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Paper No. 10.49

ABSTRACT

On September 21, 1999, Taiwan was struck by an earthquake, called Chi-Chi earthquake, one of the largest in 100 years. The epicenter was located 12.5 km west of the Sun Moon Lake (Northern Latitude 23.85°, Eastern Longitude 120.78°), with focal depth of 8 km, and magnitude of M_w=7.6 (USGS). This earthquake caused heavy casualties and severe property damages around central Taiwan. It was found that this earthquake resulted in sand boiling, differential settlement on the ground and lateral spreading around part of the Maolou River bank in Nantou City. Field investigation, geological exploration and in situ tests, which include 14 borings with standard penetration tests and 8 cone penetration test soundings, were conducted to demonstrate the soil profiles and to perform soil liquefaction potential assessment. The ground failure due to spreading liquefaction near Maolou River bank was also described. The result revealed that soils about 5~8 meters below the ground surface contains fine to medium silty sand or sandy silt which is the same strata as the highest liquefaction potential based on SPT-N and CPT-q_c liquefaction simplified procedures. It is also shown that the critical depth also has the physical properties similar to the boiled sand taken from the sand volcanoes.

KEYWORDS

Earthquake, Liquefaction, Lateral spreading, SPT-N value, CPT sounding

INTRODUCTION

The 1999 Chi-Chi earthquake caused extensive casualties and severe property damage in central Taiwan. Liquefaction phenomenon occurs around Taiwan's Mid-Western shoreline an around the inland of central Taiwan. Large areas of soil liquefaction induced by Chi-Chi earthquake have not been observed before in Taiwan. The types of ground failure in the liquefied zone include cyclic mobility, lateral spreading, grounding fracture and sand boiling. This paper focuses on Nantou city, which is one of the liquefied regions.

The metropolis of Nantou city was constructed within the Maolou River basin, and the Nantou flyover-section of the Second Freeway also pass through this basin. The severe phenomenon of soil liquefaction and soil boiling as a result of the Chi-Chi earthquake were observed in abovementioned areas areas. It is noteworthy to research the soil liquefaction behavior and the characteristics of the local soil profiles. 14 borings with standard penetration tests and 8 cone penetration test soundings were performed around the Maolou River basin that passes through this investigated zone as shown in fig. 1. This paper describes the geologic condition, ground motion, characteristics of boiled sand, field observation, and liquefaction potential assessment in Nantou City.

GEOLOGIC CONDITION

Nantou County is the only landlocked county in the Taiwan Province. Nantou city is located on North Western part of this county, and the Maulou River pass through the city. This region is formed by alluvial sector and deposit plain that are mainly composed of cementated or poor-cementated clay, silty sand, sand and gravel distributed on valleys and alluvial plateau.

According to "*The Research of Soil Liquefaction Conducted in the Areas of Nantou and Wufong.*", by Moh And Associates, INC. (2000), the cross section of the soil profiles in this region was drawn based on the boring data collected in Nantou City (See Fig. 2~4). Consequently, the subsoil located

30 m below ground level can be divided into 6 layers. The descriptions are as follow:

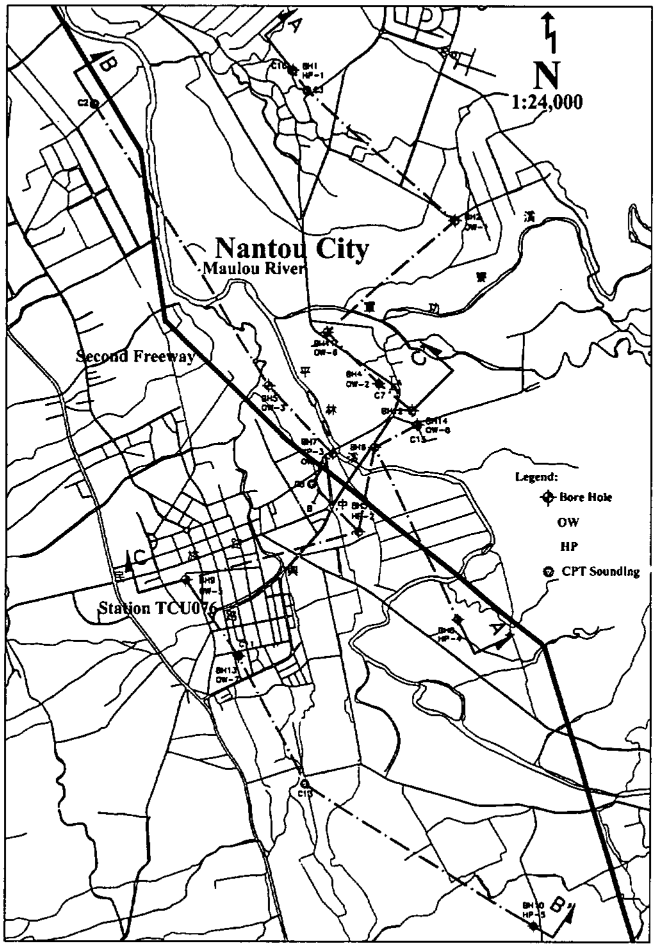

Fig. 1 The Location of SPT and CPT in Nantou City

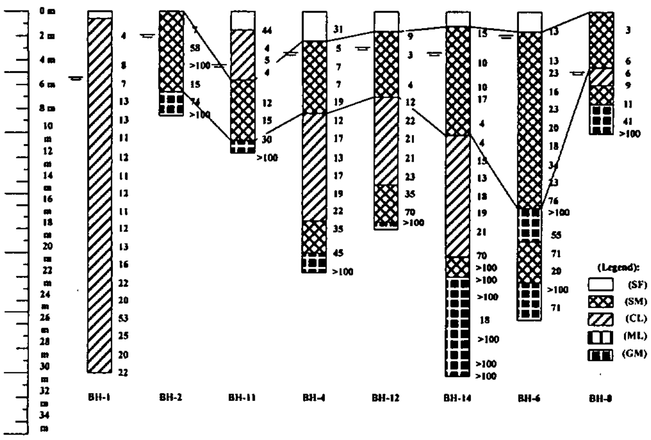

Fig. 2 The soil profiles of A-A' Section

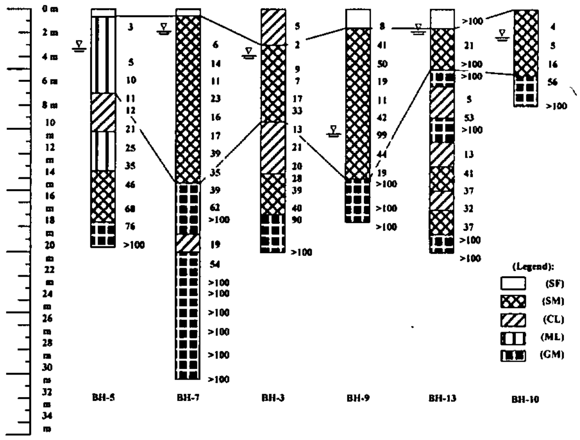

Fig. 3 The soil profiles of B-B' Section

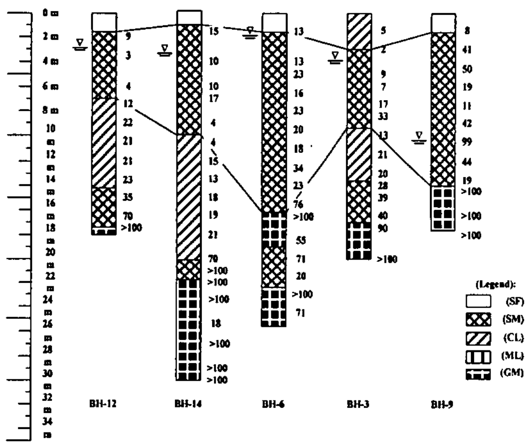

Fig. 4 The soil profiles of C-C' Section

- First layer: The first layer is mainly backfill, found between ground level and 2.4 m underground. The average thickness is about 1.5 m and it consists mostly of the graded gravel.
- Second layer: The second layer includes loose-to-medium dense silty sand and sandy silt. Its appearance changes from yellowish brown in color to grayish brown, according to its depth. It is locates between 0.8 m to 12 m underground. The average thickness of this layer is about 7m and it is also the major layer of the soil liquefaction. This layer becomes thicker near the bank of Maolou River.
- Third layer: The third layer is composed of sandy gravel, which is yellowish brown in color. The maximum grain size is about 10cm. It is also the first gravel layer in this region. It is situated between 6 m to 9 m under the ground level and about 2 m in thickness.

- Forth layer: The fourth layer contains silty clay with medium dense consistency to very dense consistency. It is gray and yellowish brown in color alternatively. This layer seldom contains sandy silt between this layer is distributed between 6 m to 20 m underground and about 4 m in thickness.
- Fifth layer: The fifth layer consists of grayish brown dense silty fine sand to silty medium sand. It is located between 14 m to 20 m underground and its average thickness is 2.5 m.
- Sixth layer: The sixth layer contains a lot of gray and coarse-to-medium sand within the gravel deposits. It is found broadly distributed 19 m under the ground surface. It cannot be penetrated with the Standard Penetration Test and represents a very dense soil layer. The average thickness of the 'sixth layer' could not be known because of the contract limitations.

GROUND MOTION DURING CHI-CHI EARTHQUAKE

The Chi-Chi earthquake occurred at 1:47 a.m. on September 21, 1999 along a 105 km long main fracture in the Chelungpu reverse fault. The earthquake had a moment magnitude of M_w = 7.6.

The North-South direction of the Chelungpu fault, which has a length of more than 10 km, passes through the eastern part of Nantou City. The Nantou elementary school observation station (TCU 076, CWB), which is about 15.25 km from the epicenter, recorded the seismic motion during the main shock, but no obvious liquefied regions were observed around the school. Seismic data also showed that the strong component of peak horizontal acceleration had been reaching 420.02 gal in the North-South direction with duration of 41.06 sec. The UD, NS and EW ground motion records are shown in Table 1.

Table 1 Strong Motion Records in Nantou City

Observation Station	Station Number (CWB)	Peak Horizontal Accelerations (gal) UD Component	NS Component	EW Component
Nantou Elementary School	TCU076	275.38	420.02	340.10

CHARASTERISTICS OF BOILED SAND

After the main shock, the field investigation was conducted in Nantou city and its surroundings to determine the location of the liquefied region. During the process of liquefaction investigation, the boiled sand collected near the sand volcano was used to conduct the soil physical property tests in the laboratory. The results reveal that the boiled sand would be yellowish brown and non-plastic silty sand. In the Unified Soil Classification System (USCS), the sampled soil can be classified as SM. The fine content of the sampled soil is between 20% and 40%. Soil samples near the sand volcano were collected from distinct sites and analyzed, and nine grain size distribution curves were drawn (See Fig 5).

With the comparison of the Code of Japan Port and Harbor Association (1989), the grain size distribution curves of boiled sand situate in the high liquefaction area and the grain of the boiled sand is also quite uniform as shown in Fig. 5. The mean grain size D_{50} of these samples ranges between 0.08mm and 0.12mm within the boundary between 0.08mm and 0.7mm that suggested by Seed (1976). It could be inferred that the soil collected near the sand volcano possess high liquefaction potential.

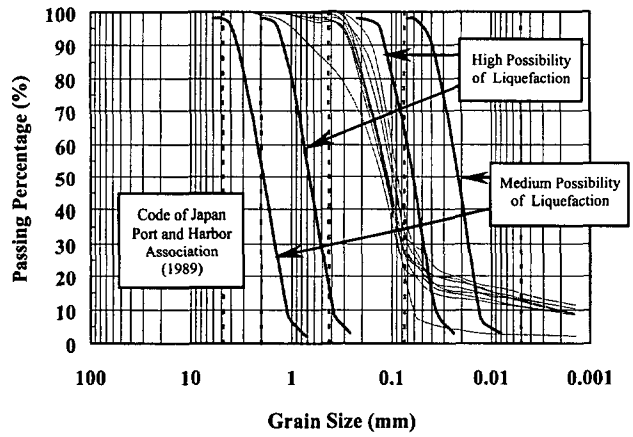

Fig. 5 The Grain Size Distribution of Boiled Sand on the Sand Volcanoes

Comparison of the boiled sand with geologic exploration data reveals that the physical nature of the boiled sand is extremely similar to the loose soil layer in the second layer with a blow count of about ten (N≈10). Moreover, through the measurement of groundwater table, the average groundwater table is 3m under the ground.

Based on the abovementioned geologic and hydrologic condition, that the second layer has high liquefaction potential, coupled with strong component of peak horizontal acceleration, which reached the strength of 420.02 gal with the duration elapse of 41.06 sec during the earthquake, the widespread devastation in terms of soil liquefaction and ground failure was inevitable.

FIELD OBSERVATION

In situ investigation and recordings, liquefaction damage descriptions from several sites and their photographs will be presented in this section. Sand boiling and sand volcano were observed around the Maolou River basin and its alluvial plateau. Photo 1 shows the sand-boiling phenomenon near the bridge pier of Second Freeway and photo 2 shows the boiled sand in the peanut yard and banana plant. Both of these sites are near the Maulou River dike. The sand eruptions were the result of ground surface rupturing, and then the excess pore water pressure dissipated from the facture. According to the descriptions of nearby residents, the eruption of excess pore pressure lasted over two days. Ground permanent failure within lateral spreading was also observed in this case history. Photo 3 and 4 show the lateral spreading failure on part of shoals of the Maulou River and on the road around the river dike respectively. Finally, the photo 5 and 6 show the separation and inclination of the buildings due to differential settlement and the dike of Maolou River settlement caused by the seismic vibration respectively. But the sand boiling does not occur obviously at the last two sites. The follow-up borings and soundings were conducted in these areas.

Photo 1 Sand Boiling near the Bridge Pier of Second Freeway

Photo 2 Sand Rupturing in the Peanut Yard and Banana Plant

Photo 3 Lateral Spreading on the Shoals of Maolou River

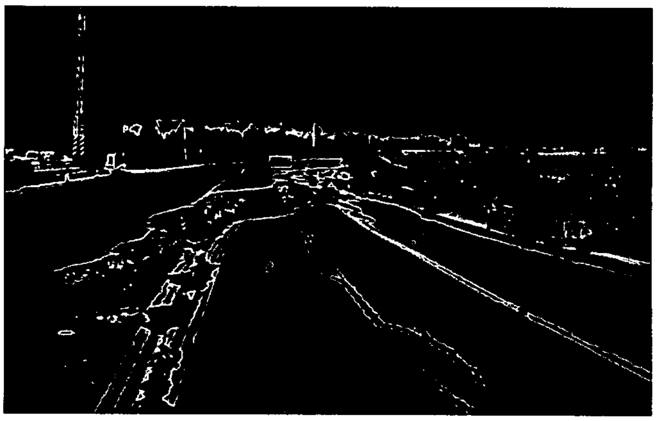

Photo 4 Lateral Spreading on the Road around the River Dike

SOIL LIQUEFACTION POTENTIAL ASSESSMENT

The evaluation of the liquefaction resistance was performed using methods mentioned in Seed Simplified Procedure (modified by 1997 NCEER Workshop) and recommended by Robertson and Wride (1998) based the SPT-N value and CPT data respectively. The parameters for analysis include peak ground acceleration recorded by the observation station situated at Nantou elementary school with the value of 420.02 gal. The other parameter is the ground water level, which was obtained through periodic groundwater level measurements between December 25, 1999 and May 17, 2000 in Nantou.

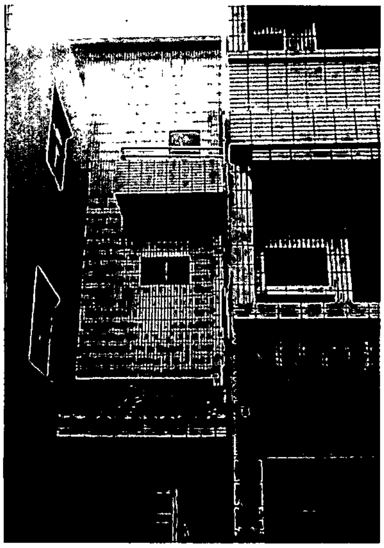

Photo 5 Separations and Inclination due to Ground Differential Settlement

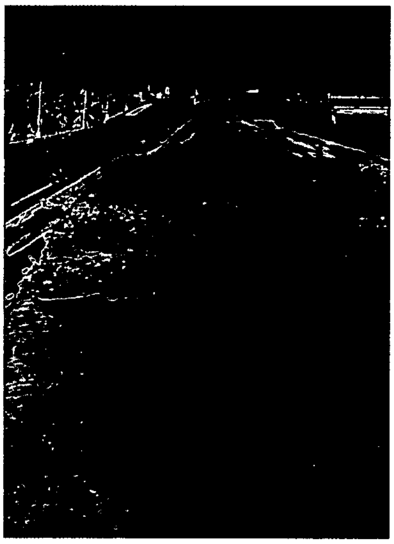

Photo 6 Settlement of Dike due to Seismic Vibration

The correction for overburden stress C_N is proposed by Liao and Whitman (1986,a) with a maximum value $C_N = 2$ as shown in equation (1):

$$C_N = \sqrt{\frac{Pa}{\sigma_o'}} \qquad (1)$$

Where C_N is a factor to correct measured penetration resistance for overburden pressure and Pa equals to 100 kPa or approximately one atmosphere in the same unit used for σ_o'. The value of hammer energy ratio ER (%) is referred to the empirical equation derived by MAA, INC. (2000) performing hammer energy test in Yuanlin, one the liquefied zone induced by Chi-Chi earthquake in Taiwan. Refer to equation 2 and 3.

$$ER(\%) = 30 \cdot \frac{z}{11} + 50 \qquad for\ z\ \leq 11\ meters \qquad (2)$$

$$ER(\%) = 80\% \qquad for\ z\ \geq 11\ meters \qquad (3)$$

Where ER is the hammer energy ratio in the depth of z (meter). By the recommendation of Seed and Idriss (1971), the evaluation of CSR based on the maximum ground surface acceleration a_{max} is used in Seed Simplified Procedure and Robertson et al. recommended method. Refer to equation (4).

$$CSR = \frac{\tau_{ave}}{\sigma_o'} = 0.65 \cdot \left(\frac{a_{max}}{g}\right) \cdot \left(\frac{\sigma_o}{\sigma_o'}\right) \cdot r_d \qquad (4)$$

Where a_{max} is the peak horizontal acceleration at ground surface generated by the earthquake, g is the acceleration of gravity, σ_o and σ_o' are total and effective vertical overburden stress, respectively, and r_d is a stress reduction coefficient. The results show that the liquefied soil distribution ranges from 4 to 8 meters under the ground surface, and also the closer to Maolou River the thicker the liquefiable layer. The soil types within this layer are mainly yellowish brown silty sand and sandy silt with seldom-low plasticity clay.

According to the soil profiles in Fig. 2-4, the simplified analysis shows that the critical depth is situated within the second layer. The results of laboratory analysis are consistent with the geologic exploration and field investigation of the boiled sand. Furthermore, laboratory analysis of the sand-gravel mixtures, which are classified as GM soils (USCS), based on the Seed Simplified Procedure shows that sand-gravel mixtures possessed liquefaction potential.

CONCLUSIONS

The hazards due to soil liquefaction in Nantou city consisting of sand boiling, cyclic mobility, lateral spreading and structures lousing are presented in this paper. Geologic exploration, field and laboratory tests and the soil liquefaction potential assessment was also preformed.

The 14 borings and 8 CPT soundings reveal the second layer below the ground with depth ranging from 1 to 12 meters mainly contains silty sand or sandy silt, but occasionally low-plastic clayey soil are also mined in that second layer. During the Chi-Chi earthquake, the liquefied layers in the Nantou city was probably between 4 to 8 m in depth within the second layer. In view of the nature of boiled sand in Fig. 5, its physical properties are also similar to the second layer. Moreover, the causes of damage due to soil liquefaction are mostly relative to the NS-direction of Maolou River basin throughout the Nantou City.

The CPT cannot be performed due to the firm layers of sandy gravel or sandy soil existing usually in shallow layer in Nantou. Therefore the removal of dense soil with 1 to 2m thick causes the lost of its boring data permanently. Moreover, results obtained from Seed Simplified Procedure, show the existence of liquefaction potential in the non-plastic sand-gravel mixtures. Due to difficulty in sampling gravelly soil, cyclic triaxial tests in laboratory have not conducted to verify whether the gravelly sand have liquefaction potential. Further cyclic loading experiments should be conducted to determine the actual liquefaction potential in sand-gravel mixtures.

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