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THE BEHAVIOR OF RETAINING WALLS UNDER 1999 CHI-CHI EARTHQUAKE

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ABSTRACT

This paper reports failure of retaining structures related to the 1999 Chi-Chi earthquake. On September 21 of 1999, an earthquake with a magnitude of 7.3 on the Richter scale struck Taiwan. At the site near Tou-Sheh, overturning failure was observed on a 2.5 m-high gravity wall located near the epicenter. At the site near the Temple of Ten-thousand Buddha, a masonry wall constructed with cobble was damaged. Upper part of wall shifted outward about 0.2 m with respect to its lower part. At the site of Cinema-Culture Town, a gravity wall built on top of the Che-Lung-Pu fault was severely damaged. The heel of the wall was uplifted by the fault rupture. At the parking lot of the Lalu Resort, the retaining wall constructed on a slope moved down the slope during the earthquake. A circular sliding surface can be observed in the collapsed backfill. At the entrance of National Chi-Nan University, a geogrid-reinforced wall was severely damaged during the earthquake. Reinforcing strips were pulled out under the seismic load and fill materials fell out.

KEYWORDS

earthquake; failure; fault; overturning; retaining wall; seismic; sliding.

INTRODUCTION

On September 21, 1999 at 1:47 a.m., an earthquake with a magnitude of 7.3 on the Richter scale struck Taiwan. The epicenter was located near Chi-Chi (sometimes translated as Ji-Ji or Gi-Gi) as indicated in Fig. 1. The focal depth is about 7.0 km. The rupture of ground along the Che-Lung-Pu fault is about 105 km long. The frequency of shaking ranged from 1.0 to 4.0 Hertz. The horizontal peak ground acceleration (PGA) measured at seismograph TCU-065 was as high as 774 gal (0.79 g). Unfortunately, more than 50,000 buildings were damaged and more than 2,300 people were killed in this incident.

Geotechnical problems observed after the earthquake include landslides, soil liquefaction, and foundation failures. This paper reports typical modes of retaining-wall failure as a result of the Chi-Chi earthquake. For the design of a rigid retaining wall, the Navy Design Manual (DM-7.2) requires to check the resistance against sliding, resistance against overturning, settlement, allowable pressures on the base, and the overall stability of the wall. Seed and Whitman (1970) described how to estimate the dynamic earth pressure based on the Mononobe-Okabe theory. Fang and Chen (1995) proposed a more rational method to estimate dynamic earth pressure by modifying the Mononobe-Okabe theory.

Although several retaining walls collapsed during the Chi-Chi earthquake, however these walls had been stable for many years under static condition. The "Foundation Design Code" of Taiwan adopted the Mononobe-Okabe method to determine the dynamic earth pressure under seismic loading. In the theory, the most important parameters to influence the dynamic pressure are the

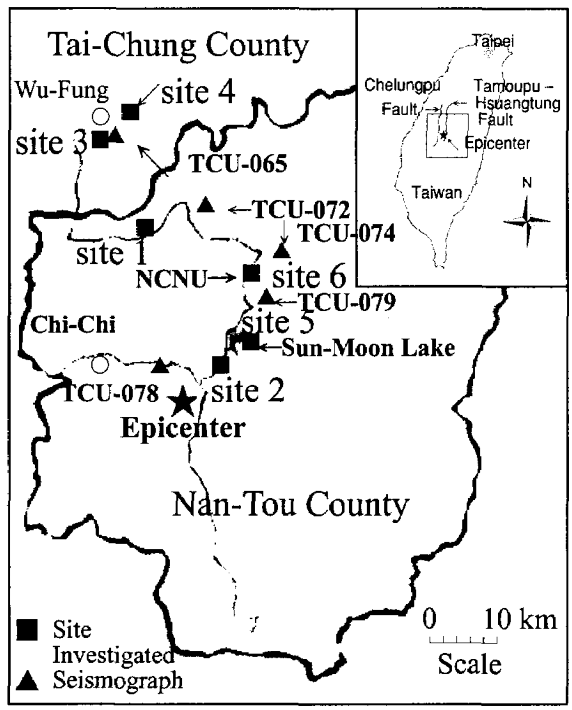

Fig. 1. Locations of sites investigated.

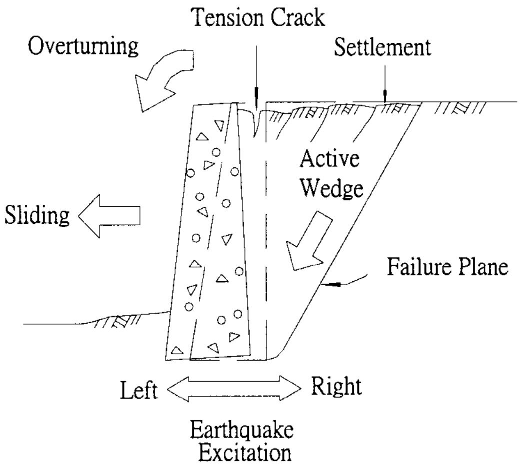

Fig. 2. Sliding and overturning of wall due to earthquake.

vertical and horizontal accelerations. Central Taiwan, the most severely damaged area, was included in zone 2 of the seismic zoning chart of Taiwan. The design horizontal-acceleration recommended for zone 2 is 0.23 g. However, on September 21, the horizontal PGA measured at seismograph TCU-079, TCU-074 and TCU-072 was 0.59 g, 0.60 g, and 0.47 g, respectively. Under such strong vibration, the retaining walls with a dynamic factor of safety of 1.2, even 2.0, probably could not assure its stability. After the earthquake, the authors joined the damage reconnaissance team organized by the National Science Council of Taiwan. Preliminary investigation was made regarding the failure of masonry, gravity and reinforced retaining structures damaged during the earthquake. It is hoped that lessons could be learned out of this tragic event.

Fig. 3. Sliding and falling of gravity wall.

Fig. 4. Shearing reinforcement at construction joint.

GRAVITY AND MASONRY WALLS

Seed and Whitman (1970) described that the lateral earth pressure on retaining walls are increased to some extent during earthquakes. Outward movement of retaining walls and wing walls had been reported for the 1960 Chilean and 1964 Niigata earthquakes.

Fig. 5. Repaired gravity wall.

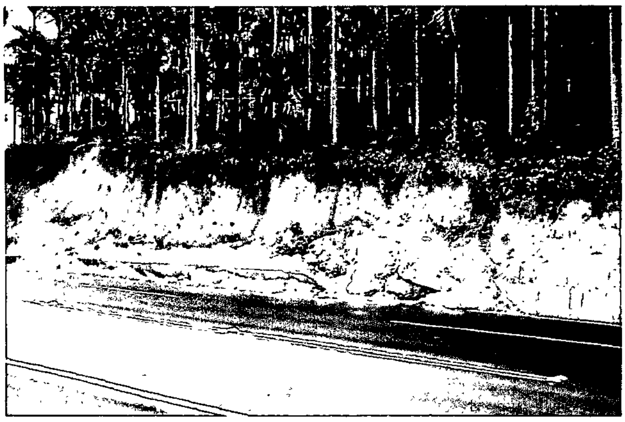

Fig. 6. Overturning failure of gravity wall.

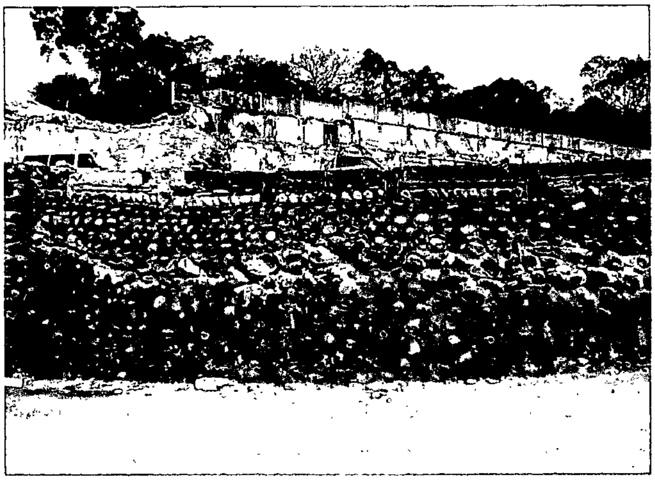

Fig. 8. Shearing failure on a masonry wall.

The behavior of a retaining wall under horizontal acceleration a_h can be explained with the help of Fig. 2. As the ground shakes from left to right, the dynamic earth pressure and inertia force of the wall would act from right to left. If the resistance at the base of the wall is not sufficient to defy the thrust, active wall movement would occur. However, if the direction of ground shaking is reversed, the wall is thrown from left to right. Due to the existence of the backfill, passive earth pressure would act between the wall and the soil, and only partial active wall-movement could be recovered. If the wall moves outward a small amount due to each cycle of a_h, with increasing effective cycles, the wall would gradually move away from the backfill. As indicated in Fig. 2, with the outward movement of the wall, the soil wedge behind the wall would slide down along the failure plane, causing settlement and tension cracks on the backfill. In the following sections, typical modes of wall failure due to the Chi-Chi earthquake are introduced. Locations of the sites investigated and seismographs are indicated in Fig. 1.

Sliding at Construction Joint

The failure of a gravity wall located near the entrance of Gan-Lin tunnel (Site 1) is shown in Fig. 3. The upper part of the 1.8 m-high wall slid along the construction joint during the earthquake, and eventually fell down to the ground. It is possible that the frictional resistance at the flat construction joint was not sufficient to resist the dynamic earth pressure and the inertia force of the upper part of the wall. It is also possible that lateral spreading of the uphill slope as a result of earthquake shaking helped to push the wall to slide. About two months after the earthquake, the damaged wall had been repaired. Shearing reinforcements were fabricated at the construction joint as indicated in Fig. 4. Steel H-piles were driven to resist earth pressure during construction. The repaired wall is illustrated in Fig. 5. A shearing key would be another efficient method to prevent sliding at the construction joint.

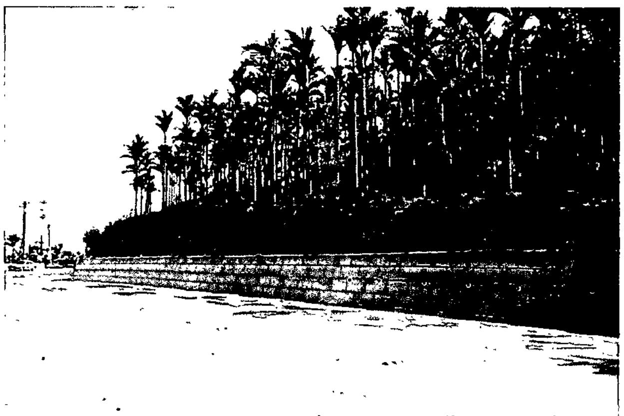

Fig. 7. Repaired retaining wall.

Overturning Failure

The overturning of a gravity wall located near Tou-Sheh (Site 2) is shown in Fig. 6. The wall is 2.5 m-high, 0.6 m-thick, and the length of collapse is about 40 m-long. Weep holes with diameters of 80 mm, spaced 2.5 m-apart were fabricated on the wall. It can be observed in Fig. 1 that Site 2 is quite close to the epicenter of the Chi-Chi earthquake. The horizontal PGA measured at the nearby seismograph TCU-078 was 440 gal (0.45 g). The unexpected strong ground shaking is probably the main cause of the overturning. Insufficient bearing capacity of the ground below the toe would be another possible reason for the wall to overturn. The repaired wall is indicted in Fig. 7. Seed and Whitman (1970) have mentioned that, as can be observed in

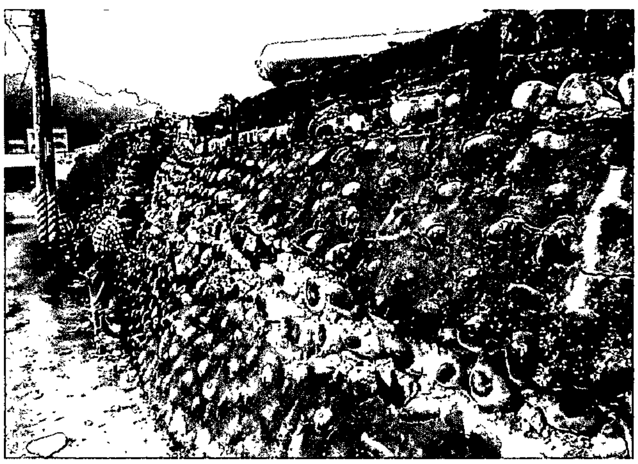

Fig. 9. Disintegration of weak mortar among cobble particles.

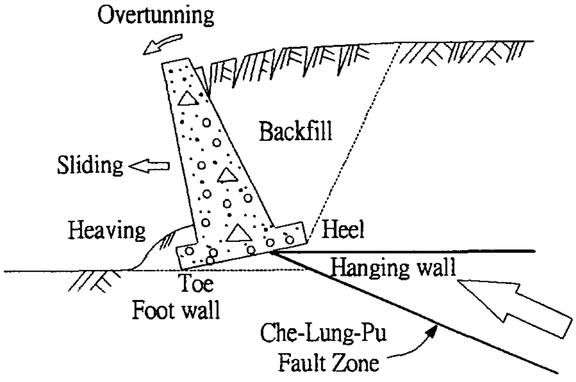

Fig. 10. Fault rupture and wall movement.

Fig. 6 and 7, retaining wall damage is not particularly dramatic compared with other forms of earthquake damage.

Shear Rupture along Weak Surface

The horizontal shear rupture of a masonry wall located at the Temple of Ten-thousand Buddha (Site 3) is shown in Fig. 8. The wall is made of 0.25 to 0.30 m-diameter cobbles cemented with mortar. After the Chi-Chi earthquake, the upper part of the wall shifted outward with respect to its lower part for about 0.2 m. It is clear in Fig. 9 that the weak mortar among cobble particles actually disintegrated. However, the high-strength cobble particles remained intact. During the earthquake, the Che-Lung-Pu fault cut through the Temple and caused total collapse of structures on its path. The horizontal PGA measured at seismograph TCU-065 was 774 gal (0.79 g). Apparently, the weak mortar among the cobble particles was not strong enough to resist the dynamic earth pressure and the inertia effect as a result of ground shaking. It should be mentioned that the use of masonry retaining walls had been abandoned by the Taiwan Highway Bureau about 15 years ago.

Failure Due to Fault Rupture

The failure mechanism of a retaining wall sitting right on top of an active fault is illustrated in Fig. 10. During the earthquake, the vertical displacement of the hanging-wall uplifts the heel, causing the wall to overturn. Horizontal displacement of the hanging-wall pushes the wall to slide, and the soil in front of the toe to heave. Sliding and overturning of the wall would induce settlement and crack on the backfill.

Fig. 11 shows the failure of a gravity wall located at the Cinema Culture Town (Site 4). The wall sits right above the Che-Lung-Pu fault. During the earthquake, the fault rupture caused the wall to slide and overturn. The ground in front of the toe heaved, and the backfill behind the wall subsided and cracked. The buildings constructed on the backfill were severely damaged by the strong ground shaking and differential settlement. It may be concluded that it is of critical importance to locate the active faults and not to construct any structure on top of or even near active fault zones.

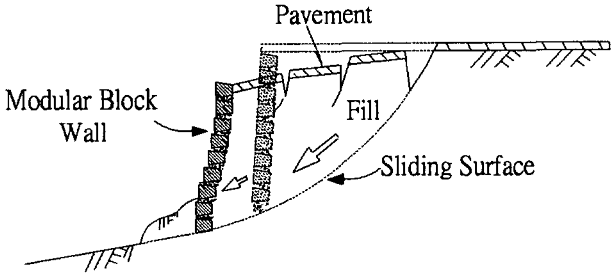

Fig. 12. Modular block wall and sliding surface.

Slope Stability Failure

Fig. 12 illustrates the downhill sliding of a modular-block retaining wall. The wall built on a slope lost its overall stability and failed during the earthquake. Fig. 13 shows the failure of a modular-block wall located at the parking lot of the Lalu Resort (Site 5). The 2.0 m-high wall was built on a slope. The wall slid down along the slope and a rotational sliding surface formed in the soils behind the wall. Fig. 14

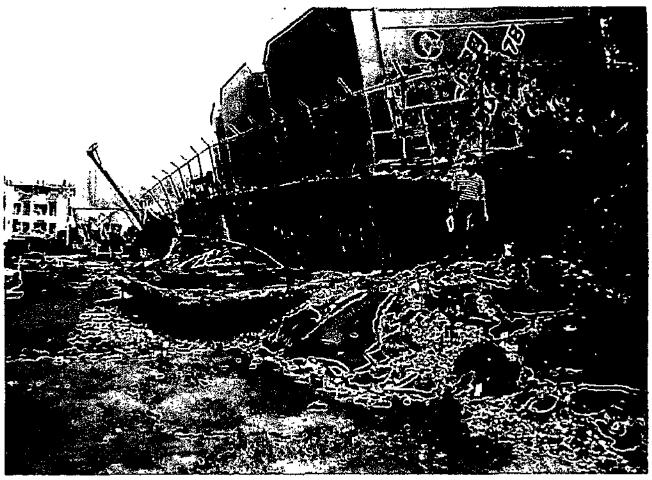

Fig. 11. Wall movement due to fault rupture.

Fig. 13. Wall built on a slope slide down.

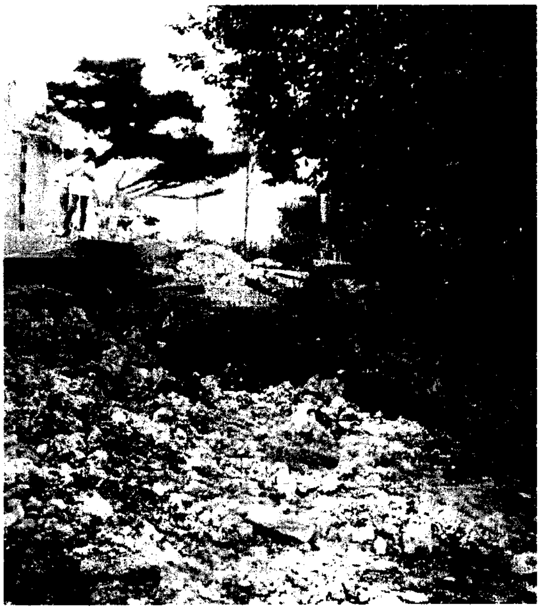

Fig. 14. Pavement and backfill damaged.

Fig. 16. Reinforcing strips pulled out and fill material fell out.

shows the pavement cracked and subsided for about 1.3 m. It may be concluded that besides checking the factor of safety against sliding, overturning, and bearing capacity failures, overall stability of the wall should also be carefully investigated

GEOGRID-REINFORCED STRUCTURE

Fig. 15 shows the failure of a geogrid-reinforced retaining structure at the entrance of National Chi-Nan University (NCNU, Site 6). The two lanes on the right-hand-side are for the traffic to enter NCNU, while the lanes on the left are for the traffic to leave NCNU. The reinforced retaining structure failed during the Chi-Chi earthquake. Fig. 16 shows the reinforcing strips were pulled out and fill maters fell out. Fig. 17 shows the lanes to enter NCNU were buried and the guard post was destroyed. It is obvious a detailed dynamic analysis of the reinforced slope should be made in future study.

Fig. 15. Failure of geogrid-reinforced wall.

CONCLUSIONS

This paper reports failures of retaining structures due to the 1999 Chi-Chi earthquake. Based on the case histories associated with gravity, masonry and geogrid-reinforced walls, the following conclusions can be made.

1. Sliding and overturning failure of retaining walls due to the earthquake have been observed. The unexpected strong ground shaking is probably the main cause of the damage.
2. A horizontal shear-rupture has been observed on a masonry wall. The weak mortar among cobble particles was obviously not strong enough to resist the dynamic earth pressure and inertia effects due to ground shaking.
3. A gravity wall constructed right above the Che-Lung-Pu fault is severely damaged during the earthquake. It is recommended not to build any structure on top of an active fault.
4. Besides checking the factor of safety against sliding, overturning, and bearing capacity failures, overall stability of the wall should also be carefully investigated.

Fig. 17. Lanes to enter NCNU buried and guard post struck.

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REFERENCES

Fang, Y.-S. and Chen, T.-J. [1995] Modification of Mononobe-Okabe theory, Geotechnique, Vol. 45, No. 1, pp. 165-167.

NAVFAC DM-7.2 [1982] Foundations and earth structures, Design Manual 7.2, Department of the Navy, Naval Facilities Engineering Command.

Seed, H. B. and Whitman, R. V. [1970] Design of earth retaining structures for dynamic loads, Proc., ASCE Specialty Conf. on Lateral Stress in the Ground and Design of Earth Retaining Structures, Cornell Univ., Ithaca, New York, pp. 103-147.