Comparison of Pile-type and Gravity-type Coastal Levees in Terms of Resilience to Tsunami

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ABSTRACT

In the Great East Japan Earthquake in 2011, many tide barriers and breakwaters collapsed due to the tsunami. On the other hand, one structure consisting of double sheet pile walls remained almost undamaged. This paper introduces a newly developed experimental apparatus called 'Tsunami Simulator', in which two types of tsunami, surge and reflux, can be simulated to investigate into the behavior of structures a part of which is embedded in the ground. It also summarizes the result of the adequately scaled model test on the behaviors of gravity-type and pile-type levees, when they are hit by surge-type tsunami. The test results showed that the pile-type levee remained resilient to tsunami while the gravity-type levee failed by sliding. This result demonstrates the effectiveness of the use of piles to improve the resilience of structures. On the other hand, the specification of piles should be adequately determined in design to assure the resilience of the system. It would be reasonable to allow some plastic deformation of piles, which cannot be adequately scaled in the model test, especially when a huge tsunami has to be considered.

Key words: *Coastal levee, Pile, Tsunami, Model test, SPT*

1. Introduction

The Press-in Method is one of the piling techniques that use a static jacking force to install prefabricated piles. In this method, a piling machine gains a reaction force from the previously installed piles, and therefore, a wall of piles is efficiently constructed without bulky weights that will occupy a large space, as shown in **Fig. 1**.

The structures with piles, where appropriate embedment depths are assured to make use of the strength and stiffness of the soil, are expected to show a greater resistance and higher resilience to the external loads on themselves. As shown in **Fig. 2**, gravity-type coastal levees without an adequate embedment depth were observed to have collapsed, while a pile-type structure was found to have remained without significant damages (Furuichi *et al.*, 2015), after the overflowing tsunami associated with the Great East Japan Earthquake in 2011.

The effectiveness of structures with piles demonstrated in these incidents had already been noticed before 2011, and efforts have been made to promote these structures by naming them 'implant structures' (Kitamura, 2017). A typical example of the results of these efforts, as reported by Ishihara *et al.* (2018), is the construction of coastal levees with piles along the Kochi Coast which is

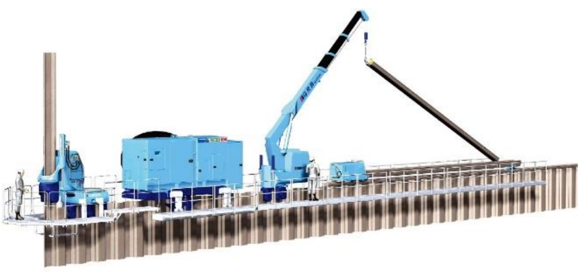


Fig. 1 Press-in piling system saving temporary works.

(a) Gravity-type levee.

(b) Pile-type structure.

Fig. 2 Different resilience to tsunami observed in 2011.

expected to be hit by a huge tsunami associated with an earthquake with a moment magnitude of 9.0 in the Nankai Trough (Cabinet Office, Government of Japan, 2012). Further activities have been carried out to investigate the effect on mitigating tsunami load of a breakwater with piles and porous fibers (Suzuki *et al*., 2016a) and a breakwater with arrays of piles (Suzuki *et al*., 2016b), using a model test apparatus that can simulate tsunamis.

This paper introduces the specification of the model test apparatus to simulate tsunamis, and reports the result and interpretation of a model test to compare the resilience against tsunami of gravity-type and pile-type coastal levees.

2. Text apparatus – 'Tsunami Simulator'

2.1. Specification of the test apparatus

The general view of the 'Tsunami Simulator' test apparatus is shown in **Fig. 3**. The apparatus consists of a surface tank for storing water, a gate, a channel, a soil tank for placing a model ground with model structures, an underground tank for storing water, pumps, a control board for operating the pumps and a measurement room for placing devices such as PCs and data loggers. The channel has a length of 19.5m, a width of 1.5m and a depth of 0.8m. The soil tank has a length of 1.5m, the same width as the channel and an additional depth of 0.5m below the bottom of the channel. The capacities of the surface tank and the underground tank are 40 and 110 cubic meters

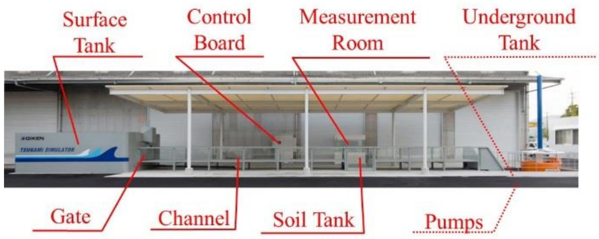
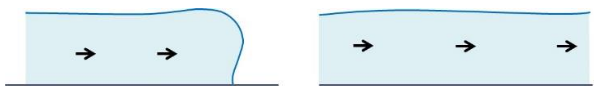


Fig. 3 General view of 'Tsunami Simulator'

respectively. The maximum flowrate of the pumps is 40 cubic meters per minute.

2.2. Types of model tsunami

In this test apparatus, two types of model tsunami can be generated, as shown in **Fig. 4**. One is a surge-type model tsunami, simulating the front part of tsunamis. This can be generated by accumulating water in the surface tank and opening the gate instantaneously. The length of the channel is designed so that appropriate values of Froude Number can be attained at the position of the soil tank. The other is a reflux-type model tsunami, simulating the continuous flow in the body of tsunamis. This can be generated by leaving the gate open, accumulating water in the underground tank and running the pumps continuously to maintain a constant flowrate.



(a) Surge-type (b) Reflux-type

Fig. 4 Model tsunami simulated in Tsunami Simulator.

3. Method of model test

3.1. Specifications of models of coastal levees

Two models of coastal levees were prepared, with a scale of 1/33. One is a gravity-type coastal levee as shown in **Fig. 5**, with a height of 11m and a weight of 980kN/m in a prototype scale. The other is a pile-type coastal levee as shown in **Fig. 6**, with an embedment depth of 16m, a height of 11m, outside diameter of 1.0m and thickness of 22mm at prototype scale.

The two models were placed side by side, with an acrylic plate sandwiched between the two models to separate the flow of the tsunami around the two levees.

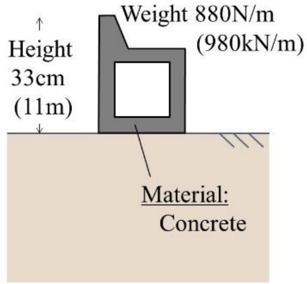


Fig. 5 Gravity-type model coastal levee.

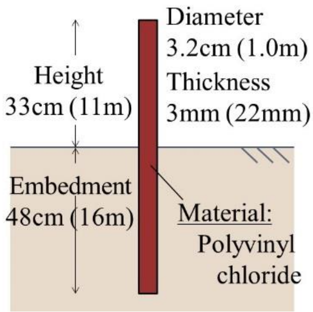


Fig. 6 Pile-type model coastal levee.

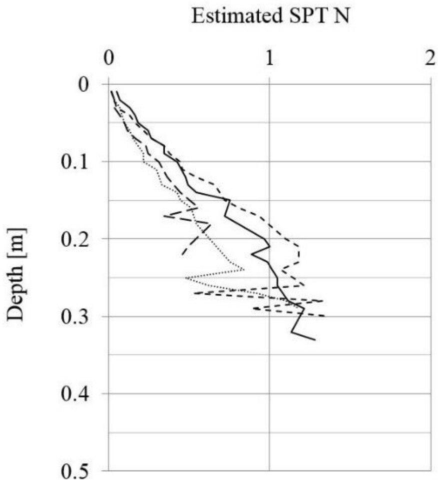


Fig. 7 Estimated SPT *N* of the Model ground.

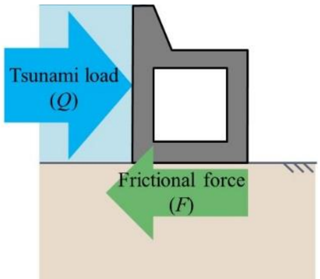


Fig. 8 Horizontal forces acting on a gravity-type levee.

3.2. Properties of model tsunami and model ground

A surge-type model tsunami was adopted in the model test. The flow velocity and the wave height were controlled to be from 10 to 15m/s and around 4m in a prototype scale, respectively.

The model ground was made of saturated crushed stones (#7), with the particle size being approximately 2.5mm to 5mm. A Cone Penetration Test (CPT) was conducted in the model ground, and SPT *N* values, which are more familiar to the Japanese engineers, were estimated from the CPT results based on the method proposed by Jefferies & Davies (1993), as shown in **Fig. 7**.

3.3. Scaling laws

Fig. 8 shows the horizontal forces acting on the gravity-type levee. The load of tsunami Q and the frictional force at the bottom of the levee F are expressed as:

$$Q = \frac{1}{2}\rho_{\mathrm{w}} g h^2 \tag{1}$$

$$F = \mu \rho_{\mathrm{c}} V_{\mathrm{c}} \tag{2}$$

where ρ_{w} is the density of water, g is the gravitational acceleration, h is the height of the levee, μ is the coefficient of friction at the bottom of the levee, ρ_{c} is the density of a concrete and V_{c} is the volume per unit horizontal depth of the body of the levee. Taking the scale as λ, both of Q and F are proportional to λ^2, since g, ρ_{w} and ρ_{c} are identical in a prototype scale and in the model test. Therefore, the equilibrium of horizontal forces can be said to have been adequately scaled in this model test.

Fig. 9 shows the horizontal forces acting on the pile-type levee. The passive and active earth pressure acting on the pile wall (P_{p} and P_{a}) are expressed as:

$$P_p = \frac{1}{2} K_{\mathrm{p}} \rho_{\mathrm{s}} g l^2 \tag{3}$$

$$P_a = \frac{1}{2} K_{\mathrm{a}} \rho_{\mathrm{s}} g l^2 \tag{4}$$

where K_{p} and K_{a} are the coefficients of passive and active earth pressure, ρ_{s} is the density of the ground and l is the embedment depth of the pile wall. Taking the scale as λ, and assuming that K_p and K_a are identical in a prototype and in the model test, the three forces (Q, P_p, P_a) are proportional to λ^2, considering that g, ρ_w and ρ_s are identical in a prototype scale and in the model test. Strictly speaking, however, K_p and K_a are dependent on the stress through the internal friction angle (φ). At smaller stress level, φ is larger, and therefore K_p is larger and K_a is smaller. Therfore, the small scale model will be more stable than the prototype.

Regarding the deformation of the pile wall, it is convenient to separate the pile wall into two, at the level of the ground surface. **Fig. 10** (a) shows the deformation of the pile wall above the ground surface, assuming it to be a cantilever fixed to a rigid ground. The horizontal displacement at the level of loading (δ_1) is expressed by the horizontal load (P), wall height (h), the Young's modulus and the second moment of area of the pile wall (E and I) as:

$$\delta_1 = \frac{Ph^3}{3EI} \tag{5}$$

Introducing subscripts 'p' and 'm' to represent the prototype and the model respectively,

$$\frac{\delta_{1p}}{\delta_{1m}} = \left(\frac{P_p}{P_m}\right)\left(\frac{(EI)_m}{(EI)_p}\right)\left(\frac{h_p}{h_m}\right)^3 \tag{6}$$

Considering $P_p/P_m = \lambda^2$ and $h_p/h_m = \lambda$, the scaling law can be satisfied if $(EI)_m/(EI)_p = \lambda^{-4}$. In this model test, the material for the model levee was chosen so that $(EI)_m/(EI)_p = \lambda^{-3.65}$, approximately satisfying the scaling law.

Fig. 10 (b) shows the deformation of the pile wall below the ground surface. If the embedment depth is great enough, the horizontal displacement of the pile wall at the ground surface (δ_2) can be expressed as (JGS, 2010):

$$\delta_2 = \frac{1+\beta h_0}{2EI\beta^3}P \tag{7}$$

$$h_0 = \frac{M}{P} \tag{8}$$

$$\beta = \sqrt[4]{\frac{k_H}{4EI}} \tag{9}$$

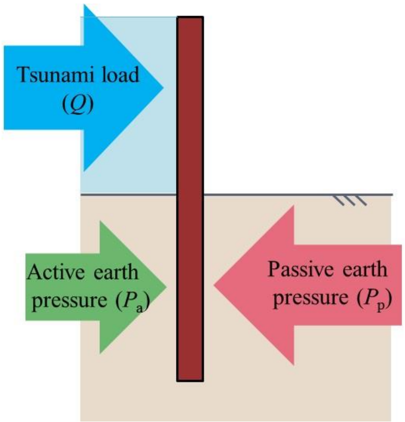
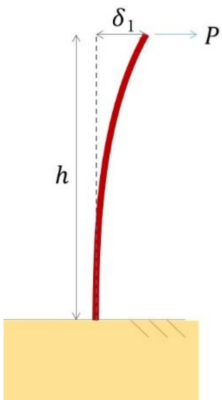
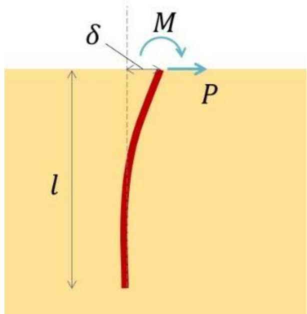


Fig. 9 Horizontal forces acting on a pile-type levee.



(a) Above the ground surface.



(b) Below the ground surface.

Fig. 10 Deformation of the pile wall.

where k_H is the horizontal subgrade reaction of soil. Therefore,

$$\frac{\delta_{2p}}{\delta_{2m}} = \left(\frac{(1+\beta_p h_{0p})\beta_m{}^3}{(1+\beta_m h_{0m})\beta_p{}^3}\right)\left(\frac{(EI)_m}{(EI)_p}\right)\left(\frac{P_p}{P_m}\right) \tag{10}$$

Considering $P_p/P_m = \lambda^2$, the scaling law is satisfied under the following condition:

$$\left(\frac{\left(1+\beta_p h_{0p}\right)\beta_m{}^3}{\left(1+\beta_m h_{0m}\right)\beta_p{}^3}\right)\left(\frac{(EI)_m}{(EI)_p}\right)=\lambda^{-1} \tag{11}$$

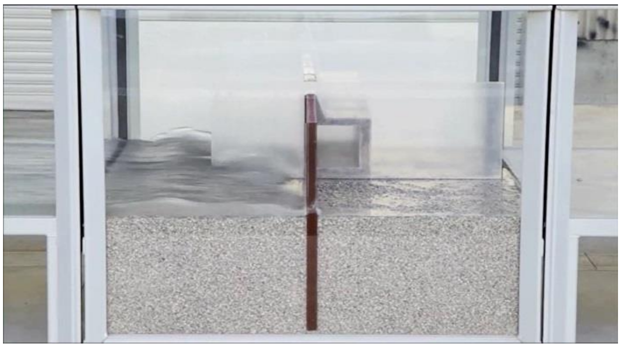
In this model test, the value of the left term of **Eq. 11** was adjusted as $\lambda^{-0.85}$, by assuming $k_{Hm} = k_{Hp}$, approximately satisfying the scaling law. Strictly speaking, k_{Hm} will be smaller than k_{Hp} due to the smaller stress level, and the deformation of the model levee will be larger than that of the prototype levee. Therefore, the model levee in this test can be said to have been safely scaled.

On the other hand, as it is difficult to scale the failure or the plastic deformation of piles, the specification of piles was determined so that the deformation of piles did not exceed their yield points both at model scale and prototype scale.

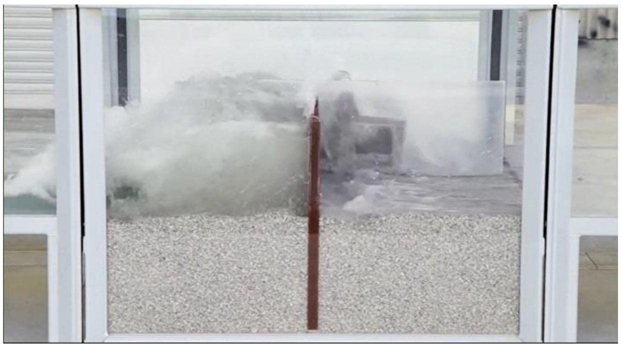
4. Results and interpretations

Fig. 11 shows the behaviors of the two model levees when they were hit by the model tsunami. Just after the gravity-type model levee was hit by the model tsunami (**Fig. 11** (a)), it slid (**Fig. 11** (b)) until arriving at the end of the soil tank, and then rotated around the edge of the soil tank (**Fig. 11** (c)). On the other hand, the pile-type model levee deformed slightly but retained its position and height (**Fig. 11** (d)).

For the gravity-type model levee, the sliding failure was caused by the greater horizontal load acting on the model levee compared with the frictional resistance at the bottom of the model levee. This failure has an engineering sense in this test, since the scaling laws are adequately satisfied as discussed in the previous section. Other mechanisms causing additional modes of failure, such as the insufficient bearing capacity of the model ground to resist to the moment load associated with the height of the acting point of the tsunami load, and the reduction of the bearing capacity of the model ground due to the liquefaction of itself, might have existed as well. These two mechanisms have less engineering sense in this test, as the scaling laws are not strictly satisfied. Considering that the sliding failure occurred before the failure of the model ground, the behavior of the gravity-type model



(a) When tsunami hit the model levees.



(b) Sliding of the gravity-type model levee.

(c) Rotation of the gravity-type model levee.

(d) Elastic deformation of the pile-type levee.

Fig. 11 Behavior of the model levees.

levee in this test can be said to have had an engineering sense in the early stage of its behavior before its rotation.

For the pile-type model levee, it is supposed that the earth pressure around the pile wall was effectively utilized to resist the horizontal and moment load due to the model tsunami. This point was adequately scaled in the test and can be expected for the pile-type levee in a prototype scale. Also, the elastic deformation of the pile wall in this test can also be scaled up to consider the elastic deformation of the pile wall in a prototype scale, as the bending stiffness of the pile wall satisfied the scaling laws. However, as discussed in the previous section, attentions must be paid to prevent the failure of the ground due to the scour and seepage when designing a real scale levee, which was ignored in this model test because of the difficulty in satisfying the scaling laws. In addition, the model test in this paper was conducted so that the deformation of the pile wall does not exceed its elastic limit, to avoid the issue of scaling in this viewpoint. Investigations should have to be made into the plastic deformation characteristics of the piles, as exemplified by Dobrisan (2016), when designing a pile-type levee against tsunamis with a substantial height, under which condition the plastic deformation of the piles might have to be allowed within the extent of assuring a required performance of the levee.

5. Conclusions

An experimental apparatus called ‘Tsunami Simulator’ was introduced, in which two types of tsunami, surge and reflux, can be simulated to investigate into the behavior of structures a part of which is embedded in the ground. The channel of this apparatus has the length of 19.5 meters and the width of 1.5 meters.

The behaviors of two models of coastal levees against tsunami, with the scale of 1/33, were compared. One was a gravity-type caisson structure with the weight of 1000kN per unit horizontal depth in a prototype scale. The other was a structure of a wall of piles whose diameter is 1m. Both levees had the height of 11m. Scaling laws were considered so that the essential behavior of these levees can be interpreted with an engineering sense.

The test results showed that the pile-type levee remained resilient to tsunami while the gravity-type levee failed with a mode of sliding. This result ensures the effectiveness of the use of piles to improve the resilience of the structure. On the other hand, the specification of piles should be adequately determined in design to assure the resilience of the system. It would be reasonable to allow some plastic deformation of piles, which cannot be adequately scaled in the model test, especially when a huge tsunami has to be considered.

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