

EARTHQUAKE DAMAGE INVESTIGATION OF GRAVITY-TYPE QUAY WALLS IN IBARAKI PORT

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ABSTRACT: One of the most common used types of quay walls in Japan is gravity type with concrete caissons. A number of gravity-type quay walls have been constructed in Ibaraki Prefecture where huge ground motion occurred in the Great East Japan Earthquake of March 11, 2011. This paper reports on damage to gravity-type quay walls in the Port of Hitachinaka, which serves as a freight transport hub for the northern Kanto region.

Key Words: Gravity-type quay walls, gantry cranes, coarse-grained rock waste, steel pile foundation, strong motion

INTRODUCTION

One of the most common used types of quay walls in Japan is gravity type with concrete caissons. A number of gravity-type quay walls have been constructed in Ibaraki Prefecture where huge ground motion occurred in the Great East Japan Earthquake of March 11, 2011. The northern wharf area in the Port of Hitachinaka has two types of deep-water public quay walls for water depths of 12 m and 14 m. The port serves as a freight transport hub for the northern Kanto region and has large gantry cranes at the top of the quay walls to handle container cargo. The walls were constructed on the surface of a stiff sandy stratum and backfilled with coarse-grained rock waste to prevent liquefaction. The seaward foundations of the gantry cranes are installed on the caisson part, and the landward foundations are mounted in the top of steel piles.

The acceleration amplitude in the earthquake reached at least 5.6 m/s^2 (2E-waves on the engineering seismic base layer). Some damage was caused to the northern wharf area quay walls as a result of the strong motion, including subsidence in the backfilled ground. The caisson part of the walls was displaced seaward by up to 56 cm, and the residual relative displacement between the

seaward and landward crane foundations resulted in derailment damage to the crane wheels. However, the quay walls were not completely destroyed because the non-liquefiable soil material prevented liquefaction in the backfill ground. This paper reports on damage to these gravity-type quay walls in the Port of Hitachinaka.

SYNOPSIS OF QUAY WALLS IN HITACHINAKA PORT

This chapter gives a synopsis of the Port of Hitachinaka in Ibaraki Prefecture and discusses the cross-section surface of the gravity-type quay walls.

Location of Hitachinaka Port and plane arrangement of quay walls

Figure 1 shows the location of the Port of Hitachinaka in Ibaraki Prefecture and the quay walls examined in this study. Hitachinaka is near the epicentral area, and experienced considerable damage in the earthquake. The plane arrangement of the quay walls in the northern wharf area is also shown in Fig. 2. These walls supported operations at one of the busiest port facilities in the northern Kanto region until the earthquake occurred. They are equipped with large gantry cranes to handle container cargo.

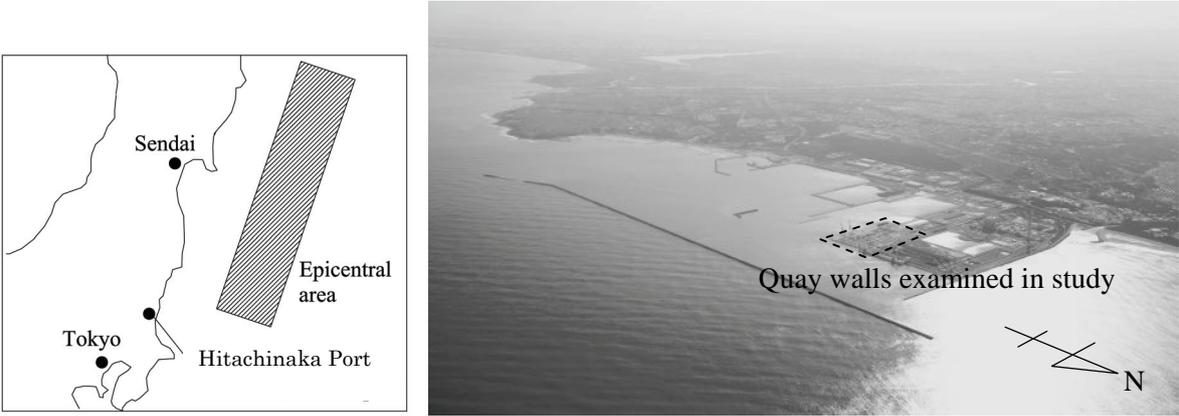


Fig. 1 Location of the Port of Hitachinaka in Ibaraki Prefecture

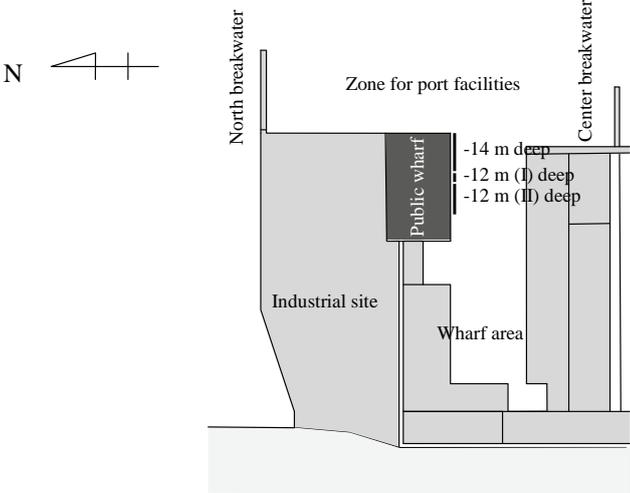
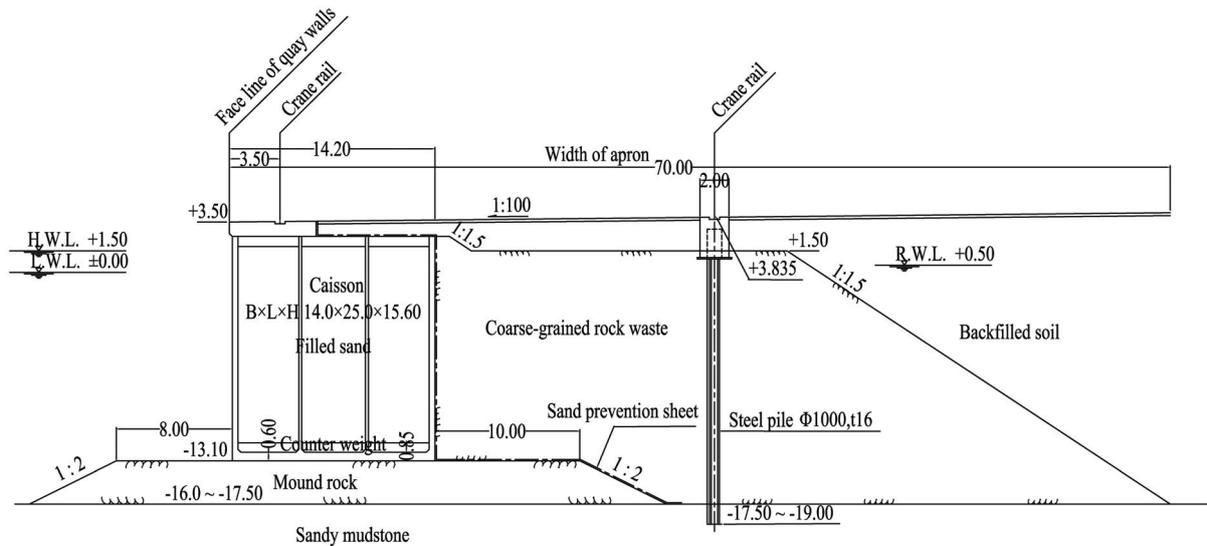


Fig. 2 Plane arrangement of quay walls in the northern wharf area

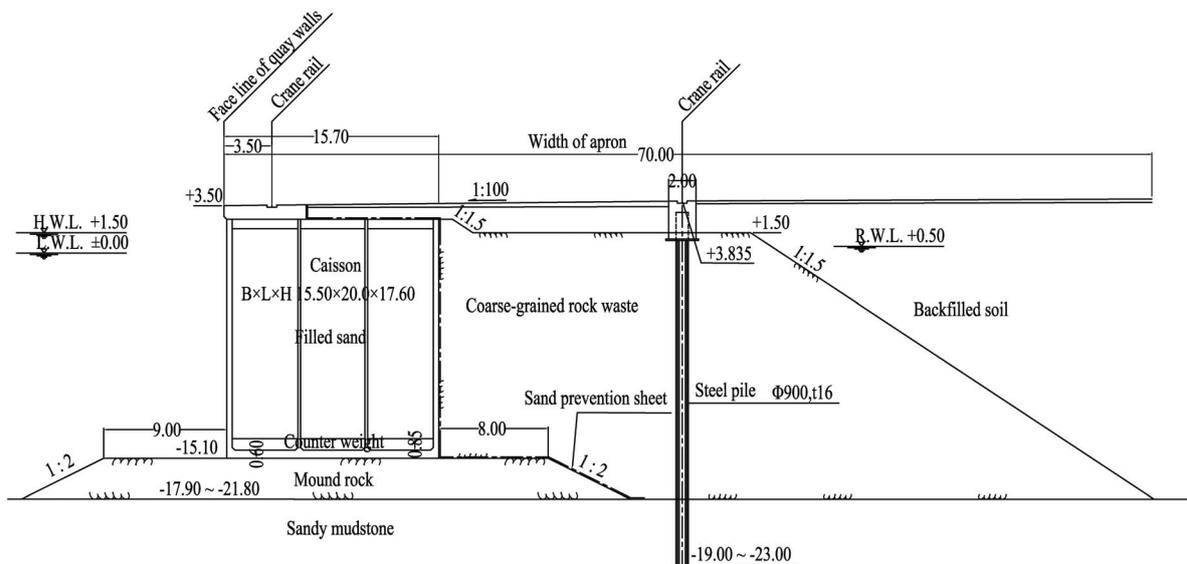
Cross-section of gravity-type quay walls

Figure 3 shows a cross-section of the gravity-type quay walls investigated in the study, which was intended to clarify damage to two walls for water depths of 12 m and 14 m with the same structure built using gravity-type caissons.

The walls were constructed on the surface of a stiff sandy stratum and backfilled with coarse-grained rock waste instead of the sandy and/or silty soil usually used as backfill material. Rock waste has the advantage of providing liquefaction resistance and reducing the earth pressure for caissons. The use of this coarse-grained rock waste was a specific feature of these quay walls. The seaward foundations of the gantry cranes are caisson-mounted, and the landward foundations are steel pile-mounted.



(a) -12 m (II) deep quay wall



(b) -12 m (I) and -14 m deep quay walls

Fig. 3 Cross-section of gravity-type quay walls in the northern wharf area

GROUND MATERIAL PROPERTIES

This chapter outlines the on-site ground strength as measured in SPT testing and the properties of the coarse-grained rock waste.

Ground conditions based on field survey

A standard penetration test (SPT) was conducted at the site to investigate strength distribution in the backfill ground consisting of coarse-grained rock waste. The N-values found from this test are shown in Fig. 4, which includes the N-values of sand as calculated using the method defined in the Japanese technical standards for port and harbor facilities (OCDI, 2009). It can be seen that the N-value of rock waste rose with increased depth, and that the values for the original ground were markedly larger than those of rock waste. The stiff sandy stratum was responsible for the large N-values of the original ground. Comparison of the N-values shows that the figure for sand (calculated as $\phi = 34^\circ$) was quite similar to that for rock waste.

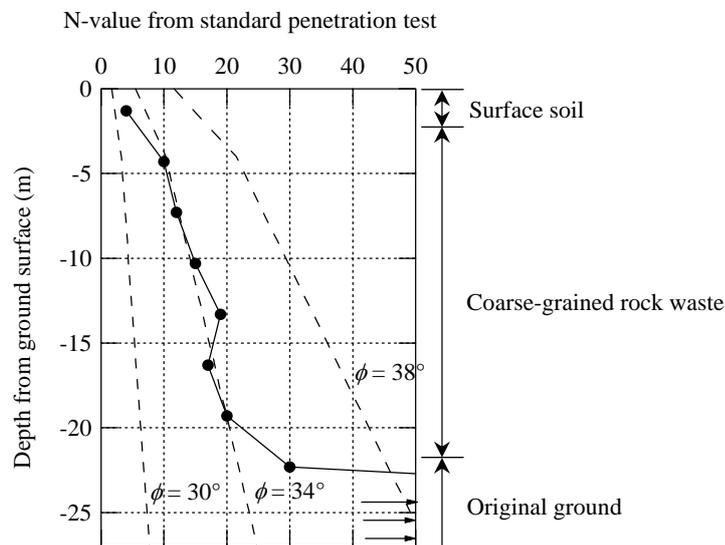


Fig. 4 SPT N-values in backfill ground of -14 m deep quay walls

Properties of coarse-grained rock waste

The coarse-grained metamorphic rock waste used in construction at the Port of Hitachinaka was mined in a mountainous area of Hitachi City in Ibaraki Prefecture, and its technical properties are summarized in Table 1. The unit weight of the waste was similar to that of the soil type normally used as backfill material.

Table 1 Technical properties of coarse-grained rock waste

Maximum grain size, D_{max}	300 mm
Average grain size, D_{50}	164 mm
Uniformity coefficient, U_c	35
Unit weight, γ_{sat}	20.4 kN/m ²
Compressive strength of original rock	117.2 N/mm ²

The grain size distribution of the rock waste used is shown in Fig. 5, which includes the typical range in which soil is known to liquefy readily (CDIT, 1997). The rock waste particles were large enough to non-liquefy due to the high permeability.

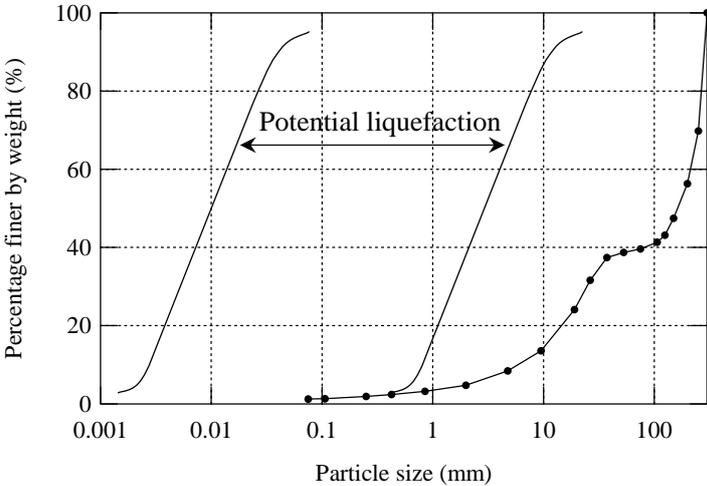


Fig. 5 Grain size distribution of rock waste

As the coarse-grained rock waste used in construction at the port was not tested to determine its shear strength, Fig. 6 shows the shear strength value for a similar type of weathered andesite rock waste mined in Hachinohe City, Aomori Prefecture. The figure shows the stress-strain curves obtained from consolidated-drained (CD) triaxial shear testing and the relationship between volumetric strain and shear strain. It can be seen that the initial stiffness was relatively low, and that the shear strain at the peak strength was high. In addition, only negative dilatancy can be seen within 15% shear strain. These characteristics can be attributed to the coarseness of the particles and the relatively low strength of soil particles. This negative dilatancy could result in significant subsidence if the ground is sheared by earthquake motion.

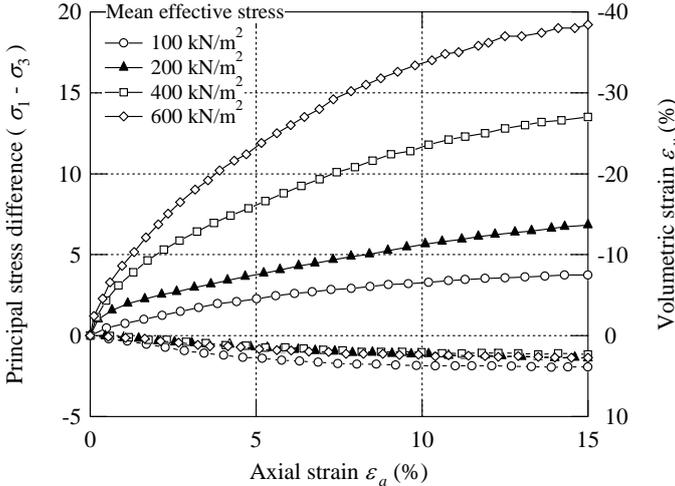
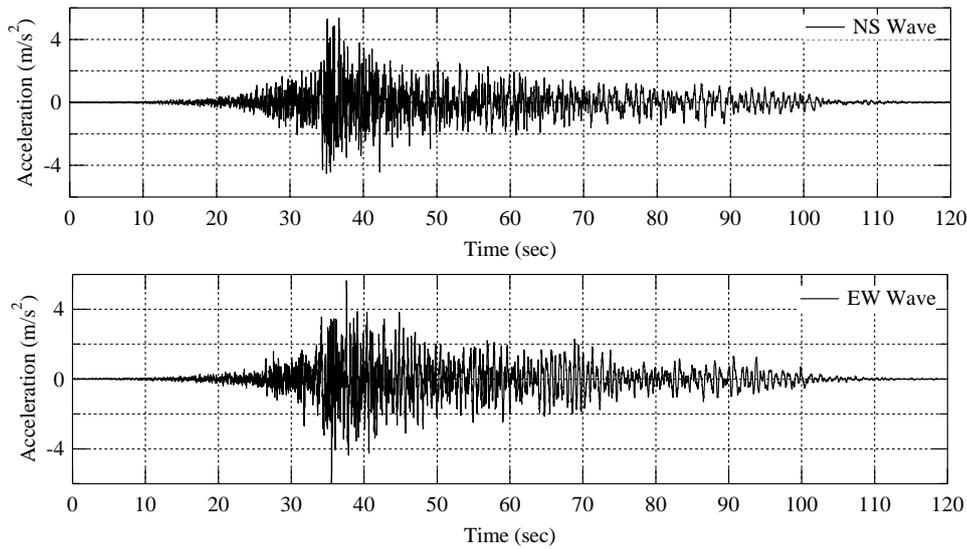


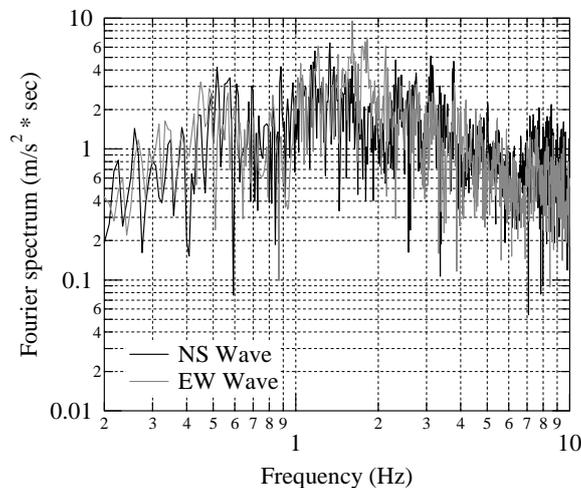
Fig. 6 Results of CD triaxial shear tests of coarse-grained rock waste

EARTHQUAKE MOTION IN HITACHINAKA PORT

As the strong-motion seismograph in the Port of Hitachinaka was destroyed by the tsunami, no ground motion waveform data are available. Accordingly, the waveform was simulated and recreated based on other waveforms recorded in the region (Hata *et al.*, 2011; Nozu and Nagao, 2005). Figure 7 shows the strong motion, which was calculated as a 2E-wave on the engineering seismic base layer. According to the waveform, the acceleration amplitude reached at least 5.6 m/s^2 .



(a) Ground motion waveform



(b) Fourier spectrum of ground motion

Fig. 7 Simulated and recreated earthquake motion

DAMAGE APPEARANCE

Photo 1 shows several instances of damage observed at the -14 m deep quay wall. The seaward caisson displacement was up to 56 cm, as shown in Photo 1 (a), and the different displacements of

each caisson created a concave-convex quay wall surface. This displacement also resulted in subsidence of at least 113 cm in the backfilled ground, as shown in Photo 1 (b). The residual relative displacement between the seaward and landward crane foundations resulted in derailment damage to the crane wheels, as shown in Photo 1 (c). However, the quay walls were not completely destroyed because the non-liquefiable soil material prevented liquefaction in the backfill ground.



(a) Seaward displacement of caissons



(b) Subsidence in backfilled ground



(c) Derailment of crane wheels

Photo 1 Damage of quay walls

DEFORMATION OF QUAY WALLS

The horizontal displacements of the caissons as measured in an on-site survey are shown in Fig. 8, in which negative values represent seaward displacement. In both quay walls, most of the caissons moved seaward except for those near the edge of a reclaimed area. The maximum horizontal displacement was 56 cm for the -14 m deep quay wall. The edge of the reclaimed area corresponding to the corner of the quay walls exhibited behavior different from that of the standard area.

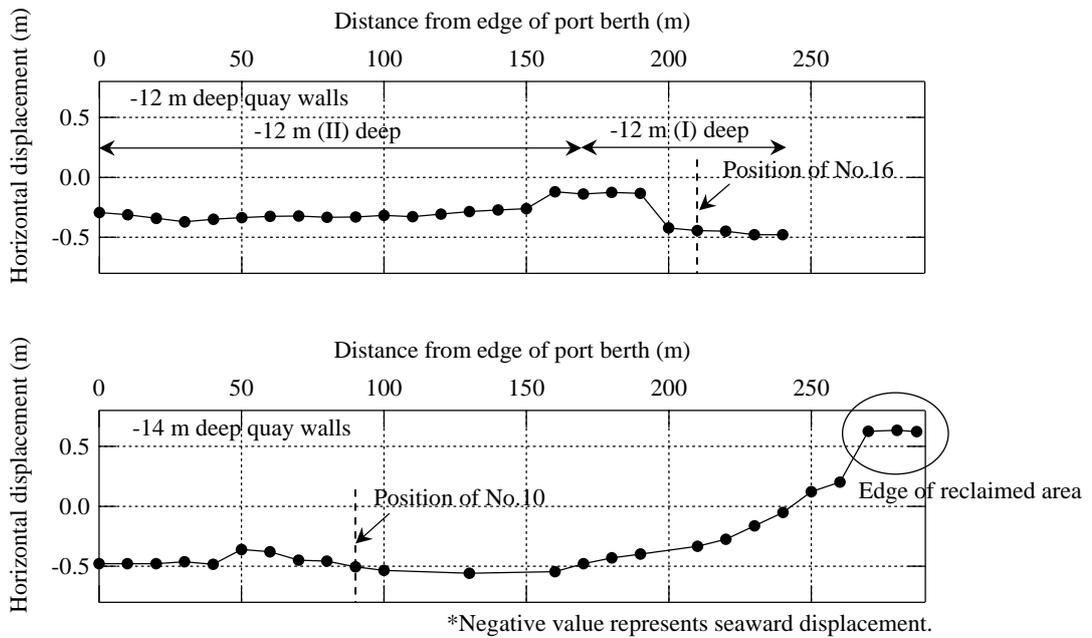


Fig. 8 Horizontal displacement of caissons

Figure 9 shows pre- and post-earthquake cross-sections of the -14 m deep quay wall. It illustrates only ground surface and caisson displacement because only measurement of surface displacement was conducted in the field. It can be seen that the incremental volume generated by caisson seaward movement was about 10.4 m^3 , and the decremental volume generated by backfill ground subsidence was about 25.0 m^3 . The volume balance resulting from these two values is 14.6 m^3 , indicating that the average volumetric strain of the backfill ground was not large.

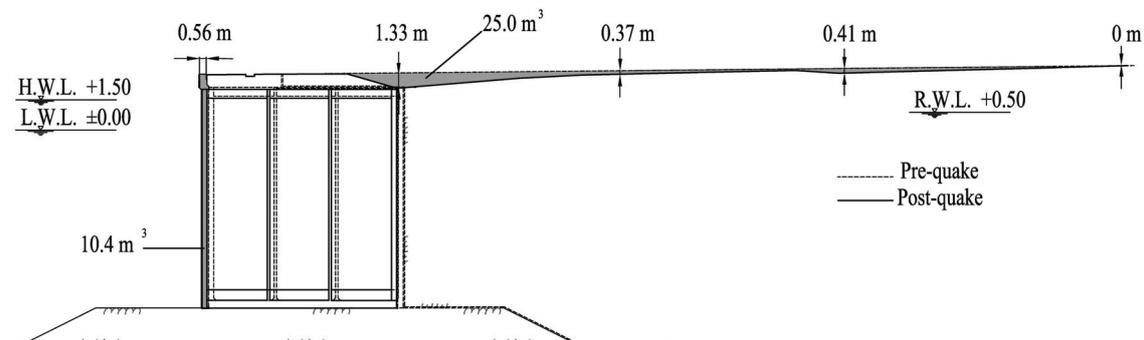


Fig. 9 Cross-section of pre- and post-earthquake

DEFORMATION OF STEEL PILE FOUNDATIONS

There is currently no established method for measuring the displacement of an inclined or bent steel pile. In this study, steel pile displacement was measured using the method shown in Fig. 10. First, an inclined pipe with relatively low stiffness was fitted into the steel pile with the aid of spacers. Then, a borehole inclinometer was inserted into the inclined pipe to measure its inclination. Finally, the horizontal displacement of the inclined pipe was calculated from the angle of integration. Its displacement was considered to be almost the same as that of the steel pile.

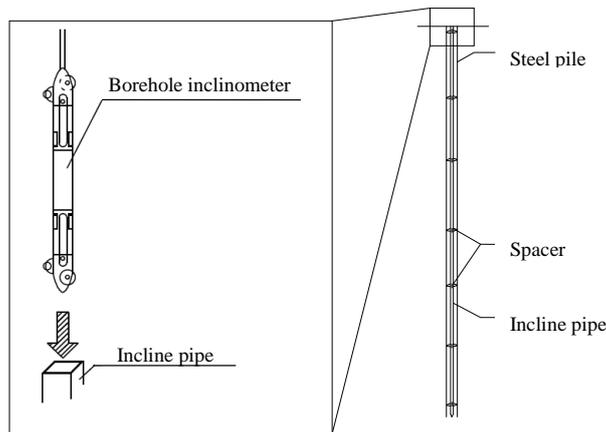


Fig. 10 Method for measuring horizontal displacement of steel pile foundation

The horizontal displacements of two representative steel piles are shown in Fig. 11, which indicates that the seaward displacements of the pile tops were 0.52 m and 0.63 m, and that the piles bent seaward from deep to shallow parts. The radius of the curvature calculated from the displacements shows that these piles reached their yield condition, indicating the need for replacement.

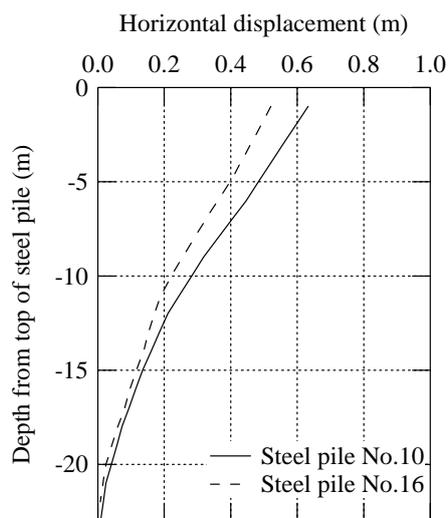


Fig. 11 Horizontal displacement of steel piles

CONCLUSIONS

This paper reports on damage to gravity-type quay walls in the Port of Hitachinaka. Quay walls subjected to strong earthquake motion in the northern wharf area experienced damage, including backfilled-ground subsidence and caisson displacement. The horizontal displacement of the walls caused the steel piles supporting the cranes to yield, and the residual relative displacement between the seaward and landward crane foundations resulted in derailment damage to the crane wheels. However, the quay walls were not completely destroyed because the non-liquefiable soil material used (coarse-grained rock waste) did not liquefy in the backfill ground. The volumetric strain of this rock waste was limited.

Restoration construction based on the previous structures is currently under way. Additionally, a series of shaking model tests and numerical analyses are planned to elucidate the mechanism of dynamic ground behavior and the damage process. In the near future, these surveys are expected to provide more information on the deformation behavior of gravity-type quay walls in the Port of Hitachinaka.

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