International Conferences on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics

2001 - Fourth International Conference on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics

28 Mar 2001, 4:05 pm - 4:25 pm

Some Geotechnical Aspects of 1999 Chi-Chi, Taiwan Earthquake

T. S. Ueng

National Taiwan University, Taiwan

M. L. Lin

National Taiwan University, Taiwan

M. H. Chen

National Center for Research on Earthquake Engineering, Taiwan

SOME GEOTECHNICAL ASPECTS OF 1999 CHI-CHI, TAIWAN EARTHQUAKE

T. S. Ueng
Department of Civil Engineering
National Taiwan University
Taipei, Taiwan

M. L. Lin
Department of Civil Engineering
National Taiwan University
Taipei, Taiwan

M. H. Chen
National Center for Research on
Earthquake Engineering
Taipei, Taiwan

ABSTRACT

The Chi-Chi, Taiwan earthquake with a magnitude of 7.3 occurred on September 21, 1999. It was the largest and most damaging earthquake in Taiwan in a century. It induced extensive geotechnical hazards including landslides, soil liquefaction, foundation failures, and ground movements in central Taiwan, and caused substantial damages to buildings, roadways, bridges, and waterfront structures. Field investigations and studies in geotechnical aspects, including landslides, soil liquefaction, foundations, retaining structures, dams and tunnels, in the affected areas were performed. The results of field explorations and laboratory tests for the study of soil liquefaction and evaluation of the secondary hazard of debris flow are also discussed.

INTRODUCTION

The Chi-Chi earthquake on September 21, 1999 is the largest and most damaging earthquake in Taiwan in a century. With a magnitude of 7.3 (M_w = 7.6) the earthquake induced ground shaking of very high intensities in central Taiwan. In this devastating earthquake, over 2,400 lives were lost, 10,000 people were injured, and more than 100,000 units of buildings suffered various degrees of damages. Among the most shocking phenomena during this earthquake were the extraordinarily large displacements of the fault ruptures along the 105-km long Chelungpu fault and a very large scale of landslides induced by the ground shaking. At the same time, extensive soil liquefaction occurred in many areas and caused severe damages to many structures such as buildings, levees, roadways, quay walls, etc. Damages to other geotechnical structures, such as retaining walls, embankment dams, and tunnels were also observed.

In order to evaluate the extend of the geotechnical hazards, to estimate the induced damages and to establish the mitigation policy for the earthquake hazard, National Center for Research on Earthquake Engineering (NCREE) has organized many geotechnical engineers from universities, consulting companies and government agencies to conduct field geotechnical investigations in the affected areas [NCREE, 1999]. Subsequent subsurface explorations and laboratory tests on the soil samples obtained in the borings were conducted for the liquefaction areas including Yuen-Lin and its vicinity, Wu-Feng, and Nan-Tou. Field investigations and analyses were performed for the potential debris flow during the upcoming rainy season in the areas with large volume of landslide deposits and loosened slope materials.

FIELD OBSERVATIONS OF GEOTECHNICAL HAZARDS

Landslides

According to the aerial photos and SPOT satellite photos, there were more than 2,000 scores of landslide caused by the earthquake. Figure 1 shows the locations of identified ground surface changes and 436 landslide sites investigated shortly after the earthquake. Most of the slope failures located on upper portion of the Chelungpu thrust fault. However, the area of the mountain terrain is also to the same side of the fault, therefore, it is not sure about the relation between the slope failure and location of the fault rupture.

There are ubiquitous shallow slides on steep slopes of stiff soils or weathered rocks, and toppling and rock falls from jointed rock slopes, especially in Tai-Chung county, and Nan-Tou county. Very severe slope failures were found along the trans-island highway. In Nan-Tou county, a large scale slope failure of Juo-Juo peaks covered an area as large as 950 hectare, which was mainly shallow sliding and spalling of weakly cemented gravelly material. Two very large catastrophic landslides were induced by this earthquake. In Juo-Feng-Err mountain area, a dip slope sliding occurred with an area of 200 hectare, 29 people were buried, the failure also caused two small dammed-up lakes. 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 sliding material. The large amount of material deposited in the valley of Ching-Sui river forming a 50 m high debris dam and created a large dammed-up lake with a capacity of about 43 million m^3.

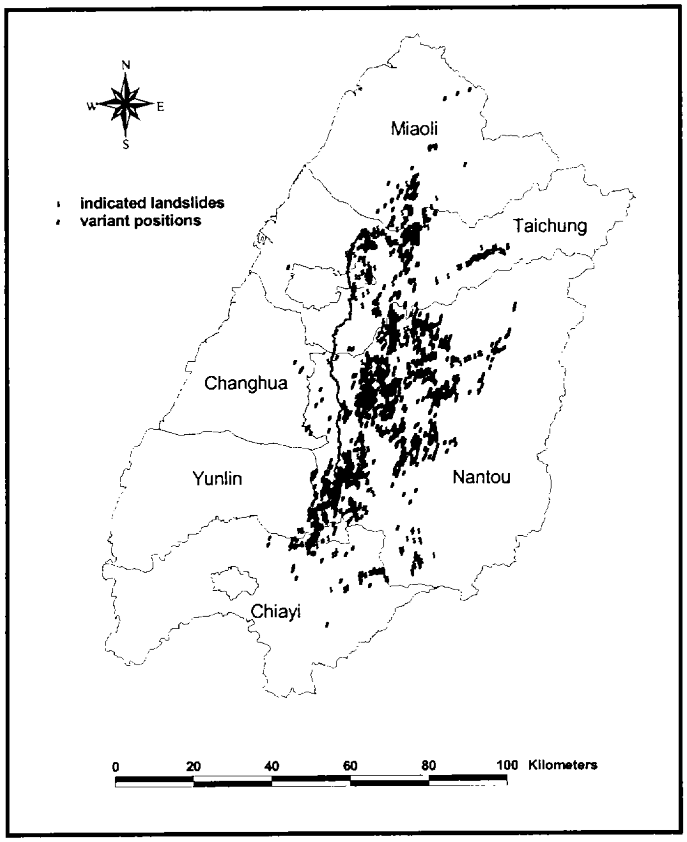

Fig. 1. Locations of investigated sites of landslide and variant points of ground surface.

The distribution of the slope angles of the failure slopes is shown in Fig. 2 [NCREE, 1999]. The slopes with angles of larger than 75° account for 30 % of all failures, and slope angle in the range of 60° to 75° takes up 38 % of the failures. Typically, the shallow slides and toppling/rock falls occurred at the slopes with steep slope angles.

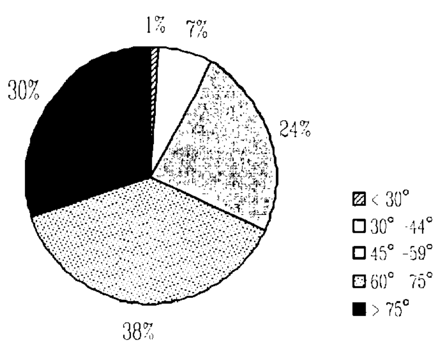

Fig. 2. Distribution of slope angles of landslides.

Soil Liquefaction

According to the field investigations, the soil liquefaction during Chi-Chi earthquake occurred mostly in three types of grounds: (1) hydraulic reclaimed lands on the west coast of Taiwan, (2) alluvial deposits of the old river channels, and (3) recent deposits along the riversides. The groundwater levels in these areas are generally high within 1 to 3 meters from the ground surface. Figure 3 shows the locations with reported soil liquefaction. The intensity contours of the ground shaking are also shown on the same figure. Among these locations, Taichung Harbor, Yuen-Lin and its vicinity, Wu-Feng, and Nan-Tou are the sites with the most widespread liquefaction and severe damages to buildings, levees, roadways, retaining walls, and other structures.

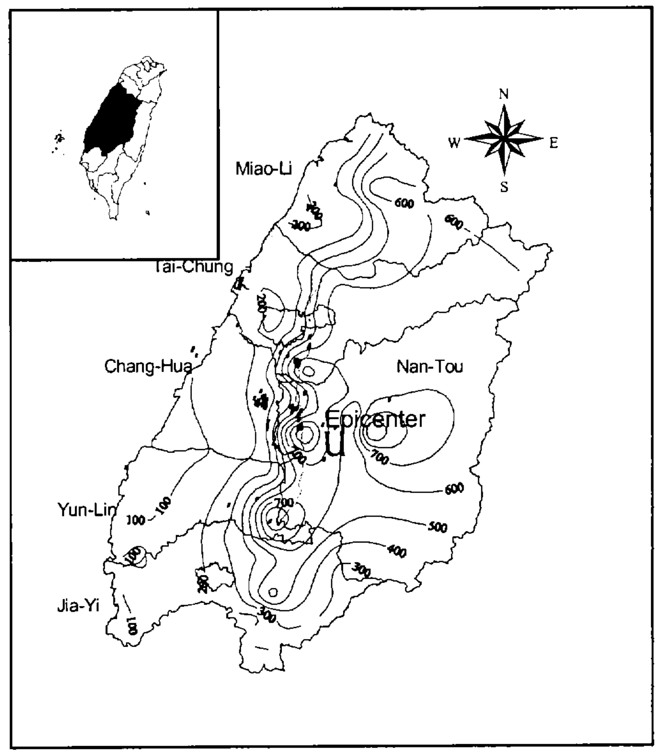

Fig. 3. Distribution of locations of soil liquefaction.

The major reclaimed lands at the west coast of Taiwan are about 45 to 60 km from the epicenter of the earthquake [Yu, *et al.*, 2000]. At Taichung Harbor soil liquefaction occurred in the backfill sandy material behind Piers 1 to 4. The material was obtained by hydraulic dredging from the seabed without any treatment. A peak ground acceleration (PGA) of 162 gal was recorded at a nearby seismograph station. The caisson type quay walls moved outwards a maximum displacement of 1.6 m. A maximum subsidence of 5 m of the ground surface was induced by the lateral spreading of the liquefied material and the subsequent erosion by the seawater.

In the other reclaimed lands, including Mailiao and Chungbin industrial parks, ground improvement measures, such as dynamic compaction, stone columns, and compaction piles, have been applied in the construction areas. During Chi-Chi earthquake soil liquefaction occurred at the locations without ground improvement or the improvement only partially completed. The performance of the improved areas was satisfactory with little damage. Even though the PGA in these areas is low at about 68 gal, the effectiveness of ground improvement to prevent soil liquefaction during earthquake was affirmed.

For the alluvial deposit areas, soil liquefaction caused quite severe damages in the towns of Yuen-Lin and its vicinity, Wu-Feng, and Nan-Tou [NCREE, 1999]. The peak ground accelerations were 188 gal, 774 gal, and 420 gal, respectively, according to the seismograms recorded at the stations in these three towns. Soil liquefaction induced extensive damages to buildings, roadways, bridges and levees in these areas. Sand boiling, subsidence and lateral spreading near water were observed. Sinking as much as 2 m and tilting of up to 10°due to uneven settlement were the most common types of building damages. Many buildings suffered lateral displacements of more than 1m. These affected buildings were often found structurally intact. Collapses of houses because of structural failures were rare in the liquefaction zones. Lateral spreading of the ground due to liquefaction was also found near the waterfront.

Along the riverbanks, many levees had substantial subsidence of the crests of up to 1.5 m and lateral deformations of more than 2 m. Sand boiling was found beside the newly constructed freeway pile foundations near the river. There has been a report on pile breakage beneath one of the piers. Large cracks and sand boiling also happened on the top of a 7-m high compacted roadway embankment with no evidence of liquefaction on the nearby original grounds. This aroused some speculations about the mechanism of its occurrence.

Failures of Foundations and Retaining Walls

The foundation failures concentrated in cities and towns located within a short distance from the epicenter. Generally, they are caused by fault movements, soil liquefaction, and failure at the interface of foundation and super structure. Foundation failures solely due to insufficient dynamic bearing capacity are rare in this earthquake.

Many retaining walls, including gravity and masonry types, failed during Chi-Chi earthquake by sliding, overturning and rupture of wall body probably due to the high dynamic earth pressure on the retaining walls [Fang, *et al.*, 2000]. Many failures of hillside retaining walls occurred because of the slope failures behind and underneath the walls. A few gravity walls right on the Chelungpu fault was also found destroyed by fault movements. A 60-m high geogrid reinforced retaining wall collapsed and slid down the slope probably due to a lack of anchoring.

Embankment Dams and Tunnels

The performance of embankment dams was quite satisfactory during Chi-Chi earthquake [Chang and Chang, 2000; Chern and Chang, 2000]. The dams are within the areas of very high ground shaking intensities. These damsites experienced PGAs of up to 0.58 g with very slight damages. Several shallow (< 2.3 m) longitudinal cracks on upstream face, crest and downstream face were found at the 30.3 m high Suisher Dam. With a peak acceleration of 0.47 g at the dam crest, Liyutan Dam (96 m in height) suffered some tension cracks (< 2.4 m in depth) near both abutments probably due to the differential settlements near the steep abutments. These damages caused no immediate danger to these dams and the remedial work were completed shortly after the earthquake. All the embankment dams within the region of strong shaking suffered various amounts of settlements during Chi-Chi earthquake. Most of them are less than 0.1% of the dam height with the maximum of 1.26% for a 21.8 high dam. It is concluded that a well constructed roller-compacted embankment dam can withstand an earthquake shaking with a PGA up to 0.6 g without serious damages.

Some damages were reported for tunnels during Chi-Chi earthquake. Only one tunnel passing through the Chelungpu fault was shut off because of a 4-m fault movement. Cracks and spalling of tunnel lining are the most common types of damages. Tunnels in the landslide areas suffered portal damages due to the nearby slope failures.

FIELD EXPLORATIONS AND LABORATORY TESTS FOR SOIL LIQUEFACTION STUDY

Extensive subsurface explorations were conducted in Yuen-Lin, Wu-Feng and Nan-Tou [MAA, 2000a,b]. Standard penetration tests (SPT), cone penetration tests (CPT), and seismic wave velocity measurements were also performed. Disturbed and thin-walled tube soil samples were obtained during the subsurface explorations. Laboratory tests including particle size analyses and dynamic triaxial tests were also performed on these samples.

The subsurface soil profiles obtained from the investigations show that liquefaction occurred in layers of sandy materials with low SPT-N values, usually less than 10. Sand boiling was not usually observed in the areas with thick clay layers on top of the liquefiable sandy layers. But some subsidence also occurred in this type of ground. Severe damages were found in the ground with thin layers or completely missing of clay coverage. This is consistent with the findings by Ishihara [1985]. Sand boiling was observed along the perimeter and through the basement slab of an apartment building with its basement founded on a liquefied layer beneath a 4.6-m non-liquefiable layer.

Samples of the ejected sand at the sand boiling sites were collected and Fig. 4 shows the grain size distribution curves of some of these soils. They are mostly uniform fine sand and silt, which are considered potentially liquefiable materials. It can be seen that most of them contain high percentages of fines. It was first suspected that some of the fines were carried out in the process of sand boiling during liquefaction. The grain size analyses were also performed for the soil samples obtained in the subsurface explorations. Figure 5 shows the grain size distributions of those soils that were probably liquefied during the earthquake judging from the field observations, the SPT results, and the soil type. There seems a similar large amount of fines content in these materials. According to the grain size analyses, the fines are predominantly silt size with no plasticity. Gravel contents of about 20% to 30% are also found in two of these soils.

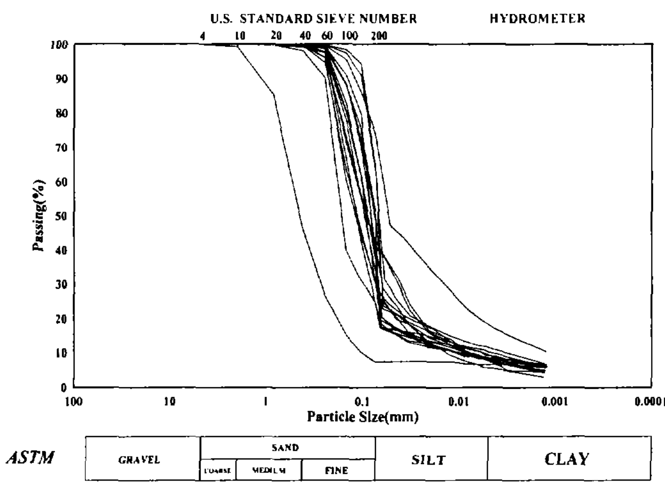

Fig. 4. Grain size distribution curves for the ejected soils at sand boiling sites.

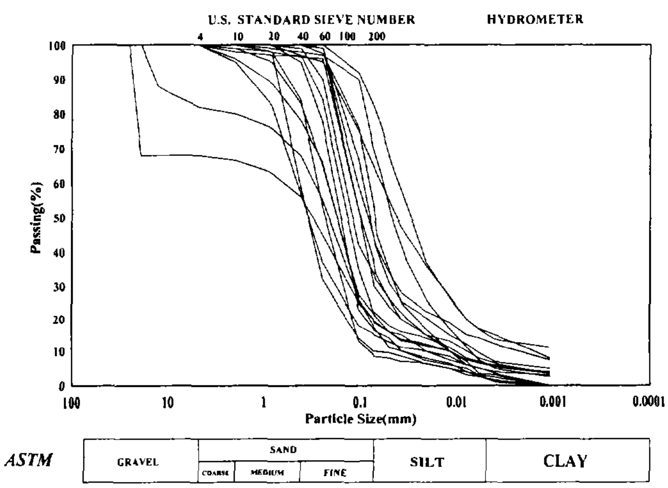

Fig 5. Grain size distribution curves for the probable liquefied soil samples from boreholes.

At present, only a limited number of laboratory tests have been performed on the thin-walled tube samples obtained from the liquefaction sites [Ueng, et al., 2000]. The preliminary results of dynamic triaxial tests indicated that liquefaction would occur under the cyclic stress ratio equivalent to the seismically induced dynamic loading at the sites during Chi-Chi earthquake.

The observations of the wide-spreading soil liquefaction during Chi-Chi earthquake provided a unique opportunity for the geotechnical engineers in Taiwan to collect the data to develop their own liquefaction evaluation criteria. Figure 6 shows the preliminary data on the plot of seismic stress ratio versus corrected SPT-N value. The Seed's liquefaction evaluation criteria are also shown on the same plot.

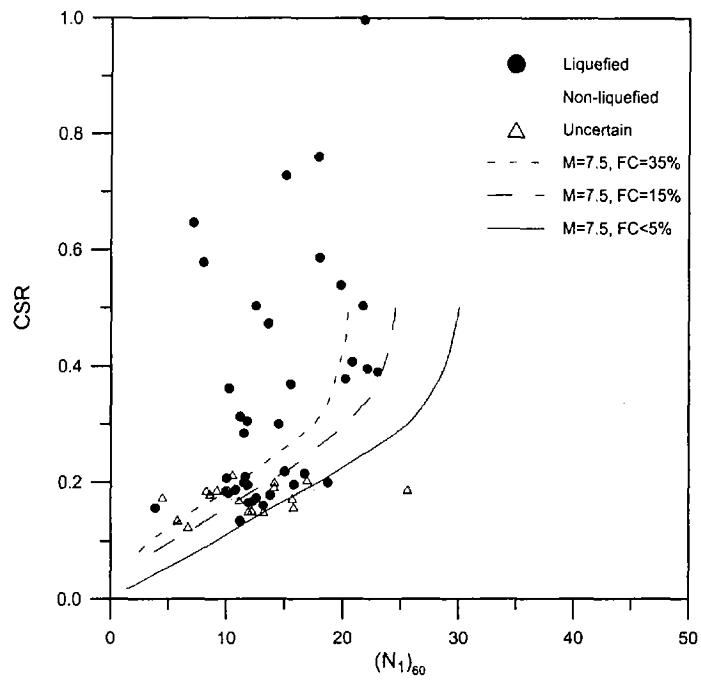

Fig. 6. Seismic stress ratio versus corrected SPT N-values for soils in the liquefaction areas.

EVALUATION OF DEBRIS FLOW AS POTENTIAL SECONDARY HAZARD

The large volume of loosened soil and rock derived from the slope failures during Chi-Chi earthquake becomes the source of debris flow when the rainy season arrives. For the slopes with soils and rocks loosened up during the earthquake, land slides and rock falls will very likely occur during the aftershocks or a heavy rain. The water can easily carried these materials down the slopes or the streams and caused tremendous damages to the properties in the path of the debris flow. There already had been devastating losses of properties during the rainy periods in February and April 2000.

Field investigations and analyses were conducted for the potential debris flow in the areas with large quantities of landslide deposits and loosened slope materials [Lin, *et al.*, 2000]. Special attention was given to the streams in the watershed areas. Four factors, i.e., geology, topography, deposit area, and fragment size are considered in the evaluation of the potential of debris flow. Among 148 streams investigated to date, the hazard potential for debris flow of 68, 67, and 33 streams are classified as high, medium, and low, respectively.

RETROFITS AND REMEDIAL MEASURES

Many damaged buildings were retrofitted if they are structurally sound. Grouting and underpinning are the most commonly used methods to raise and put the buildings in upright position. The grouting method was not always successful depending on the application technique and understanding of the subsurface soil conditions. Underpinning with a strong reaction surface, e.g., reinforced concrete slab, and jacks beneath the low-rise building was used successfully in many cases.

For the dammed-up lakes, the collapse of the debris dams by overtopping and piping is a devastating disaster to the downstream communities. At Tsao-Ling, a temporary overflow channel with proper erosion protection was built to avoid overtopping of the dam. The water inflow and seepage were also closely monitored for a timely evacuation if necessary. Other long-term measures are underway. In Juo-Feng-Err mountain area, partially filling up of the dammed-up lakes and lowing of the temporary spillway are planned.

CONCLUSIONS

1999 Chi-Chi, Taiwan earthquake induced very high shaking intensities in many areas in central Taiwan and caused extensive geotechnical hazards. Large scales of landslides were induced by this earthquake. The debris flow in the areas of loose landslide deposit becomes a secondary hazard. Building, roadways, and waterfront structures were damaged due to the soil liquefaction. The liquefied materials are generally uniform fine sand and silt with rather high fines contents. The ground improvement to prevent liquefaction was proved to be effective in the reclaimed lands. The performances of embankment dams and tunnels were found satisfactory. The data obtained in the geotechnical investigations for Chi-Chi earthquake will provide very useful information for the development and revision of the practices in geotechnical engineering.

ACKNOWLEDGEMENT

This study is partly supported by the National Science Council, Taiwan, ROC.

REFERENCES

Chang, C.T. and S.Y. Chang, [2000]. Preliminary Geotechnical Examination of Dams and Tunnels in Chi-Chi Earthquake, *Sino-Geotechnics*, No. 77, pp. 101-108.

Chern, J.C. and S.Y. Chang, [2000]. A Preliminary Review on the Seismic Safety Assessment Method for Earth Dam Based on Chi-Chi Earthquake Experience, *Sino-Geotechnics*, No. 77, pp. 109-117.

Fang, Y.S., T.J. Chen, Y.C. Yang and C.C. Tang, [2000]. Failure of Earth Retaining Structures Under Chi-Chi earthquake, *Sino-Geotechnics*, No. 77, pp. 87-92.

Ishihara, K. [1985]. Stability of Natural Deposits During Earthquakes, Proceedings, 11th International Conference on Soil Mechanics and Foundation Engineering, San Francisco, CA, pp. 321-376.

Lin, M.L., F.C. Yu, P.S. Lin, and J.C. Fan, [2000]. Evaluation of Debris Flow as Potential Secondary Hazard Caused by Chi-Chi Earthquake, International Workshop on Annual Commemoration of Chi-Chi Earthquake, Taipei, September 2000.

MAA, [2000a]. *Field Investigation of Soil Liquefaction in Nan-Tou and Wu-Feng Areas*, Report to National Science Council, February 2000.

MAA, [2000b]. *Soil Liquefaction Evaluation and Mitigation Study, Phase I (Yuen-Lin, Da-Chun and Sheh-Tou)*, Final Report to National Science Council, April 2000.

NCREE, [1999]. *Reconnaissance Report of the geotechnical hazard caused by Chi-Chi earthquake*, National Center for Research on Earthquake Engineering, NAPHM, and Taiwan Geotechnical Society, Taipei, Taiwan.

Ueng, T.S., M.H. Chen, and I.Y. Li, [2000]. Preliminary Study of Soil Properties in Yuen-Lin Liquefaction Area, International Workshop on Annual Commemoration of Chi-Chi Earthquake, Taipei, September 2000.

Yu, M.S., B.C. Shieh, and Y.T. Chung, [2000] Liquefaction Induced by Chi-Chi earthquake on Reclaimed Land in Central Taiwan, *Sino-Geotechnics*, No. 77, pp. 35-50.