THE CHI-CHI EARTHQUAKE AND THE SEISMIC GEOTECHNICAL ENGINEERING PRACTICE IN TAIWAN

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Abstract: The Chi-Chi earthquake struck central region of Taiwan on September 21, 1999, with a magnitude of 7.3, caused severe ground failures and damages to lives and properties. In this paper, the geotechnical hazard caused by the Chi-Chi earthquake is summarized. Based on the reconnaissance of the hazard, the significances of types of failures are identified and the effects on the seismic geotechnical engineering practice are discussed.

INTRODUCTION
Taiwan is situated at the juncture zone of the Euro-asia Continental Plate and the Philippine Sea Plate with a northwest tectonic movement of the Philippine Sea Plate. As the consequences of the tectonic actions, the Philippine Sea Plate subducts underneath the Euro-asia Plate in the northward direction, while the Euro-asia Plate subducts underneath the eastward direction as illustrated in Fig.1. Due to this active tectonic activity, the Central Mountain Range as well as the Coastal Mountain Ranges are produced, and the prevailing geological formations and structural patterns align approximately parallel to the longitudinal

Figure 1 Geotectonic actions in the vicinity of Taiwan (After Angelier, 2001).
axis of the island. The distribution of active faults with estimated magnitude larger than 6 and geological formations of Taiwan are shown in Fig. 2. In Fig. 2, only the faults with length longer than 5 km which correspond to earthquake magnitude of 6, and being active in the last 10000 years are considered. The topography and geological conditions are highly related to the tectonic activity, where the mountain area composes about 77% of the whole area and the geological formations are highly fractured and fragile. As the results of the tectonic activity, Taiwan is among the most active seismic districts in the world. With the earthquake records since early 1900, it was found that the earthquakes have been triggered by the subduction of the plates and faulting action inland, and earthquakes with magnitude larger than 6 were most likely to be hazardous. In Fig. 3, the epicenters of the historical earthquakes with magnitude greater than 6 in the period from 1900-1999 are plotted (Shin, 1999). As shown in Fig. 3, although most of the earthquakes with magnitude larger than 6 have been triggered by the subduction action, the earthquakes triggered by faulting action inland were usually more hazardous and caused more catastrophic damages because of the shallow focal depth and being close to the heavily populated areas.
THE CHI-CHI EARTHQUAKE AND ITS EFFECTS

The Chi-Chi earthquake struck central region of Taiwan on September 21, 1999, with a local magnitude of 7.3, had caused severe ground failures and loss of lives and properties. The total casualties were 2505, and 11305 people were injured. The number of houses collapsed were 51392, and 55455 houses were damaged. The direct loss caused by the earthquake summed up to 11.4 billions US dollars, and the indirect loss was 22.8 billions US dollars. The total loss added up to 34.2 billions US dollars. The earthquake was triggered by the faulting action of the Chelungpu fault, with a fault rupture length of 105 km. The Chelungpu fault is a shallow thrust east-dipping fault which moved westward. The focal depth of the earthquake was only 8 km, which meant a tremendous amount of energy was released near the ground surface. The maximum peak horizontal ground acceleration recorded was about 1 g, and the maximum peak vertical ground acceleration recorded was 0.7 g. The distribution of the measured ground motion along with the seismic intensity was as shown in Fig. 4 (Shin, 1999). Noted that three
triggered events were also recorded, and the effects could be observed as some areas far away from the Chelungpu fault were displaying higher seismic intensity in Fig. 4. The final ground displacements caused by the thrusting of the fault were surveyed using GPS (Huang, et. al., 1999), and the distribution of the displacements was as shown in Fig. 5. The maximum horizontal displacement was about 9 m, and the maximum vertical displacements was about 6 m. With such strong ground motion and large displacements, the damages were tremendous. A reconnaissance effort was called by the National Center for Research on Earthquake Engineering, National Science Council. Based on the reconnaissance report of the geotechnical hazard investigation group called upon by NCREE (2000), the geotechnical hazard caused by the earthquakes includes: landslide, foundation failure, liquefaction and subsidence, retaining wall failure, and damages to tunnels, etc. Due to the significant extents of the damages caused by the earthquake, only the failures associated with liquefaction, foundation failures, and landslides and the subsequent effects on the practicing geotechnical engineering will be discussed in this paper.
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120.1 120.5 120.9

Longitude (E)

24.0

Latitude (N)

Final Displacement Distribution
21 Sep. 1999 Chi-Chi Earthquake

Fig. 5. The distribution of final ground displacements caused by Chi-Chi earthquake. The arrows indicate displacement quantity and its direction whereas values appeared in parenthesis. (Huang, et. al.,1999; the Central Weather Bureau)

Soil Liquefaction and Associated Ground Subsidence

Field investigation of soil liquefaction was conducted at designated areas reporting signs of soil liquefaction and ground subsidence. A total number of 176 items were reported and documented for the investigated area. The distribution of the items and the surface rupture of the Chelungpu fault are as shown in Fig. 6. Because soil liquefaction would only occur at specific ground condition, therefore there is no clear relationship between distribution of reported items and the fault. However, the distribution of liquefaction cases appeared to correspond well to the seismic intensity distribution.

Severe condition of soil liquefaction was reported at wharf 1 to 4, Tai-Chung Harbor where sink holes with diameters as large as 5 m were observed. The area with most widely spread soil liquefaction condition was in the town of Yuan-Lin, while Nan-Tou city and Wu-Fong also reported fairly large number of liquefaction items. The largest single area suffering soil
liquefaction was 4 hectare. Soil liquefaction could cause damages to all kinds of buildings and infrastructures. Based on the data collected, statistical analyses were performed, and distribution of damages to different types of structure was as shown in Fig. 7.

Figure 6. The distribution of the soil liquefaction cases. (Lin, Liao, and Ueng, 1999)

Figure 7. The distribution of types of structures damaged by soil liquefaction
In Fig. 7, the damages to buildings out number other types of structures, because buildings are the most encountered structures in the areas. The damages to buildings could be divided into three different types, i.e. subsidence, tilting and collapse. Typically soil liquefaction causes the ground to lose bearing capacity, which induces subsidence and unequal settlement of the building. Therefore, subsidence is the most encountered type of damage, while tilting due to unequal settlement is the second most reported damage. Soil liquefaction seldom induces collapse of building. In the areas surveyed, more than 200 buildings have undergone subsidence of more than 0.5 m, and about 50 buildings have undergone lateral displacement of more than 1 m.

**Foundation Failures**

Field investigation of foundation failure was conducted in 19 towns and cities where population densities were higher. The reconnaissance subgroup for foundation failure has reported and documented a total number of 457 items, the locations of the failure and the surface rupture of the Chelungpu fault are as shown in Fig. 8. The items of foundation failure concentrated in cities and towns located within a short distance from the epicenter, such as Wu-Fong, Ming-Chien, and Chi-Chi. In addition, the towns and cities where the fault rupture passed through also reported a significant amount of foundation failures, such as Juo-Lang, Tong-Shi, and Tang-Ji. A close relationship between the locations of foundation failure and fault rupture could be found. The foundation failures in the area close to the epicenter were likely caused by the excessive ground motion, while foundation failures along the fault were likely caused directly by surface rupture. Some items of foundation failure were also reported where soil liquefaction occurred. However, in these areas, the major effect of liquefaction was subsidence; foundation failure caused by liquefaction was not so significant.

Accordingly, the characteristics of foundation failures could be classified into three different types:

1. foundation failures caused by fault rupture,
2. foundation failures caused by soil liquefaction,
3. failures at the interface of foundation and super-structure.

Statistical analysis was performed on the collected data, and the distribution of different types of failure mechanism reported is as shown in Fig. 9. In Fig. 9, the failure at the interface of foundation and super structure is the most encountered failure type, which accounts for 60% of the failure cases, while foundation failure caused by faulting is the second one with 26%. Foundation failure caused directly by soil liquefaction only takes up 14% of all the foundation failure items. The results indicated that proper connection at the interface of foundation and super-structure was essential.

**Slope Failures**

The subgroup for slope failure has reported a total number of 436 items of slope failure, and the distribution of slope failure along with the surface rupture of Chelungpu fault are as shown in Fig. 10. Following the initial reconnaissance, the Council of Agriculture took actions in surveying of landslides based on the aero-photo and SPOT satellite images taken a few days after the earthquake. There were more than 21,900 landslides with total area of more than 8,600 hectare identified as shown in Fig. 11. The slope failures distributed from Miao-Li to Jai-Yi counties as shown in the figure, and almost all items located to the right or hanging wall of the thrust fault, where the mountain terrain located. The slope failures in Tai-Chung county, and Nan-Tou county were most widely spread. In Tai-Chung county, the most severe slope failure was along the Central Trans-island Highway; and in Nan-Tou county, a large
Figure 8. The distribution of foundation failure cases

- Foundation failure caused by faulting,
- Foundation failure caused by soil liquefaction,
- Failure at the interface of foundation and super-structure.

Figure 9. The distribution of types of foundation failure
Figure 10. The distribution of the slope failure cases

Figure 11. Distribution of landslide caused by Chi-Chi earthquake based on SPOT images. (Council of Agriculture, 2000)
scale slope failure of Juo-Juo peaks covered an area as large as 950 hectare, which was major shallow sliding and spalling of gravelly material. In Juo-Feng-Err mountain area, a dip slope sliding occurred with an area of 200 hectare, 29 people were buried. In Yun-Lin county, a massive dip slope failure occurred in the Tsao-Ling area which covered an area of 400 hectare and with an amount of 120 million cubic meter of deposit material. The large amount of material deposited in the valley of Ching-Sui river, and a dammed-up lake was formed.

![Pie chart showing the distribution of type of slope failure cases.](image)

**Figure 12. The distribution of type of slope failure cases**

![Pie chart showing the distribution of slope angle of slope failure cases.](image)

**Figure 13. The distribution of slope angle of slope failure cases**

Preliminary statistical analyses were performed on the data to identify the characteristics of the slope failure. Types of failure mechanism, and the slope angle of the failure slope, of all...
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items reported are as shown in Fig.12 and Fig.13. The distribution of the slope angle compared relatively well with the distribution of the types of the slope failure, because typically the debris slide and toppling/rock fall would occur at the slope with steep slope angle. Due to the extensive slope failures caused by the earthquake, tremendous amount of landslide materials deposited in the up-stream areas of watershed, and were prone to induce the secondary hazard. Measures for the secondary hazard prevention and further hazard reduction including the rating of landslide potential, field investigation and rating of possible debris flows, and emergency remedial measures for slope stability were taken.

GROUND MOTION AND SEISMIC ZONATION

The ground motions are directly related to the seismic forces acting on structures, and hence seismic zoning for ground motion addresses one of the most fundamental aspects of seismic hazard. Zoning for ground motions is therefore an essential part for hazard reduction caused by the earthquake. The seismic codes for building called for the exceeding probability of 10% for 50 years, which corresponded to a return period of 475 years for the design earthquake. Based on the statistic of the earthquake records prior to the Chi-Chi earthquake, the seismic zonation was determined as shown in Fig.14(a). After the Chi-Chi earthquake, the detailed mapping of the Chelungpu fault was conducted, and the peak ground acceleration (PGA) data were traced by National Center for Research on Earthquake Engineering from records of 387 strong motion stations. The PGA contour of motion caused by the main shock is shown in Fig. 15. By taking into account the ground motion records of the Chi-Chi earthquake in the statistic model, the seismic codes were revised, and the new seismic zonation for design earthquake called for 2 zones with peak ground accelerations of 0.23g and 0.33g, respectively, as shown in Fig.14(b). The seismic codes for building were revised again in July, 2005, in

![Figure 14. Seismic zonation of Taiwan (a) before Chi-Chi Earthquake (4 zones), (b) revised after Chi-Chi Earthquake (2 zones). (NCREE, 2000)](image-url)
which for the maximum earthquake with return period of 2500 years, ductility requirement of structure, and other additional requirements were supplemented. During the Chi-Chi earthquake, it was found that the ground motion is strong for area next to the fault, and decreases rapidly with distance as illustrated in Fig. 15. When reviewing the foundation failures caused by the earthquake, it was found that the building failure immediately in the vicinity of the Chelungpu fault was caused major by the faulting action. For buildings far from the fault, the most important geotechnical factor causing damages to the buildings was soil liquefaction. The first cause could be mitigated by detailed mapping of the fault and regulations on building construction; therefore, the problem of the soil liquefaction is of major concern. The landslide caused by the earthquake is also a major concern due to the extensiveness of failure and the potential of causing the secondary hazard after the earthquake. In fact, ground motion is the most important factor causing soil liquefaction and landslides.

CONSIDERATIONS OF LIQUEFACTION POTENTIAL
Soil liquefaction is one of the major factors for causing damages of buildings during earthquake. If the liquefaction potential of each area could be evaluated in advance, it would be possible to plan for earthquake hazard mitigation program. The preliminary liquefaction potential maps were developed by NCREE (2001) to provide as a basic reference for drafting of hazard mitigation policy. Data from more than 8000 boreholes were collected and analyzed using method such as Modified Simplified Procedures proposed by Seed, et.al. (1985). Liquefaction potential map displayed according to the evaluation results of borehole data is as shown in Fig. 16 for Taipei Basin. Contours of liquefaction potential index are also generated as shown in Fig. 17 for areas with sufficient density of borehole data. For the liquefaction potential mapping of an over-all area, the sedimentary history and geomorphological factors can be used, which would provide a reasonably good comprehensive result (Youd and Perkins,
For the liquefaction potential analysis, the codes for building foundation require that for the design earthquake, either the liquefaction analysis can base on the laboratory testing results or methods based on the field penetration test results such as the Simplified Procedures using standard penetration test blow count or methods using cone penetration test tip resistance. The overall liquefaction potential can be evaluated using relative thickness of soil layers proposed by Ishihara (1985), or the liquefaction potential index proposed by Iwasaki et. al., (1982). For the newly designed building susceptible to soil liquefaction, the foundation should be properly designed to withstand the possible damages caused by soil liquefaction, and a reduction factor is applied to the soil parameters. The reduction factor such as that proposed by Japan Road Association (1996) can be used. For the buildings damaged by soil liquefaction during the earthquake, both the repairing and reinforcing techniques can be applied. The repairing technique is referred to the methods for retrofitting of the damaged buildings. The retrofitting methods such as underpinning, foundation reinforcement and jacking were used for the buildings damaged during the Chi-Chi earthquake. The reinforcing technique is referred to improvement of the ground stability to withstand the possible soil liquefaction. Such techniques include grouting, dynamic compaction, stone column, compaction pile, etc. For the buildings damaged in the Chi-Chi earthquake, grouting method was one of the most commonly used techniques.

Figure 16. Liquefaction potential map of Taipei Basin. (NCREE,2001)

Figure 17. Contours of liquefaction potential index of Taipei City. (NCREE, 2001)
SEISMIC SLOPE STABILITY
Due to the extensiveness of slope failure induced by the earthquake and the potential of causing secondary hazard, the landslide caused by the earthquake is also a major concern. Typically, analyses of dynamic slope stability are performed using three different methods: the pseudo-static method, the Newmark’s method, and ground response analysis. The pseudo-static method adopted the critical equilibrium concept to calculate the factor of safety using a pseudo-static force acting on a slope under horizontal acceleration (Chen & Snithban, 1975; Seed, 1979). Newmark (1965) proposed a sliding block model to simulate slope behavior under seismic forces, and calculate the block movement when acceleration exceeded the critical acceleration of the slope. However, these two methods do not take into account the dynamic slope behavior and soil amplification. With the help of numerical methods, the ground response analysis using the finite element method and/or finite difference method (Clough & Chopra, 1966) can take into account the dynamic ground responses as well as the nonlinear behavior of soil, and the elastic-plastic constitutive laws can be applied. For the earth dam, the shear beam method (Ambraseys & Sarma, 1967) simplifies a 2-dimensional dam into a 1-dimensional analysis, and acceleration along the height of dam can be obtained quickly.

Although it was suggested that the pseudo-static analysis might not be able to represent the seismic slope behavior, and the safety factor might not be a good indication of seismic slope stability (Seed, 1979), the method appeared to provide reasonable results for the dynamic slope analysis if the failure surface was shallow and close to the toe of slope (Huang and Lin, 2003). For the Newmark’s method, the failure of the slope was assessed by the permanent displacement of the sliding block. The threshold displacement of 5-10 cm was suggested by Jibson (1993). Based on the analyses performed on the landslide cases induced by the Chi-Chi earthquake, the displacement of 10 cm appeared to be a reasonable threshold value (Lin and Kao, 2005) for causing failure of the slope.

Fig. 18 Distribution of the geometric mean PGA of the earthquake induced slope failures
From the field data collected on landslides induced by the Chi-Chi earthquake, it was found that most of the landslides were with small to medium size and were typically shallow debris slide of steep slope. The statistical analysis of the data (Lin, Wang, and Chen, 2000) indicates that the slopes subjected to ground motion with horizontal mean PGA larger than 150 gal, and vertical PGA larger than 200 gal are likely to be susceptible to landslide as illustrated in Fig.s 18 and 19. Generally, the failure surface appeared to be quite shallow, in somewhat circular shape, and close to the crest of slope. Thus, the horizontal peak ground acceleration of 150 gal, and a vertical PGA of 200 gal appear to be appropriate conditions to adopt in the seismic slope analysis. Research by Chen, Lin, and Hung (2004) also suggested that for the slope located near to the epicenter or fault, the vertical ground acceleration could have a significant effect on the slope stability, and the strength of the material would range somewhere between the peak strength and residual strength. It could be concluded that for the earthquake induced
shallow landslides, ground motion might be the most important factor.

Due to the severe slope failures caused by the Chi-Chi earthquake, the slope material was loosened and with fissures and cleavages. New landslides, rock falls and debris flow may be easily triggered by other earthquakes or rainfall. Field investigations were conducted to identify the potential debris flow rivers, and models for evaluation of hazard potential and risk were developed. Potential analysis of the debris flow rivers of the Central Taiwan areas were performed and the debris flow rivers were rated as with high, intermediate, and low potential as shown in Fig. 20. Emergency remedial and reinforcing measures for slopes and debris flow rivers identified with high potential were conducted before the typhoon season in order to prevent further damages and secondary hazard.

In 2001, typhoon Toraji caused severe landslide and debris flow hazard, and it was found that most of the landslides and debris flows occurred at locations identified with previous landslides caused by the Chi-Chi earthquake as illustrated in Fig.21. In 2004, typhoon Mindule again caused severe landslides and debris flow hazard in the Central Taiwan area. The reconnaissance report again indicated that a close relationship between the hazard induced by the typhoon Mindule and landslides induced by the Chi-Chi earthquake as illustrated in Fig.22. Thus, the landslide induced by a large magnitude earthquake could cause severe and prolonged secondary hazard such as subsequent landslides and debris flows. Mitigation efforts are required in order to reduce the effects of such secondary hazard.

![Figure 21 Landslides and debris flows induced by typhoon Toraji in 2001 versus landslides induced by the Chi-Chi earthquake](image.png)
CONCLUSIONS

The Chi-Chi earthquake with a magnitude of 7.3 caused all kinds of severe geotechnical hazard. Based on the reconnaissance results, three major types of failure were discussed, i.e. soil liquefaction, foundation failures, and slope failures, respectively. For all types of the failures, ground motion appeared to be the most important factor, and liquefaction and slope failures were the geotechnical hazard of more concerns for causing extensive damages and the potential of causing secondary hazard.

Based on the data of the Chi-Chi earthquake, the seismic zonation of building codes was revised, and more requirements on ductility of buildings were proposed. For area susceptible to soil liquefaction, methods for potential analysis and reduction factor for the soil parameters were used in general practice. In addition, mapping of the liquefaction potential could provide preliminary information for hazard mitigation. For the seismic slope stability, analysis could be performed using different methods, which would all provide reasonable results when applied with discretion. Further mitigation of the potential secondary hazard is very important when a catastrophic earthquake strikes and extensive slope failures are induced. In view of the scale of the hazard and lessons learned from the Chi-Chi earthquake, more efforts are needed for researches in seismic geotechnical engineering, and for reduction of secondary hazard effects for years to come.

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