Instability on the sandy ground under breakwater due to earthquake and tsunami

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ABSTRACT

In 2011, the Great East Japan Earthquake occurred and it generated a long-period earthquake motion and tsunami. Many coastal structures were damaged with instability of the bearing ground under structure due to earthquake and tsunami. However, the mechanism of the earthquake-tsunami disaster for the coastal structure has not yet been completely revealed. This paper focused on the destabilization of breakwater due to an earthquake and a tsunami. Additionally, destabilization of a breakwater due to earthquake motion and liquefaction were examined using a soil-water coupled finite element analysis based on the elasto-plasticity constitutive equation and tsunami simulation was calculated by using the particle method. In the case of a complex disaster caused by a huge earthquake followed by tsunami, when the earthquake includes long-period motion on a breakwater for a long time, the excessive pore water pressure was generated in the sandy ground and consequently liquefaction occurred. As the result, the breakwater was settled. Therefore, tsunami will overflow on the breakwater. Next, we investigated stability of breakwater that received tsunami force after the earthquake acted. The margin of bearing capacity on the breakwater was loss by the decreasing of strength in the sandy ground due to tsunami seepage when tsunami acted on it. Moreover, we discussed on the performance of the breakwater by use of numerical simulation result of tsunami flood depth in the land with damage level of the breakwater.

Keywords: earthquake, tsunami, breakwater, bearing capacity failure, liquefaction

1 INTRODUCTION

Many coastal structures are damaged when the huge tsunami acted. Despite studies on such events, the mechanism by which tsunami disasters damage coastal structures has yet to be thoroughly explained. The establishment of countermeasures for minimizing risk and the elucidation of the damage mechanisms of tsunamis are urgently required. To these ends, we examined the destabilization of caisson type breakwaters upon tsunami-induced damage to the seabed. In the experiments, drum-type centrifuge model testing and a numerical simulation were conducted (Miyake et al., 2009; Imase et al., 2011a, 2011b). The results show that shear deformation was localized; that is, when a tsunami wave was applied, slippage occurred under the simulated breakwater from its center to the toe structure of a rubble mound by way of the seabed (Photograph 1). The increment in excess pore water pressure (EPWP) was measured, and sand blowout from the mound by rapid tsunami seepage was observed around sliding zones at the same period at which the local shear deformation occurred. The tsunami-induced soil seepage brought the fluidization and reduced the bearing capacity of the breakwater.

Photograph 1 Breakwater deformation due to tsunami

In the current work, we examined the instability of a breakwater under a scenario of external actions; that is, under conditions wherein the earthquake settled down, gravity effects occurred and a tsunami generate. Seismic responses, liquefaction, and self-weight were in-
vestigated by soil–water coupled finite element (FE) analyses using an elasticity–plasticity model: DUBLEAVES. Then, the breakwater damage due to the tsunami was examined by the smoothed particle hydrodynamics (SPH) method. To evaluate the performance of the breakwater, we analyzed the margin of bearing capacity.

2 INSTABILIZATION OF THE BREAKWATER DUE TO EARTHQUAKE

2.1 Analysis condition

We investigated the instability of the seabed under a breakwater during an earthquake. The seismic response analysis was tentatively calculated using an FE analysis code developed by Zhang et al. (2007). Figure 1 and Figure 2 shows the schematic of the calculated sections for a typical caisson breakwater: Type-A, and a concrete-block breakwater: Type-B. With regard to boundary conditions, displacements in the x- and z-directions were applied at the bottom of the breakwater, and displacement in the z-direction was projected onto the side of the breakwater for static analysis. For dynamic analysis, the deformations of the bottom and side boundaries were fixed in the x- and z-directions. In particular, the side boundary was assumed an equal-displacement boundary. With regard to hydraulic conditions, the bottom and side of the breakwater were assumed to possess an undrained boundary, whereas the surface was assumed to possess a drained boundary.

The parameter As layer was assumed to be a loose sand layer, and the Ac layer was assumed a loose clay layer. The values of the analytical parameters were determined on the basis of previous analytical examples; one of typical materials, Toyoura-sand and Fujinomori-clay, was employed in the analysis of the hydraulic conditions. A caisson, a concrete block and a rubble mound were assumed elastic.

We used two-type wave profiles as the input earthquake motions, one of which was the waveform of a presumed trench-type earthquake presented by Prof. Masata Sugito of Gifu University (Figure 3(a): EQ-Case1). Otherwise, we used the waveform of a presumed Tokai-Tonankai earthquake presented before the 2011 by Central Disaster Prevention Council in Japan (Figure 3(b): EQ-Case2).

![Figure 3 Input waves](image)

2.2 Results and discussions of earthquake motion analyzed

Figure 4 shows the distributions of EPWP ratio after earthquake motion was applied. The earthquake produced EPWP in the sand layer, and liquefaction occurred in the sandy ground where the load exerted by the weights of the caisson and rubble mound was small in type-A and type-B breakwater. It was also generated the excess pore water pressure in the clay layer. About the type-A breakwater, the high EPWP ratio persisted for a long period, thereby causing in-stability in the seabed. This tendency was observed in both EQ-Case1 and EQ-Case2. About Type-B, the EPWP in sandy ground was dissipated with time. The EPWP in clay layer was persisted for a long period as with the type-A.

Figure 5 shows the time history of the subsidence of the caisson crown. Even after earthquake motion, the
After the earthquake motion
90 minutes after the earthquake motion

(a)

Figure 4 Distribution of the excess pore water pressure ratio in the seabed with earthquake subsidence continued. Extending to about -1.18m in Type-A and about -0.759 in Type-B.

3 INSTABILIZATION OF THE BREAKWATER DUE TO EARTHQUAKE AND TSUNAMI

3.1 Analysis condition
The SPH method is a Lagrangian and particle-based continuum method originally developed by Gingold and Monaghan (1977) and Lucy (1977) in the field of astrophysics to solve galaxy motion.

One of the authors attempted to adapt the method to the geotechnical field with soil–fluid coupling (Maeda and Sakai, 2004, 2010; Maeda et al., 2006). Under this approach, the physical quantity \( f(x') \) of a marked particle element at center \( x \) (position vector) is calculated by interpolating the physical quantity \( f(x') \) of a particle element \( x' \) within the area of influence by using smoothing function \( W \):

\[
\langle f(x) \rangle = \int f(x')W(x-x',h)dx'
\]

where \( h \) is an effective radius. The discretization of a finite number (\( N \) is the number of total particles) of particle elements is considered.

In this study, the soil is a material made up of soil skeleton, water, and air. Therefore, soil–fluid coupling was expressed in the SPH method by separately calculating a soil phase and a fluid phase that consists of water and air in each layer. The stress–strain behavior and pore water pressure in the soil and the analytical configuration that was distorted by the earthquake calculated by FE were incorporated into the initial conditions of the SPH simulation.

3.2 Results and discussions of earthquake and tsunami analyzed
The time history of breakwater instability due to a tsunami after an earthquake was investigated by observing the margin of bearing capacity; this margin was determined by calculating the difference between external action force and bearing capacity. Bearing capacity was calculated by using the simple Bishop’s method, which is widely employed in bearing capacity analysis as a design standard in Japan.

The effects of the residual EPWP in the seabed and the subsidence due to earthquake–liquefaction, the EPWP induced by seepage into the soil, and the overflow caused by tsunami damage to bearing capacity were individually considered. The tsunami flow was
generated by a dam break 90 minutes after the earthquake. Table 1 shows the analysis cases. $\Delta h$ mean an initial water difference by dam-break. About the calculation of bearing capacity, we considered the change of seabed strength by an earthquake and tsunami seepage.

Figure 6 shows the time histories of the margin of bearing capacity of the breakwater due to tsunami after the earthquake acted; Cases 1-6, 1-3-1, and 1-3-2: (a) and Cases 2-1 and 2-2: (b).

4 CONCLUSIONS

This paper discussed the stability of the caisson-type breakwater and the concrete-block type breakwater due to an earthquake and a tsunami. The breakwater instability due to earthquake-tsunami events was elucidated by focusing on the interactions among tsunami waves, caisson structures and seabed. A breakwater becomes unstable not only because of wave pressure, but also because of seepage and overflow into soil. These problems, in turn, weaken or destroy the bearing capacity of soil, where the increment in EPWP induces fluidization/liquefaction. Moreover, liquefaction due to earthquake motion before tsunami occurrence exacerbates breakwater instability; in such cases, a disaster is strongly influenced by the mode and severity of damage. The simulation results qualitatively indicate that breakwaters can withstand such damage. Simulations are highly beneficial in that they enable researchers to forecast the damage caused by earthquake–tsunami events.

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