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Discussion on the Relevance of Old Low-lying Land Reclamation and Soil Liquefaction

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ABSTRACT

On February 6th, 2016, an earthquake of magnitude 6.6 occurred in southern Taiwan, causing large-scale soil liquefaction in Tainan city. This study compared the topographic maps of the disaster areas taken in 1924 and 2016, and found most of this disaster areas were located in the low-lying places. This observation expressed a strong association between the low-lying reclaimed land and soil liquefaction. In addition, this study collected the sand boil sample from field, and compared the grain size distribution with official borehole report. The preliminary results indicated the liquefied soil layer might occurred in 4.5-m depth beneath the reclaimed soil. The results of this study showed liquefaction potential evaluation should be take account carefully for urban development in low-lying reclaimed land in the future.

KEY WORDS: 0206 earthquake; soil liquefaction; low-lying reclamation.

INTRODUCTION

On February 6, 2016, an earthquake of magnitude 6.6 occurred in the Meinong District of Kaohsiung; it struck at a depth of 14.6 km, causing earthquake intensity over 4 that were felt in areas south of Chiayi. The most severe earthquake intensity measured 7 at Xinhua, Tainan. This earthquake is called 0206 Earthquake; it caused large-scale soil liquefaction in numerous areas of Tainan, including the Xinshi District, Yongkang District, Annan District, West Central District, and North District. The soil liquefaction was accompanied by building settlement, damage to houses, and sand boil, all of which severely affected the lives of the residents.

According to historical records, the land stretching from Yunlin to Kaohsiung in southern Taiwan was covered with lagoons in the seventeenth and eighteenth centuries. At that time, western Tainan was part of the Taijiang Inland Sea (Fig. 1); it stretched from the Jiangjun River estuary in the north to the Erren River estuary in the south; the eastern coastline extended to the current Xinshi District (Chang et al., 1996). In 1823, a great flood struck Chianan area, and washed large amounts of debris and sand into the Taijiang and Daofeng Inland Seas, filling a large area of the inland seas and creating new land. Following river deposition and urban development, land reclamation was implemented on low-lying lands, creating new land for fish farms and new residential areas. For the new developed alluvial plain in Tainan, the soil particle size is comparatively uniform, and its groundwater level is high. According to the geological criteria (Youd & Hoose, 1977; Kramer, 1996), soil liquefaction may occur in these regions during an earthquake.

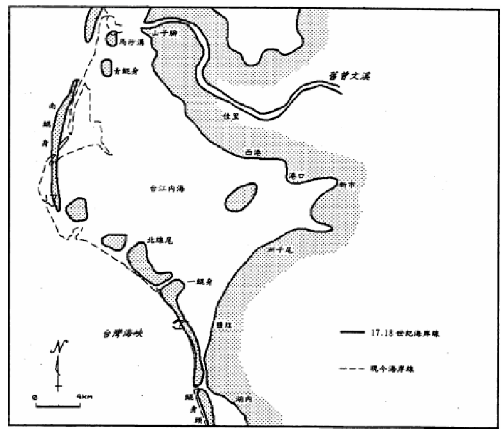

Fig. 1 Comparison between seventeenth- and eighteenth-century Taijiang Inland Sea and present coastline (Chang *et al*., 1996)

Although the low-lying characteristic in Tainan may be prone to soil liquefaction, the soil liquefaction may not necessarily occur during earthquake. The key point is whether appropriate soil improvement methods were applied to the liquefiable soil to improve liquefaction resistance or reduce damage caused by liquefaction. According to land reclamation regulations (Ministry of the Interior, 2015), new land development is permissible in areas that have soil liquefaction potential if the proposed construction method can overcome the hazards of geological disasters. Although the regulations ask the development project must overcome the natural geological hazards, in reality, during construction, because of factors such as uncertain estimates of land characteristics, poor quality construction, and careless inspections, disasters may occur. In addition, according to the Design Code and Specifications of Building Foundations (Ministry of the Interior, 2001), for the construction of private buildings of less than four floors, if the foundation area is less than 600 m^2, the depth of the foundation is less than 5 m, and the site has no potential geological hazards, then the subterranean survey can be replaced with an existing, reliable subterranean report of the neighboring land. In other words, the government did not demand that geological drilling be in place for the construction of low-rise residential buildings; hence, information about the geological characteristics of such construction sites cannot be known.

To examine soil liquefaction in the Tainan region during the 0206 Earthquake and its relevance to land reclamation, the present study conducted site investigations and collected the sand boil samples from the disaster area in the North District of Tainan City; the physical properties of the soil samples were tested. In addition, the study used existing borehole data from soil liquefaction sites provided by the Tainan City Government to compare the physical properties of the site soil samples with the characteristics of the various soil layers in the existing borehole data. With the comparisons, the study first inferred the locations of liquefied soil layers, and discussed the connection between reclaimed lowlands in Tainan City and occurrences of soil liquefaction. The research results can serve as a reference for preventing soil liquefaction in future constructions on reclaimed lands.

THE DISASTER STATUS OF THE NORTH DISTRICT OF TAINAN CITY

Change in Land Use in the North District of Tainan City

The study analyzed the characteristics of soil liquefaction areas in the North District of Tainan City, and tested the physical properties of soil samples taken from liquefaction sites to examine the causal relationships between land reclamation and soil liquefaction. Figure 2 shows the administrative region of the North District of Tainan City; North Distric has a triangular shape; the Chaitougang Stream on the north-east and the Yanshui River on the north-west form the boundary line of the administrative region; the Chaitougang Stream joins the Yanshui River from the southeast to the northwest. The shaded area on the map represents the area where soil liquefaction occurred during the 0206 Earthquake; the disaster area is located northeast of the North District, near the south side of the Chaitougang Stream. The round dots on the map represent the locations where the Tainan Public Works Bureau had carried out soil drillings before the earthquake. Figure 3 shows an overlap figure comparison of the present North District of Tainan City, the Taijiang Inland Sea during the seventeenth and eighteenth centuries, and a topographical map of Taiwan from the Japanese occupation in 1924. Figure 3 shows that, during the seventeenth and eighteenth centuries, half of the surface area of the present North District of Tainan City was sea area; in 1924, this region still included inland water regions; the region was finally developed into a residential area after years of urban development.

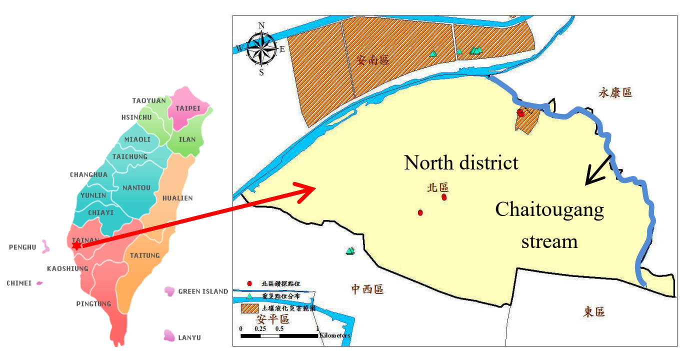

Fig. 2 Administrative region of the North District of Tainan City and the location of the soil liquefaction disaster area

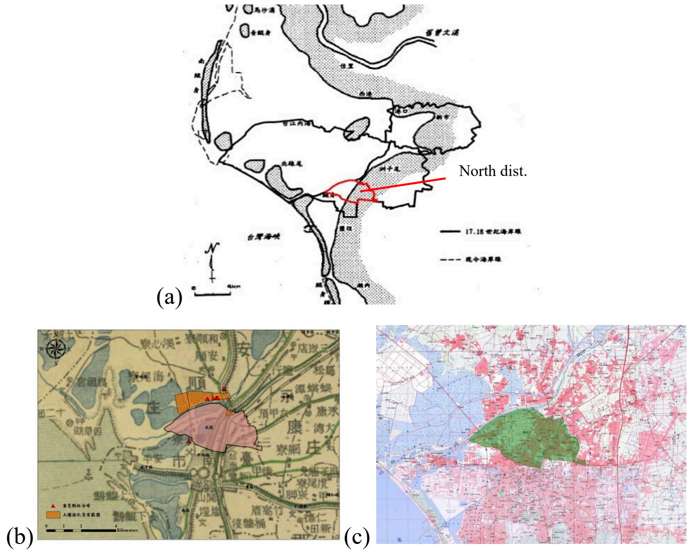

Fig. 3 Overlapping maps of the present North District of Tainan City and old topographical map: (a) seventeenth- and eighteenth-century Taijiang Inland Sea, (b) map of Taiwan from the Japanese occupation in 1924, and (c) 1999 topographical map

Soil Liquefaction Disaster Status of the North District of Tainan City

The study conducted site investigations of soil liquefaction areas in the North District of Tainan City. The investigation results showed that over 20 households were affected by soil liquefaction; damages included damages to accessory structures, cracks in walls and floors, building settlement, and sand boil on the ground, as shown in Fig. 4. The accessory structures of one house particularly showed evident damage. Among the affected households, the relative elevation difference between the ridged area inside the house and the edge of the wall was 10 cm at the most.

Fig. 4 (a) Damaged wall beside the front porch of a residence, (b) building subsidence caused by soil liquefaction, (c) formation of ridges on the floor of the house, and (d) cracks on the surface of the road and sandblast on the ground

Existing Drilling Data of North District of Tainan City

To determine the soil layer characteristics of the soil liquefaction sites in the North District of Tainan City, this study obtained, through the Tainan City Government, 4 (B-1 to B-4) existing sets of borehole data from liquefaction sites, among which the drilling depth of B-3 was 35 m; the other drilling sites had drilling depths of 25 m. Figure 5 shows a histogram of the borehole data; the figure indicates that the soils near the soil liquefaction sites of the North District of Tainan City were primarily sandy silt (ML), followed by low plasticity silty clay (CL-ML), and silty sand (SM).

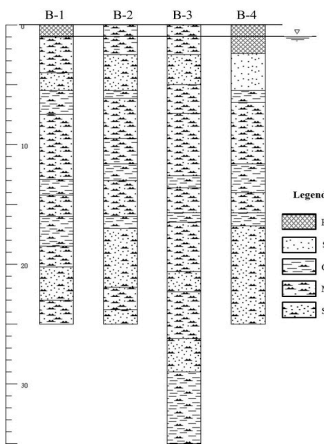

Fig. 5 Histogram of existing boreholes from liquefaction sites in the North District of Tainan City

ANALYSIS OF SOIL SAMPLES FROM AREAS OF SOIL LIQUEFACTION

Basic Physical Properties of Sand Boil Samples

To determine the relationships between soil liquefaction during the 0206 Earthquake and the geological characteristics of the alluvial land of Tainan, the study collected sand boil samples from disaster sites and tested soil properties, including specific gravity, sieve analysis, and hydrometer analysis. The study also compared the color and particle size distributions of the procured samples with old drilling report data to assess the locations of the liquefied soil layers, and compared the results with the soil liquefaction analysis.

There were clear signs of sand boil beside several roads and at the corners of several walls. Figure 6 shows two neighboring sand boil spots that spewed soils of different colors, indicating that these two soils may have originated from different soil layers.

The soil samples obtained from the disaster site in the North District of Tainan City included two types of soil, yellow soil (Soil A) and grey soil (Soil B), as shown in Fig. 6. After the laboratory test, the specific gravity values were determined to be 2.62 (Soil A) and 2.64 (Soil B); the soil particle size distribution (PSD) curves are shown in Fig. 7. The figure shows the PSDs of the two types of soil were fairly close; the median particle size D_{50} was 0.097 mm; the uniformity coefficient C_u of Soil A was 3.93, and the coefficient of gradation C_c was 1.83; the uniformity coefficient of Soil B was 5.5, and the coefficient of gradation was 2.56. The soil samples taken from the field were noncohesive. According to the Unified Soil Classification System, the soil samples collected for this study were all silty sand (SM).

Fig. 6 Different colored sand boil samples

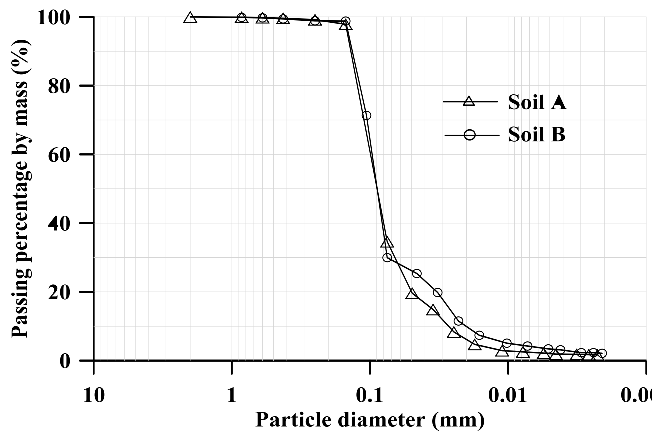

Fig. 7 Sand boil sample particle size distribution curves

Comparisons of Sand Boil Samples and Borehole Data

The study obtained a total of four existing borehole data sets (B-1 to B-4) for the study site; the borehole data were from 1996. According to the borehole report, the groundwater is located at a level 1 m below the ground surface which is prone to soil liquefaction.

To determine the source of the sand boil samples, Fig. 8 was drawn from the borehole report data to show the PSD and soil classifications of the study site soil within 20 m of the surface. The PSD of a sand boil sample was included in the diagram for comparison purposes (because the PSDs of Soil A and Soil B were fairly close, only the PSD of Soil A was shown).

To determine the liquefaction characteristics of the study site, the study calculated the factor of safety against liquefaction F_L ($F_L < 1$ indicates the soil is liquefiable, and that the soil is not liquefiable if otherwise) for the soil sample. The results are shown in Fig. 8. The liquefaction potential assessment of each borehole showed that the soil layer where liquefaction could occur was located within 6 m of the surface; soil layers deeper than 6 m had fairly high F_L values. Although the F_L of the B-1 borehole at a depth of 4.5 – 6 m was less than 1, the soil was cohesive in nature and that layer was considered to be nonliquefiable; therefore, in this study, the notion of a liquefiable soil layer was restricted to sandy soil layers within 4.5 m of the surface. Comparison of soil PSD values showed that the PSD curves of the site soil samples best matched the PSD values of soils from 1.5 - 4.5 m deep soil layers. In addition, the borehole report showed that liquefiable soil layers of within 1.5 - 3 m of the surface were generally composed of yellow soil, and the soil layers deeper than 3 m were mostly composed of grey soil. Therefore, it was determined that the Tainan City North District soil liquefaction occurred in new soil layers which were less than 4.5 m deep; Soil A (yellow soil) mainly originated from a liquefaction layer positioned 1.5 - 3 m from the surface, but Soil B (grey soil) mainly originated from a liquefaction layer positioned 3 - 4.5m from the surface.

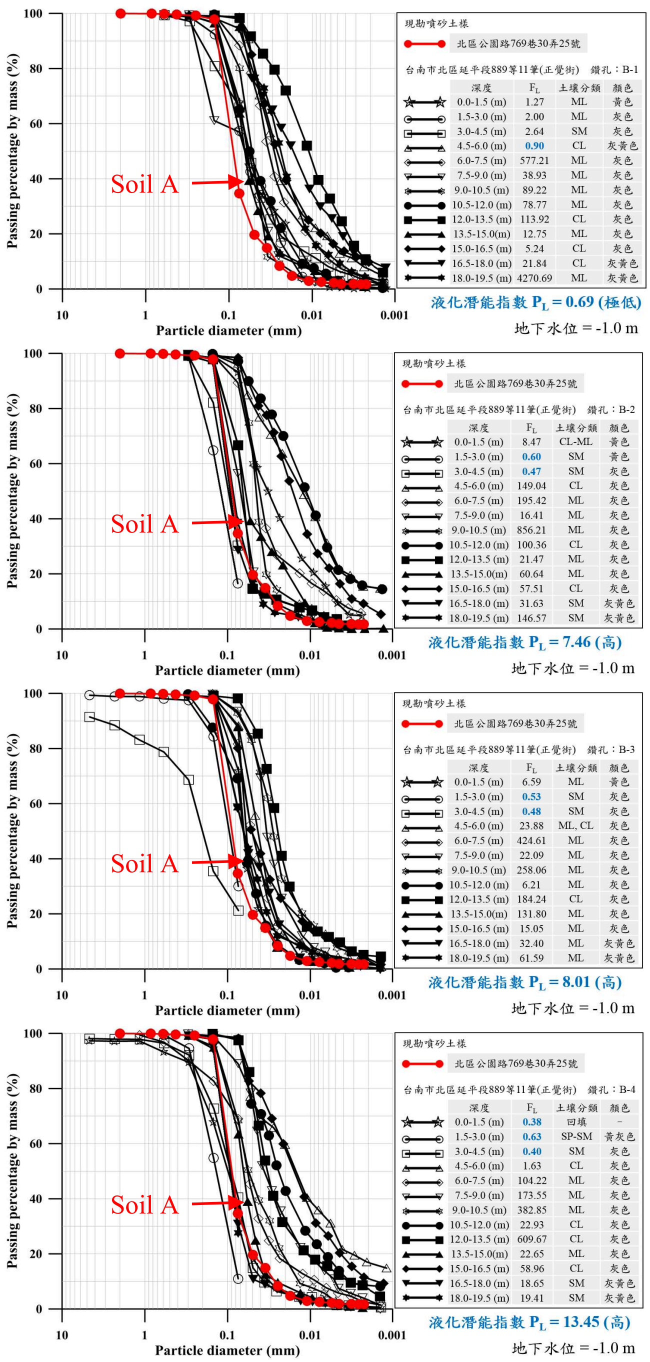

Fig. 8 Comparison of PSDs of sand boil sample and study site soils

CONCLUSIONS

The study conducted site investigations and laboratory tests of Tainan City North District sites that had experienced soil liquefaction during the 0206 Earthquake, and the study compared geological properties of deposited lowland soils in the Tainan region. The following conclusions were drawn from the research results:

1. Land formed from alluvial rivers or reclaimed by infilling lowlands has a high risk of liquefaction. The study site used to be the Taijiang Inland Sea; soil liquefaction may occur in the new aquifer of the surface layer during earthquakes.
2. The research results showed that soil liquefaction in the study site may have occurred in the 4.5-m-deep alluvial layer or the infilled soil layer, and included two different sources of liquefiable sol.
3. The geological characteristics of land formed by infilling lowland and alluvial rivers were weaker; the surface soil of the Tainan region was mostly of this type. Soil liquefaction hazards were often ignored during the construction of low-rise buildings. The study recommends drawing up regulations for soil liquefaction prevention for construction projects on reclaimed land.

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