Geosynthetics, J. Kuwano & J. Koseki (eds)
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Shake table tests for caisson-type quay walls retrofitted by geogrids

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Keywords: quay walls, retrofit, shake table test, geogrid, caisson wall

ABSTRACT: Seismic retrofit of quay walls has been recognized as an important task for port engineers since the Kobe earthquake disaster in 1995. Caisson-type quay wall is one of the most common styles for Japanese port structures; however, it is difficult to improve the seismic performance of existing caisson-type quay walls. The authors propose an application method of geogrid for seismic retrofit of caisson-type walls. In the new method, the back-fill of the caisson wall will be replaced with geogrids and stabilized sludge. The performance of the proposed method was verified by shake table test, and the residual deformation or the reinforced quay wall can be reduced. The test result also reveals that the effect of the proposed method is based on the reduction of rocking behaviors of the caisson wall.

1 INTRODUCTION

Seismic retrofit of quay walls has been recognized as an important task for Japanese port engineers since 1995 Kobe earthquake disaster. Caisson-type quay wall is one of the most common styles for Japanese port structures; however, it is difficult to improve the seismic performance of existing caisson-type quay walls.

Caisson-type quay walls are made of concrete caisson placed on a foundation, sustaining earth pressures from backfill soil behind the wall by its own weight, and the typical failure mode of the wall due to an earthquake is a seaward displacement and tilting of the walls as shown in Figure 1. The deformation of the wall cause cracks at the apron and a large gap of elevation between the wall top and the backyard. These are the barriers for the operation of the quay wall after the earthquake.

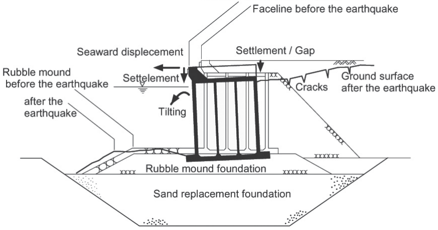


Figure 1. The typical failure mode of caisson-type walls.

Usually, the weight of the caisson causes a huge inertia force during a shaking. It means that increase of the weight for the stability against earth pressure is not efficient for the stability against inertia. Thus this huge inertia force is the reason of the difficulties in seismic performance improvement. Mohajeri et al. (2004) reveals the rocking behavior of the wall is the key mechanism of the deformation. It implies that a new method to reduce the rocking behavior of the wall could be a good improvement.

Based on such a concept, an application of geogrid for seismic retrofit of caisson-type walls has been presented. Although geosynthetics rarely applied for coastal structures due to the difficulties in the underwater construction scheme, the proposed method solved these difficulties with the application of geogrid and stabilization technique of dredged sludge.

2 THE SG-WALL METHOD

The SG-Wall method is the new construction scheme for quay Walls with the combination of Soil stabilization technique and Geogrids. In the caisson type SG-Wall method, the backfill of the caisson wall is replaced with geogrids and stabilized sludge as shown in Figure 2. The mixture of geogrid and the stabilized sludge are supposed to behave as a kind of a block, and the geogrids are connected to the caisson wall. Thus, every time the caisson moved towards sea by inertia, the backfill material is pulled towards sea either. This interaction contributes to maintain the balance of caisson, and the rocking behavior of the caisson should be reduced.

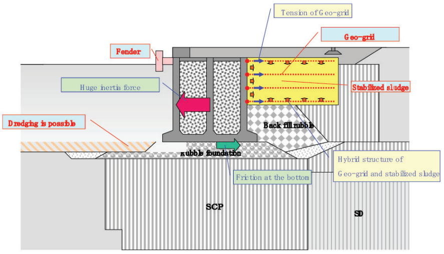


Figure 2. Concept of the SG-wall (Caisson-type).

Thus, the effect of SG-Wall is supposed to be not reduction of earth pressure behind the wall but restriction of wall behavior via constraint of geogrids.

3 SHAKING TABLE TEST

3.1 *Test conditions and materials*

The performance of the new method was experimentally investigated. Small model (1/24 scale) for a large caisson wall (–16 m front water depth) was constructed on an underwater shake table. This test was performed at the Port and Airport Research Institute, Japan. Used shake table is circular whose diameter 6m, and it is installed in the bottom of a square pool 13m long and 2m deep. Although the shake table has two horizontal and one vertical axis with a maximum displacement of ±30 cm, and a maximum acceleration of 2G, one-directional shaking is applied for simplicity.

The cross section of the model is shown in Figure 3. In order to predict the behavior of prototype models at full scale, the model walls followed the similitude proposed by Iai (1989).

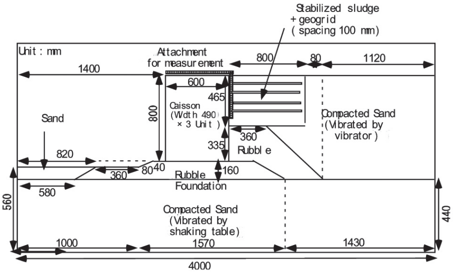
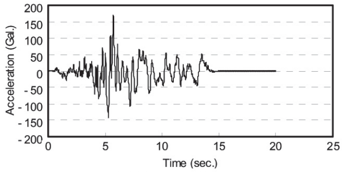


Figure 3. Cross section of test model.

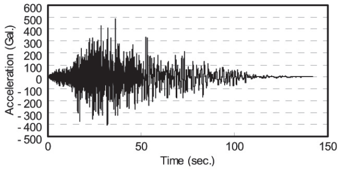
Three different shaking motions and sinusoidal waves in two different frequencies were applied. The loading steps are summarized in Table 1. Hachinohe wave is the recorded motion at Hachinohe site in 1968, and most commonly used as the design motion for Japanese port structures. Haneda motion is a synthesized motion for Haneda site and supposed to be a typical shaking for inter-plate earthquake in Japan. Port Island wave is the recorded motion at Kobe Port in 1995, and supposed to be a typical ground shaking for intra-plate earthquake. Note, these waves are applied to the same model and the latest case should be affected by the results of former cases. The wave records are summarized in Figure 4; however, the shape and the actual acceleration level are slightly different in each case due to the limitation of shake table performance.

Table 1. Loading step in the shaking table test.

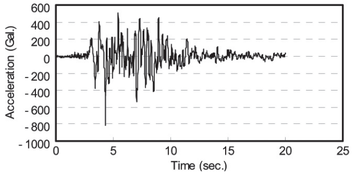
Step	Waves	Max. acceleration
1	Hachinohe waves (4 steps)	85, 170, 255, 340 Gal
2	Haneda waves (2 steps)	243, 487 Gal
3	Port Island waves (4 steps)	409, 817, 1225, 1634 Gal
4	Sinusoidal 10.8 Hz, 20 waves	200 Gal
5	Sinusoidal 20.16 Hz, 20 waves	200, 400, 600, 800 Gal
6	Sinusoidal 10.8 Hz, 20 waves	300, 600 Gal



(a) Hachinohe wave



(b) Haneda wave



(c) Port Island wave

Figure 4. Input motions for shake table tests.

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Especially, the peak acceleration in Port island wave is very spiky and it is very difficult to simulate such a spiky peak. Therefore, the maximum acceleration level compiled in table 1 is only the target acceleration level and the simulated level is different.

The model materials are summarized in Table 2. The caisson is assumed as a rigid box, and the strength and the rigidity of geogrid were overestimated in the model test due to the limitation of available materials. Treated soil was prepared as the stabilized sludge by pre-mixing method. Unconfined compressive strength test for the treated soil was performed for sample cured in the water for 4 days because the shaking test were conducted at the 4th day from the construction of the model on the shake table.

Table 2. Main test material.

Caisson	Aluminum box filled with sand
Geogrid	HDPE geogrid (Tensile strength = 17 kN/m)
Sand	So-ma sand (Relative density = 90%)
Treated soil	Cement mixed Kibu-shi clay (Unconfined compressive strength = 150 kPa)

3.2 *Test results and considerations*

Another shake test of caisson wall without any reinforcement was conducted. Therefore, the effect of SG-Wall can be calibrated with the comparison of these shake table tests. Note, the shake test without reinforcement was conducted with same scale, same model, and same material, except the stabilization and geogrid.

First of all, residual displacement of caisson is reduced by the reinforcement as shown in Figure 5. Since the deformation of the caisson is significant in the case without reinforcement, some of the shaking steps were skipped. In most of the case, the residual deformation of the caisson is reduced to less that 1/3 with the reinforcement by SG-Wall method. Note, this deformation is shown in a prototype scale, and it is about 117 times of the measured displacement.

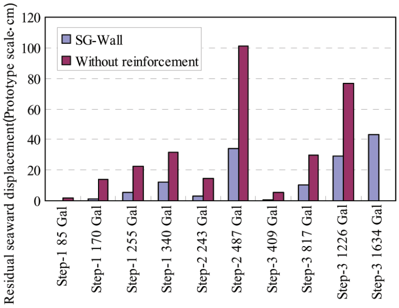


Figure 5. Effect of SG-Wall in terms of residual displacement.

The effect of reinforcement is more significant in the case of larger shaking amplitude as shown in Figure 6. It shows the observed displacement per a sinusoidal wave in the case of sinusoidal input of 20.16 Hz, and the difference of the observed displacement between with and without reinforcement becomes larger for the case of larger input level.

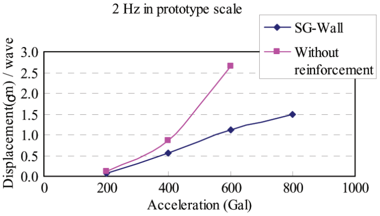
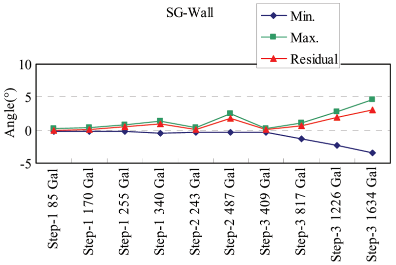


Figure 6. Observed displacements per one sinusoidal wave (20.16Hz: 2Hz in prototype case).

The rocking angle of the caisson was measured to clarify the reinforcing mechanism. The maximum, the minimum and the residual angle of the caisson in each shakings were summarized in Figure 7.

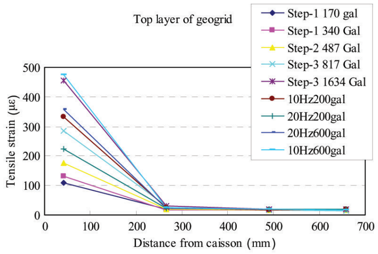


(a) Case with SG-Wall reinforcement

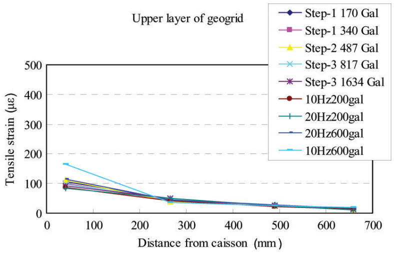
(b) Case without reinforcement

Figure 7. Recorded rocking angle of the caissons.

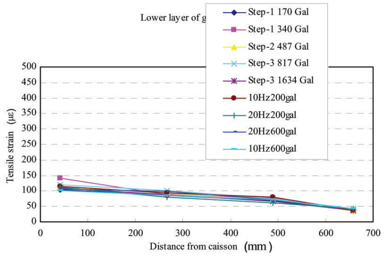
Figure 7 indicate the rocking angles in SG-Wall case are reduced as about the half of that in the case without reinforcement. Note, the magnitude of deformation shown in Figure 5 is roughly proportional to the rocking angle level shown in Figure 7. It is consistent with the concept that the rocking behavior is the key mechanism of caisson deformation, and the restriction of such rocking behavior could be an effective reinforcing approach. The strains in geogrids were also measured in the test. Figure 8 is the distribution of the maximum strain, and the upper geogrid shows the largest tensile strain.



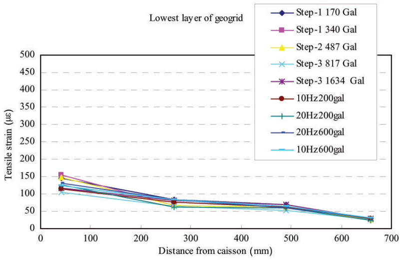
(a) Top layer of geogrid



(b) 2nd layer of geogrid from the top



(c) 3rd layer of geogrid from the top



(d) 4th layer of geogrid from the top

Figure 8. Distribution of tensile strains in geogrids.

This is consistent with the concept that the rocking behavior of the caisson is constraint by the existence of geogrid, since the tilting of the caisson toward sea shall cause this kind of strain distribution in geogrids. The strain is not uniformly distributed along the length of geogrid. This is because the rigidity of stabilized sludge is relatively strong considering the similitude of 1 g field shaking tests. Therefore, another series of shaking test in centrifuge might be necessary to capture the inner interaction of stabilized sludge and geogrid. Note, the rigidity and strength of stabilized sludge can be controlled by amount of cement, and the prototype of reinforcement in this rigidity is possible but cost-ineffective.

4 CONCLUSION

The seismic performance of the new seismic retrofit method for caisson-type quay walls was experimentally investigated. The major findings of the shake table tests can be concluded as follows.

First, a practical usage of geogrid for quay wall is confirmed by a construction of small model. The combination of treated sludge and geogrid enables the practical construction of geosynthetics in marine environment. Second, the proposed method can retrofit existing quay wall, and the residual deformation or the quay wall can be reduced as less than 1/3 of un-reinforced walls. Third, the effect of the retrofit is based on the reduction of rocking behaviors of the wall, and it is consistent with the measured rocking angle and strain distribution of the walls.

ACKNOWLEDGEMENTS

This research is a result of research project “development of earth reinforcement technique for the port facilities” in the Port and Airport Research Institute, Japan. The authors greatly appreciate all members who attend this project.

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