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A CASE STUDY ON THE SOIL LIQUEFACTION MONITORING AT A HIGH POTENTIAL OF SOIL LIQUEFACTION AREA IN TAIWAN

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The Meinong earthquake that impacted southern Taiwan in 2016 resulted in over a thousand buildings in Tainan being damaged due to soil liquefaction. To aid future building foundation design considerations and reduce the possibility of building damage, the Taiwan government has established a medium precision 3D soil liquefaction susceptibility map by conducting extensive site investigations and laboratory tests. Preliminary assessments and past experience indicate a high liquefaction potential area near Dawan Elementary School in Tainan City. To verify the accuracy of the soil liquefaction susceptibility map and provide subsoil monitoring data for updates, this study establishes a soil liquefaction monitoring station at Dawan Elementary School. A steel mini suction bucket, installed using jacking and suction penetration methods, was employed as the monitoring platform. On April 3, 2024, a magnitude 7.3 earthquake occurred in Hualien, Taiwan, with an acceleration of about 30 gal recorded at the Tainan seismic station. The soil liquefaction monitoring station successfully detected an accumulation of excess pore water pressure responses, demonstrating that the system can reliably provide monitoring data for liquefiable soil layers, which serves as a reference for updating the 3D soil liquefaction susceptibility map.

Keywords: Soil liquefaction, mini suction bucket, monitoring system.

1. Introduction

After the 2016 Meinong earthquake in Taiwan, many gravity-based foundation houses in Tainan's Annan, West Central, and Xinshi districts tilted due to soil liquefaction (Tsai et al., 2018). Past earthquake disaster cases indicate that gravity-based foundations in liquefied soils are susceptible to differential settlement, causing superstructures to tilt.Interestingly,many areas classified as having high liquefaction potential did not experience liquefaction, while liquefaction occurred in areas with medium to low liquefaction potential.In 2021, the Taiwan government released the liquefaction susceptibility map, allowingpublic to directly access liquefaction potential information for various regions online. The maps are categorized into high susceptibility (LPI> 15), medium susceptibility (LPI = 5~15), and low susceptibility (LPI< 5). The Liquefaction Potential Index (LPI) is calculated based on thesafety factor against liquefaction over depths with a weighting function(Iwasaki et al., 1982). The susceptibility map is updated every five years, requiring the development of monitoring technology to validate and update the data.Therefore, Taiwan is actively developing soil liquefaction monitoring systems to ensure the accuracy of the liquefaction susceptibility map. However, challenges remain, as sensors embedded in liquefied soils may shift due to settling or floating, making it difficult to determine whether liquefaction has occurred in the soil surrounding their original positions.

A suction bucket foundation is a cylindrical structure made of steel or reinforced concrete with an open bottom and sealed top. It has been used since the 1990s in offshore oil and gas industries. During installation, the bucket first penetrates the soil under its self-weight. Then, the water is then pumped out from inside the bucket to create a pressure differentialbetween the interior and exterior of the bucket to aid in installation.As seepage occurs during suctioninstallation, soil filling inside the bucket forms a soil plug. As a result, the DNVGL-ST-0126 standard classifies the behaviour of suction buckets after installation as similar to gravity-based foundations. However, scaled experiments and numerical simulations by Wang et al. (2017, 2022) demonstrate that suction buckets exhibit stability in liquefied soils, contrasting the behaviour of gravity-based foundations in past disaster cases. To understand the behaviour of buried buckets during soil liquefaction, Kuo et al. (2024) conducted shaking table experiments usingmini suction bucket. The tests monitored the excess pore water pressure responses of the soil inside and around the bucket during shaking to study phase changes in the soil plug. Results indicate that steel mini buckets have the advantage of resisting settlement in liquefied soils, making them a stable platform for measuring excess pore water pressure in liquefied conditions.

2. Soil liquefaction potential at Dawan Elementary School

This study conducted one set of SPT and CPT field investigation tests at Dawan Elementary School. The results of the SPT and CPT test were shown in Fig. 1. The groundwater table is located at a depth of 1.4 m below the ground surface. Within the upper 30 m, the soil layers can be generally classified into four types based on soil composition and strength: loose sand from 0–6 m, medium dense sand from 6–12 m, soft to medium stiff clay from 12–21m, and dense sand from 21–30 m.

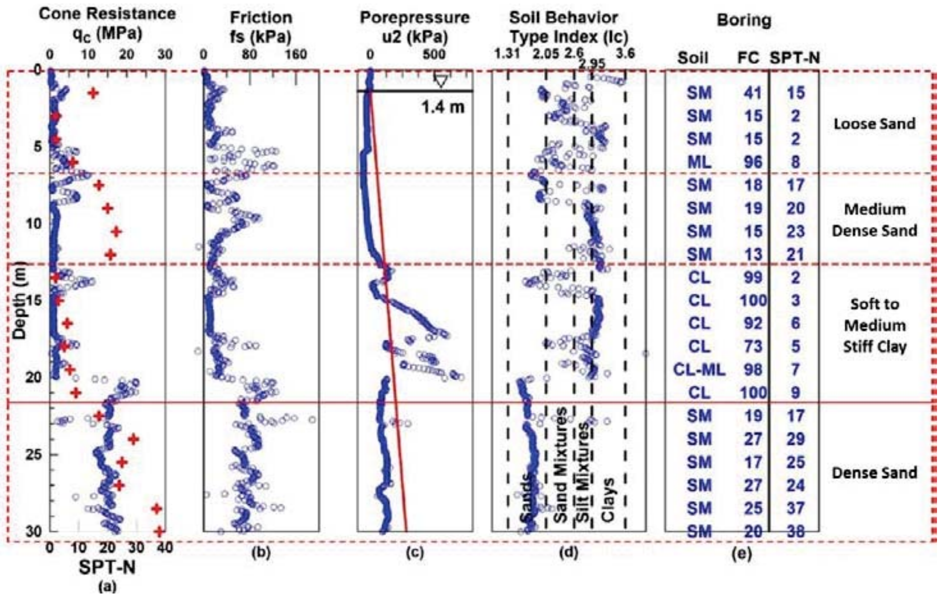

Fig. 1.SPT and CPT investigation profile[Geological Survey and Mining Management Agency (2023)]

To reasonably determine the installation depth of the mini bucket as a monitoring platform, this study adopts the CPT-based methods proposed by Robertson (2009) and Ku &Juang (2012) to evaluate the Factor of Safety against Liquefaction (*FS*) and the Probability of Liquefaction (P_L). It indicates a potential for soil liquefaction at that depth if *FS*< 1, otherwise, the soil is considered resistant to liquefaction. Under the conditions of a groundwater table located 1.5m below the ground surface, an earthquake magnitude of 7.1, and a peak ground acceleration (PGA) of 0.28g, the simplified CPT-based methodwasused to assess liquefaction potential. As shown in Fig. 2, the results indicate that the loose sand layer between 2 m and 4 m below the ground surface, the *FS* is less than 1, and the P_L exceeds 70%, suggesting a high liquefaction potential at that soil layer. Consideringlong-term variations in the groundwater level, this study installs the soil liquefaction monitoring system at a depth of 4 m below the ground surface.

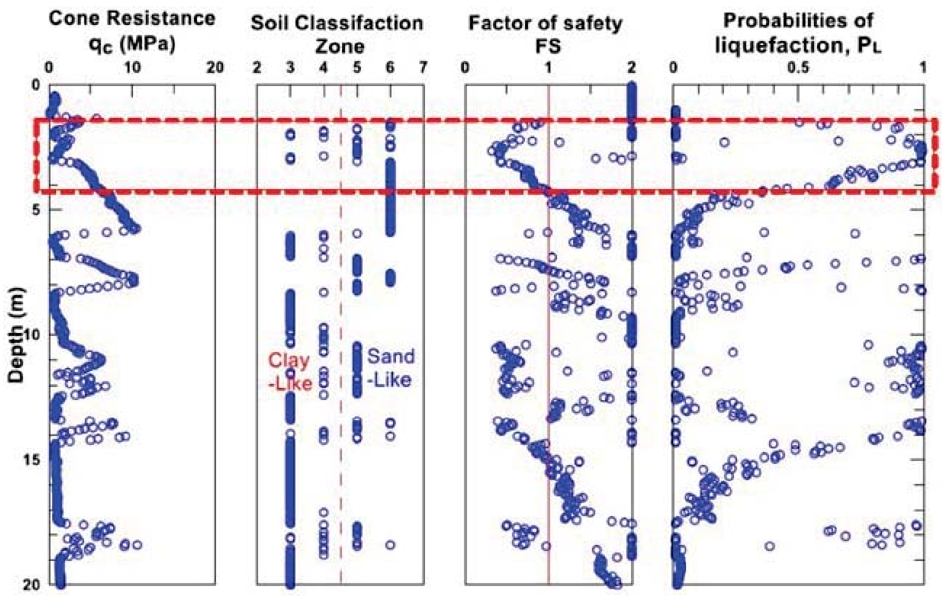

Fig. 2.Results of the CPT-based method for evaluating soil liquefaction potential[Geological Survey and Mining Management Agency (2023)]

3. Soil liquefaction monitoring station at Dawan Elementary School

This study utilizedTaiwan patent No. I821140 (as well as Japan patent No. 7544421) to establish a soil liquefaction monitoring station at Dawan Elementary School in Tainan City. The monitoring station comprises a steel mini bucket, piezometer, total pressure transducer, data logger, solar power supply, and wireless network transmission modules. The piezometer and total pressure transducer are mounted on the top lip of the mini bucket. A schematic diagram of the soil liquefaction monitoring system is shown in Fig. 3. The piezometer and total pressure transducer sample data at a frequency of 200 Hz. Data was actively recorded on-site using a data logger andwirelessly transmitted every 30 minutes for backup.

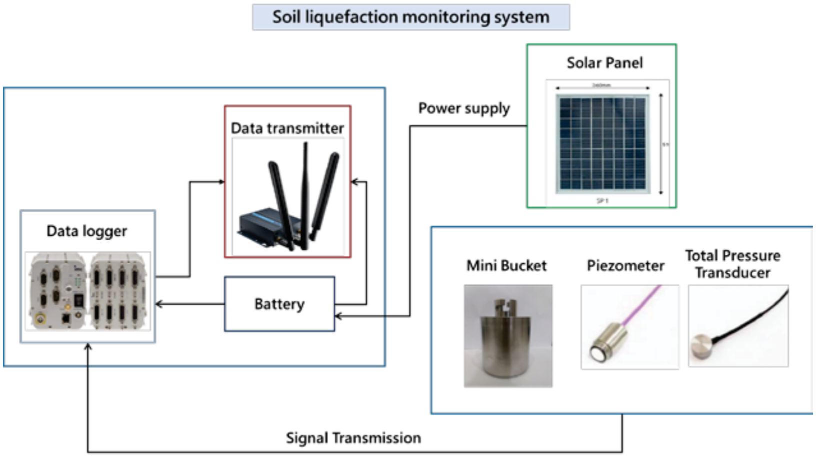

Fig. 3.Schematic diagram of the soil liquefaction monitoring system

This study selected a depth of 4 m below the ground surface at Dawan Elementary School for installing the soil liquefaction monitoring system. The construction process was as follows:

(i) Drilling and soil preservation: Begin by drilling and carefully removing the overburden.The extracted soil is properly preserved to maintain its natural stratigraphy.

(ii) Mini suction bucket installation: Drill to the target installation depth, use the jacking method to press the mini bucket into the soil. Then use a pump to extract water from inside the mini bucket, creating a pressure difference between the interior and exterior. This step is critical to reduce the potential movement of the mini bucket during monitoring operations.

(iii) Backfilling: After the mini bucket installation is complete, backfill the overburden in layers.This step is crucial for restoring site conditions and ensuring accurate future analyses.

(iv) System integration and circuit testing: The power supply, data logger, and wireless transmission modules are connected and integrated into the system. Extensive testing is carried out to confirm that all components operate correctly and the system can reliably transmit monitoring data.

Fig. 4.The construction process for the soil liquefaction monitoring system[Geological Survey and Mining Management Agency (2023)]

4. Earthquake and monitoring results

Astrong magnitude 7.2 earthquake occurred 25 km off the shore of the HualienCountyin the morning hours of April 3, 2024. This earthquake was relatively shallow, with afocal depth of 15.5 km, and occurred on a reverse fault with a northeast-southwest orientation, likely resulting from the subduction of the Philippine Sea Plate beneath the Ryukyu Island Arc. The Tainan Yongkang C064 seismic station, located approximately 2.6 km from the Dawan Elementary School monitoring station, recorded a maximum horizontal ground acceleration of about 30 gal.Previous shaking table experiment results indicate that during soil liquefaction, the excess pore water pressure measured by the total pressure transducers and piezometer inside mini bucket were nearly identical, as shown in Fig. 5. However, due to a defective of the piezometer inside the mini bucket at the time of the Hualien earthquake, only data from the totalpressure transducer were available for analysis.The earthquake induced a maximum excess pore water pressure of approximately 0.7 kPa, as shown in Fig.6.

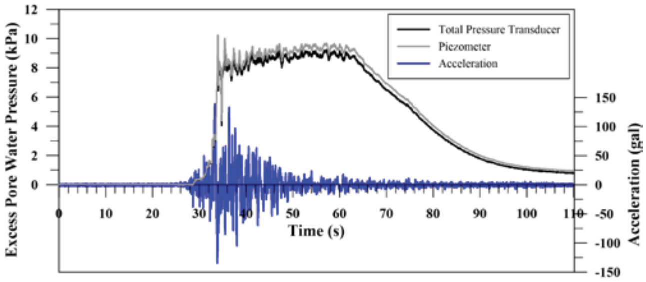

Fig. 5. Resultsfrom previous shaking table experiment

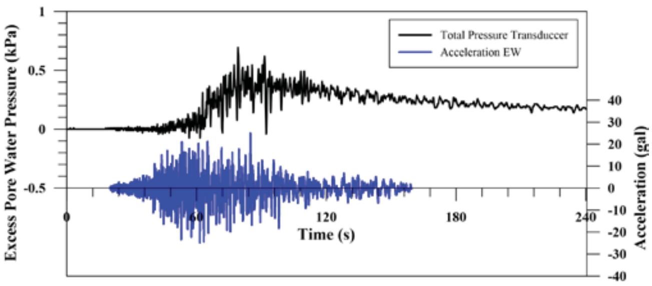

Fig. 6. Excess pore water pressure monitoring results at Dawan Elementary School during Hualien earthquake

5. Conclusion

This study developed a soil liquefaction monitoring system, which successfully detected the accumulation of excess pore water pressure responses during the 2024 Hualien earthquake, demonstrating its practical applicability. In the future, additional soil liquefaction monitoring stations should be established, and the monitoring results can serve as a reference for the Taiwan government in updating soil liquefaction potential maps.

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