Failure Analysis of Modular-Block Reinforced-Soil Walls during Earthquakes

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Abstract: Several modular-block reinforced-soil retaining walls failed during the 1999 Ji-Ji (Chi-chi) earthquake of Taiwan. Similar walls showed distress during the 1994 Northridge, Calif., earthquake. The instability or failure of these walls offered an opportunity to validate the simplistic pseudostatic limit-equilibrium procedures. In this study, the Ta Kung Wall of the Ji-Ji earthquake is analyzed, and the Gould and Valencia Walls of the Northridge earthquake are revisited with an improved estimation of local site acceleration. The local acceleration was estimated by using simple attenuation relationships obtained through the earthquake records. The results of analysis indicate that these three walls had adequate internal stability under estimated site acceleration. The geosynthetic length was inadequate to resist compound modes of failure where the potential failure surface extends beyond the reinforced zone. The external stability was most critical in the presence of horizontal and vertical accelerations.

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Introduction

Several case histories have shown satisfactory performance of geosynthetic-reinforced soil-retaining structures under earthquake loading (Eliahu and Watt 1991; Collin et al. 1992; Sandri 1997; White and Holtz 1997; Tatsuoka et al. 1995, 1997). However, a reinforced-soil structure with modular-block facing is a relatively new wall system (Collin 1997), and they have therefore not been subject to many earthquakes. Sandri (1997) reported the performance of four modular-block walls during the 1994 Northridge earthquake in California, with most of them showing satisfactory performance, except for two that showed minor cracking at the crest of backfill. In the 1999 Taiwan earthquake, two modular-block reinforced-soil retaining walls failed catastrophically (Ling et al. 2001, 2003). In addition, two modular-block reinforced-soil retaining walls failed during the 2001 Nisqually earthquake in Washington State (Kramer and Paulsen 2001). Although the failure of pipelines was observed for the walls in Washington, it is not certain whether the failure of the wall induced the failure of the pipeline, or vice versa. These walls represented different proprietary systems, and the failures may not indicate a weakness of a particular system. Typically, failures are attributed to design and construction deficiencies. Thus, postfailure analysis enables a better understanding of the design procedure and possibly a better understanding of ways to improve it.

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A brief summary is given below for the modular-block reinforced-soil retaining walls during the Ji-Ji and Northridge earthquakes:

The Ji-Ji (or Chi-Chi) Earthquake occurred in Taiwan on September 21, 1999, with a Richter magnitude of 7.3. The main shock was recorded at 23.87°N, 120.75°E, in central Taiwan at a depth of 7 km, as shown in Fig. 1(a). The earthquake was caused by rupture of the Chelungpu fault. The largest value of peak horizontal ground acceleration recorded was more than 1g (1g=980 Gal). The ratio of vertical to horizontal acceleration was very large. For one of the recording stations (TCU129), which was 13.5 km from the epicenter, the east–west (EW), north–south (NS), and up–down (UD) components of acceleration were 983, 611, and 335 Gal, respectively. Many conventional retaining-wall systems located close to the fault collapsed. The performance of six reinforced-soil structures, which included four geosynthetic-reinforced soil retaining walls having modular block facing and two reinforced slopes, were reported (Ling et al. 2001, 2003). One of the walls that was located along the Ta Kung Roadway of Tai Chung City failed catastrophically (Fig. 2), whereas the other wall, at Nai Lu Shi Park, deformed largely. The Ta Kung Wall was 3.4 m high, had a slope angle of 75°, and was of four-block (80 cm) vertical reinforcement spacing. The backfill material was a silty sand, and the reinforcement was a polyester geogrid that had a strength of 75 kN/m. The strength of the soil is obtained from standard penetration resistance, as discussed subsequently. A major crack was observed at a distance of 5.6 m behind the wall. A minor crack was also formed about 2.5 m behind the wall that corresponded to the length of geogrid (70% of the wall height). The transverse rib of the geogrid reinforcement was torn at the location of the connection pins in the modular blocks. Some of the pins were bent and yielded. The plane of maximum wall-face deformation is apparently of three-dimensional configuration, which varies across the width of the wall (see Fig. 2).

The Northridge earthquake occurred on January 17, 1994, in California and had a Richter magnitude of 6.6. The epicenter was located at 34.21°N, 118.541°W. The Northridge earthquake was also characterized by the relatively large ratio of peak vertical to

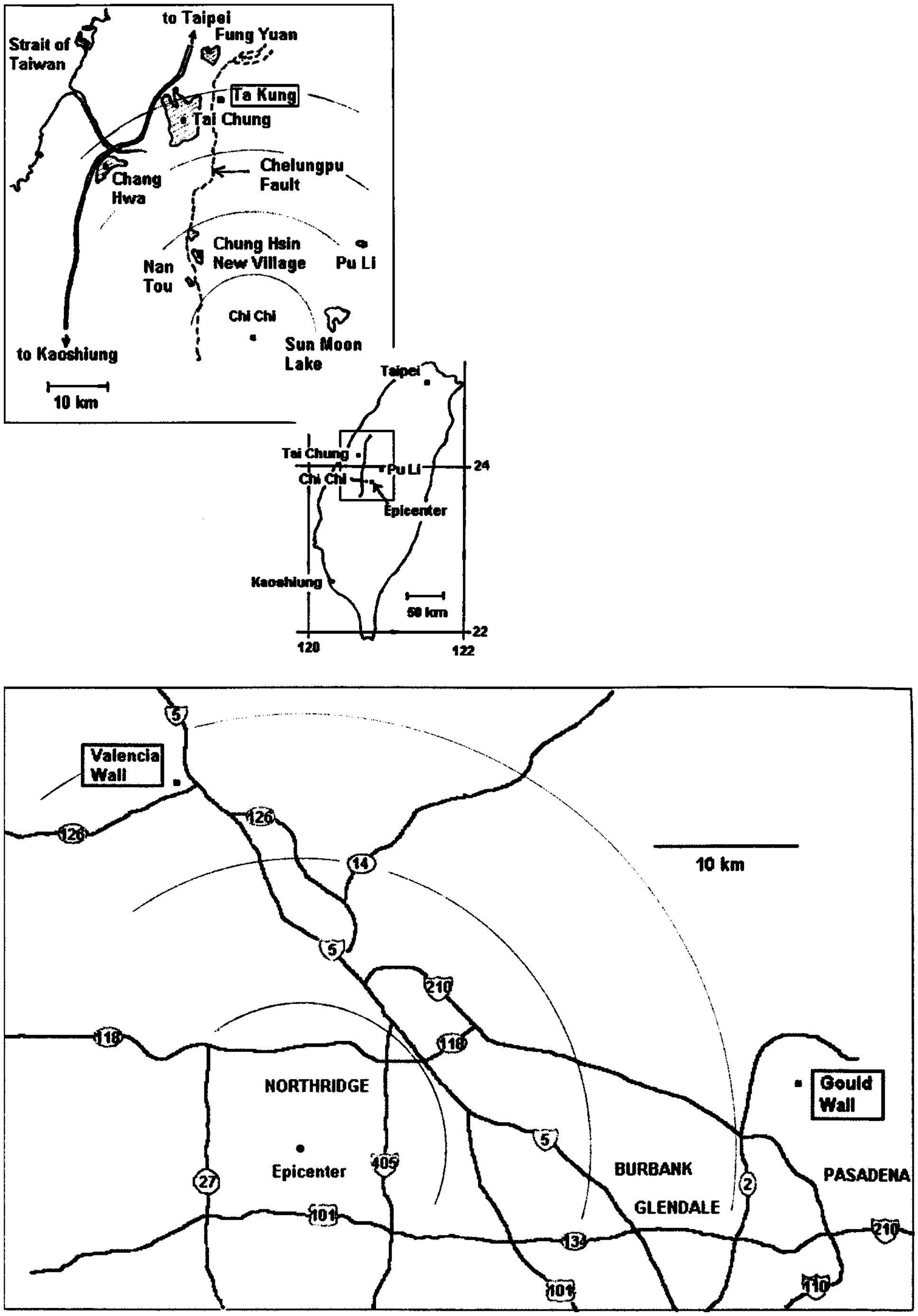

Fig. 1. Location of modular-block reinforced-soil retaining walls: (a) Ji-Ji earthquake; and (b) Northridge earthquake

horizontal acceleration. Ling and Leshichinsky (1998) analyzed the performance of two modular-block reinforced-soil retaining walls, called the Gould Wall and the Valencia Wall [Fig. 1(b)]. The walls were 4.6 and 6.4 m high, respectively, and had a face slope angle of 86.4°. The backfill soil was a silty sand having a unit weight of 20 kN/m^3. The angle of internal friction of the soil was estimated as 33°. A polyester geogrid of strength 36 kN/m was used. These values were also used in a previous analysis (Ling et al. 1997), where the earthquake acceleration was selected as 0.3 and 5*g*, respectively, for the Gould Wall and the Valencia Wall. The values of earthquake acceleration were quoted from Bathurst and Cai (1995). In addition, the vertical acceleration was not considered.

Fig. 2. Failure of modular-block reinforced-soil retaining wall (Ta Kung Wall)

The objective of this paper is to analyze the stability of modular-block reinforced-soil retaining walls during the Ji-Ji and Northridge earthquakes with a better estimation of local site accelerations. The earthquake accelerations were estimated on the basis of attenuation relationships obtained from the earthquake records. An existing pseudostatic procedure that accounts for different modes of failure was used for the stability analysis. Based on the results of the analysis, the cause of the failure is discussed.

Local Site Accelerations

The peak horizontal and vertical accelerations recorded during an earthquake vary with the distance from the epicenter. The degree of attenuation depends also on the wave characteristics, bedrock properties, the magnitude of earthquake, and so on. Several mathematical models are available to generate synthetic ground motion (e.g., Zhang and Deodatis 1998), but they have not been widely used among geotechnical communities. Empirical functions, for example, the functions that correlate peak ground acceleration (PGA) with the distance from the epicenter (e.g., Boore et al. 1997; Sadigh et al. 1997; Toro et al. 1997; Young et al. 1997) are commonly used. Seismic probabilistic maps are usually generated with the help of these empirical functions. These functions are relevant for representing a particular region, and the accuracy depends on available earthquake records. Typically, the coefficients of the function are updated after every earthquake event thereby improving the accuracy.

In this study, a simple correlation between the earthquake accelerations and distance is proposed using following function:

$$\log k_o = a + bD + cD^2 \tag{1}$$

where k_o and D are the peak horizontal or vertical acceleration and the distance from the epicenter, respectively; and a, b, and c are coefficients.

Taiwan has a strong motion instrumentation program with a network of more than 600 seismometers to collect free field ground motion. The Weather Bureau of Taiwan released a set of three component accelerations for more than 422 stations related to the Ji-Ji earthquake. Loh et al. (2000) compared the recorded peak acceleration with the Taiwan "hard site" PGA attenuation formula and revealed that a smaller attenuation was obtained from the records than with the existing attenuation formula.

Fig. 3(a) shows the regression analysis for the acceleration attenuation of the three components of earthquake records for a broad region covering a distance of more than 200 km. For the reinforced-soil retaining wall (Ta Kung Wall) under study, the distance to the epicenter was 37 km. The records for the three stations closest to the location of the reinforced-soil retaining wall are marked as filled dots. The attenuation relationship does not give a satisfactory fit to the records obtained at the sites close to the epicenter. To obtain a better correlation, a regression analysis was conducted, with the distance narrowed down to less than 50 km [Fig. 3(b)], where the horizontal and vertical accelerations were obtained as 0.2 and 0.14g, respectively (Table 1).

A similar regression analysis was conducted to estimate the local site acceleration of two modular-block reinforced soil walls (Gould Wall and Valencia Wall) for the Northridge earthquake using the records of the California strong motion instrumentation program (CSMIP). The records from a total of 26 stations were used. The regression analysis was made for the horizontal and vertical directions (Fig. 4). Note that specific orientation was not mentioned for the horizontal direction. On the basis of the dis-

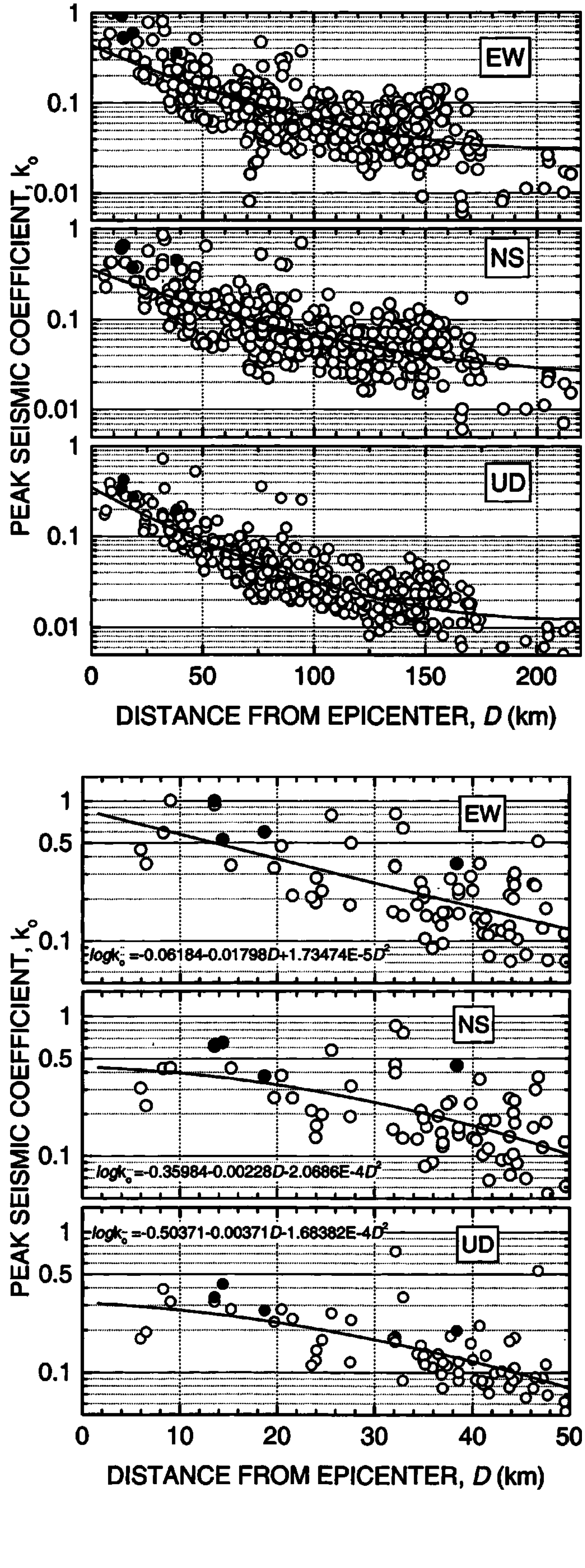

Fig. 3. Ji-Ji earthquake attenuation relationship based on records covering distance up to: (a) 200 km; and (b) 50 km

Table 1. Correlations between Accelerations and Distance from Epicenter

Earthquake	Epicenter	Direction	Coefficients a	b	c	D (km)	k_o
Ji-Ji (Magnitude=7.5)	23.86°N, 120.82°E	EW	−0.0618	−0.0180	0.00002	36.6	0.20
		NS	−0.3598	−0.0023	−0.00020		0.19
		UD	−0.5037	−0.0037	−0.00020		0.14
Northridge (Magnitude=6.6)	34°13′N, 118°2′W	Horizontal	−0.0752	−0.0155	−0.00010	35 (Gould)/26.6 (Valencia)	0.167/0.263
		Vertical	−0.2831	−0.0078	−0.00040	35 (Gould)/26.6 (Valencia)	0.09/0.168

tance of the Gould and Valencia Walls from the epicenter, the horizontal accelerations were obtained as 0.167 and 0.263*g*, respectively, and the vertical accelerations were 0.09 and 0.17*g*, respectively (Table 1). The values of horizontal acceleration were smaller than the 0.5*g* of the previous analysis (Ling and Leshchinsky 1998). It appears that the previously used values were a few times larger than the correlation.

Stability Analysis and Comparison

The stability of reinforced soil structures was analyzed by using the method proposed by Leshchinsky (e.g., Leshchinsky et al. 1995), which was also extended for seismic analysis (Ling et al. 1996, 1997; Ling and Leshchinsky 1998). In the seismic analysis, the earthquake inertia force is considered pseudostatic and was expressed as a percentage of the gravity through the horizontal and vertical seismic coefficients. The procedure encompassed internal and external stability analyses.

The internal stability is evaluated by using a tieback analysis, assuming a log-spiral mechanism so that the length and strength of reinforcements are determined. The stability is achieved by anchoring potential failure soil mass into stable backfill. In the external stability evaluation, direct sliding and compound failure are considered. Direct sliding analysis is conducted by using a two-part wedge mechanism. Compound analysis considers the potential failure surface, which is a log-spiral, that occurs beyond the reinforced soil mass. A component that is based on permanent displacement has also been proposed for design. The details of the analysis are not included in this paper. In this study, the analysis was conducted using ReSlope (Leshchinsky 1999), which is a computer program that incorporates the previously mentioned failure modes and methods of analysis.

The procedure has been validated by Ling et al. (1997) with eight case histories, which included the 1994 Northridge earthquake (M=6.6), the 1995 Kobe earthquake (M=7.3), the 1993 Kushirooki earthquake (M=7.8), and the 1987 Chiba-ken Tohooki earthquake (M=6.7). None of these walls were instrumented, so the earthquake acceleration could only be estimated by using the records obtained from the nearest station. In this study, the two walls of the Northridge earthquake are reanalyzed by using the accelerations obtained from the attenuation relationships [Eq. (1)]. Since failure analysis was a concern that is different from design, the factor of safety has to be unity in the calculation for different modes of failure.

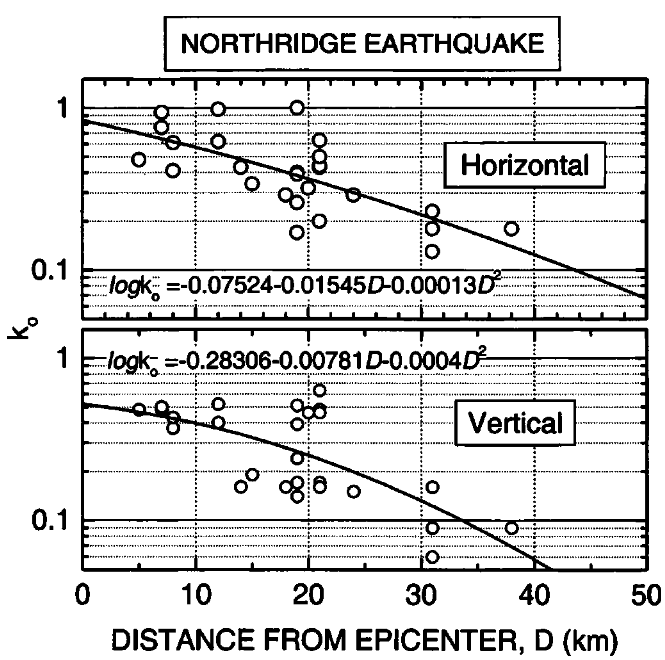

Fig. 4. Northridge earthquake attenuation relationship

Ta Kung Wall, Ji-Ji Earthquake

The backfill soil properties obtained for the Ta Kung Wall are summarized in Table 2. The standard penetration resistance of the backfill soil was $N=13$, which was estimated to be 30° using the correlation of Peck et al. (1974). The interaction coefficient between the soil and grid was assumed as 0.8. Fig. 5 shows the failure surfaces for the static and seismic conditions under estimated accelerations, and Fig. 6 shows the corresponding required length and strength of reinforcement. For geosynthetic force, the most critical condition was for vertical acceleration that acts downward, whereas the most critical failure surfaces were for vertical acceleration that acts upward. The facing blocks were not included in the tieback and compound analyses. The bottom reinforcement layer did not pass through the base of the wall, so the direct sliding failure surface is shown in Fig. 5 for reference only. It can be seen from these figures that the wall was free from tieback and compound failures under static conditions.

Table 3 summarizes the results of the analysis. In the Ji-Ji earthquake, three geosynthetic layers were available to arrest the tieback failure surface, and the total available geosynthetic strength (225 kN/m) exceeded the required value (43 kN/m when vertical acceleration is considered). Even if construction damage and degradation are considered, the available strength was still many times larger than the required strength. Thus, the wall had adequate geosynthetic length and strength against tie-

Table 2. Backfill Soil Properties of Ta Kung Wall

Depth (m)	N-value	Sand (%)	Fine (%)	Soil type	w_n (%)	γ_t (kN/m^3)	e
0–1	8	52.6	47.4	SM	17.8	20.3	0.53
1–2	11	52.5	47.5	SM	15.8	19.1	0.58
2–3	11	45.2	54.8	CL	18.9	20.2	0.54
3–4	12	37.0	57.1	ML	20.4	19.7	0.59

back failure. However, the results showed that the outermost compound failure surface passes behind the bottom reinforcement layer and reinforced zone when horizontal and vertical seismic accelerations of 0.2 and 0.14g, respectively, were considered. That is, compound failure was anticipated for the Ta Kung Wall during the Ji-Ji earthquake. When the vertical acceleration is not considered, the end of the bottom geosynthetic layer is very close to the failure surface. Considering that the blocks were not included in the analysis, it is reasonable to say that the wall would have been stable against compound failure in the absence of vertical acceleration. However, with the vertical acceleration, the wall was no longer stable against compound failure (available length of 2.7 m versus required length of 3.2 m). Thus, the failure of the Ta Kung wall was attributed to compound failure in the presence of horizontal and vertical seismic accelerations. The cracks that developed at the back of the backfill zone provided evidence of the failure surface.

Gould Wall and Valencia Wall, Northridge Earthquake

Figs. 7 and 8 show the configuration of the Gould and Valencia Walls, respectively, with the associated failure surfaces. The direct sliding surfaces for the Valencia Wall were extremely long because of the large earthquake acceleration, so they are not included for seismic conditions. The total strength and length of reinforcement required to resist different modes of failure are summarized in Table 3. The surfaces for the most critical directions of vertical acceleration, which are downward for the strength and upward for failure surfaces, respectively, are shown. The results show that the Gould Wall was stable against tieback, compound, and direct sliding modes of failure under static and seismic conditions, including vertical accelerations. The stability was evidenced during Northridge earthquake. The Valencia Wall was stable under static conditions, with all potential surfaces located within the reinforced zone. It was also stable internally under estimated seismic loadings. Although the wall was subject to compound failure, it was also at risk of failure by direct sliding with the estimated local site acceleration. Sandri (1997) reported cracking at the surface of backfill that gave evidence of external instabilities.

Summary and Conclusions

In this study, the cause of failure for a modular-block wall during the Ji-Ji earthquake was discussed. The performance of two modular block walls during the Northridge earthquake was revisited. An empirical function was calibrated against earthquake records and used to estimate the local site accelerations. The stabilities were determined on the basis of the pseudostatic approach.

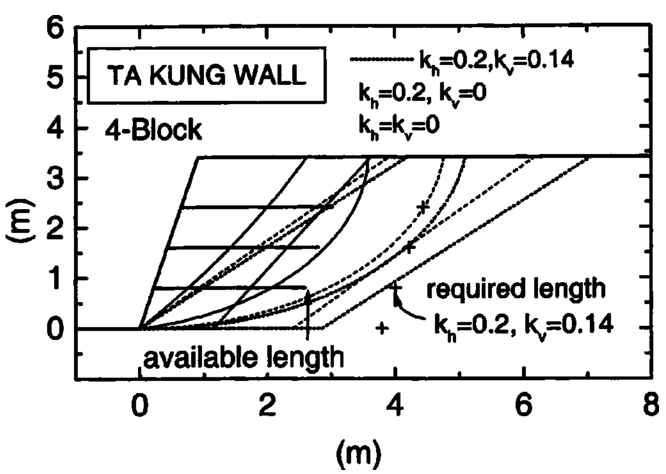

Fig. 5. Geometry and associated failure surfaces for Ta Kung Wall under static and seismic conditions

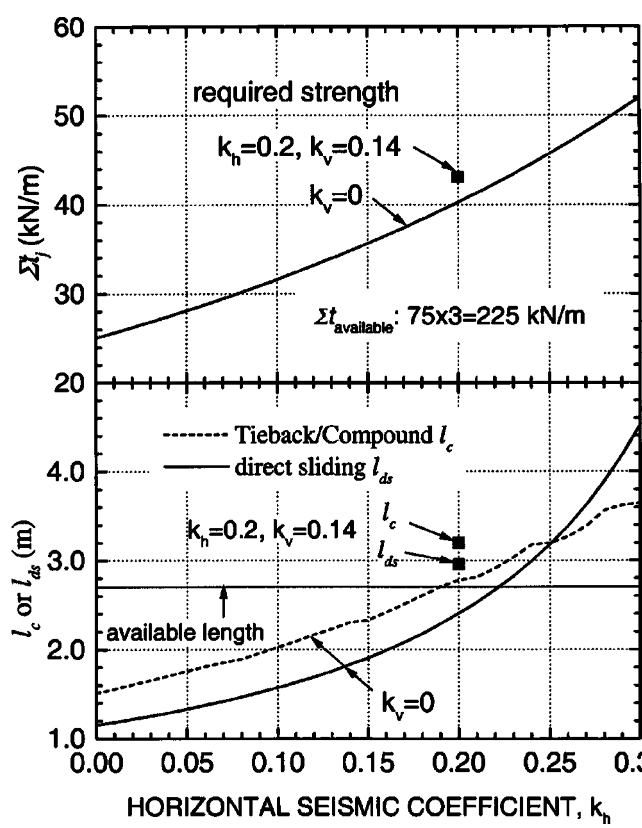

Fig. 6. Required length and strength for Ta Kung Wall under static and seismic conditions

Table 3. Required and Available Strength and Length of Reinforcement under Static and Seismic Conditions

Wall	Loading conditions	Direct sliding: Required length (m)	Direct sliding: Available length (m)	Tieback strength: Required (kN/m)	Tieback strength: Available (kN/m)	Compound available strength (kN/m)
Ta Kung	Static	—	—	—	225 (3 layers)	75 (1 layers)
	$k_h=0.2$ $k_v=0.0$	—	—	40.3	225 (3 layers)	0 (0 layer)
	$k_h=0.2$ $k_v=0.1$	—	—	43.1	225 (3 layers)	0 (0 layer)
Gould	Static	1.14	3.0	55.5	432 (12 layers)	288 (8 layers)
	$k_h=0.167$ $k_v=0.1$	2.73	3.0	77.7	432 (12 layers)	216 (6 layers)
	$k_h=0.167$ $k_v=0.09$[a]	3.05	3.0	82.3	432 (12 layers)	216 (6 layers)
Valencia	Static	1.58	4.9	107.5	288 (8 layers)	288 (8 layers)
	$k_h=0.263$ $k_v=0$	8.2	4.9	182.6	288 (8 layers)	180 (5 layers)
	$k_h=0.263$ $k_v=0.168$[a]	16.2	4.9	197.4	288 (8 layers)	144 (4 layers)

[a]Most critical direction of vertical acceleration.

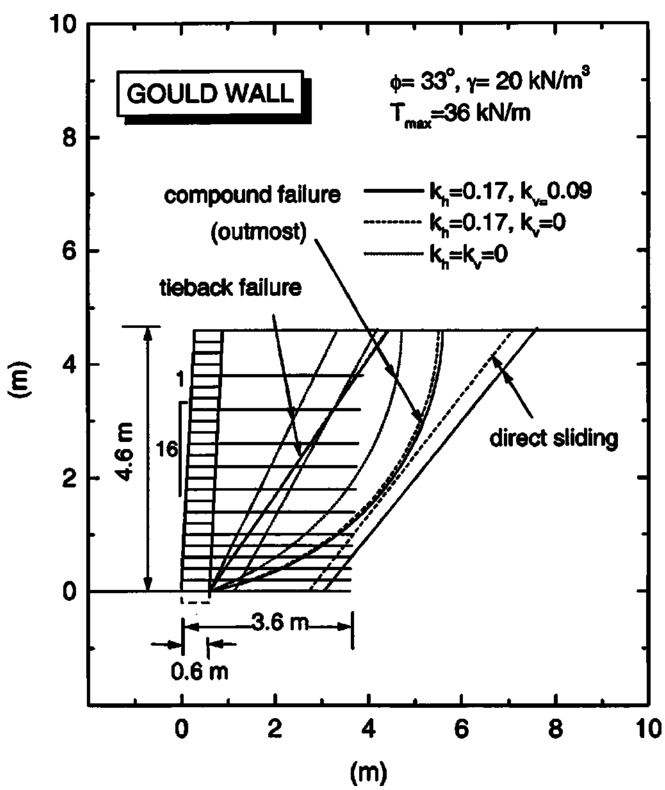

Fig. 7. Geometry and associated failure surfaces for Gould Wall under static and seismic conditions

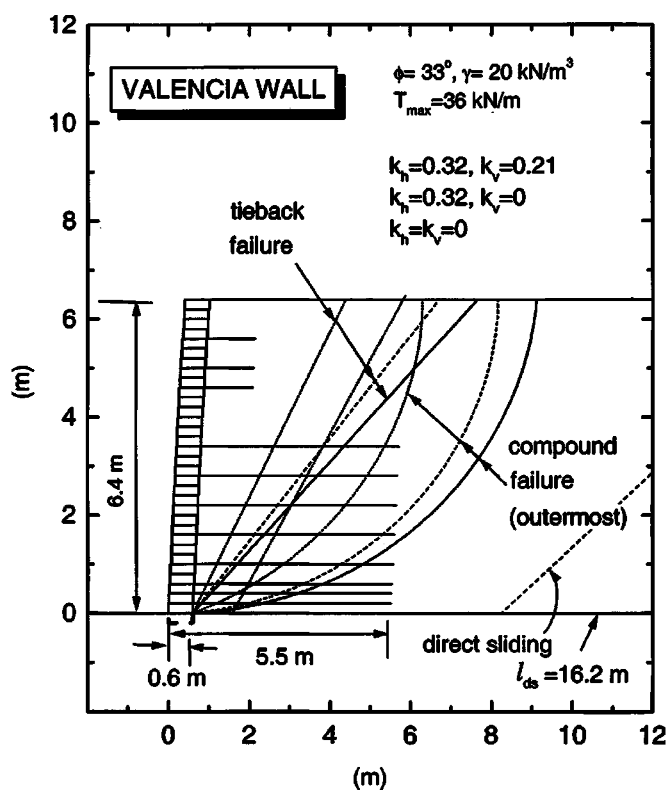

Fig. 8. Geometry and associated failure surfaces for Valencia Wall under static and seismic conditions

The results showed that in the presence of vertical acceleration, compound failure was the most likely cause of failure of the wall during the Ji-Ji earthquake.

For the Valencia Wall, a combination of direct sliding and compound modes could have lead to cracking and deformation.

Although the acceleration used in previous studies (Ling et al. 1998) was more conservative than the present analysis using attenuation relationships, the results of the performance of the Gould Wall remained the same.

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References

Bathurst, R. J., and Cai, Z. (1995). "Pseudo-static seismic analysis of geosynthetic-reinforced segmental retaining walls." *Geosynthet. Int.*, 2(5), 787–830.

Boore, D. M., Joyner, W. B., and Fumal, T. E. (1997). "Equations for estimating horizontal response spectra and peak acceleration from Western North American earthquakes: A summary of recent work." *Seismol. Res. Lett.*, 68(1), 128-153.

Collin, J. G. (1997). *Design manual for segmental retaining walls*, 2nd Ed., National Concrete Masonry Association, Herndon, Va.

Collin, J. G., Chouery-Curtis, V. E., and Berg, R. R. (1992). "Field observations of reinforced soil structures under seismic loading." *Proc. Int. Symp. on Earth Reinforcement*, Ochiai et al., eds., Balkema, Rotterdam, The Netherlands, 223–228.

Eliahu, U., and Watt, S. (1991). "Geogrid-reinforced wall withstands earthquake." *Geotech. Fabr. Rep.*, 9, 8–13.

Kramer, S. L., and Paulsen, S. (2001). "Seismic performance of MSE structures in Washington State." International Geosynthetics Engineering Forum, Taipei, Taiwan, 145–173.

Leshchinsky, D. (1999). "Putting technology to work: MSEW and ReSlope for reinforced soil structure design." *Geotech. Fabr. Rep.*, 17(3), 34–38.

Leshchinsky, D., Ling, H. I., and Hanks, G. (1995). "Unified design approach to geosynthetic reinforced slopes and segmental walls." *Geosynthet. Int.*, 2(5), 845–881.

Ling, H. I., and Leshchinsky, D. (1998). "Effects of vertical acceleration on seismic design of geosynthetic-reinforced soil structures." *Geotechnique*, 48(3), 347–373.

Ling, H. I., Leshchinsky, D., and Chou, N. N. S. (2001). "Post-earthquake investigation on several geosynthetic-reinforced soil retaining walls and slopes during 1999 Ji-Ji earthquake of Taiwan." *Soil Dyn. Earthquake Eng.*, 21(4), 297–313.

Ling, H. I., Leshchinsky, D., and Perry, E. B. (1996). "A new concept of seismic design of geosynthetic-reinforced soil structures: Permanent displacement limit." *Earth reinforcement* Ochiai et al., eds., Balkema, Rotterdam, The Netherlands, 797–802.

Ling, H. I., Leshchinsky, D., and Perry, E. B. (1997). "Seismic design and performance of geosynthetic-reinforced soil structures." *Geotechnique*, 47(5), 933–952.

Ling, H. I., Leshchinsky, D., Tatsuoka, F. (2003). "Reinforced soil engineering: Advances in research and practice." Marcel Dekker Inc., New York.

Loh, C.-H., Lee, Z.-K., Wu, T.-C., and Peng, S.-Y. (2000). "Ground motion characteristics of the Chi-Chi earthquake of 21 September 1999." *Earthquake Eng. Struct. Dyn.*, 29, 867–897.

Peck, R. B., Hansen, W. E., and Thornburn, T. H. (1974). *Foundation engineering*, Wiley, New York.

Sadigh, K., Chang, C.-Y., Egan, J. A., Makdisi, F., and Youngs, R. R. (1997). "Attenuation relationships for shallow crustal earthquakes based on California strong motion data." *Seismol. Res. Lett.*, 68(1), 180–189.

Sandri, D. (1997). "A summary of reinforced soil structures performance in the Greater Los Angeles area after the Northridge earthquake." *Mechanically stabilized backfill*, J. T. H. Wu, ed., Balkema, Rotterdam, The Netherlands, 433–442.

Tatsuoka, F., Koseki, J., and Tateyama, M. (1997). "Performance of reinforced soil structures during the 1995 Hyogo-ken Nambu earthquake." *Earth Reinforcement*, Ochiai et al., eds., Balkema, Rotterdam, The Netherlands, 979–1008.

Tatsuoka, F., Tateyama, M., and Koseki, J. (1995). "Behavior of geogrid-reinforced soil retaining walls during the Great Hanshin-Awaji earthquake." *Proc., 1st Int. Symp. on Earthquake Geotechnical Engineering*, Ishihara, ed., 55–60.

Toro, G. R., Abrahamson, N. A., and Schneider, J. F. (1997). "Model of strong ground motions from earthquakes in Central and Eastern North America: Best estimates and uncertainties." *Seismol. Res. Lett.*, 68, 41–57.

White, D., and Holtz, R. D. (1997). "Performance of geosynthetic-reinforced slopes and walls during the Northridge California earthquake of January 17, 1994." *Earth reinforcement*, Ochiai et al., eds., Balkema, Rotterdam, The Netherlands, 965–972.

Youngs, R. R., Chiou, S. J., Silva, W. J., and Humphrey, J. R. (1997). "Strong ground motion attenuation relationships for subduction zone earthquakes." *Seismol. Res. Lett.*, 68(1), 58–73.

Zhang, R., and Deodatis, G. (1996). "Seismic ground motion synthetics of the 1989 Loma Prieta Earthquake." *Earthquake Eng. Struct. Dyn.*, 25(5), 465–481.