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SANDWICHED BACKFILLING TECHNIQUE FOR EARTHQUAKE PROTECTION OF GEOTECHNICAL STRUCTURES

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ABSTRACT

An innovative and cost-effective earthquake resistant design technique is developed using a novel and smart geosynthetic material, known as tire chips, which can reduce the damages of structures during devastating earthquakes. 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. The other case involves a similar quay wall with tire chips reinforced backfill. The seismic increment of the earth pressures acting on the quay wall and the associated displacements, as well as the excess pore water pressures in various locations of the backfill were measured. The test 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 displacements of the quay wall and the associated backfill subsidence.

Keywords: Earthquake resistant; Gravity quay wall; Seismic retrofitting; Shaking table test; Tire chips

INTRODUCTION

Devastation caused to more than 90% of the waterfront structures (JGS/JSCE, 1996; Kamon et al, 1996; PIANC, 2001) during the 1995 Hyogoken-Nanbu earthquake, Kobe, Japan, has led to an increasing concern about the seismic stability of the existing and newly built port and harbor facilities. Typical example of devastating damage caused to a gravity type quay wall located in Kobe, Port, Japan is shown in Figure 1. Most of the reported damages to waterfront structures during the 1995 Hyogoken-Nanbu earthquake 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. Significant theoretical and experimental works have been done on the subject (Dickenson and Yang, 1998; Iai and Sugano, 2000; Inagaki et al, 1996; Ishihara, 1997; Ishihara et al, 1996; Towhata et al, 1996) trying to evaluate the cause and the preventive measures.

Seismologists in Japan have predicted that large-scale devastating earthquakes (Tokai Earthquake, Tonankai-Nankai Earthquake, Strong metropolitan Earthquake) are going to strike the Tokai area, the

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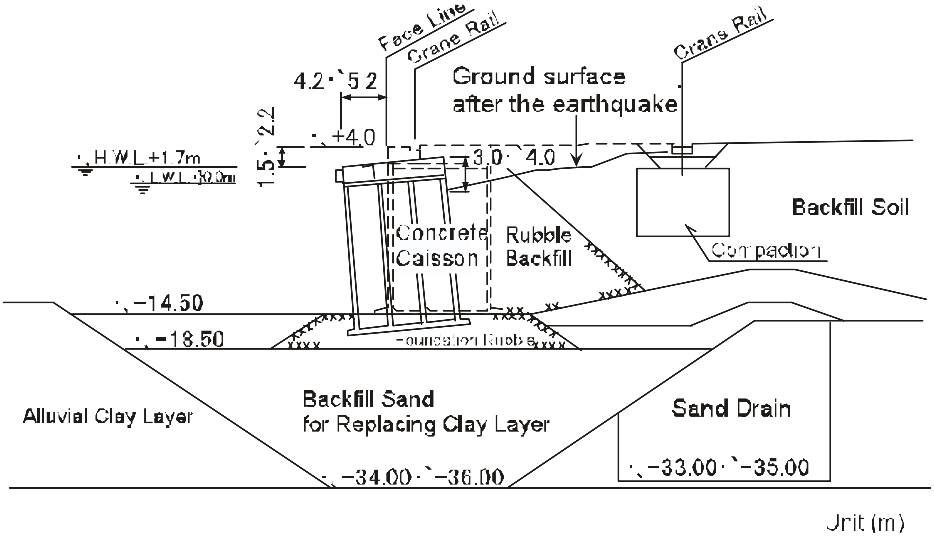
Nankai area and the Kanto area of Japan any time in the near future. The central disaster management council, government of Japan (http://www.bousai.go.jp, 2006), have been making concerted efforts designed to mitigate the disasters and minimize the economic implications from these earthquakes. This demands the development of novel and cost-effective disaster mitigation technique that can protect and reduce the damages of structures during devastating earthquakes. This research is a step forward in that direction. To this end, an environmentally friendly earthquake resistant technique is developed, wherein, a lightweight, compressible, highly permeable, and elastic material is utilized as a seismic performance enhancer.

(a) Damage to a caisson quay wall at Kobe port, Japan



(a)Cross section of the damaged caisson quay wall at Kobe port, Japan

Figure 1. Damage to waterfront structures during devastating earthquake (PIANC, 2001)

Typical gravity type quay wall has rubble backfill immediately behind the wall (Figure 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 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 (PIANC, 2001), 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 geomaterial material known as tire chips. Tire chips is a material that is lightweight, elastic, compressible, highly permeable, earthquake resistant, thermally insulating and durable. Such material has been coined a *smart geomaterial* by Hazarika et al (2006a). Various beneficial applications of tire-derived geomaterials have been described in Humphrey (1998).

In this research, an innovative cost-effective disaster mitigation technique is developed using tire chips, a newly emerging smart geosynthetic product, which can be utilized as a seismic performance enhancer of geotechnical structures. The objective of this research is to examine whether the geosynthetic 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, the permanent displacement of the wall, and the backfill subsidence were investigated for each earthquake loading.

SANDWICHED BACKFILLING TECHNIQUE

The environmentally friendly and the cost-effective disaster mitigation technique that has been developed involves placing cushion layer made out of tire chips as a vibration absorber immediately behind the structures. The beneficial effects of such sandwiched cushioning technique have been described in Hazarika et al (2006b). In addition, vertical drains made out of tire chips can be installed in the backfill to prevent the soil liquefaction. Yasuhara et al (2004) used tire chips in vertical drains that act as an agent for reducing liquefaction induced deformation.

Figure 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 permanent displacement of the structure due to inherited flexibilities derived from using such elastic and compressible material.

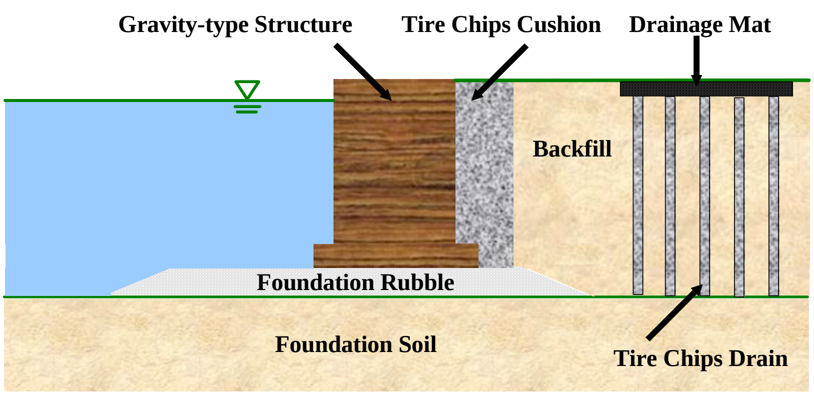


Figure 2. Sandwiched earthquake resistant technique

UNDERWATER SHAKE TABLE TESTING PROGRAM

Shaking Table, Soil Container and Experimental Setup

The large three dimensional underwater shaking table assemblies 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. The details of the shaking table can be found in Iai and Sugano (2000)

A caisson type quay wall (model to prototype ratio of 1/10) was used in the testing. Figure 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.

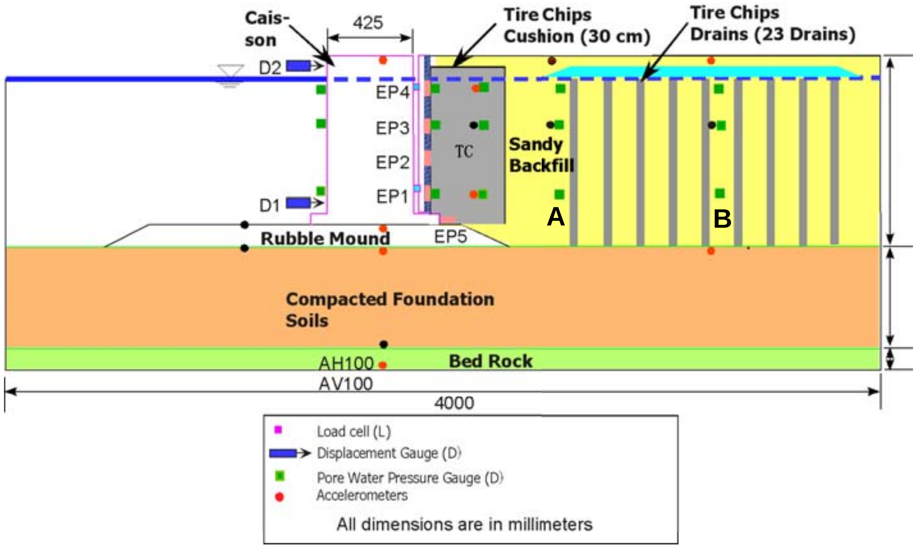


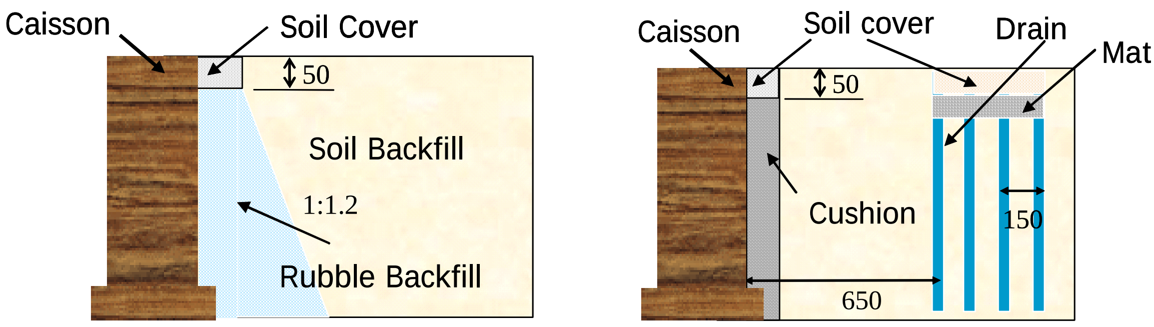
Figure 3. Cross section of the experimental model

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.

Test Cases

As shown in Figure 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 buffer 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 in Hazarika et al (2006c).



(a) Conventional type **(b) Sandwiched type**

Figure 4. Test cases of backfill

Test Procedures

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.

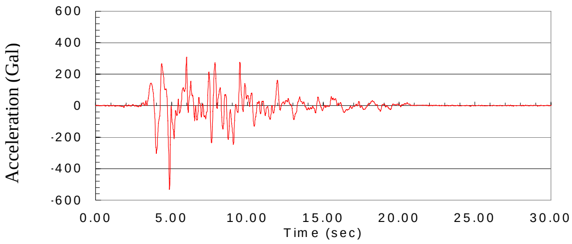
The relative densities that was achieved after the preparation of the backfill were about 50% to 60%. This implies that the backfill soil is partly liquefiable. Since liquefaction tends to increase the earth pressure, the presence of tire chips cushion is expected to protect the structure from the adverse 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 7.0 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.

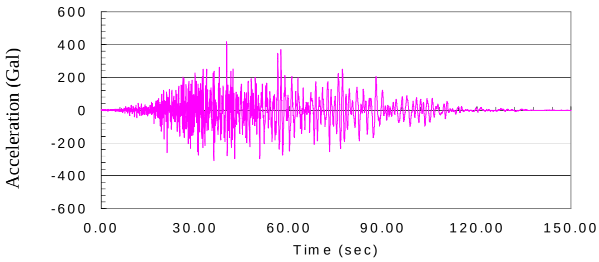
The similitudes of various parameters in 1g gravitational field for the soil-structure-fluid system were calculated using the relationship given in Iai (1989) for a model to prototype ratio of 1/10. It is worthwhile mentioning here that, the material particles size and compressibility of the material 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 Figure 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 earthquake)

Figure 5. Strong motion wave records

Table 1. Loading sequences

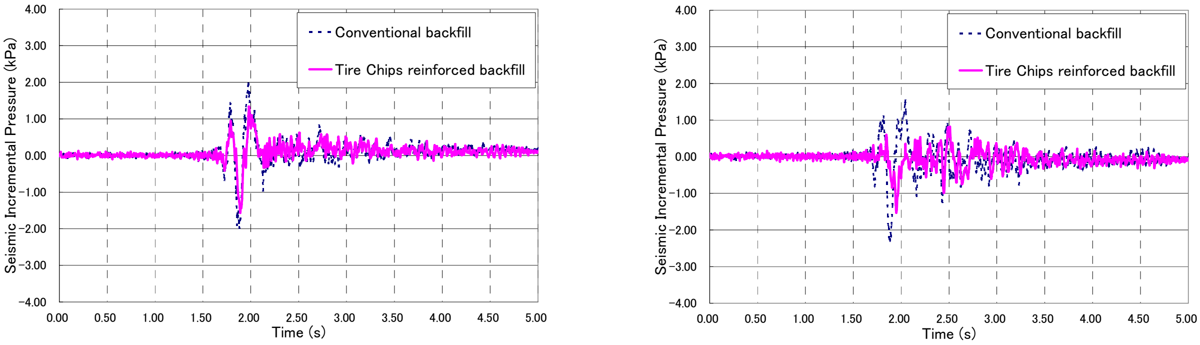
Series	Earthquakes Types (Code Names)	Acceleration Ratio (Maximum Acceleration)
No. 1	PI (PI 0.5)	0.5 (339.39 Gal)
No. 2	OW (L2 0.5)	0.5 (243.47 Gal)
No. 3	PI (PI 1.0)	1.0 (678.78 Gal)
No. 4	PI (PI 1.2)	1.2 (814.54 Gal)
No. 5	OW (L2 1.0)	1.0 (486.94 Gal)
No. 6	PI (PI 1.5)	1.5 (1018.17 Gal)

TEST RESULTS AND DISCUSSION

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.

Incremental Seismic Thrust

Figure 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 Figure 4), the seismic increment is decreased to a considerable extent in tire chips reinforced backfill (Case B in Figure 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. The end result, thus, is the reduction of the total earth pressure, which will contribute towards the stability of the structure during earthquakes.



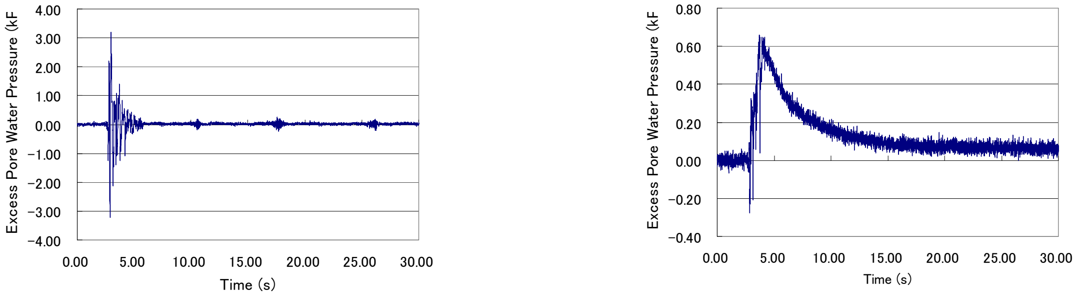
(a) At lower middle (EP 2 of Fig. 3) **(b) At upper middle (EP 3 of Fig. 3)**

Figure 6. Time history of incremental seismic thrust

Excess Pore Water Pressures

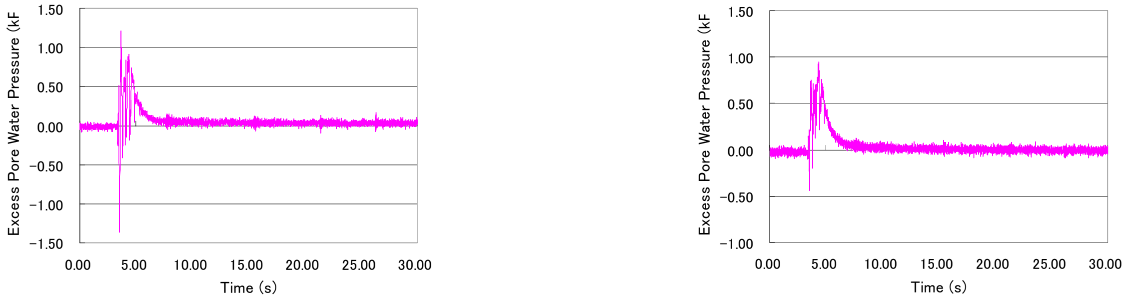
In order to evaluate, whether the developed method can minimize the liquefaction related damages, the time histories of the excess pore water pressure during the loading at two particular locations (**A** and **B** in Figure 3**)** for the two test cases are compared in Figures 7 and 8.

Comparisons reveal that the pore water pressure build up is different for the two cases. In the case of conventional backfill, at location closer to the gravel backfill (**A**), the pore water build up is restricted due to dissipation of the permeable gravel backfill. However, at far away location (**B**), the pore water pressure builds up and it takes considerable time (about 25 second) to dissipate. However, in the case of tire chips reinforced backfill, the built up pore water pressure dissipates within a very short interval (2.5 second), preventing any chance for the backfill to liquefy.



(a) At location A **(b) At Location B**

Figure 7. Excess pore water pressure (Conventional backfill)

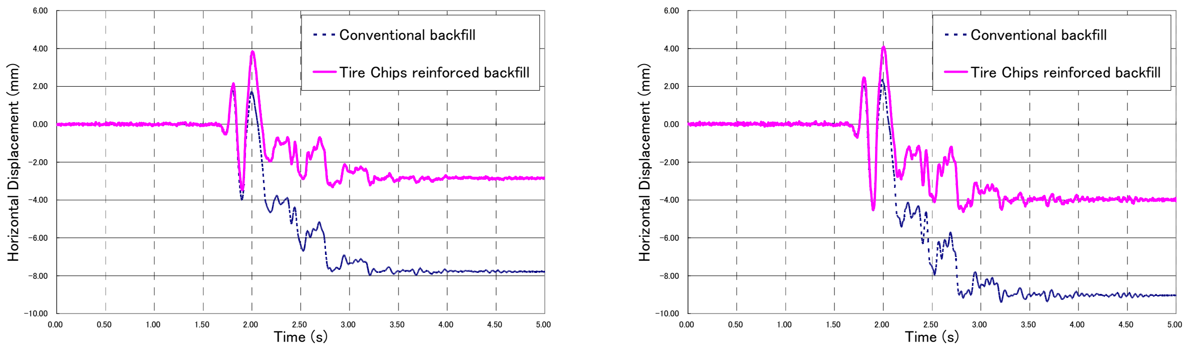


(a) At location A **(b) At location B**

Figure 8. Excess pore water pressure (Sandwiched backfill)

Seaward Displacement of Structures

The time histories of the horizontal displacements (D1 and D2 in Figure 3**)** during the loading for the two test cases are compared in Figure 9**.** 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.

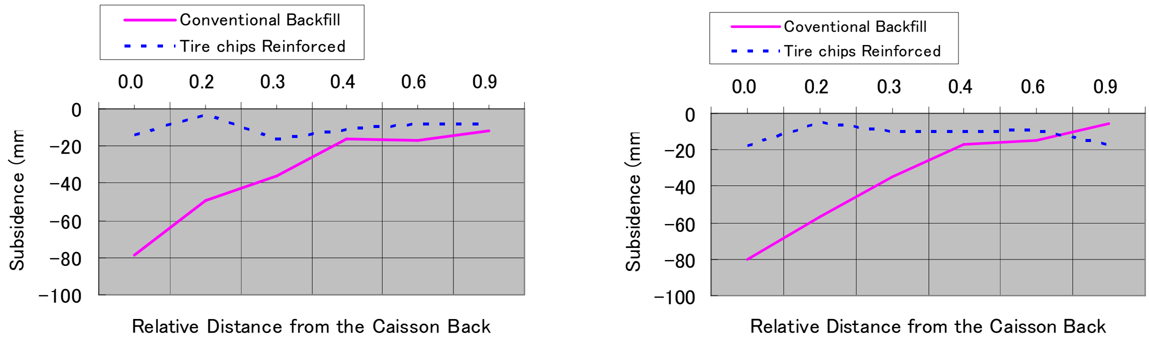


(a) At caisson bottom (D1 of Fig. 3) **(b) At caisson top (D2 of Fig. 3)**

Figure 9. Time history of the caisson displacements

Backfill Subsidence with Repeated History of Earthquake Loading

Backfill subsidences were measured at the end of each test series of Table 1 by installing targets on the surface of the backfill. Figure 10 compares the subsidence of the backfill from the start of the first earthquake loading in Table 1 (PI 0.5) to the end of the last earthquake loading (PI 1.5). It can be seen that as compared to the conventional backfill with gravel, the sandwiched backfilling technique could substantially reduce the backfill subsidence. This indicates that the developed technique can contribute towards the safe operation of port facilities even after experiencing many devastating earthquakes, since the differential settlements in the backfill were significantly less and uniform.



(a) North side (37.5 mm from the side wall) **(b) South side (37.5 mm from the side wall)**

Figure 10. Backfill subsidence

CONCLUSIONS

A series of model shaking table tests (1g gravitational field) were conducted to examine the performance of a newly developed sandwiched backfilling technique for earthquake disaster mitigation. In the technique, sandwiched cushion and vertical drains (made out of an emerging and *smart geomaterial* 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. The technique also could prevent the bumpiness of the backfill after an earthquake, thus maintaining the performance of the facilities after strong earthquakes. Reduction of the load against structure implies lowering of the design seismic load, which in turn yields a slim structure with reduced material cost. Such applications of scrap tire derived material, 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.

When the developed technique is going to be applied in practice, the choice of design parameters of the tire chips cushion will assume importance. The design cushion thickness will depend upon factors such as height and rigidity of the structure and stiffness of the cushion material. The particle size and shape of tire chips, compacted unit weight, shear strength, compressibility etc, will thus influence the design. Due to the differences between tire chips and other geologic geomaterials such as sand and gravel, physical characterization of such material represents the specific challenge to the design and application of the technique.

The benefit of the sandwiched backfilling 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.

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