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BACK CALCULATING THE SEISMIC SHEAR STRENGTHS OF THE TSAOLING LANDSLIDE ASSOCIATED WITH ACCELEROGRAPH AND GPS DATA*

J. H. WU** AND C. H. CHEN

Dept. of Civil Engineering, National Cheng Kung University, Tainan, Taiwan
Email: jhwu@mail.ncku.edu.tw

Abstract– In this study, the seismic displacement-based back-calculation is discussed and is conducted to analyze the shear strength parameters of the Tsaoling landslide under the impact of the Chi-Chi earthquake. Since the intensive earthquake tilted the ground shifted velocity when integrating seismic acceleration records, the co-seismic displacements measured by neighboring GPS stations played an essential role on baseline corrections of the acceleration time-history adjoining the Tsaoline landslide. In addition, an analysis process of combining empirical formula with Newmark's sliding model simplifies the back-calculation procedure that only assuming the cohesion is required to calculate the internal friction angle of the sliding surface. Although the baseline correction changes the time-history of seismic accelerations, it has an insignificant impact on calculating the shear strength parameters of the Tsaoling landslide. The analysis results indicate that the cohesion is 0 kPa and the internal friction angle is 27.5° for the sliding surface.

Keywords– Back-calculation, Tsaoling, landslide, Chi-Chi earthquake, Newmark sliding model, GPS

1. INTRODUCTION

The epicenters of the Chi-Chi earthquake in Taiwan in 1999 (M_L=7.3), Chuetsu earthquake in Japan in 2004 (M_w=6.6), and Wen Chuan earthquake in eastern Sichuan, China in 2008 (M=7.9) were located in mountainous areas. These intensive earthquakes triggered numerous landsides and highlighted the importance of investigating slope stabilities under seismic impacts. The rock avalanche is defined as its volume exceeds 10^6 m^3, and its moving distance can be over several kilometers under very high velocity [1]. Local geology is the inherent factor to the repeat occurrence of rock avalanches at the same locations, and intensive earthquake is a relevant triggering force. Therefore, countermeasures are required to mitigate the natural hazard because a rock avalanche not only significantly changes local landforms but also seriously damages the life of local residents. The discrete numerical analysis is a suitable method to simulate the post failure of a landslide because the analysis explicitly concerns the geometry of local landform and the shear strengths of discontinuities [2- 4].

Obtaining correct shear strengths along the sliding surface is a key issue before conducting numerical simulation to analyze a landslide. An existing landslide provides a well-defined configuration of sliding surface relative to the topography and external loading conditions at the time of failure. In addition, the case study can be used to estimate the average shear strengths along the failure surface by mathematical methods. This procedure is generally referred to as back-calculation or back-analysis.

In a seismic slope stability analysis, back calculations can be conducted by pseudo-static and displacement-based approaches [5]. The pseudo-static approach involves peak ground horizontal and vertical accelerations to seismic analysis; while, the displacement-based one [6] calculates slope stability

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**Corresponding author

by double integrating the dip-slope accelerations generated by the gravity and seismic force when they exceed the shear strengths of the sliding surface.

In this study, the Tsaoling landslide triggered by the Chi-Chi earthquake is taken as a case study. When conducting a pseudo-static analysis back-calculation of the Tsaoling landslide, Chen et al. [7] applied a reduction factor of 2/3 for both vertical and horizontal peak ground accelerations, as well as 30% of material strength degradation to have reasonable simulation results. However, the determination process of both the investigated seismic acceleration reduction factor and material degradation for another landslide remains a difficult task and would cause error since peak ground horizontal and vertical accelerations do not occur simultaneously. On the other hand, the displacement-based back-calculation includes the seismic accelerations of whole time-history and is expected to be an alterative approach to obtain shear strength parameters of the sliding surface. The displacement-based calculations evaluate slope stability by double integrating the dip-slope accelerations when the down-slope force exceeds the shear resistance of the sliding surface.

However, Boore [8] discovered that intensive ground vibrations during the Chi-Chi earthquake shifted the near-field acceleration records and caused significant error when calculating ground velocities and displacements. The baseline corrections must be done to diminish the acceleration shift. The influence of baseline correction on displacement-based back-calculation of the Tsaoling landslide has not been investigated and will be discussed in this study.

2. DISPLACEMENT-BASED SEISMIC SLOPE STABILITY ANALYSIS

Different from the conventional pseudo-static method, Newmark [9] proposed the displacement-based method to evaluate the seismic slope stability from the seismic induced cumulative displacement, but not the equilibrium of forces along the sliding surface. Fig. 1 illustrates a simplified free-body diagram of a displacement-based model [10]. The resultant forces normal and tangential to the sliding surface under an earthquake can be calculated by the following Eqs. (1) and (2), respectively:

$$\text{Resultant forces normal to the slope, } N = mg \cdot \cos\delta \tag{1}$$

$$\text{Downhill driving forces tangential to the slope, } T = m \cdot (g \cdot \sin\delta - a_d) \tag{2}$$

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

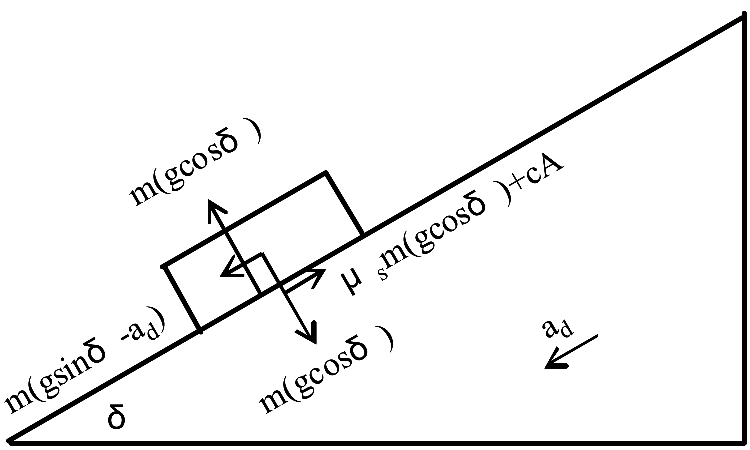


Fig. 1. Free-body diagram of the Newmark sliding model with concerning the normal accelerations

Acceleration a_d is derived in terms of a_N (north acceleration), a_E (east acceleration) and a_V (vertical acceleration) using Eq. (3) [10]:

$$a_d = a_E \cos\delta \cos\phi_s - a_N \cos\delta \sin\phi_s - a_V \sin\delta \tag{3}$$

where, ϕ_s is the strike angle from the north.

Assume,

$$S = (T - N \cdot \tan\phi - cA) / m \tag{4}$$

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

The safety factor of the slope is given by $F_S=(N\tan ø +cA)/T$. When F_S is smaller than 1, the value of S in Eq. (4) is larger than 0. Then, block motion is initiated. The co-seismic Newmark displacement of the block above the sliding surface is cumulated one by double integrating the down-dip sliding accelerations when S>0.

In conventional pseudo-static back-calculation procedure as shown in Fig. 2 [11], the safety factor and cohesion are assumed to get internal friction angle, ø. Similarly, in displacement-based back-calculation, the geometry of unstable block and sliding surface, unit weight of the rock mass, and the time-dependent seismic accelerations are known parameters; while specific displacement corresponding to the landslide, cohesion c, and internal friction angle ϕ are unknowns. The cohesion and the specific displacement must be assumed or calculated to find the unique internal friction angle; however, the specific displacement of the Tsaoling landslide during the Chi-Chi Earthquake is hardly defined.

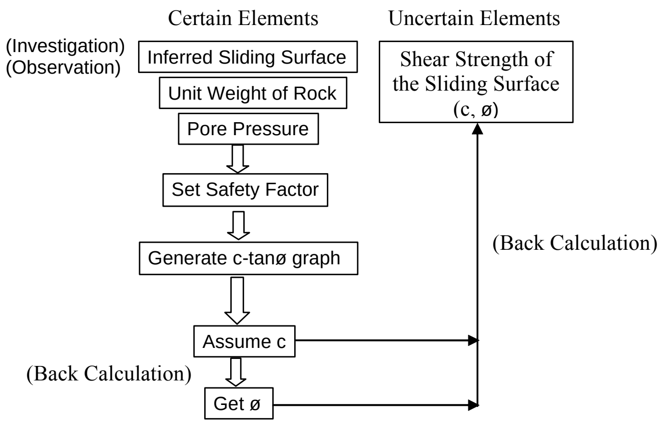


Fig. 2. Pseudo-static back-calculation procedure for a landslide

Fortunately, empirical formula provides another approach to analyze seismic slope stability without neighboring accelerograph stations. Wang [12] gathered 445 acceleration data in total recorded during ten earthquakes in Taiwan from 1991 to 1999. The empirical formula included the data of the Chi-Chi earthquake. In addition, the Richter's magnitude of those selected earthquakes were larger than 5. The longest horizontal distance from the epicenter of an individual earthquake to every selected accelerograph station is 50 km. Wang [12] regressed an empirical formula (Eq. (5)) in estimating the co-seismic horizontal Newmark displacements (D_N) for landslides with planar sliding surfaces :

$$\log(D_N) = -5.645 + 0.943 M_L - 0.017R + \log[(1-q)^{1.87}(q)^{-1.392}] + 0.411p \tag{5}$$

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 the best fitted curve, the value of p is 0.

The Eq. (5) gives an additional equation for Newmark displacement assessment and releases the constraint on assuming specific displacement in displacement-based back-calculations.

3. TSAOLING LANDSLIDE

During the Chi-Chi earthquake, rocks and soils at the Tsaoling slope with an elevation of 450 to 1200 m slide and their deposit area reached 3.4 km^2. The volume of the debris is estimated to be 125 million m^3 and is the largest landslide triggered by the Chi-Chi earthquake [13]. Four huge landslide histories before the Chi-Chi earthquake [14] indicate that earthquake and rainfall are primary factors inducing landslides in the Tsaoling area.

a) Geological outline

Figure 3 illustrates the geological outline near the Tsaoling landslide [15]. The Dajianshan fault is located to the west of Tsaoling and is the geological boundary of the west foothill area in the east and the hills and the plains in the west. In addition, the fault extends northward and connects the Chelungpu fault, which caused the Chi-Chi earthquake. The Cingshuei River cut through the toe of the slope and was blocked to form a huge reservoir by the slide blocks. The parent rocks of the Tsaoling landslide slope consist of Choulan sandstone at the upper part, and Chinshui shale at the lower part. The formations are consistent with the sliding surface and strike N35°W and dip 11-14° in the direction of south to southwest [16]. Thus, the Tsaoling landslide is a dip-slope failure.

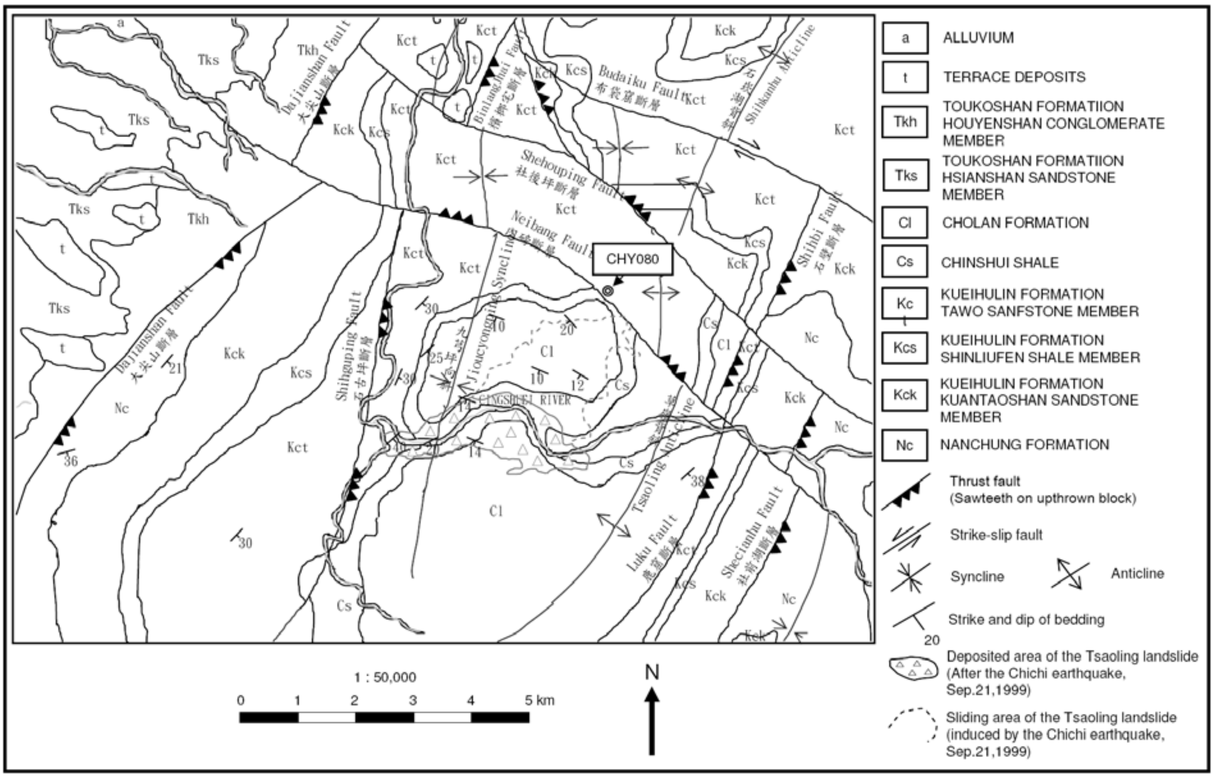


Fig. 3. Geological map near Tsaoling Landslide

b) Seismic data

The triangles in Fig. 4 illustrate the locations of CWB strong-motion network to acquire the movement of the Chi-Chi earthquake [17]. The "star" indicates the location of the main shock. Surface ruptures of the Chelungpu fault, extending roughly 80 km north-south, are shown to the left of the main shock. The Tsaoling landslide is located about 30 km southwest from the epicenter and thus is in the investigated area to generate Eq. (5). CHY080 is the nearest free-field accelerograph station at an elevation of 840 m next to the Tsaoling landslide as shown in Fig. 3 and is demonstrated in the solid triangle in Fig. 4. The recorded three-component pre-event offset corrected accelerations are shown in Fig. 5a. Each seismic data is a 90 sec acceleration record, including 20 sec of pre-event records and 70 sec of earthquake ones. The peak seismic accelerations of CHY080 are 792.4 gal (E-W), 841.5 gal (N-S), and 715.9 gal (Up-Down). The topographic effect [18] of CHY080 and three nearby earthquakes, whose magnitudes are larger than 6.0, occurred soon after the Chi-Chi earthquake [16] and are assumed to be the main reason causing the high accelerations.

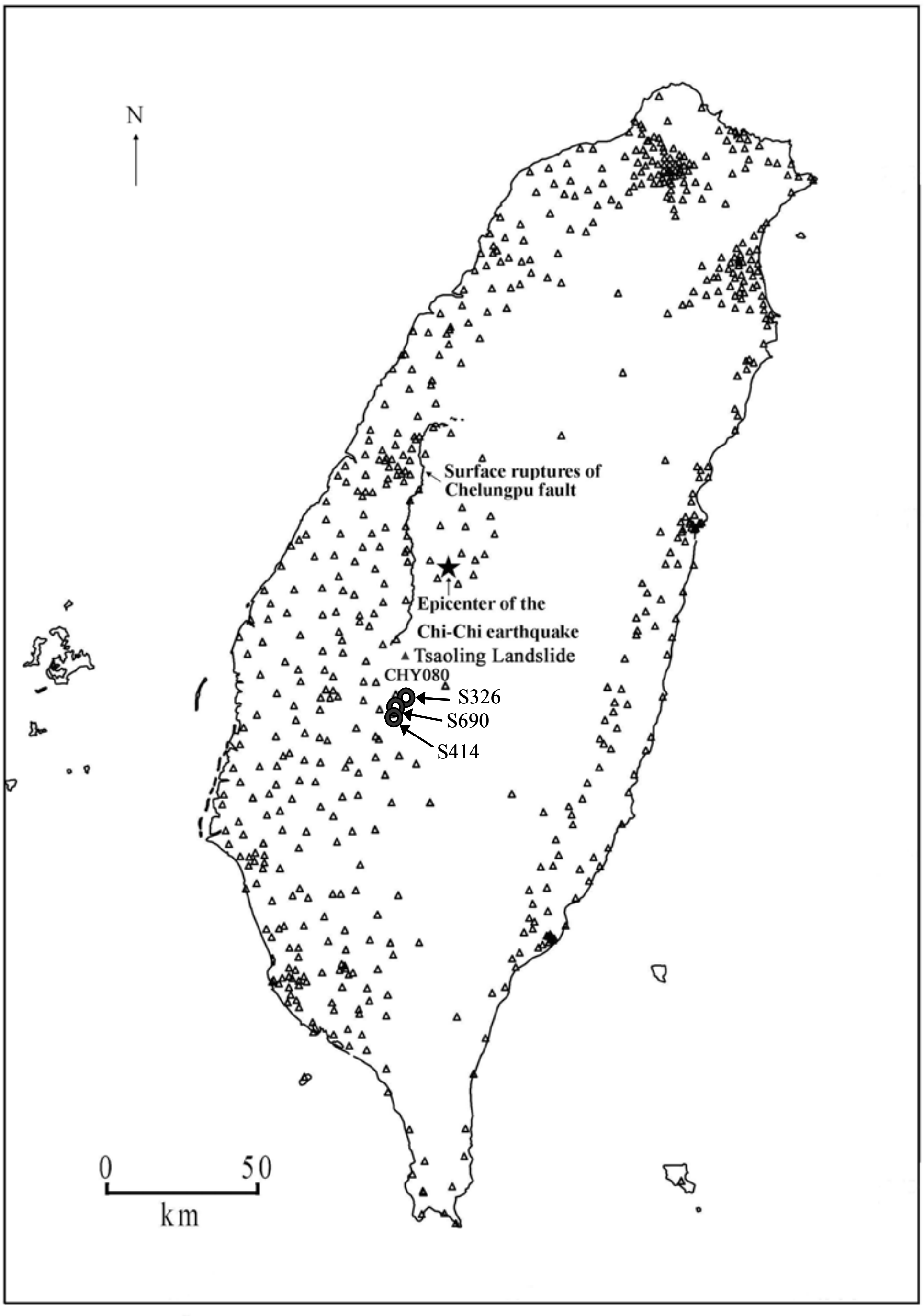
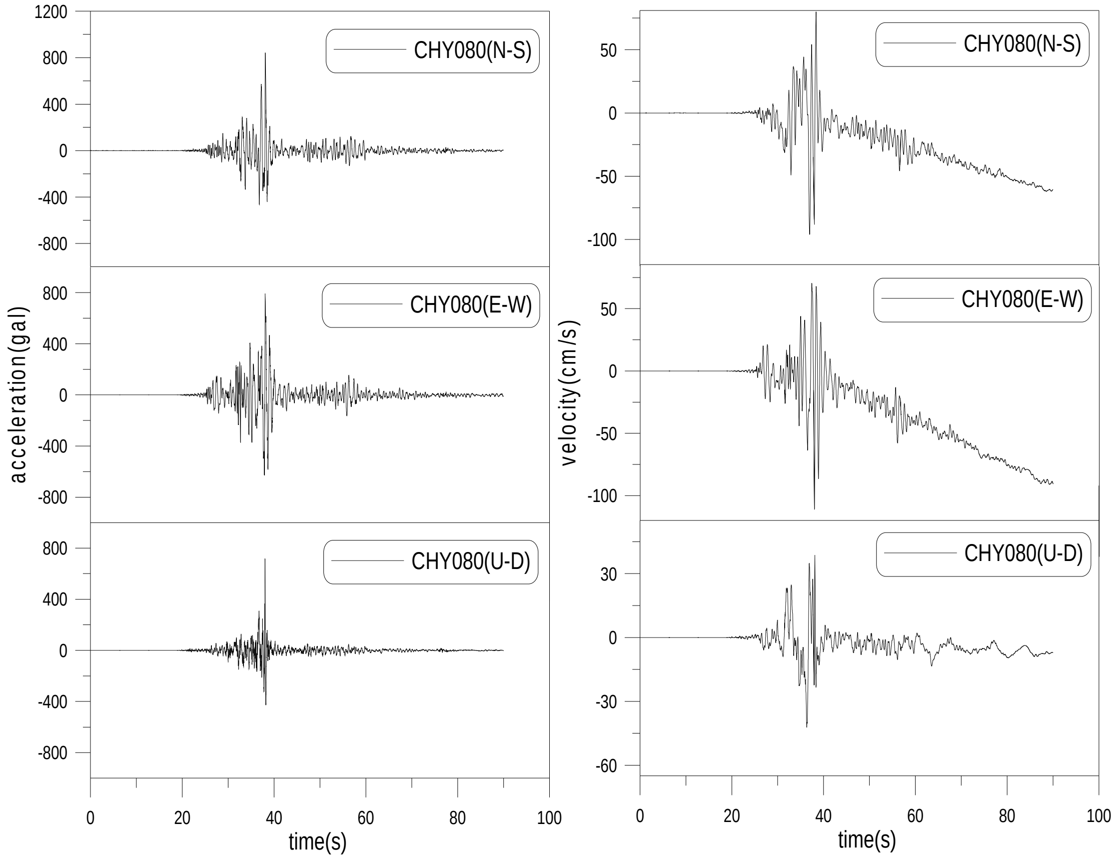


Fig. 4. Locations of the free-field digital accelerograph stations

4. BACK CALCULATIONS OF SHEAR STRENGTHS

a) Baseline corrections

The three-component velocities of CHY080 integrated by the seismic accelerations drifted (Fig. 5b) when only simple pre-event offset correction was applied. The analysis results were inconsistent with the physical phenomenon that ground stops moving at the end of an earthquake. Thus, additional modifications were required to diminish the drift during mathematical integrations [8]. The source to the zero level shift remains unknown; however, tilting ground during a strong earthquake is likely one cause.



(a) Acceleration (b) Velocity

Fig. 5. Three-component accelerations and integrated velocities before baseline correction

Nevertheless, co-seismic ground movement or velocity is essential data to validate the correctness of additional baseline correction. In Taiwan, a dense installation of GPS stations was completed before the Chi-Chi earthquake. The co-seismic displacements measured by GPS stations nearby CHY080 gave valuable data in checking the correctness of double integrated displacements from baseline corrected accelerations (Table 1). The spatial distribution of the nearby GPS stations, S690, S326, and S414, is demonstrated in Fig. 4. To avoid different seismic behavior being performed in different geologic zones [6], the GPS stations of S690, S326, and S414, accelerograph station of CHY080, and Tsaoling landslide are located at the same geologic zone of the western foothill in Taiwan. The de, dn, and du indicate the coseismic ground displacements in the directions of east, north, and up, respectively [19].

In baseline correction, t_2 and t_f are two vital parameters. The t_f is defined as the time at the end of the record, which is t=90 sec in Fig. 5b. Additionally, the velocity drift, t_2, is arbitrarily selected in the first calculation. The velocity at t_2 is defined to be v_2; while the one at t_f is v_f. Therefore, the shifted acceleration, a_{shift}, is determined to be the difference of v_f and v_2 divided by the difference of t_f and t_2 as Eq. (6).

$$a_{shift} = \frac{v_f - v_2}{t_f - t_2} \tag{6}$$

So, the time dependent displacement calculated by double integrated baseline corrected acceleration is the co-seismic displacement and then is compared with the displacements measured by the nearby GPS stations. The t_2 was modified through trial and error to fit the GPS co-seismic displacement. Figure 6 illustrates the seismic displacements with different t_2 in the direction of Up-Down; then, t_2=24 sec is selected. Table 2 shows the peak accelerations before baseline correction, the corresponding time of each peak acceleration, t_2 and t_f of CHY080, as well as the velocities at t_f=90 sec before and after baseline correction in the directions of E-W, N-S, and Up-Down. The analysis results show that the peak acceleration in each direction occurs between individual t_2 and t_f. Therefore, the peak accelerations are affected by baseline corrections. In addition, the baseline corrections minimize the velocity shifts after comparing the time history of the velocities before and after the baseline correction shown in Figs. 5b and 7, respectively.

Table 1. 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

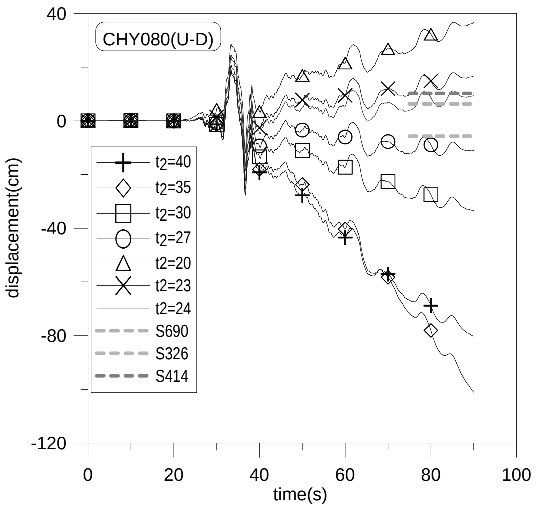


Fig. 6. Baseline corrected ground displacement

Table 2. Peak accelerations before and after baseline corrections

Item		E-W	N-S	Up-Down
Acceleration	Peak acceleration before baseline correction (gal)	792.4	841.5	715.9
	Corresponding time (sec)	38.05	38.08	38.025
	t_2 (sec)	35.77	34.93	24.0
	t_f (sec)	90	90	90
	Peak acceleration after baseline correction (gal)	794.1	842.7	716.0
Velocity	before baseline correction at t_f= 90 sec (m/s)	-90.699	-60.524	-7.194
	after baseline correction at t_f= 90 sec (m/s)	0.536	2.148	0.417

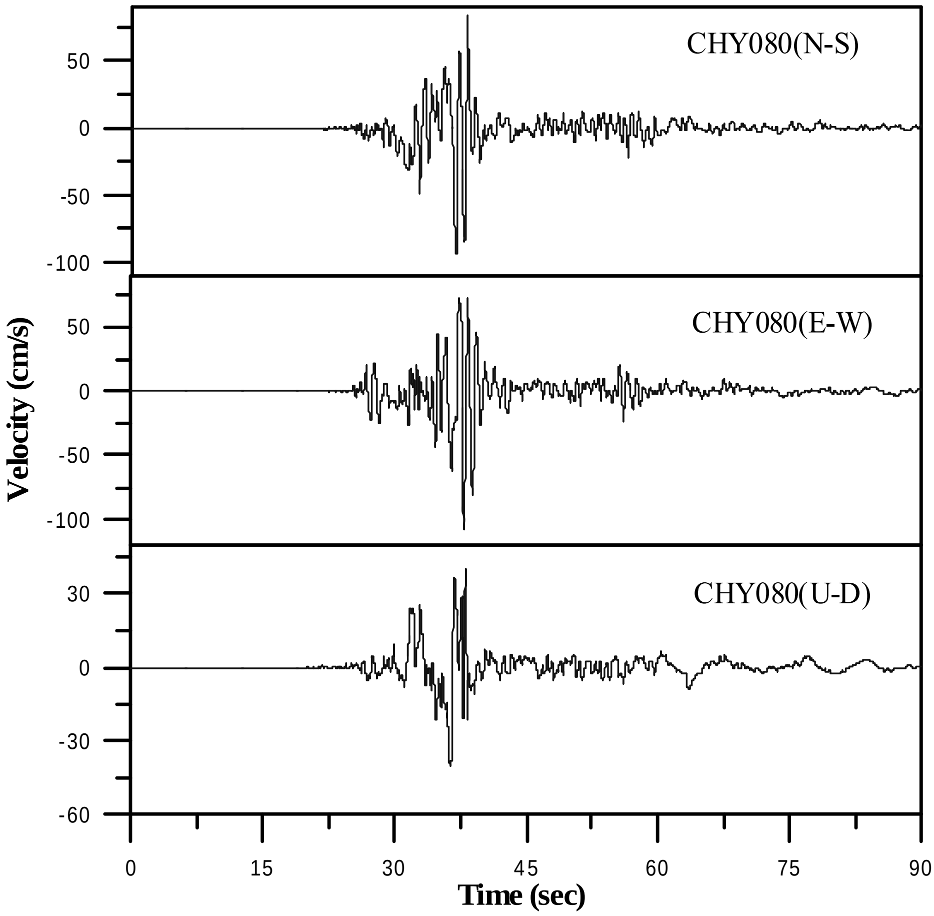


Fig. 7. Three-component integrated velocities after baseline corrections

b) Displacement-based analysis

In the empirical analysis using Eq. (5), the intensity M_L=7.3 for the Chi-Chi earthquake, the focal distance R=33.4 km, and the horizontal critical acceleration, A_c, can be calculated by the Eq. (6) for an infinite slope failure [20]:

$$A_c = \frac{(c/d\gamma\cos\delta - \tan\delta + \tan\phi)}{1+\tan\delta\tan\phi}g \tag{6}$$

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

On the other hand, the Newmark sliding model simplifies the Tsaoling landslide to be a block sliding above the other inclined block as shown in Fig. 1. The horizontal seismic acceleration conducted for the Newmark displacement calculation parallel to the dip direction of the Tsaoling landslide, S55°W as positive, (Fig. 8) was transformed from the baseline corrected N-S and E-W seismic accelerations; while the vertical accelerations are the same as the seismic data. The cumulative down-dip displacement results from double integrating the down-dip sliding acceleration when Eq. (4) exceeds 0. On the other hand, the horizontal Newmark displacement, D_N, is calculated by Eq. (5) and results in different directions from the one analyzed by the Newmark sliding model. The following Eq. (7) is then applied to convert the horizontal displacement generated by the empirical formula (Eq. (5)) to the down-slip sliding movement [20].

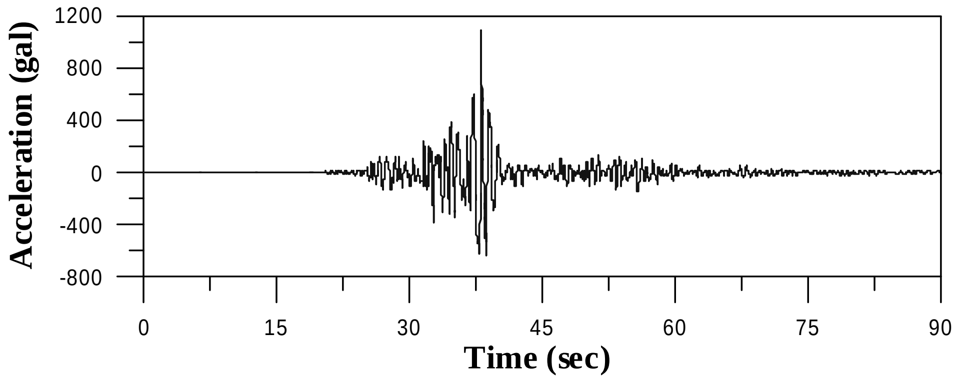


Fig. 8. Horizontal acceleration of CHY080 paralleling to S55°W

$$Coeff = \frac{\cos(\phi - \delta)}{\cos\phi} \tag{7}$$

Figure 9 shows the Newmark displacements using the empirical formula and Newmark sliding model before and after baseline corrections under different internal friction angles. The black solid line and the triangles are the calculation results using the empirical formula before and after the baseline corrections while the gray solid line and the diamonds are the analysis results of Newmark's model before and after baseline corrections, respectively. In the case of the Tsaoling landslide, the baseline correction has an insignificant impact on the results of the Newmark displacement calculated by the empirical formula and the Newmark sliding model, although it modifies the seismic peak accelerations as shown in Table 2.

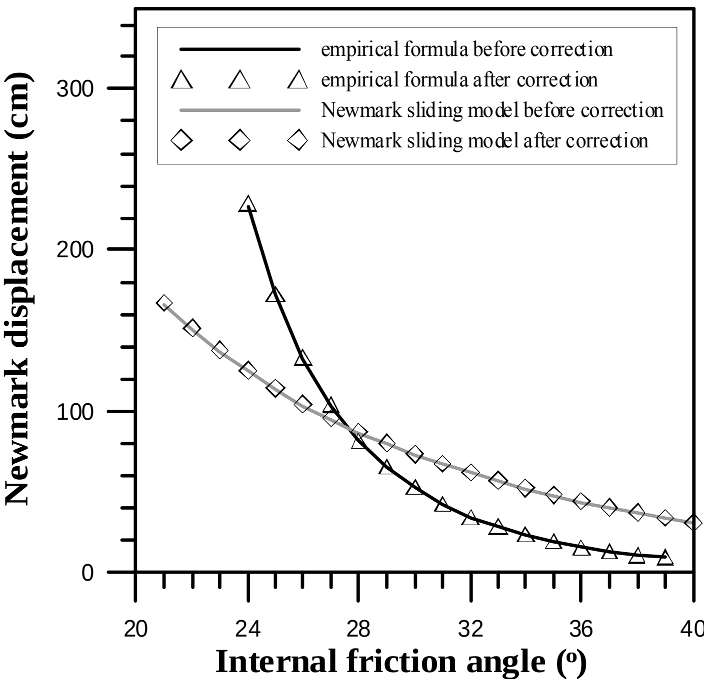


Fig. 9 Analysis results of Newmark displacement

When the solid and dashed lines intersect at a point with ø=27.5° and co-seismic displacement=90 cm, it simultaneously fulfills the requirements of the empirical formula and Newmark's sliding model. Table 3 lists the available shear strengths of Choulan sandstone and Chinshui shale conducted by the laboratory tests. The value of the displacement-based back calculated internal friction angle was between the peak internal friction angle and the residual ones. In addition, Wilson and Keefer [22] suggested that a macroscopic slope failure occurs when the cumulative displacement calculated by Newmark's sliding model exceeds 10 cm; while Chen et al. [23] assumed 5 cm as a critical displacement for slope failures in central Taiwan during the Chi-Chi earthquake. The calculated co-seismic displacement of 90 cm at the Tsaoling slope exceeds the critical displacement when c=0 kPa and ø=27.5°. The analysis results correlate well with the occurrence of the Tsaoling landslide during the Chi-Chi earthquake. Next, the analyzed internal friction angle ø=27.5° is larger than the dip angle of the sliding surface δ=11-14°, which can be used to explain why the sliding blocks did not fail before the Chi-Chi earthquake.

Table 3. Shear strength parameters of local materials [21]

Item	Peak		Residual	
	Cohesion (kPa)	Internal friction angle (°)	Cohesion (kPa)	Internal friction angle (°)
Choulan sandstone	980	38.5	0	13.4
Chinshui shale	664	36.8	0	18.9

5. CONCLUSION

This study applied the displacement-based method of Newmark's sliding model incorporating the empirical formula to back-calculate the shear strengths of the Tsaoling landslide under the impact of the Chi-Chi earthquake. In displacement-based back-calculations, incorporating the Newmark sliding model with the empirical formula simplified the assumption that only cohesion is required.

The installations of an accelerograph and GPS stations significantly contributed to the correctness of co-seismic movements and baseline corrections. Additionally, although the baseline correction changed the peak accelerations of the CHY080, it had an insignificant impact when applying the displacement-based back-calculation method to calculate the shear strength parameters of the Tsaoling landslide.

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