MITIGATION OF EARTHQUAKE INDUCED GEOTECHNICAL DISASTERS USING A SMART AND NOVEL GEOMATERIAL

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ABSTRACT:
In this paper, an innovative disaster mitigation technique is described in which scrap tire derived recycled wastes are utilized to reduce the earthquake related hazards of geotechnical structures. A series of model 1G shaking table experiments were conducted to validate the performance of the developed technique. The test results have demonstrated that the mitigation technique not only reduces the seismic load but also the earthquake induced permanent displacement of structures. Such mitigation measure also can lead to cost-effective design and retrofitting of geotechnical structures by reducing the material and construction cost.

KEYWORDS:
Liquefaction, Quay wall, Seismic retrofitting, Shake table test, Tire chips

1. INTRODUCTION

In the 21st century, cost, environment and seismic performance are going to be the three most decisive factors in the design, construction and retrofitting of infrastructures against earthquake loading. Fears loom large over three large-scale devastating earthquakes (Tokai Earthquake, Tonankai-Nankai Earthquake, Strong metropolitan Earthquake) that are predicted to strike the Tokai area, the 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. With tough government policy of cutting expenditure on infrastructural projects, demands on engineers are mounting for developing novel and cost-effective disaster mitigation technique that can protect and reduce the damages of geotechnical structures during devastating earthquakes.

This research is an attempt towards achieving a better seismic performance of geotechnical structures using a less expensive and recycled geomaterial. The recycled geomaterials, which are of interest here, are the scrap tire derived geomaterials such as tire chips and tire shreds. They are obtained by cutting scrap tires into small pieces (Figure 1). These recycled materials are lightweight, elastic, compressible, highly permeable, earthquake resistant, thermally insulating and durable. Because of such beneficial characteristics, Hazarika (2007) coined the term *smart geomaterials* to describe these materials. They have been increasingly used worldwide in various geotechnical constructions. Although technological advancement in Japan regarding the effective use of scrap tires as geomaterials is still in its infancy, researches on their application as tire chip-mixed solidified soil (Kikuchi et al., 2006), earthquake-resistant reinforcement (Hazarika et al. 2006) and fill improvement (Mitarai et al., 2006) have been actively conducted. The Japanese experiences on these novel and *smart geomaterials* have been described in Yasuhara et al. (2006). A compilation of technical information relating to worldwide research and application of the scrap tire derived recycle materials can be found in Hazarika and Yasuhara (2007).

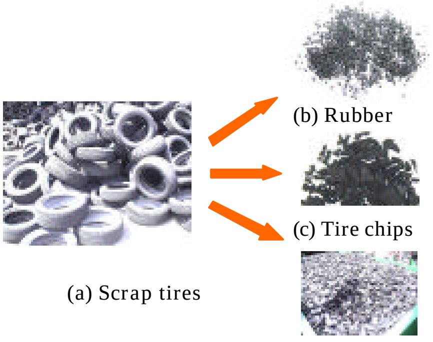

(a) Scrap tires
(b) Rubber
(c) Tire chips
(d) Tire shreds

Figure 1. Tire derived geomaterials

On the other hand, concerns have been growing on the seismic stability of the existing and newly built port and harbor facilities in Japan after her bitter experiences of the 1995 Hyogoken-Nanbu earthquake, Kobe. The earthquake caused severe damage to more than 90% of the waterfront structures (Inagaki et al., 1996; Ishihara, 1997; JGS/JSCE, 1996; Kamon et al, 1996; Towhata et al., 1996). Typical waterfront structure such as gravity type quay wall has rubble backfill immediately behind the wall. 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 induce large permanent deformations to the structures. If we can substitute this material with *smart geomaterials* such as tire chips, 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.

In this research, an innovative cost-effective disaster mitigation technique is developed using tire chips, the emerging geomaterial, which can be utilized as a seismic performance enhancer of geotechnical structures. The objective of this research is to examine whether the developed mitigation technique can reduce the earthquake related damages to geotechnical structures. To that end, an underwater shaking table test (1G condition) was performed using the actual earthquake loading of the 1995 Hyogoken-Nanbu earthquake, Kobe and the structural performances under such level 2 earthquake motion (PIANC, 2001) were investigated.

2. OUTLINE OF THE MITIGATION TECHNIQUE

Figure 2 shows typical cross section of the earthquake hazard mitigation technique that is being developed. First step of the novel technique involves placing cushion layer made out of tire chips as a vibration absorber immediately behind the structures (Hazarika, 2007). In addition, vertical drains made out of tire chips are installed in the backfill as a preventive measure against soil liquefaction. Yasuhara et al. (2004) used such tire chips as vertical drains for reducing liquefaction induced deformation. 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.

3. 1G SHAKING TABLE TEST

3.1. Test setup

The large three dimensional underwater shaking table assemblies of Port and Airport Research Institute (PARI) were used in the testing program. The shaking table is mounted on a 15 m long by 15 m wide and 2.0 m deep water pool, and thus can simulate the actual state of waterfront structure.

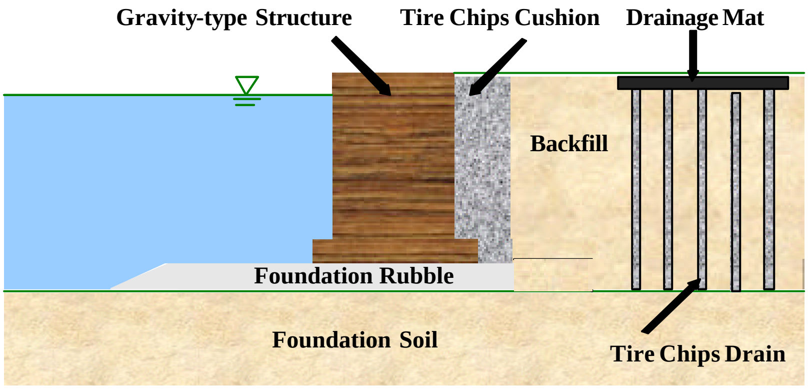


Figure 2. Outline of the developed earthquake hazard mitigation technique

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.

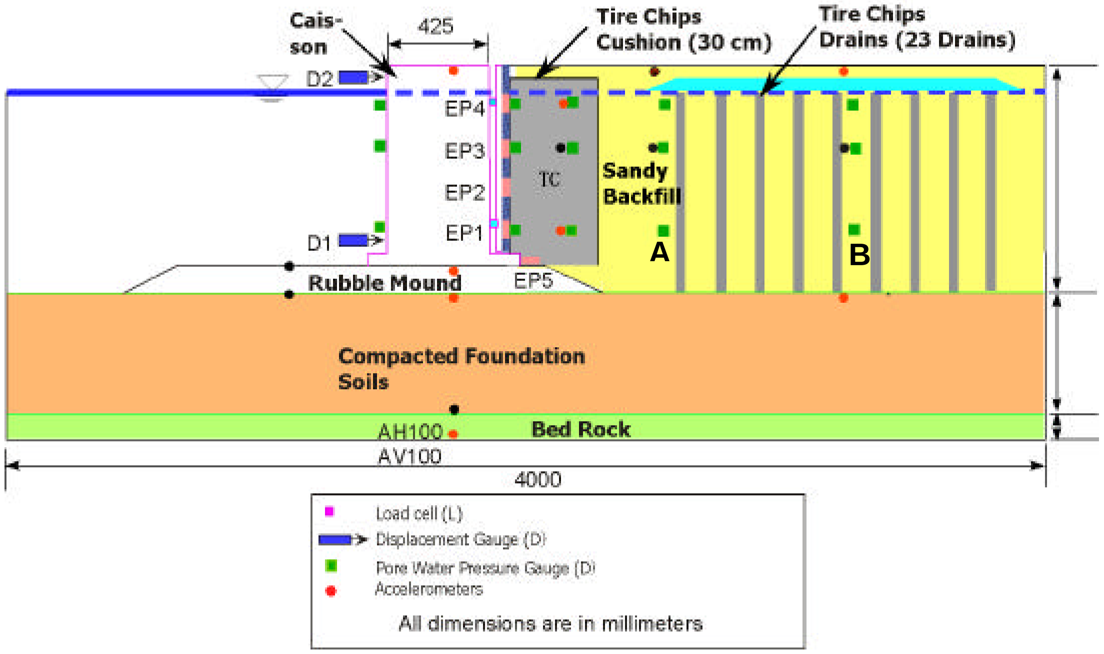


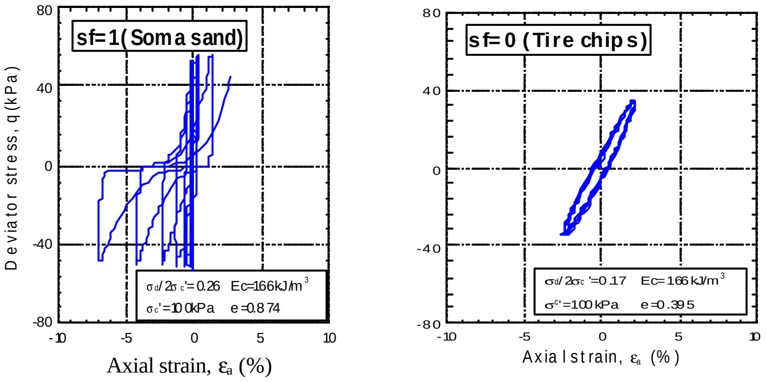
Figure 3. Cross section of the test model

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. Backfill (Sohma sand No. 5) was prepared in stages using free falling technique, and then compacting using a manually operated vibrator to achieve the target relative density of 50%. 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.

3.2. Materials and their dynamic properties

The backfill and the seabed layer were prepared using Sohma sand (No. 5). The tire chips cushion layer was prepared from tire chips of average grain size 20 mm. The vertical drains were made out of tire chip of average grain size 7.0 mm.

Hyodo et al. (2007) conducted undrained shear testing of Sohma sand and tire chips mixtures to understand the shear behavior and strength characteristics of these materials under cyclic loading conditions. Typical results obtained from the undrained cyclic triaxial tests for Sohma sand and tire chips are shown in Figure 4 in terms of the deviator stress (q) - axial strain (ε_a) relation, respectively. The physical properties of the tested materials are shown in Table 1. It is to be noted that in these element tests, tire chips of average grain size less than 2.0 mm were used due to limitation of the triaxial testing machines, whereas in the model tests much bigger sizes of tire chips were used. In the experiment, two levels of compaction energy (E_c=51kJ/m^3, 116 kJ/m^3) were used to obtain different relative densities. The saturated specimens were isotropically consolidated under a confining pressure of $\sigma_c{}'$=100 kPa and undrained triaxial tests were conducted at a loading frequency of 0.1 Hz.



(a) Sohma sand

(b) Tire chips

Figure 4. Typical results of undrained cyclic shear tests

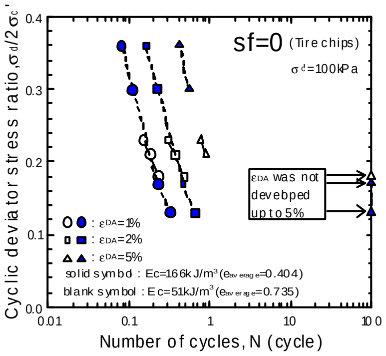


Figure 5. Cyclic shear stress and the number of cycles required to produce the double amplitude

Table 1. Physical Properties of soil samples (After Hyodo et al., 2007)

Sand fraction	ρ_s(g/cm^3)	ρ_{dmin}(g/cm^3)	ρ_{dmax}(g/cm^3)	e_{max}	e_{min}	D_{50}(mm)	U_c
sf=1(Soma sand)	2.645	1.273	1.574	1.077	0.680	0.395	1.65
sf=0.9	2.576	-	-	-	-	0.399	1.67
sf=0.8	2.498	-	-	-	-	0.403	1.67
sf=0.7	2.410	0.939	1.234	1.565	0.953	0.407	1.69
sf=0.6	2.309	-	-	-	-	0.414	1.72
sf=0.5	2.192	0.744	0.988	1.948	1.218	0.423	1.75
sf=0.3	1.892	0.563	0.735	2.361	1.576	0.453	1.91
sf=0 (Tire chips)	1.150	0.347	0.442	2.318	1.600	0.655	2.72

The relationship between the deviator stress and axial strain showed visco-elastic behavior of tire chips. From Figure 4, it is evident that tire chips show linear behavior when the axial strain is less than 1%. However, axial strain as large as 2% occurred during the first cycle. Figure 5 shows the plots of cyclic shear stress ratio, $\sigma_d/2\sigma_c$' and the number of cycles N required to produce the double amplitude axial strain of ε_{da}=1%, 2% and 5%. In the figure, $e_{average}$ corresponds to the average void ratio of each specimen after consolidation at $\sigma_c{}'$= 100 kPa. It can be seen from this figure that the relationship practically lies on the same curve, indicating that compaction energy has almost no contribution to the dynamic strength of tire chips specimen.

The results of the test series conducted by Hyodo et al. (2007) have confirmed that excess pore water pressure does not generate inside tire chips, and hence, liquefaction does not occur. Therefore, such material has enormous potential in mitigating liquefaction when used them as drainage materials.

3.3. Test procedures

Two test cases were examined using the same soil box by mounting two gravity type model quay walls with different backfill conditions. In one case, a caisson with a rubble backfill with conventional sandy backfill behind it was used. In another case, behind the caisson, a cushion layer of tire chips (average grain size 20 mm) was placed vertically down. Also, vertical drains made out of tire chip (average grain size 7.0 mm), were installed in the backfill as shown in Figure 3. The cushion thickness was adopted to be 0.4 times of the wall height. In actual practice, the design cushion thickness will depend upon a lot of other factors such as height and rigidity of the structure, compressibility and stiffness of the cushion material. The effect of cushion thickness using a small-scale model shaking table test has been described in Hazarika et al. (2006). The average dry density of the tire chips cushion achieved after filling and tamping was 0.675 t/m^3.

About 50% to 60% of the relative densities were achieved after the preparation of the backfill. 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 input motion used was the N-S component of the strong motion acceleration recorded at the Port Island, Kobe, Japan during the 1995 Hyogo-ken Nanbu earthquake (M 7.2). The wave record of the motion is shown in Figure 6. 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. 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.

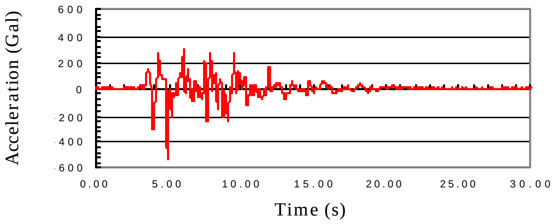
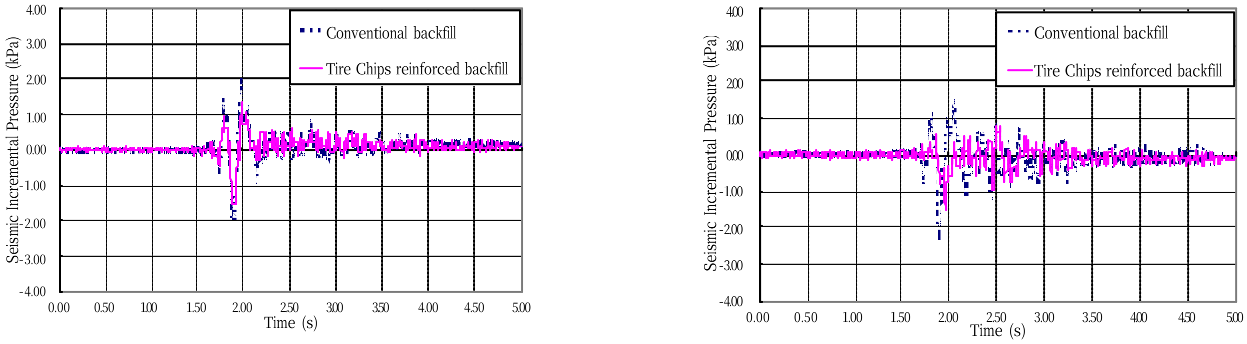


Figure 6. Input strong motion record (The 1995 Hyogo-ken Nanbu Earthquake)

4. MODEL TEST RESULTS

4.1. Seismically induced lateral thrust

Figures 7(a) and 7(b) show 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, the seismic increment is decreased to a considerable extent in tire chips reinforced backfill using the developed technique. Considering the fact that the static earth pressure itself will also be reduced (Hazarika et al., 2008) due to low weight and compressible characteristics of the cushion materials, the total seismic thrust acting on the structure can, 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.

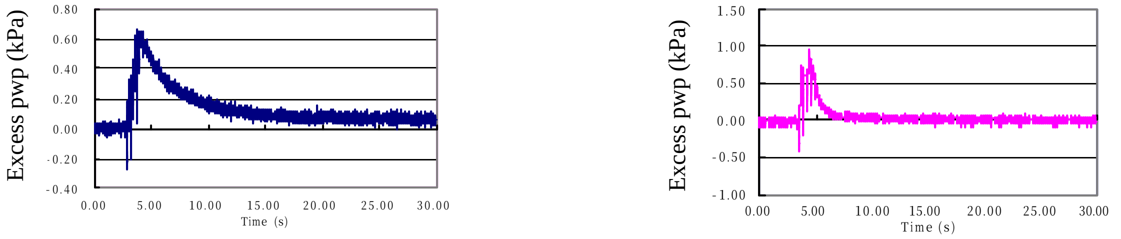


(a) At lower middle part (EP2 of Figure 3) (b) At upper middle part (EP3 of Figure 3)

Figure 7. Lateral seismic pressure on the quay wall

4.2 Liquefaction mitigation

In order to evaluate, whether the developed technique can minimize the liquefaction related damages, the time histories of the excess pore water pressure during the loading at a particular locations (B in Figure 3) for the two test cases are compared in Figures 8(a) and 8(b). Comparisons reveal that the pore water pressure build up is restricted due to dissipation by the permeable backfill condition. In the case of conventional backfill, the pore water pressure builds up and it takes considerable time (about 25 second) to dissipate. However, in the case of backfill improved by the new technique, the built up pore water pressure dissipates within a very short interval (2.5 second), preventing any chance for the backfill to liquefy.



(a) Conventional backfill (b) Improved by the new technique

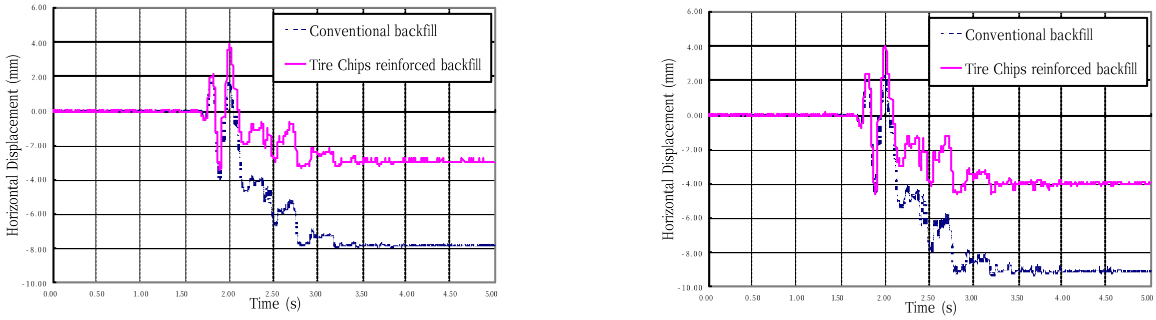
Figure 8. Liquefaction behavior

4.3 Seismically induced horizontal displacement

The time histories of the horizontal displacements (D1 and D2 in Figure 3) during the earthquake loading for the two test cases are compared in Figures 9. Comparisons reveal that the maximum displacement experienced by the quay wall with improved backfill (thick continuous line) is toward the backfill in contrast to the quay wall without any earthquake resistant 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 cannot move back to the opposite side and ultimately suffers from a huge permanent seaward displacement.

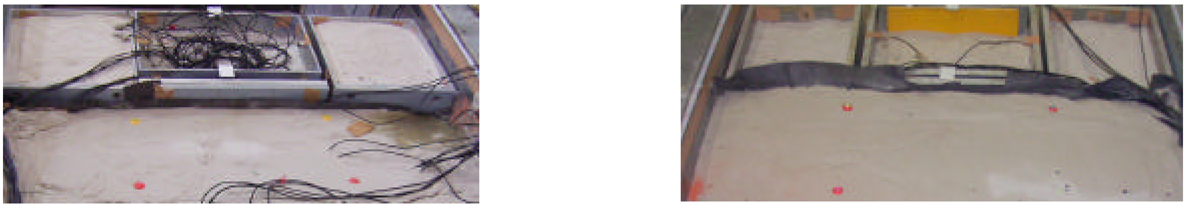
4.4 Qualitative evaluation of the seismic performances

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 tire chips material need to be compared. Figure 10 shows such comparison, in which the states of the backfill settlement at the end of the earthquake loading of maximum acceleration 1.5 times that of the 1995 Hyogoken Nanbu earthquake 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, the port facilities can remain operational, if the structure is reinforced with the earthquake resistant technique described here.



(a) Bottom of the wall (D1) (b) Top of the wall (D2)

Figure 9. Measured structural performance



(a) Conventional backfill (b) Improved by the new technique

Figure 10. Subsidence of the ground surface

5. CONCLUSIONS

Earthquake disaster mitigation technique described and evaluated here contains three most important and beneficial elements: low cost, good seismic performance and sustainable environment. 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 infrastructural 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 contribute towards a sustainable environment by recycling of the scrap tires as materials. The technique, thus, is expected to have a great potential in the cost-effective seismic design and retrofitting of structures. If adequate design method is established, the developed disaster mitigation technique could also be applied for upgrading (retrofitting) of the existing structures that run the risk of damages during devastating future earthquakes in Japan (such as strong metropolitan earthquake, Tokai earthquake, Tonankai-Nankai earthquake) as well as other earthquake prone countries in the world.

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