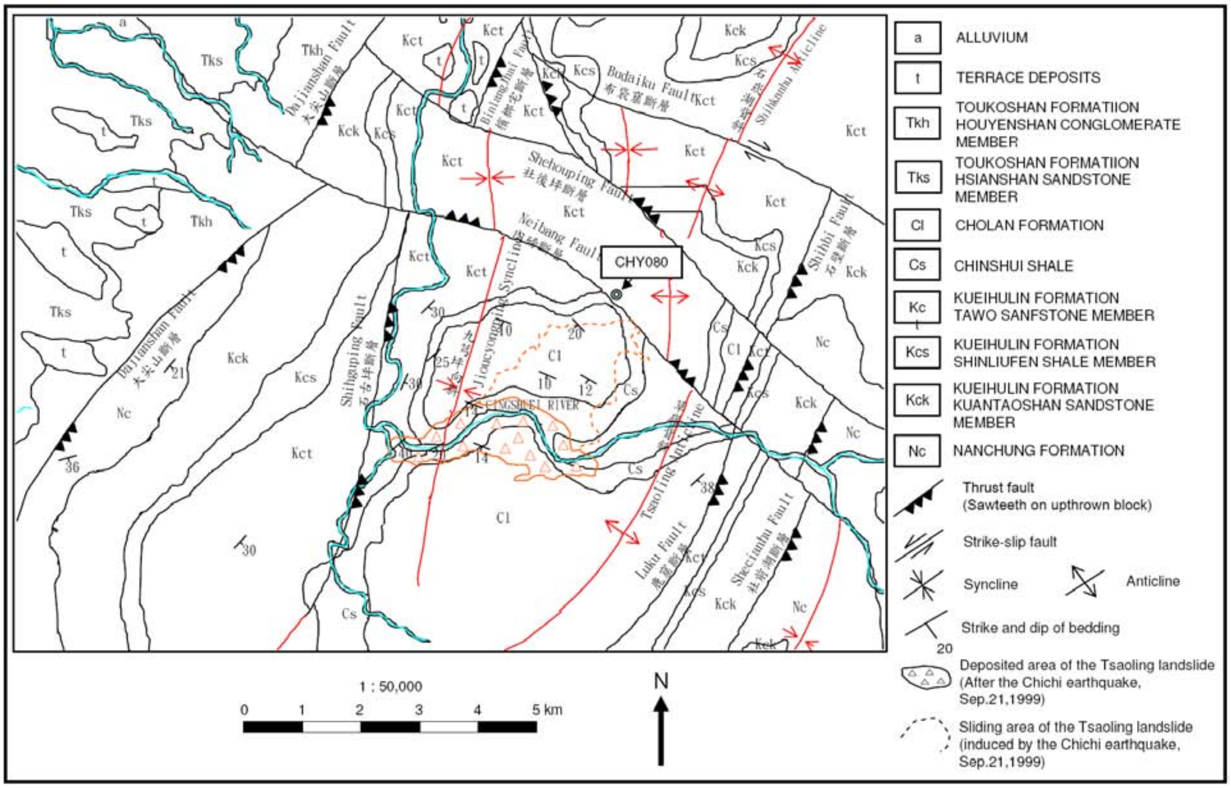


Fig. 3 Geological map near Tsaoling Landslide (after [9])

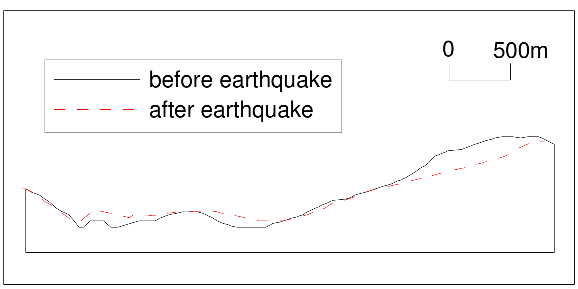


Fig. 4 Landforms of Tsaoling landslide before and after the Chi-Chi Earthquake

at the sliding surface strikes N35°W and dips 10-14° to the directions of south to southwest [7].

5 Accelerograph and GPS Stations

The conventional pseudo-static seismic analysis, which involves the peak ground acceleration of an earthquake to calculate the equilibrium forces along a sling surface. On the other hand, the Newmark sliding model needs not only the peak ground acceleration, but also the complete seismic acceleration data to conduct the displacement-based seismic analysis [6]. Fortunately, a CWB strong-motion network acquired an ever-exhaustive set of ground motion data during the Chi-Chi Earthquake (Fig. 5). The "star" indicates the location of the main shock. Surface ruptures of Chelungpu fault extending about 80 km north-south are shown to the left of the main shock. Thus, the database provides valuable information for seismically induced landslide analysis [10]. In this study, the free-field station, CHY080, next to the Tsaoling landslide slope will be selected as shown in Fig. 3 and the time dependent accelerations (Fig. 6) will be applied to the succeeding analysis.

The correctness of the seismic data is essential in conducting Newmark sliding model because the offset in acceleration produces significant drift when double integrating the acceleration to the displacement. Despite of having intensive strong-motion network, earthquake scientists also installed dense GPS network to monitor regional tectonic movement in Taiwan. Since the co-seismic displacement is required to calibrate the integration errors, Yang et al. [11] accurately determined the co-seismic displacements of each GPS station during the Chi-Chi earthquake before and after the earthquake. The abundant information contained in the data set could be further inverted to not only determine the rupture geometry and slip distribution of faults but also the landslides associated with the Chi-Chi earthquake.

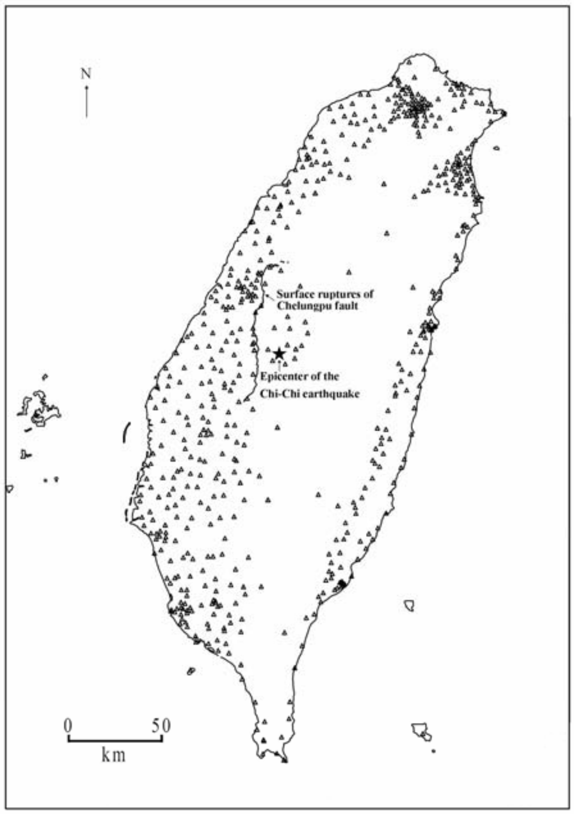


Fig. 5. Locations of the free-field digital accelerograph stations. (after Shin et al., 2000)

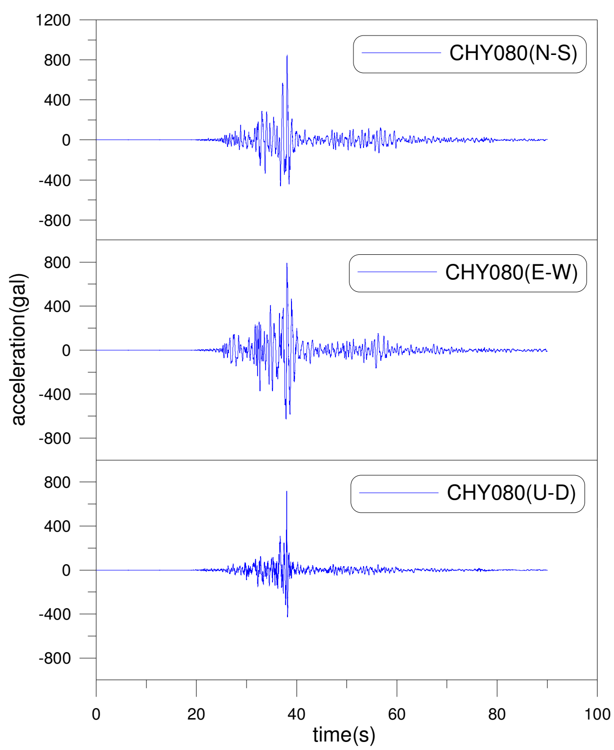


Fig. 6 Accelerations of CHY080

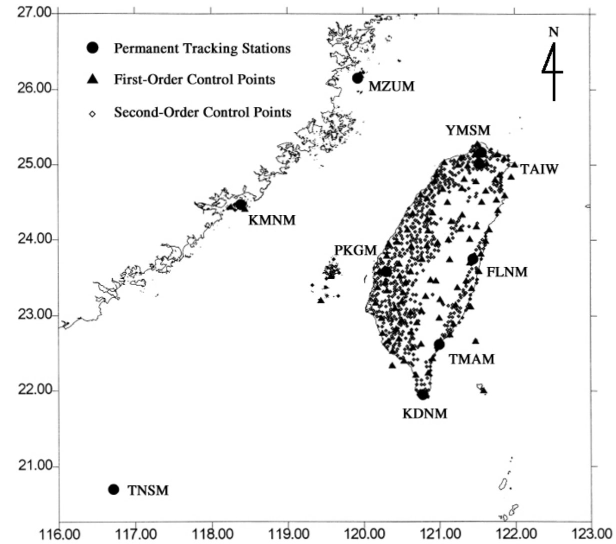
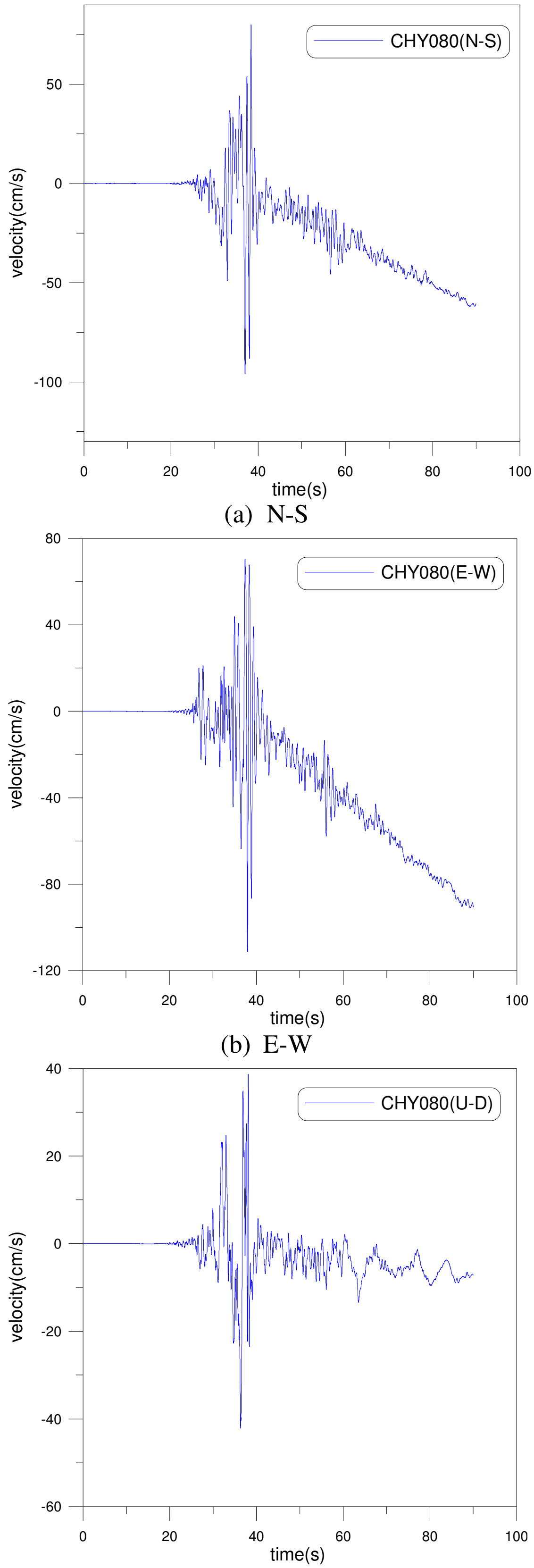


Fig. 7 Spatial distribution of GPS stations in Taiwan (after Yang et al., 2000)

5.1 Baseline Correction

The displacement of strong motion can be obtained by double integrating seismic accelerations. However, the three-component velocities of the CHY080 derived from the near-field seismic accelerations of the Chi-Chi Earthquake drifted (Fig. 8) when only simple pre-event offset correction is applied. The analysis results are inconsistent with the physical phenomenon that ground will stop vibrating after the earthquake. Thus, additional modifications are required to modify the drift during mathematical integrations because remarkable error will arise when double integrate the accelerations to ground displacements [10]. The source to the zero level shift remains unknown; however, the tilting ground during a strong earthquake is likely a cause.

Nevertheless, the lack of additional index to judge the correctness of additional baseline correction will not result in satisfied modifications of accelerations. Fortunately, a dense installation of GPS stations was completed before the Chi-Chi Earthquake as shown in Fig. 7. The co-seismic displacements measured by GPS stations nearby the CHY080 provide valuable data to check the correctness of double integrated displacement from baseline corrected acceleration. Table 2 lists the locations and co-seismic displacements of nearby GPS stations. The de, dn, and du indicate the ground displacements in the directions of East-West, North-South, and Up-Down, respectively. The neighboring GPS stations coincidently moved to the direction of southwest, which is the same as the sliding direction of Tsaoling landslide.



(a) N-S

(b) E-W

(c) U-D

Fig. 8 The shifts of velocities after integrations

Table 2 Nearby GPS stations and displacements

Station	S690	S326	S414
Longitude	120.6579°	120.6949°	120.6487°
Latitude	23.4370°	23.4701°	23.4044°
de(cm)	-6.4	-13.3	-9.4
dn(cm)	-6.3	-8.6	-8.7
du(cm)	6.3	-5.7	10.2

In the baseline correction, t_2 and t_f are two vital parameters. In this study, t_f is defined as the time at the end of the record. Additionally, the start time of the velocity drift, t_2, is arbitrarily selected in the beginning. The gradient of the velocity change between t_2 and t_f is supposed to be the shifted acceleration that needs to be corrected. Then, the time dependent displacement calculated from double integrated the baseline corrected acceleration indicates the co-seismic permanent displacement (Fig. 9) and is compared with the displacements measured by the nearby GPS stations. For example, Fig. 9a presents the time dependent displacement in N-S direction of CHY080 under different t_2. The t_2 remarkably affects the displacement integrated by accelerations. The best fit result for the N-S displacements is obtained by trail and error when t_2=34.93 sec. The same procedure is conducted for the three dimensional acceleration for the baseline corrections. The t2 is 35.77 sec and 24 sec for the E-W and U-D displacements, respectively, as shown in Fig. 9b and 9c. The corrected accelerations are used to the Newmark sliding model to calculate the Newmark displacement [6].

6. Back Calculations of Shear Strengths

Fig. 10 shows the Tsaoling landslide cross section used in Stabl 6.0. The solid line indicates the landform before the Chi-Chi Earthquake; while the dashed line is the one after the earthquake. Thus, the dashed line also presents the profile of sliding surface in the earthquake.

6.1 Force-based analysis

Since the peak ground accelerations are vital parameters for force-based seismic analysis, the baseline corrected maximum vertical and horizontal accelerations of CHY080 are 715.985 gal and 1099.297 gal, respectively, and are applied to Stabl 6.0 analysis. The horizontal acceleration parallels to the dip direction of Tsaoling landslide and is the vector summation of N-S and E-W accelerations. The unit weight of the rocks is assumed to be 25

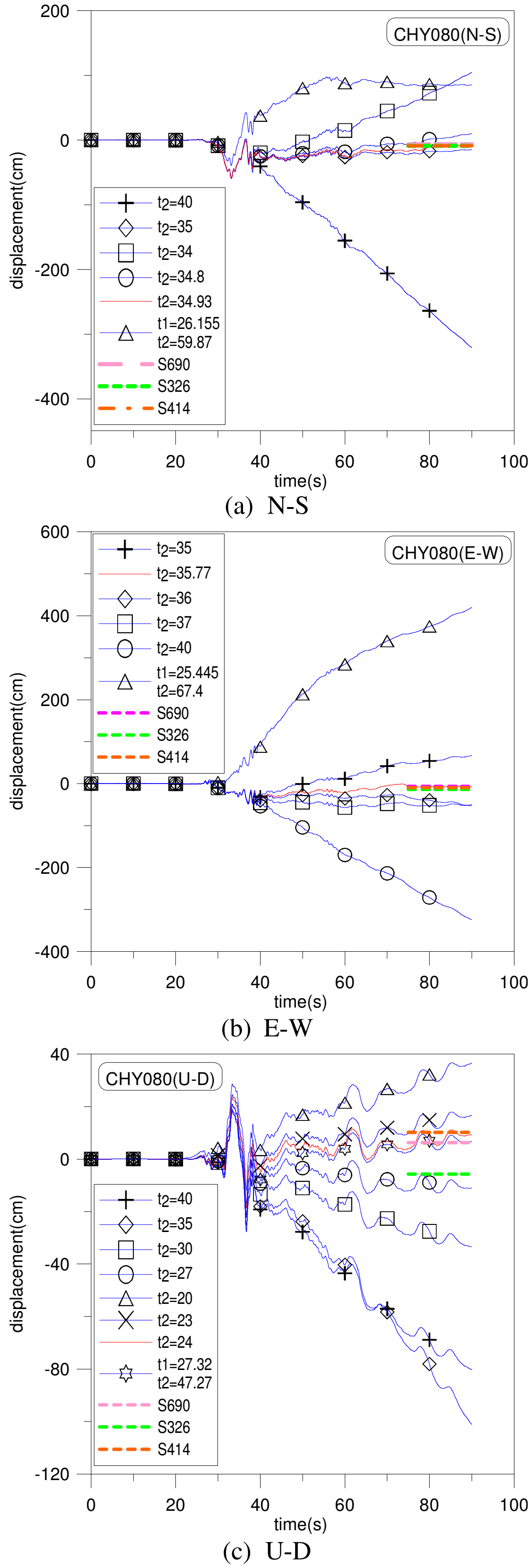


Fig. 9 Baseline corrected ground displacement

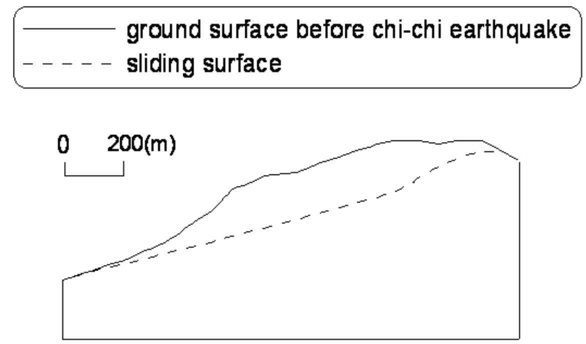


Fig. 10 The cross section of Tsaoling landslide

KN/m[3] [12]. The cohesion is 0 kPa for analyzing the residual strengths of the landslide [12]. The calculation result indicates that the safety factor is 0.853 even when the internal friction angle is 90°.

Hung et al. [12] proposed to conduct 2/3 peak ground accelerations (a_{max}) on seismic analysis in the Tsaoling area. Fig. 11 shows the relation between cohesion and internal friction angle of the landslide when F_s=1.0. The analysis result show that the internal friction angle=68.7° when the safety factor and cohesion are assumed to be 1 and 0, respectively. The internal friction angle is too high to be a reasonable answer. Fujiwara [15] proposed that F_s=0.9 can be used to assume a slope in a sliding state. Thus, Fig. 12 shows the relation between cohesion and internal friction angle of the landslide when F_s=0.9. The internal friction angle is 66.6°, which is slightly smaller than the one of F_s=1, and is still an unreasonable value.

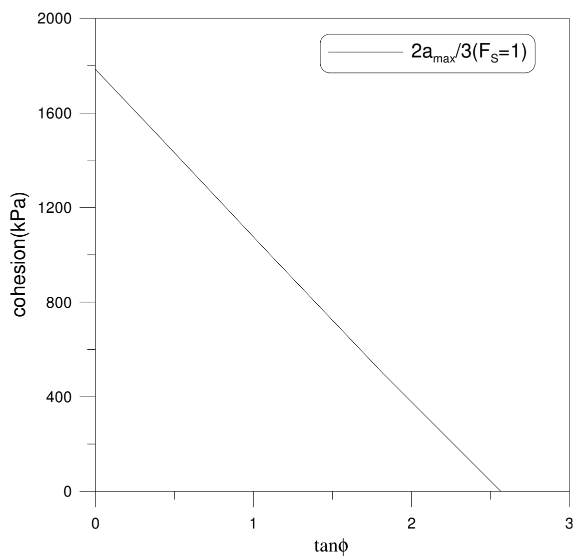


Fig. 11 c-tanø curve for F_S=1

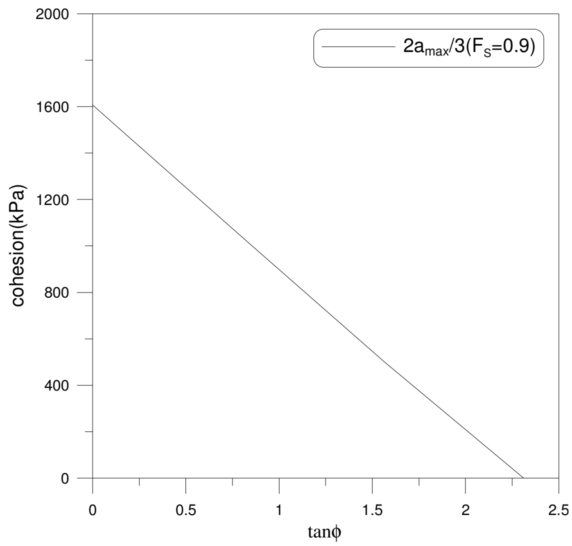


Fig. 12 c-tanø curve for F_S=0.9

The analysis result shows that an engineer must concern the following three difficulties when using force-based method to back calculate the accurate shear strengths of Tsaoling landslide under the seismic impact:

(1) The conventional force-based analysis assumes that the interested object is continuously subjected to peak ground acceleration in an earthquake without considering the decay of seismic wave. This assumption overestimates the seismic impact.

(2) The cohesion and the safety factor must be assumed to obtain internal friction angle and will significantly govern the accuracy of the shear strengths in the back calculation.

(3) The Tsoaling landslide failed during the Chi-Chi Earthquake. Certainly, the safety factor must be smaller than 1 during the earthquake, but it is very difficult to evaluate the correct safety factor for the back calculations.

6.2 Displacement-based analysis

In the empirical analysis, the intensity M_L=7.3 for the Chi-Chi earthquake. The focal distance R=33.4 km. The A_c can be calculated by the Eq. (7) [13]:

$$A_c = \frac{(c/d\gamma\cos\alpha - \tan\alpha + \tan\phi)}{1+\tan\alpha\tan\phi} g, \qquad (7)$$

where, γ is the unit weight of the geomaterial. c is the cohesion. α indicates the dip angle of the sliding surface and is 12° for Tsaoling landslide. d is the thickness of the layer of geomaterial in motion. In the study, the cohesion is assumed to be 0 for analyzing the residual strengths of the landslide.

On the other hand, the Newmark sliding model simplify the Tsaoling landslide to be a block sliding above the other inclined block as shown in Fig. 2. The displacement comes from the double integration of the Newmark sliding model (Eq. 5) when the down-dip sliding acceleration is larger than 0. The Fig. 13 shows the analysis results of Newmark analysis model under c=0 kPa and ø=30°. The Newmark displacement calculated by empirical formula indicates horizontal movement; however, the one double integrated from the Newmark sliding model is in the down-dip sliding direction. The following Eq. 8 is applied to convert the horizontal displacement generated from empirical formula (Eq. 6) to the down-slip sliding movement. Fig. 14 shows the comparisons of calculated Newmark displacements with empirical formulas and Newmark sliding model under different internal friction angles. The two lines intersect at a point, which indicates that mechanical property showing at the intersected point fulfills the requirements of empirical formula and Newmark's sliding model at the same time. Therefore, the intersected point indicates the value of local internal friction angle as 30.3°.

$$A = \frac{\cos(\phi-\alpha)}{\cos\phi}, \qquad (8)$$

Table 3 lists the shear strengths of Choulan Formation and the Chinshui Shale. The value of displacement-based back calculated internal friction angle is between the peak internal friction angle and the residual ones.

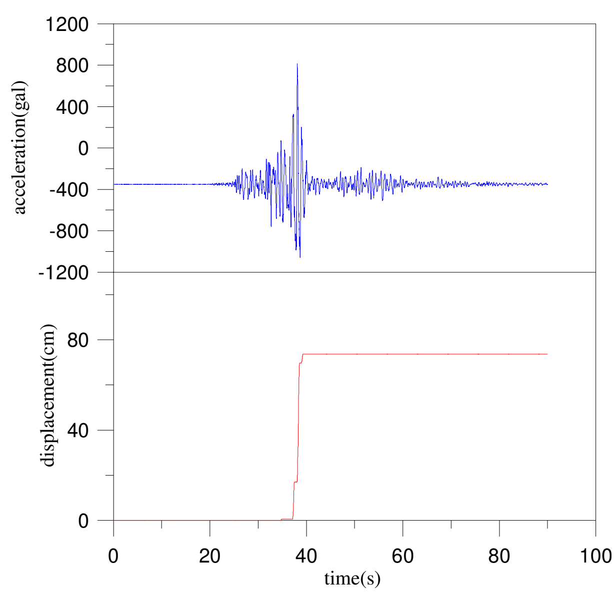


Fig. 13 A analysis result of Newmark sliding model

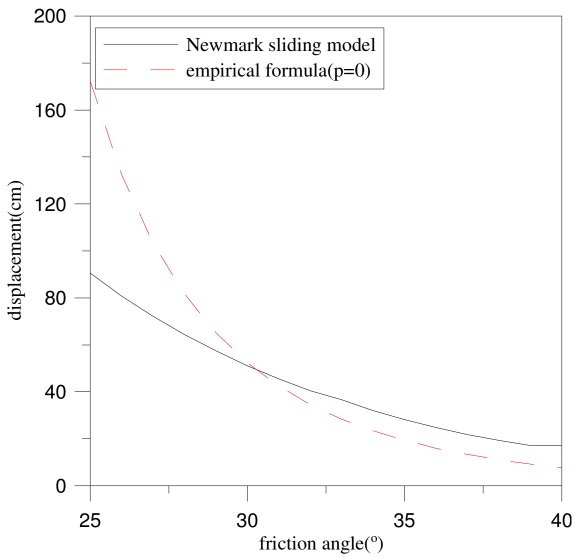


Fig. 14 Analysis results of Newmark displacement

Table 3 Shear strengths of the local materials [14]

Item	Peak		Residual	
	Cohesion (kPa)	Friction Angle (°)	Cohesion (kPa)	Friction Angle (°)
Choulan Formation	980	38.5	0	13.4
Chinshui Shale	664	36.8	0	18.9

Compared with the force-based analysis, the displacement-based analysis concerns the impacts from the whole seismic wave. Additionally, although the displacement back calculation also needs to assume the cohesion in the analysis, the empirical formula simplify the process to evaluate the internal friction angle without further assumptions, such as safety factor in force-based analysis.

7 Conclusion

This study performed a case study of applying force-based and displacement-based methods to back calculate the shear strengths of a slope under a seismic impact. The analysis results show that the displacement-based back-calculation incorporating with Newmark's sliding model and empirical formula results in better shear strengths than the force-based analysis.

When applying force-based method to back calculate the shear strengths of a sliding surface caused by an earthquake, the cohesion, the impacts of the whole seismic wave, and the safety factor are governing factors and need further studies.

The installations of accelerograph and GPS stations significantly guarantee the correctness of the seismic wave after calibrations. Additionally, the baseline correction is essential when applying the near field data of Chi-Chi Earthquake to a seismic slope analysis.

8 Acknowledgement

The first author would like to appreciate to the partial financial support from the Landmark Project of National Cheng Kung University (Project No. C0043) for this research.

References:

[1] W.N. Wang, H. Nakamura, T. Kamai, M.C. Lee, A Photogeologic Study on the Earthquake-induced Slope Failure in Central Taiwan on September 21, 1999, Kobe. *Proceedings of the 39th Conference of Japan Landslide Society,* 2000, pp. 417– 420.

[2] S.W. Lee, 921 Chi-Chi Earthquake and Debris Disasters, *Journal of Japan. Landslide Society*, Vol. 37, No. 1, 2000, pp. 51-59.

[3] M. Chigira, W.N. Wang, T. Furuya, T. Kamai, Geological Causes and Geomorphological Precursors of the Tsaoling Landslide Triggered by the 1999 Chi-Chi Earthquake, Taiwan, *Engineering Geology,* Vol. 68, No. 3-4, 2003, pp. 259-273.

[4] C.S. Huang, H.C. Ho, H.C. Liu, The Geology and Landslide of Tsaoling Area, Yunlin, Taiwan. *Bulletin of Central Taiwan Geologcal Survey,* Vol. 2, 1983, pp. 95–112.

[5] G.P. Giani, *Rock Slope Stability Analysis*, A.A.Balkema, Rotterdam, 1992.

[6] N.M. Newmark, Effect of Earthquakes on Dams and Embankments, *Geotechnique*, Vol. 15, No. 2, 1965, pp. 139-159.

[7] C.C. Huang, Y.H. Lee, H.P. Liu, D.K. Keefer, R.W. Jibson, Influence of Surface-normal Ground Acceleration on the Initiation of the Jih-feng-erh-shan Landslide during the 1999 Chi-Chi, Taiwan, earthquake, *Bulletin of the Seismological Society of America*, Vol. 91, No.5, 2001, pp. 953–958.

[8] S.J. Wang, Analysis the Plain Failure of Natural Slope under Earthquake Condition by Displacement Method, Master Thesis, Department of Resources Engineering,

National Cheng Kung University, Tainan, Taiwan, 2001.

[9] H.C. Liu, J.F. Lee, C.C. Chi, *Geologic Map of Taiwan, Yunlin*, Central Geological Survey, MOEA, Taiwan, 2004.

[10] D.M. Boore, Effect of Baseline Corrections on Displacements and Response Spectra for Several Recordings of the 1999 Chi-Chi, Taiwan, Earthquake, *Bulletin of the Seismological Society of America*, Vol. 91, No. 5, 2001, pp. 1199-1211.

[11] M. Yang, R.J. Rau, J.Y. Yu, T.T. Yu, Geodetically Observed Surface Displacements of the 1999 Chi-Chi, Taiwan, Earthquake, *Earth Planets Space*, Vol. 52, 2000, pp. 403–413.

[12] J.J. Hung, *Extend Research on Tsao-Ling Landlides*, National Center for Research on Earthquake Engineering, NCREE-00-057.

[13] T. Crespellani, C. Madiai, G. Vannucchi, Earthquake Destructiveness Potential Factor and Slope Stability, *Geotechnique*, Vol. 48, No. 3, 1998, pp. 411-419.

[14] C.N. Lee, Preliminary Study on the Tsao-Ling Landslide Area under Earthquake, Master Thesis, Institute of Civil Engineering, National Taiwan University, Taipei, Taiwan, 2001.

[15] A. Fujiwara, Landslide Investigation and Analysis Revised, 2nd edition. Rikohtosho Co., Ltd., Tokyo, Japan, 1999.