Stability analysis of caisson type seawall against tsunami in comparison with model tests

Satoru Ohtsuka[1], Y. Fukumoto[1], H. Yamazaki[2], and K. Kaneda[3]

[1] Department of Civil & Envr. Eng., Nagaoka University of Technology, 1603-1, Kamitomioka, Nagaoka 964-2188, Japan.
[2] Port and Airport Research Institute, 3-1-1, Nagase, Yokosuka 239-0826, Japan.
[3] R&D Institute, Takenaka Corporation, 1-5-1, Otsuka, Inzai 270-1395, Japan.

ABSTRACT

In the 2011 Great East Japan Earthquake, many caisson type seawalls were damaged by the tsunami. The stability assessment of seawalls against tsunami is a current important issue in earthquake engineering. This paper applied the rigid plastic finite element method to the stability assessment of seawalls by taking account of seepage force in the mound which supported the seawalls. The applicability of the analysis method was systematically verified through the comparison with the centrifuge model tests conducted by the Port and Airport Research Institute. The applicability of conventional design method was also discussed through case studies.

Keywords: caisson type seawall; stability analysis; hybrid analysis method with seepage analysis; countermeasure

1 INTRODUCTION

In the Great East Japan Earthquake occurred in 2011, many caisson type seawalls were damaged by the tsunami. The characteristic of the seawall damage is not only the sliding of the caisson and mound system due to the water pressure applying to the caisson, but also the overturning of the caisson due to scouring of the mound caused by the overflowing waves. In addition, the ultimate bearing capacity of the mound is pointed out to decrease by the effect of seepage force in the mound induced by the difference in sea level between two sides of the caisson type seawall during the tsunami. As a reinforcement work for caisson type seawall, a widening of embankment has been proposed on the mound inside the port to retain the caisson against tsunami. With this countermeasure, it is possible to prevent the caissons from sliding off the mound and overturning even if a horizontal load due to the tsunami occurs. However, the analysis method to assess the stability of caisson has not been sufficiently established against the vertical/horizontal load caused by the tsunami and the influence of the seepage force.

This paper applied the rigid plastic finite element method to the stability assessment of seawalls against the vertical/horizontal load by taking account of seepage force in the mound. The applicability of the analysis method was systematically verified through the comparison with the centrifuge model tests conducted by the Port and Airport Research Institute (Takahashi et al., 2015a & b). The applicability of the conventional design method was also examined through case studies by the comparison of model tests and numerical simulations.

2 ANALYSIS METHOD

This study applies the rigid plastic finite element method (RPFEM) for the analysis method. The features of RPFEM include 1) direct analysis of the limit state of the structure, 2) ground constants necessary for the analysis are strength constants only, 3) initial stress of structure is unnecessary and it reduces the uncertainties in analysis constants, 4) pre-assumption for possible failure mode is unnecessary. Thus, it is simple and easy handling, it is applicable to wide use in practice.

RPFEM has been developed in the field of plastic processing in mechanical engineering. The rigid plastic constitutive equation was developed for the metal and applied to deformation analysis. In geotechnical engineering, RPFEM was developed by Tamura to assess the stability of earth structure based on the upper bound theorem in the limit analysis (Tamura et al. 1990). He derived the rigid plastic constitutive equation for soil and proved that the stability analysis with the rigid plastic constitutive equation coincided with RPFEM developed based on the upper bound theorem.

Eq. (1) is the Drucker-Prager yield function for the soil as the friction material. The effective stress is employed to consider the coupling analysis with the pore water pressure in the soil. The parameters, ω and ψ are the correlated with the strength parameters, c' and ϕ' of the soil. $I_1{}'$ is the first invariant of the effective stress and J_2 is the second invariant of the deviator stress as shown in the equation.

$$f(\boldsymbol{\sigma}') = \omega I_1' + \sqrt{J_2} - \psi = 0$$

$$where\ \ I_1' = tr(\boldsymbol{\sigma}')\ \&\ J_2 = \frac{1}{2}\boldsymbol{s}:\boldsymbol{s} \qquad (1)$$

Ohtsuka et al. (Hoshina et al. 2010; Yagi et al. 2010) developed the following rigid plastic constitutive equation for the Drucker-Prager yield function where κ and $\dot{\varepsilon}_v$ is the penalty constant and the volumetric strain rate. $\dot{e} = \sqrt{\dot{\boldsymbol{\varepsilon}}:\dot{\boldsymbol{\varepsilon}}}$ indicates the equivalent strain rate which implies the norm of strain rate. The second term of the equation is determined by solving the boundary value problem in consideration of equilibrium equation.

$$\boldsymbol{\sigma}' = \frac{\psi}{\sqrt{3\omega^2+1/2}}\frac{\dot{\boldsymbol{\varepsilon}}}{\dot{e}} + \kappa\left(\dot{\varepsilon}_v - \frac{3\omega}{\sqrt{3\omega^2+1/2}}\dot{e}\right)\left\{\boldsymbol{I} - \frac{3\omega}{\sqrt{3\omega^2+1/2}}\frac{\dot{\boldsymbol{\varepsilon}}}{\dot{e}}\right\} \qquad (2)$$

When the stress of the soil is inside the yield function, the stress described by the constitutive equation of Eq. (2) is indeterminate because the soil provides no displacement velocity. In the case of the equivalent strain rate is smaller than the threshold value of $\dot{e_o}$ which is set very small, the constitutive equation is provided by the following equation in which the equivalent strain rate, $\dot{e}$ in the denominator is replaced by $\dot{e_o}$ to avoid the division by zero. This equation manages to express the stress inside the yield function by $\dot{e}/\dot{e_o}$ the magnitude of which is less than unity.

$$\boldsymbol{\sigma}' = \frac{\psi}{\sqrt{3\omega^2+1/2}}\frac{\dot{\boldsymbol{\varepsilon}}}{\dot{e}_o} + \kappa\left(\dot{\varepsilon}_v - \frac{3\omega}{\sqrt{3\omega^2+1/2}}\dot{e}\right)\left\{\boldsymbol{I} - \frac{3\omega}{\sqrt{3\omega^2+1/2}}\frac{\dot{\boldsymbol{\varepsilon}}}{\dot{e}_o}\right\}$$

$$where\ \ \frac{\dot{\boldsymbol{\varepsilon}}}{\dot{e}_o} = \left(\frac{\dot{e}}{\dot{e}_o}\right)\frac{\dot{\boldsymbol{\varepsilon}}}{\dot{e}}\ \ \&\ \ \frac{\dot{e}}{\dot{e}_o} < 1 \qquad (3)$$

Stability analysis with this constitutive equation is implemented by the hybrid method with the seepage analysis, in which the pore water pressure distribution in soil is specified against the hydraulic boundary condition.

3 NUMERICAL SIMULATION

3.1 Centrifuge model tests by Port and Airport Research Institute

Takahashi et al. (2015a) conducted a series of centrifuge model tests on caisson type seawall to investigate the ultimate horizontal resistance of caisson under various seepage conditions of the mound. In Case A, the water levels of both sides of caisson were set same while they were set different in Case B. The ultimate horizontal resistance of the caisson was surveyed for the prescribed water levels, respectively. It was obtained as 3,740*kN/m* in Case A and 3,144 - 3,363*kN/m* in Case B. In Case B, the ultimate horizontal resistance wasn't obtained exactly in the model test, but shown to exist in the specific extent. The failure pattern was observed that the mound underneath the caisson displaced downward toward the downstream and the wedge and sliding line was formed in the mound. In the model tests, the weight blocks (unit weight as 22.5kN/m^3) were applied to the mound in the downstream side of the caisson, which modeled the surface protection structure of the mound against the overflowing water.

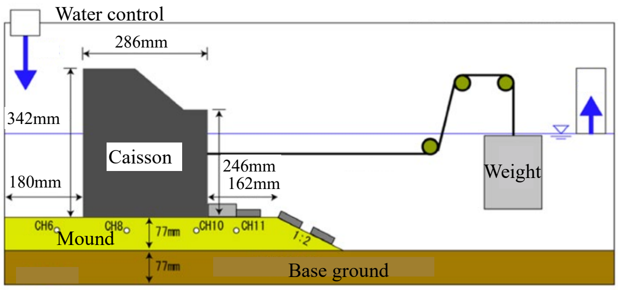

Fig. 1. Centrifuge model test for ultimate horizontal resistance.

3.2 Simulation of centrifuge model tests

The conventional stability analysis method of caisson type seawall has been developed with the use of the water pressure model shown in Fig.2 (Ports and Harbours Association of Japan 2007). In this model, the distribution in water pressure applying to the caisson is simplified, especially at the bottom of the caisson. Besides, the effect of seepage force in the mound is not considered in the stability assessment. The applicability of the conventional method has not been intensively examined due to the lack of the alternative methods. In this study, two analysis methods were performed in the simulation of the centrifuge model tests. One is the conventional method and the other is the hybrid analysis method which employs the seepage analysis and the effective stress based stability analysis method. Analysis cases are shown in Table 1. In case of Analysis A the conventional method coincides with the hybrid analysis method due to no seepage in the mound. On the contrary,

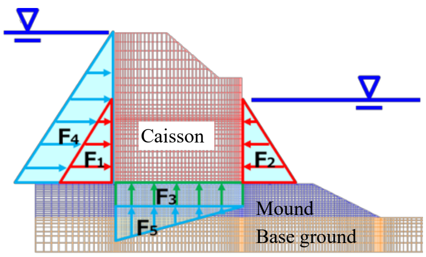

Fig. 2. Water pressure model of caisson in conventional method.

Table 1. Analysis cases for model tests

Analysis cases	Model test	Simulation method
Analysis A	Case A	Conventional method
Analysis B-1	Case B	Conventional method
Analysis B-2	Case B	Hybrid analysis method

the effect of seepage force in the mound on the stability is greatly expected in case of Analysis B. In this study both analysis methods used the rigid plastic finite element method which directly analyzes the limit state of the caisson and mound system more precisely than the limit equilibrium method used in the practical design.

The finite element mesh is shown in Fig. 3 in which the singular point due to stress concentration was treated by introducing the multiple nodes around the bottom corner of the caisson. Unfortunately, the material strength parameters of the mound were not surveyed in the literature by Takahashi et al. (2015a). The internal friction angle of the mound can be evaluated by the report on the strength parameters on rubbles by Shoji (1983). While the cohesion of the mound is unclear, it was determined by back analyzing the model test of Case A. The parameters employed for analysis are collectively exhibited in Table 2. The seepage analysis for the mound is conducted under the steady state condition.

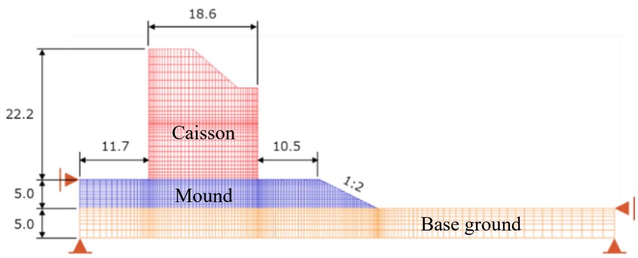

Fig. 3. Finite element mesh and boundary conditions.

Table 2. Material constants in analysis for model tests

Material	Cohesion	Friction angle	Unit weight
Mound	1.0 *kPa*	47°	19.7 kN/m^3
Base ground	20.0 *kPa*	47°	19.6 kN/m^3

3.3 Discussion on the simulation results

Table 3 shows the simulation results for model tests. While it is difficult to exactly discuss the adaptability of the analysis method to the model tests owing to the lack of detailed information on the material property, it can be observed good agreements in all cases. It is interesting the conventional method gave the good estimation for model tests although the simplified assumption is introduced into the analysis method and the seepage force isn't taken into account. It is noted the seepage force was exerted in the mound due to the difference in water levels at two sides of the caisson in Case B-2. On the other hand, the hybrid analysis method also gave the good estimation for the model test, but it is unexpected to give the greater resistance than that by the conventional method as seen in the comparison of Analyses B-1 and B-2. It is because the hybrid analysis method took account of the effect of seepage force on the stability, which may enhance the instability of the mound.

Fig.4 exhibits the failure pattern of the mound in case of Analysis B-2, where the equivalent strain rate is illustrated. It is noted the obtained result matched with the result of the model test well. It can be seen the mound formed the slip line along the base line and deformed laterally. The partly sliding at the mound slope is observed in the figure. It is explained by the effect of modelling the surface protection structure. The failure pattern was obtained almost same regardless of model cases.

Table 3. Simulation results for model tests

Analysis cases	Model test	Simulation
Analysis A	3,740 *kN/m*	3,756 *kN/m*
Analysis B-1	3,144 - 3,363 *kN/m*	3,240 *kN/m*
Analysis B-2	3,144 - 3,363 *kN/m*	3,295 *kN/m*

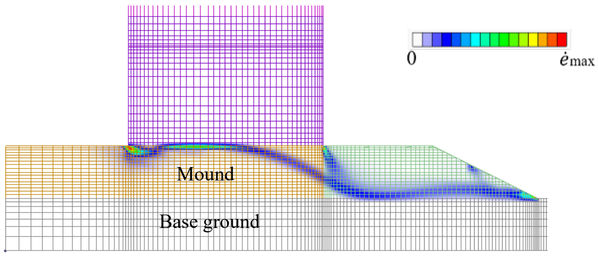

Fig. 4. Failure pattern of the mound in Analysis B-2.

4 REINFORCEMENT WORK FOR CAISSON TYPE SEAWALL

4.1 Centrifuge model tests by Port and Airport Research Institute

Takahashi et al. (2015b) conducted a series of centrifuge model tests on the effect of reinforcement work for caisson type seawall against tsunami. The effect of widening of embankment for the mound on the stability was examined by the model test as shown in Fig.5. The water levels of both sides of caisson were set same and the horizontal resistance of caisson on the mound was investigated by the centrifuge model test at 50*g*. Two model tests of Cases C-1 and C-2 were conducted; Case C-1 is the case without reinforcement work and Case C-2 is the case with reinforcement work. The ultimate horizontal resistance was obtained as 1,200*kN/m* in Case C-1 and 2,100*kN/m* in Case C-2. It is apparent that the widening of embankment is effective for stabilization of caisson against horizontal load as tsunami.

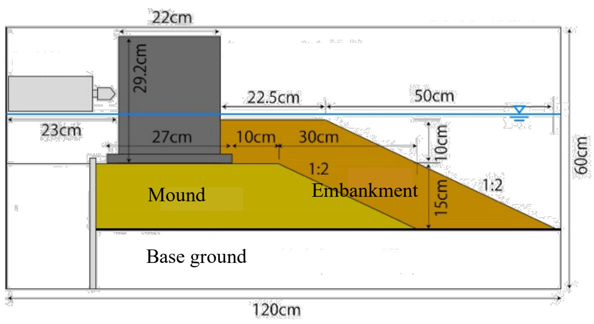

Fig. 5. Centrifuge model test for widening of embankment.

4.2 Simulation of centrifuge model tests

The test results of Case C-1 and C-2 were analyzed by RPFEM based on the conventional analysis method since there is no effect of seepage force in the mound in the tests. The material constants of model tests were reported as Table 4 by Takahashi et al. (2015b). The computation results were obtained as shown in Table 5. Although some discrepancy in resistance force between the model tests and the simulation results was observed, the model test was generally simulated and the reinforcement effect could be suitably analyzed. Fig.6 indicates the failure pattern of the mound in case of Case C-2. The failure pattern of the mound is similar with Analysis B-2, however the slip line was generated shallower in the mound and partly inside the widening of embankment. Case study for the stabilization effect by the dimension of widening of embankment is shown in Table 6. The stabilization effect is shown to depend on the dimension of widening embankment clearly. The optimum design of reinforcement work needs to be examined by tradeoff analysis of stability and cost.

Table 4. Material constants in analysis for model tests

Material	Cohesion	Friction angle	Unit weight
Mound	0.1 *kPa*	44.7°	19.5 kN/m^3
Widening of embankment	0.1 *kPa*	44.7°	19.5 kN/m^3
Base ground	0.1 *kPa*	45°	20.2 kN/m^3

Table 5. Simulation results for model tests

Test cases	Widening embankment	Model test	Simulation
Case C-1	No	1,200 *kN/m*	1,316 *kN/m*
Case C-2	Yes	2,100 *kN/m*	2,291 *kN/m*

Table 6 Case studies for widening of embankment

Analysis cases	Height	Width	Horizontal resistance
Analysis C-1	-	-	1,316 *kN/m*
Analysis C-2	5.0 *m*	15.0 *m*	2,291 *kN/m*
Analysis C-3	5.0 *m*	7.5 *m*	1,912 *kN/m*
Analysis C-4	2.5 *m*	7.5 *m*	1,775 *kN/m*

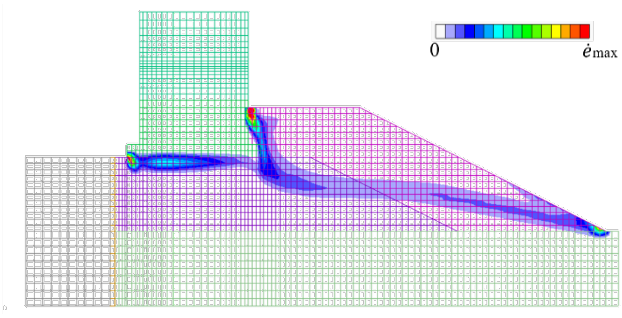

Fig. 6. Computation result on failure pattern for Case C-2.

5 CONCLUSIONS

This study surveyed the applicability of the rigid plastic finite element method to stability assessment of caisson type seawall against horizontal force induced by tsunami. Through the simulation of the centrifuge model tests conducted by Takahashi et al., the applicability of the analysis method was confirmed. The hybrid method to consider the effect of seepage force in the mound provided the good estimation for the model test. However, the conventional method assuming the simplified water pressure model applied to the caisson was also shown to give the good estimation without the consideration of seepage force. The reason why the conventional method gave the good estimation is not clear, but the harmony in the plus and minus errors was expected from the obtained results. The widening of embankment is one of possible reinforcement works for caisson type seawall. The effectiveness of the method was confirmed through numerical case studies.

ACKNOWLEDGEMENTS

This work was supported by JSPS KAKENHI Grant Number JP15K06223 (Yamazaki, H.).

REFERENCES

Hoshina. T., Takimoto, H., Tanaka, T., Isobe, K. and Ohtsuka. S. (2010). Estimation of Reinforcement Effect on Slope Stability by Nailing Method based on Rigid Plastic Finite Element Analysis, Journal of Applied Mechanics:JSCE, Vol.13, 391-400. (in Japanese)

Ports and Harbours Association of Japan (2007). Technical Standards and Commentaries for Port and Harbour Facilities in Japan, Ports and Harbours Association of Japan, 298-299 & 457-458. (in Japanese)

Shoji, Y. (1983). Study on Shearing Properties of Rubbles with Large Scale Triaxial Compression Test, Report of the Ports and Harbours Research Institute, Ministry of Transport, Japan, Vol.22, No.4, 59-120. (in Japanese)

Takahashi, H., Sassa, S., Morikawa, Y., Takano, D., Matsubara, T., Tooyama K., Hirata, A. and Maruyama, K. (2015a). Reduction of Bearing Capacity of Breakwater Mound by Tsunami-induced Seepage Force, J. Japan Society of Civil Engineers B3, Vol.71, No.2, I_1041-I_1046. (in Japanese)

Takahashi, H., Sassa, S., Morikawa, Y., Takano, D., Hashizume, H. and Maruyama, K. (2015b). Model Tests and Analyses on Bearing Capacity of Caisson-type Breakwater Mound Containing Reinforcing Embankment, J. Japan Society of Civil Engineers B3, Vol.71, No.2, I_1047-I_1052. (in Japanese)

Tamura, T., Kobayashi, S. and Sumi, T. (1990). Rigid Plastic Finite Element Method in Geotechnical Engineering Computational. Current Japanese Material Research, 15-23.

Yagi, K., Nakamura, T., Isobe, K. and Ohtsuka, S. (2010). Estimation of Reinforcement Effect on Slope Stability by Nailing Method based on Rigid Plastic Finite Element Analysis, Journal of Applied Mechanics: JSCE, Vol.13, 379-389. (in Japanese)