Liquefaction Potential and Residual Deformation of Ground Behind a Wharf Pier with Minimal Damage Caused by the 2011 off the Pacific Coast of Tohoku Earthquake

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ABSTRACT: We conducted a sounding test using Piezo Drive Cone technology on ground behind a wharf pier subjected to the off the Pacific coast of Tohoku Earthquake. The ground improvement for liquefaction mitigation was carried out before the earthquake. The settlement of the ground due to the earthquake was measured. Survey of the liquefaction potential indicated that the factor of safety against liquefaction in the ground improvement for liquefaction mitigation was greater than 1. The data indicated that the wharf pier was slightly damaged. Although the ground behind the pier settled by 0.1 to 0.3 m as a result of the great earthquake, the wharf pier itself sustained minimal damage.

1 INTRODUCTION

The widespread liquefaction of reclaimed land and saturated loose sand deposits in old river channels throughout eastern Japan as a result of off the Pacific coast of Tohoku Earthquake caused enormous damage to residential homes and social infrastructure. However, no damage was observed to buildings in the areas where ground improvement for liquefaction mitigation was made prior to the disaster. Among the various methods of ground improvement for liquefaction mitigation which have been proposed, in this paper, the discussion will be focused on the excess pore pressure dissipation method.

The excess pore pressure dissipation method facilitates the flow of pore water into a drain by placing high drainage materials such as gravels and synthetic resin at regular intervals in the ground in order to prevent the excess pore pressure in rising (JGS (2004)). In the 2011 off the Pacific coast of Tohoku Earthquake, the quay walls in areas where ground improvement for liquefaction mitigation had been made were either not damaged at all or only slightly damaged (Unno et al (2014)). For instance, the periphery of Tokyo bay experienced no damage. In addition, the pier-type quay walls experienced minimal horizontal displacement and inclination at the Koyo wharf in Sendai-Shiogama port. This port, which was close to the epicenter, was beyond design expectation and it was reported that the ground behind wharf piers had settled by 15 cm. But this port were so robust, it was possible to ship in and deliver emergency supplies after earthquake.

Although, the excess pore pressure dissipation method is an effective method for averting liquefaction in the fields, settlement is inevitable. The mechanism of this settlement was studied in the laboratory using partially-drained cyclic shear tests. The soil element conditions among the drains were simulated. Based on experimental results, Sento et al (2013) proposed an estimation method of settlement associated with pore water pressure dissipation. It has been reported that increased density accompanied with settlement increased liquefaction strength (Saito et al (2013)).

Because detailed soil investigations are rarely conducted in cases of no damage or slight damage caused by an earthquake, the effect of improved ground cannot be verified.

Sounding tests using Piezo Drive Cone technology (PDC) were conducted in order to evaluate resistance against liquefaction in cases of ground treated by ground improvement for liquefaction mitigation and of untreated ground behind the quay walls at Sendai-Shiogama port. A summary of investigation and the results follow.

Fig. 1 Investigation site (Rivised Denshi Kokudo)

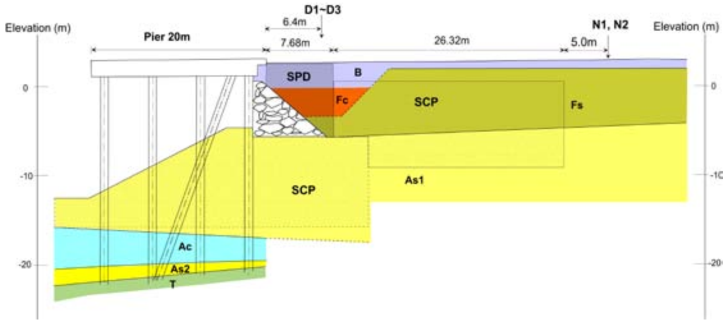

Fig. 3 Cross section of Koyo wharf (Construction area I)

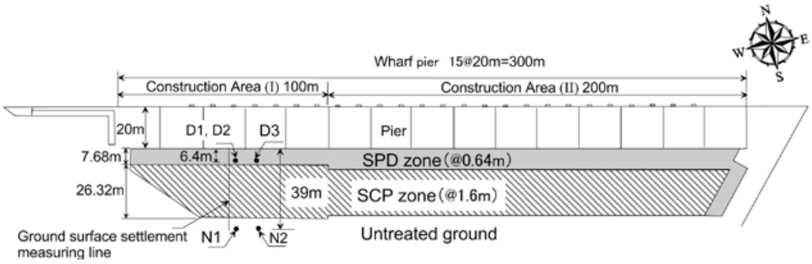

Fig. 2 Plan of Koyo wharf

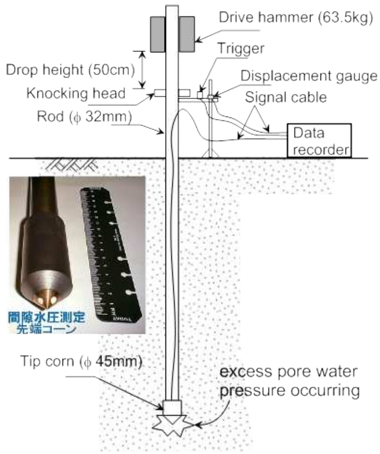

Fig.4 Schema of PDC (Rito et al 2010)

2 INVESTIGATION SUMMARY

2.1 *Investigation site*

The Koyo wharf is located in the south-eastern area of Sendai-Shiogama port, as shown in Fig. 1. The plan of the quay wall is shown in Fig. 2 and the cross section is shown in Fig. 3. The planned water depth of the quay wall is -12 m and the wharf pier is supported by a pile foundation. Ground improvement for liquefaction mitigation was carried out on the 34 m reclaimed land zone behind the wharf pier. Coal was unloaded and stocked at this wharf and at that time of earthquake, the pile of coal was 5 m or more in height.

This investigation was carried out at the Construction area I on the west side. The Spiral Drain Method (SPD), an excess pore water pressure dissipation method, was conducted on a zone estimated at 7.7 m from the end of the wharf pier. The Sand Compaction Pile Method (SCP) was conducted on the remaining zone. Different liquefaction mitigations were conducted because it was expected that SCP construction would have resulted in an increase in the earth pressure on the wharf pier. On the other hand, in the case of SPD construction, only a slight increase was expected in the earth pressure. The SPD method employs a polyethylene cylindrical drain (spiral drain) for drainage. Each drain was 10 cm in diameter and they were placed at 64 cm intervals. Countermeasure construction was completed in 1995.

The investigation was conducted in October 2013 in an area 6.4 m (D1~D3) and 39 m (N1 and N2) from the wharf pier. D1~D3 were located in the center between drains more than one meter away from the boundary between where the SPD and SCP methods were applied. N1 and N2 were the untreated ground 5 m from the boundary of the applied SCP method. The distance was decided in order to avoid the effect of increased earth pressure due to the SCP method.

2.2 *Investigation method*

A soil investigation was carried out using PDC and surface settlement measurement of the ground. The schema of the PDC, a testing method classified as Dynamic Cone Penetration Testing, is shown in Fig. 3 (Rito et al (2010)). The dynamic penetration resistance of the ground (the N_d value) was measured using PDC. The N_d value is almost same as N value obtained by Standard penetration test. Measurements of the excess pore water pressure occurring in the peripheral ground at the tip of the cone at the time of percussive penetration were taken to estimate the groundwater level and fine content (F_c) of the soil. PDC is an in situ test for the evaluation of safety factors against liquefaction (F_L value) which utilizes these measurement results (JGS (2013)). Because continuous penetration is used in this method, it is possible to take higher resolution measurements in depth direction those of standard penetration test. This makes it possible to investigate the sedimentary state of uneven ground in laminated strata and the alternation of strata.

The tip of the cone was 45 mm in diameter, the rod was 32 mm in diameter, the drive hammer was 63.5 kg, and the drop height was 50 cm in accordance with the DPH (Super Heavy) conditions in the ISO 22476-2 classification (JGS (2013)).

After considering the top end height of the wharf pier, the height of the asphalt pavement was measured at intervals of two meters for 40 m, as shown in Fig. 2.

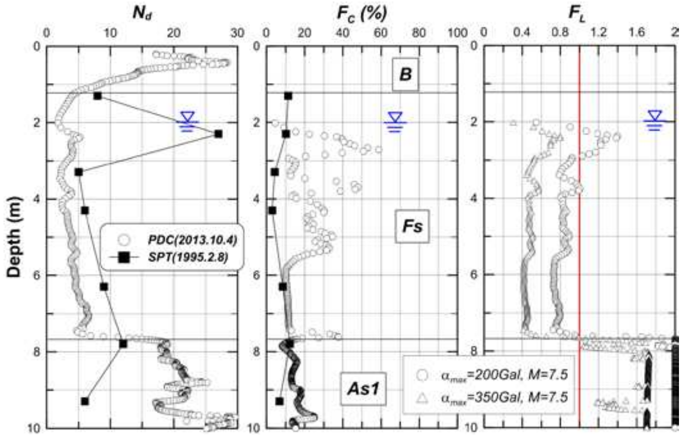

Fig. 5 Distribution of N_d value, F_c, and F_L value in untreated ground (N2)

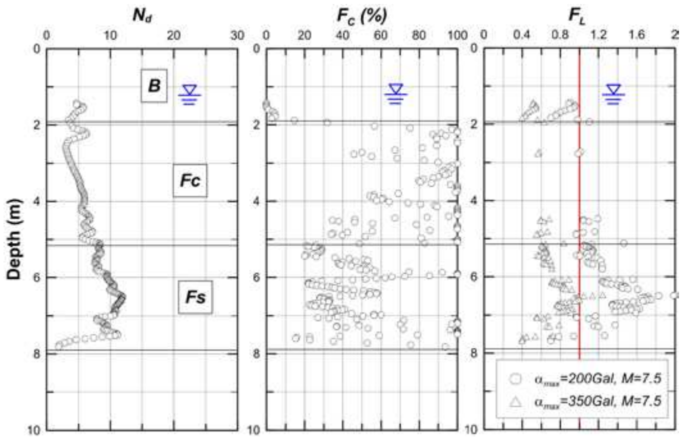

Fig. 6 Distribution of N_d value, F_c, and F_L value in treated ground (D3)

3 INVESTIGATION RESULTS

3.1 *Investigation results using PDC*

In this section, the soil profile and liquefaction potential in untreated and treated ground is discussed based on the results of the PDC investigation. The distribution of the measurements for the untreated ground is shown in Fig. 5. The F_L value was obtained by considering 200 Gal peak ground acceleration as a moderate earthquake and 350 Gal as a great earthquake and using the recommendations for the design of building foundations (AIJ (2001)). From the top to the bottom, the embankment soil was composed of sandy soil (Bs), reclaimed soil (sandy soil) (Fs), sandy soil in old seabed (As1). The groundwater level was about two meters. An N_d value of 5 or less for the reclaimed sand indicates that the reclaimed sand was loose. The fine content in the lower part of reclaimed sand was as low as 10%, while in the upper part, the fine content, F_c, was greater and fluctuation increased with depth. It is assumed that this F_c fluctuation was result of the classification of sediment under water at the time of reclamation or a change in the fraction of the fines fraction during the pore water pressure dissipation process after the earthquake. Since old seabed sand is considered sediment in the old beach ridge, it is denser than other soils. The factor of safety against liquefaction (F_L) is mostly less than one in reclaimed sand, indicating a high possibility of liquefaction occurrence. Therefore, it is assumed that severe liquefaction occurred in the 2011 the off the Pacific coast of Tohoku Earthquake. In addition, if a moderate earthquake occurs again, there is a high possibility of reliquefaction.

The measurements taken from the treated ground are shown in Fig. 6. The soil was composed of embankment (gravelly soil) (Bs), reclaimed soil (cohesive soil) (Fc), and reclaimed soil (sandy soil) (Fs) from the top. It should be noted that the fines fraction was significantly higher than that of the landfill materials. The distribution of F_c varied considerably in the depth direction. This tendency was also seen at D1 and D2 points about 10 m to the west. The N_d value obtained for the reclaimed soil (Fs) was approximately twice that of the untreated ground. In addition, because F_c was great, the value of F_L exceeded 1 in most depths in the case of a moderate earthquake, indicating a low likelihood of liquefaction occurrence. During the earthquake, settlement occurred as the pore water flowed into the drain, in effect increasing the density of the soil. While it is possible that the tsunami that followed the earthquake destroyed the evidence of liquefaction, and there is evidence of this occurring at several sites, there is no indication that liquefaction occurred at this site.

3.2 *Ground surface settlement*

The distribution of heights of the paved surface with regard to the height of the wharf pier end is shown in Fig. 7. The paved surface settled by about 30 cm at the observation point closest to the wharf pier end. Less settlement of the paved surface occurred as the observation point moved inland. When settlement exceeded 25 m, the result was upheaval. The height of the paved surface prior to the earthquake is shown in Fig. 8. There was a drainage slope from land to sea before the earthquake. In Fig.8, the two types of slopes (Type 1 and Type 2) represent the slopes in the design drawing of this wharf. Settlement of the ground, calculated based on the paved surface height before and after the earthquake, is shown in Fig. 9. The untreated ground settled by 0.1 to 0.2 m. Settlement of the treated ground was equal to or more than that of the untreated ground. The large amount of settlement in the SPD zone can be attributed to the movement of the wharf pier towards the sea, while the ground behind the pier settled during the earthquake.

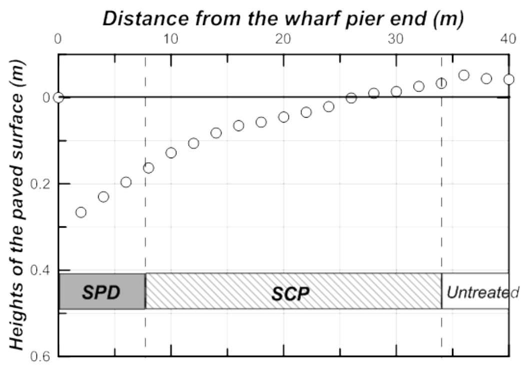

Fig. 7 Distribution of heights of the paved surface after the earthquake

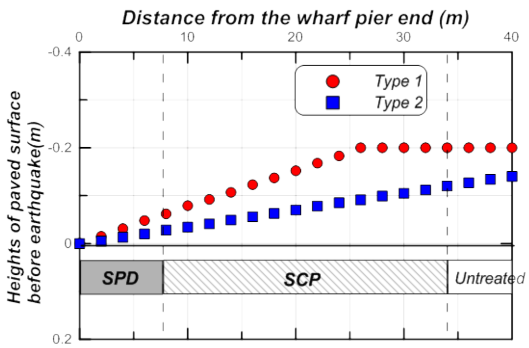

Fig. 8 Distribution of heights of the paved surface before the earthquake

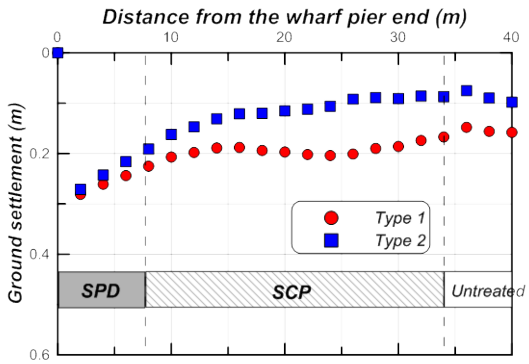

Fig. 9 Distribution of ground settlement due to the earthquake

4 CONCLUSIONS

A PDC sounding test was conducted and ground settlement measurements were taken on ground behind a wharf pier which subjected to the 2011 the off the Pacific coast of Tohoku Earthquake. The factor of safety against liquefaction in the treated ground was found to be greater than 1. The results show that the wharf pier was slightly damaged by the earthquake. The ground behind the pier was found to have settled by 0.1 to 0.3 meters despite ground improvement work to mitigate liquefaction. The wharf piers experienced less deformation due to ground improvement prior to the earthquake which had been carried out to mitigate liquefaction.

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