ジオシンセティックス論文集
第21巻(2006. 12)

Flexibility and Stability Enhancement of Structures during Earthquakes using a Novel Geosynthetic Material

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In this research, an innovative and cost-effective earthquake resistant design technique is developed using a novel geosynthetic materials that can reduce the damages of structures during devastating earthquakes. In the developed earthquake resistant technique a smart geosynthetic material known as tire chips is utilized as a seismic performance enhancer.

A series of underwater 1g shaking table test was conducted on a model gravity type quay wall. Two test cases were examined. One case involves a quay wall with the conventional backfill. Another case involves a similar quay wall but reinforced with tire chips. The seismic increment of the load acting on the quay wall and the associated displacement, as well as the excess pore water pressure in various locations of the backfill were measured during the tests. The results reveal that the seismic load against the caisson quay wall could be significantly reduced using the sandwiching technique. In addition, the technique could significantly reduce the earthquake-induced residual displacement of the quay wall.

Keywords : Earthquake resistant structures; Gravity retaining wall; Retrofitting; Shaking table test; Tire chips

1. INTRODUCTION

Japanese seismologists have predicted that large-scale devastating earthquakes (Strong metropolitan earthquake, Tokai Earthquake and Tonankai-Nankai Earthquake) are going to strike the Kanto, Tokai and Nankai areas of Japan any time in the near future. Concerted efforts have been undergoing to mitigate the disasters and minimize the economic implications from these earthquakes [1].

As evident from devastating damage of many historical earthquakes, the waterfront structures are vulnerable to earthquakes. The damages suffered by many waterfront retaining structures during the 1995 Hyogo-ken Nanbu earthquake, Kobe have been documented in [2, 3, 4]. Since then, significant theoretical and experimental works have been done on the subject[5, 6, 7, 8, 9]. Most of these reported damages were attributed to the following major factors; (1) soil failures due to liquefaction, subsidence of the backfill soil and liquefaction of the foundation soils beneath the caisson walls, and (2) The structural failures due mainly to unexpected seaward ground movement induced by the strong inertia force.

Typical gravity type quay wall has rubble backfill immediately behind the wall (**Fig. 1**). One of the reasons for using rubble backfill is to reduce the earth pressure due to friction. However, such granular material is vulnerable to deformation under seismic load, and hence

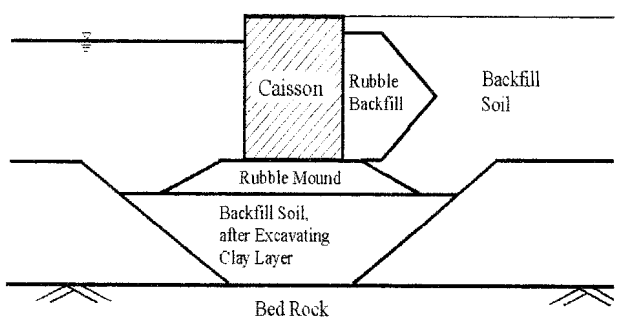

Fig. 1 Typical cross section of a caisson type quay wall

can cause large permanent deformations to the structures. If we can substitute this material with some other lightweight granular materials with other beneficial characteristics, then the earth pressure during earthquake can be reduced to a greater extent along with the curtailment of earthquake induced permanent deformation of the structures. Performance based design [4], which is becoming the norm of the present design codes of port and airport structures necessitates the curtailment of permanent deformation. as well. One material of choice, is an emerging and *smart* geomaterial [10] material known as tire chips.

Material properties researches on this new material have been

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receiving worldwide attention [11), 12), 13), 14), 15), 16)]. This scrap tire derived recycled geomaterials can be called as *smart* geomaterial since it is lightweight, elastic, compressible, highly permeable, earthquake resistant, thermally insulating and durable. Tire chips is a recent entrant to the geosynthetic community, and due to its infancy, very little attention has been paid on this smart geosynthetic material. With myriad of many outstanding characteristics, this type of material can be exploited to be used behind waterfront structures to function as geosynthetics instead of conventionally used gravelly material. In this research, an innovative cost-effective disaster mitigation technique is developed that can protect and reduce the damages of structures during devastating earthquakes. Tire chips, the newly emerging geosynthetic product, is utilized as a seismic performance enhancer of geotechnical structures.

The technique involves placing a cushion layer as a vibration absorber immediately behind the structures. In addition, vertical drains can be installed in the backfill to prevent the soil liquefaction. **Fig. 2** shows typical cross section of the earthquake resistant reinforcement technique. One function of the cushion is to reduce the load against the structure, due to energy absorption capacity of the cushion material. Another function is to curtail the permanent displacement of the structures due to inherited flexibilities derived from using such elastic and compressible geosynthetic material. The beneficial effects of such sandwiched cushioning technique have been described in Hazarika et al [17)]. By making use of the granular and highly permeable nature of tire chips, it was used in vertical drains [18)] as an agent for reducing liquefaction induced deformation.

The objective of this research is to examine whether the geosynthetics materials, such as tire chips, can reduce the earthquake related damages to structures. To that end, an underwater shaking table test (1g condition) was performed to confirm, how the load on the structures and the permanent displacements are affected during the earthquake loading. Actual earthquake loadings were imparted to the composite type soil-structure system. The response accelerations, the seismic load on the wall, the excess pore water pressure and the permanent displacement of the wall were investigated for each excitation.

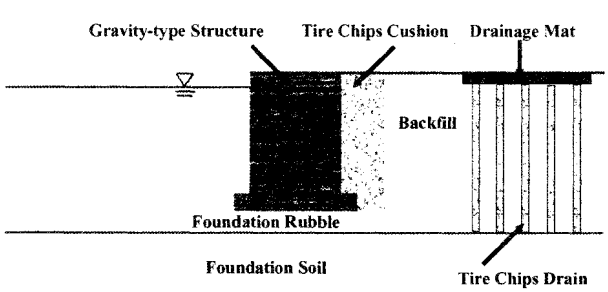


Fig. 2 Earthquake resistant reinforcement technique

2. SHAKING TABLE TEST

(1) Model preparation

The large three dimensional underwater shaking table assembly of Port and Airport Research Institute (PARI)was used in the testing program. The shaking table is circular with 5.65 m in diameter and is installed on a 15 m long by 15 m wide and 2.0 m deep water pool.

A caisson type quay wall (model to prototype ratio of 1/10) was used in the testing. **Fig. 3** shows the cross section of the soil box, the model caisson and the locations of the various measuring devices (load cells, earth pressure cells, pore water pressure cells, accelerometers and displacement gauges). The model caisson (425 mm in breadth) was made of steel plates filled with dry sand and sinker to bring its center of gravity to a stable position. The caisson consists of three parts; the central part (width 500 mm) and two dummy parts (width 350 mm each). All the monitoring devices were installed at the central caisson to eliminate the effect of sidewall friction on the measurements.

The soil box was made of a steel container 4.0 m long, 1.25 m wide and 1.5 m deep. The foundation rubble beneath the caisson was prepared using Grade 4 crushed stone with particle size of 13 mm ~ 20 mm. The backfill and the seabed layer were prepared using Sohma sand (No. 5).

The dense foundation sand representing the seabed layer was prepared in two layers. After preparing each layer, the whole assembly was shaken with 300 Gal of vibration starting with a frequency of 5 Hz and increasing up to 50 Hz. Backfill was also prepared in stages using free falling technique, and then compacting using a manually operated vibrator. After constructing the foundation and the backfill, and setting up of the devices, the pool was filled with water gradually elevating the water depth to 1.3 m to saturate the backfill. This submerged condition was maintained for two days so that the backfill attains a complete saturation stage.

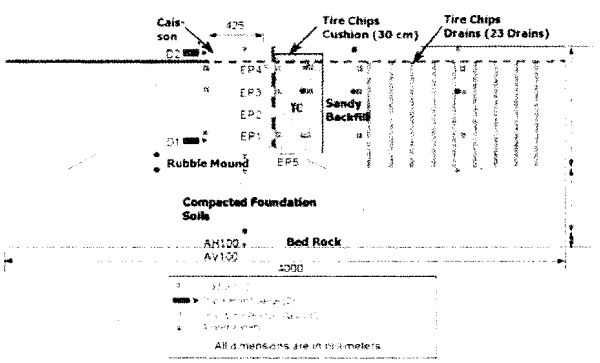
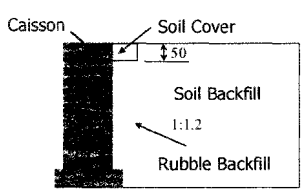
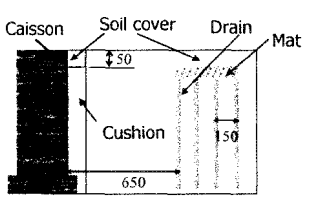


Fig. 3 Model Setup



(a) Case A (Conventional type backfill)



(a) Case A (Geosynthetic reinforced backfill)

Fig. 4. Test conditions (Units are in mm)

(2) Test Cases

As shown in **Fig. 4**, two test cases were examined. In one case (Case A), a caisson with a rubble backfill with conventional sandy backfill behind it was used. In another case (Case B), behind the caisson, a cushion layer of tire chips (average grain size 20 mm) was placed vertically down whose thickness was 0.4 times of the wall height. In actual practice, the design thickness will depend upon a lot of other factors such as height and rigidity of the structure, compressibility and stiffness of the cushion material. In compressible inclusion applications, there seems to be an optimum value for the cushion thickness, beyond which an increase in thickness will not lead to a proportionate decrease of the load. The effect of cushion thickness using a small-scale model shaking table test has been described elsewhere[19], and will not be discussed here.

(3) Test Materials

The cushion layer was prepared by filling the tire chips inside a bag made from geotextile product. Geotextiles are required to wrap the tire chips so that they do not mix with the surrounding soils. Such confinement also makes the execution of backfilling process easier. Furthermore, the presence of geotextiles also prevents flowing of sand particles into the chips structure, and thus prevents clogging and mixing, which may affect the compressibility and permeability of the chips. The average dry density of the tire chips achieved after filling and tamping was 0.675 t/m^3.

The relative densities that was achieved after the preparation of the backfill were about 50% to 60%. This implies that the backfill soil is partly liquefiable. Since liquefaction tends to increase the earth pressure, the presence of tire chips cushion is expected to protect the structure from the adverse effect of liquefaction within a limited region surrounding the structures during earthquake. Liquefiable backfill was thus selected on purpose. On the other hand, the foundation soils were compacted with mechanical vibrator to achieve a relative density of about 80%, implying a non-liquefiable foundation deposit.

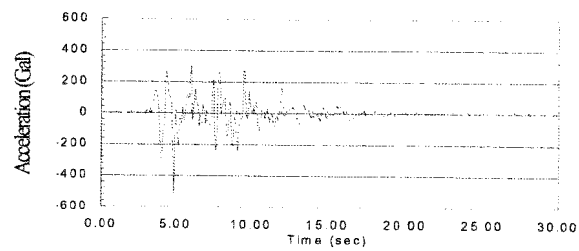
Vertical drains made out of tire chip (average grain size 2 mm), were installed in the backfill. Geotextile bags with the specific drain size were first prepared, which then were filled with the tire chips with a pre-determined density. They were then installed with a spacing of 150 mm in triangular pattern.. The drain diameter was chosen to be 50 mm. The top of the entire drains were covered with a 50 mm thick gravel layer underlying a 50 mm thick soil cover. The purpose of such cover layer is twofold: one is to allow the free drainage of the water and other is to prevent the likely uplifting of the tire chips during shaking due to its lightweight nature.

(4) Test Procedures

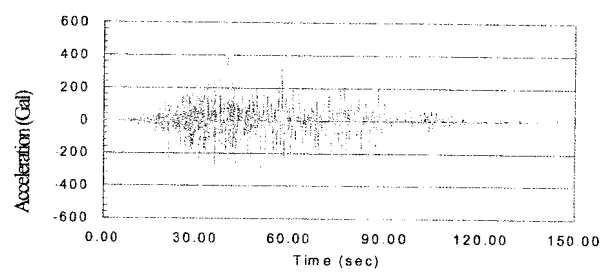
The similitudes of various parameters in 1g gravitational field for the soil-structure-fluid system were calculated using the relationship given in [20] for a model to prototype ratio of 1/10. It is worthwhile mentioning here that, the material particles size and compressibility of the material are assumed to remain unchanged, for the model and the prototype.

Earthquake loadings of different magnitudes were imparted to the soil-structure system during the tests. The input motions selected were: (1) PI (Port Island) wave: the N-S component of the strong motion acceleration record at the Port Island, Kobe, Japan during the 1995 Hyogo-ken Nanbu earthquake (M 7.2), and (2) OW (Ohta Ward) wave: a scenario synthetic earthquake motion assuming an earthquake that is presumed to occur in the southern Kanto region with its epicenter at Ohta ward, Tokyo, Japan. It is to be noted that the 1995 Hyogo-ken Nanbu earthquake is an intra-plate earthquake, while the scenario earthquake (synthetic) was constructed assuming an inter-plate earthquake. The wave records of the two input motions are shown in **Fig. 5.**

The loading intensities were varied using the various maximum acceleration ratios (0.5, 1.0, 1.2 and 1.5), which is ratio of the target acceleration to the actual acceleration. The loading steps in the test series are summarized in Table 1. The table also shows the code names used according to the acceleration ratios used and the target maximum acceleration in each test series. Durations of the shaking in the model testing were based on the time axes of these accelerograms, which were reduced by a factor of 5.62 according to the similitude relationship.



(a) Port Island, Kobe (The 1995 Hyogo-ken Nanbu earthquake)



(b) Ohta Ward, Tokyo (Synthetic Southern Kanto earthquake)

Fig. 5. Input strong motion records

Table 1 Loading sequences

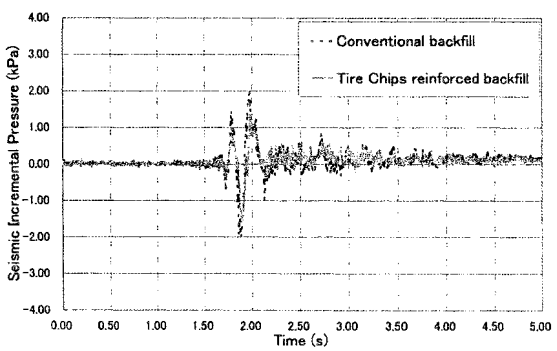
Series	Earthquakes Types (Code Names)	Acceleration Ratio (Maximum Acceleration)
No. 1	PI (PI 0.5)	0.5 (339.39 Gal)
No. 2	OW (L2 0.5)	0.5 (243.47 Gal)
No. 3	PI (PI 1.0)	1.0 (678.78 Gal)
No. 4	PI (PI 1.2)	1.2 (814.54 Gal)
No. 5	OW (L2 1.0)	1.0 (486.94 Gal)
No. 6	PI (PI 1.5)	1.5 (1018.17 Gal)

3. TEST RESULTS

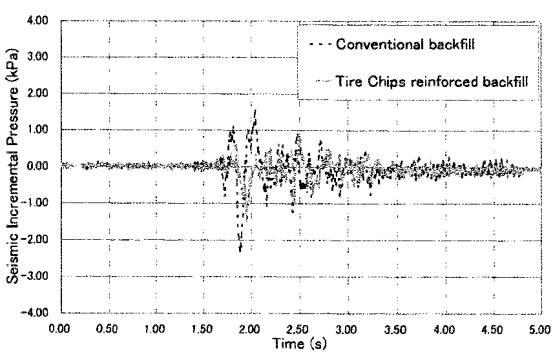
As displayed in Table 1, various types of earthquake motion with different magnitudes were adopted in this study. However, the discussion here will be mostly limited to the series no. 3 (PI 1.0). PI 1.0 is the actual recorded data at Port Island, Kobe, with the time axes scaled to fit the model to prototype ratio of 1/10.

(1) Seismic Increment of Earth Pressure

Fig. 6 shows the time history of the increment of the seismic earth pressure acting on the quay wall at the lower middle and the upper middle part of the caisson. It can be observed that as compared to conventional backfill condition (Case A in **Fig. 4**), the seismic increment is decreased to a considerable extent in tire chips reinforced backfill (Case B in **Fig. 4**). Considering the fact that the static earth pressure itself will also be reduced due to low weight and compressible characteristics of the cushion materials, the total earth pressure acting on the structure will, thus, be reduced to a greater extent. Reduction of the static earth pressures in such application of tire chips have been explained in [18]. The end results, thus, is the reduction of the total earth pressure, which will contribute toward the stability of the structure during earthquakes.



(a) At lower middle (EP 2 of Fig. 3)



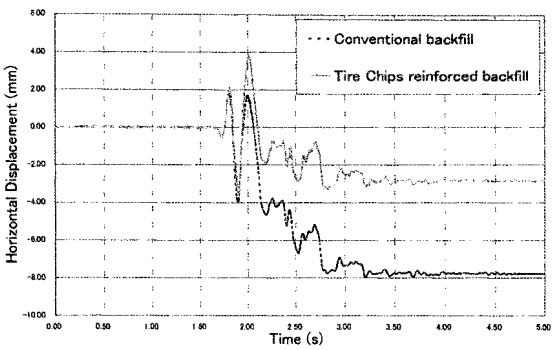
(b) At upper middle (EP 3 of Fig. 3)

Fig. 6. Time history of seismic increment of pressure on caisson

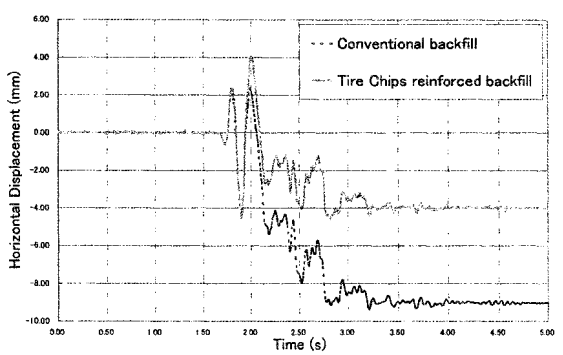
(2) Deformation of the Structures

In order to evaluate, whether the developed method can minimize the residual horizontal displacement experienced by the caisson, the time histories of the horizontal displacements (D1 and D2 in **Fig. 3**) during the loading for the two test cases are compared in **Fig. 7**.

Comparisons reveal that the maximum displacement experienced by the quay wall with tire chips reinforced caisson (thick continuous line)is toward the backfill in contrast to the quay wall without any reinforcement (shown in dotted line), in which case it is seaward. The compressibility of the tire chips renders flexibility to the soil-structure system, which allows the quay wall to bounce back under its inertia force, and this tendency ultimately (at the end of the loading cycles) aids in preventing the excessive seaward deformation of the wall. However, the wall with conventional backfill experiences very high seaward displacements right from the beginning due to its inertia. As a consequence, the structure can not move back to the opposite side and ultimately suffers from a huge permanent seaward displacement.



(a) At caisson toe (D1 of Fig. 3)



(b) At caisson top (D2 of Fig. 3)

Fig. 7. Time history of the caisson displacements

(3) Influence of Earthquake Motions on Permanent Displacement

The seaward permanent displacements under different earthquakes motions (PI and OW) tabulated in Table 1 are compared in **Fig. 8** for the two test conditions (Case A and the Case B in **Fig. 4**). This figure reveals further that, the tire chips reinforced caisson experiences less residual displacements than the unprotected caisson during an earthquake. However, in the case of the OW type motion, even though the residual displacement itself is less compared to the unprotected case, the magnitude is relatively high (comparable to the reinforced caisson under PI 1.0 type wave). The trend of the residual displacements in the case of the conventional backfill (shown by the dotted line in the figure) shows an exponential increase. However, geosynthetic reinforced backfill displays a very mild linearly increasing trend. It is noteworthy here that the maximum acceleration

alone has got nothing to do with such trend. Furthermore, except for the L2 1.0 type motion, all the other motions yield the permanent displacements of less than 5 mm. In the prototype scale, using the similitude relationship, this gives a permanent displacement of 15.81 cm, which is a reasonable values as far as the performance based design is concerned.

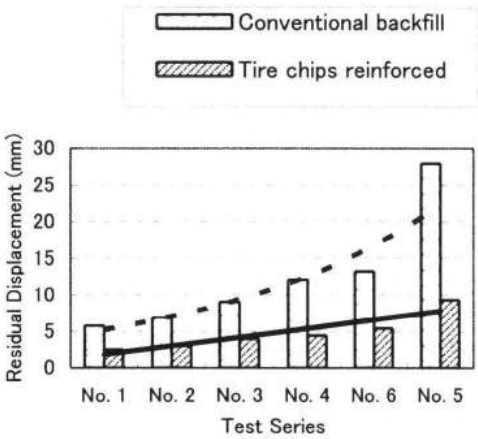
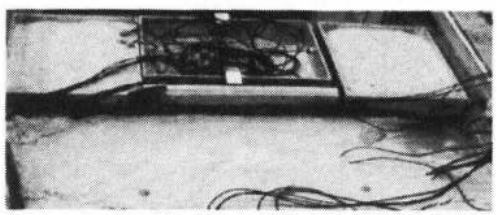


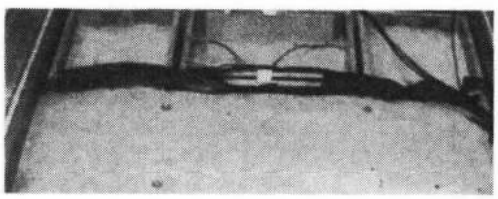
Fig. 8. Comparison of residual displacements with different earthquake magnitudes

(4) Ground Surface Settlement

In order to examine, whether the developed technique can contribute towards the safe operation of port facilities after any devastating earthquakes, differential settlements in the backfill with and without reinforcing material need to be compared. **Fig. 9** shows such comparison, in which the states of the backfill settlement at the end of the 6th loading step of Table 1 are compared. It can be observed that, the structure with conventional backfill experiences a very severe differential settlement. However, the structure with reinforced backfill does not undergo appreciable differential settlement, confirming that even in such high intensity earthquake conditions (Maximum acceleration is 1.5 times that of the 1995 Hyogoken Nanbu earthquake), the port facilities can remain operational, if the structure is reinforced with the earthquake resistant technique described here.



(a) Conventional backfill case



(b) Reinforced backfill case

Fig. 9. Ground surface settlements

CONCLUSIONS

In this research, a series of model shaking table tests (1g gravitational field) were conducted to examine the performance of a newly developed technique, in which sandwiched cushion and vertical drains (made out of an emerging and novel geosynthetic product known as tire chips) was used as a reinforcing material behind rigid and massive structures such as caisson quay wall. Test results have indicated that the use of the technique leads not only to reduction of the seismic load, but also the seismically induced permanent displacement of the structure. Reduction of the load against structure implies lowering of the design seismic load, which in turn yields a slim structure with reduced material cost. Recycled geosynthetic material such as tire chips can contribute to the satisfactory performance of structures by rendering flexibility and stability to structures during the earthquake. Such applications of scrap tire derived geosynthetic product, thus, not only reduce considerably the execution and construction cost of a project, but also contributes towards a sustainable environment by recycling of the scrap tires as materials.

The benefit of the technique described here can also be applied for upgrading (retrofitting) of the existing structures, which do not satisfy the current seismic design criteria and, thus, run the risk of damages during devastating future earthquakes (such as strong metropolitan earthquake, Tokai earthquake, Tonankai-Nankai earthquake). The technique, thus, is expected to have a great potential in the cost-effective seismic design and retrofitting of retaining structures.

ACKNOWLEDGEMENTS: This research was started as a collaborative project of PARI, Ibaraki University, Bridgestone Corporation and Toa Corporation. A part of the financial support for this project was provided by the Japan Society of Promotion of Science (JSPS) and Ministry of Education, Culture, Sports, Science and Technology (MEXT), Japan under the Grant-in-Aid for scientific research (Grant No. 18206052, Principal Investigator: Hemanta Hazarika) and by the Ministry of Land, Infrastructure and Transport under the Grant-in-aid for Research and Development of Construction Technology (Principal Investigator: Kazuya Yasuhara). The authors gratefully acknowledge this support.

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新ジオシンセティックス材を用いた構造物の地震時の柔軟性および安定性の向上について

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軽量で圧縮性および透水性に優れたタイヤチップを構造物の背面に緩衝材およびドレーン材として使用することによって，構造物に柔軟性を与え、抗土圧構造物に作用する動的荷重の軽減工法を本研究で開発した．本研究では，圧縮性を有するタイヤチップクッションを用いたサンドイッチ型裏込め構造の地震時の性能に関して大型水中振動台を用いてケーソン式岸壁の振動実験を行った。実験では様々な地震波を用いて相互作用システムの耐震評価の検討を行った。

実験結果から，本研究で開発した耐震対策法を有するケーソン式岸壁に対して地震時の荷重を軽減できることが明らかになった。また，ケーソンの残留変位は耐震対策のない構造物に比べて小さくなる事が実証された．本研究成果を用いることによって，社会基盤をより安全かつ経済的に設計・施工するだけではなく，廃タイヤのリサイクルはサーマルからマテリアルへの転換に対しても効果があることから，より良い環境づくりに貢献するという利点もある。従って、本工法は高い安全性と環境負荷縮減効果の両面を有するコストパフォーマンスが高いことから，構造物の耐震補強工法として有効な工法であると言える。