USE OF GRANULAR MATERIAL MADE FROM RECYCLED GLASS AS COUNTERMEASURE AGAINST EARTHQUAKE-INDUCED UPLIFT OF UNDERGROUND PIPES

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ABSTRACT: In order to study the validity of use of granular materials made from recycled glass as a countermeasure against earthquake-induced uplift of underground pipes, their permeability test was conducted, while referring to the results from relevant centrifugal model tests. Moreover, an estimation method on the validity of use of granular materials as the countermeasure against earthquake-induced uplift of underground pipes was proposed.

Key Words: granular material, liquefaction, underground pipe, recycled glass, permeability

INTRODUCTION

In Japan, a lot of transparent and brown colored glass bottles are recycled. However, a lot of other colored glass bottles are not recycled. It is difficult to reproduce uniformly-colored glass bottles from them because there are various kinds of other colored glass bottles. Thus, these glass bottles become wastes after single use. The total amount of the waste of glass bottles in Japan was 580,000 ton/year as of 2006 (GBRPA,2009). Therefore, granular materials made from recycled glass bottles have been developed for their effective re-use.

Since the above material having diameters in the range of 5 to 10 mm has a high permeability, it can be used as a countermeasure against earthquake-induced uplift of underground pipes. In order to confirm its applicability, Sugita et al. (2008) conducted a series of centrifugal model tests. Based on these results and permeability test results conducted by the authors, seismic behavior of the above material in prototype scale was estimated. Moreover, an estimation method on the validity of use of granular materials as the countermeasure against earthquake-induced uplift of underground pipes was investigated.

TEST CONDITIONS AND PROCEDURES

Model test conditions conducted by Sugita et al. (2008) are shown in Table 1. Granular materials made from recycled glass bottles are called simply as “Glass” below. Particle size distributions of backfill materials used in these tests are shown in Fig. 1.

In this study, the idea of particle size in prototype was used in order to take the “particle size effect”

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into account. In usual centrifugal model tests conducted under a centrifugal acceleration of nG, a model having a geometrical scale of 1/n is employed. However, as the geo-material model, the same material as used for the prototype is frequently employed, since it is in general difficult to reduce its geometrical scale without changing its mechanical properties. The effect due to the disagreement between the geometrical scales of the model and the geo-material is called herein as "particle size effect". In this study, the prototype Glass to be examined is relatively coarse as mentioned above. If the same material is used in centrifugal model tests, the uplifting displacement of underground pipe might be underestimated because relative larger particles can hardly move into the space under the pipe model when it starts to uplift. Therefore, the particle size effect should be considered properly in these tests.

Table 1. Test conditions (Sugita et al., 2008)

case	Backfill material	Degree of compaction	Centrifugal acceleration	Excitation condition	Pore fluid
06-00	Glass 1	91.3(%)*	25G	sin***, 10G	solution of
	Glass 2	91.3(%)*		25Hz,	methyl
	Glass 3	91.2(%)*		20cycles	cellulose (25cs)
07-00	Toyoura sand	96.6(%)**	15G	sin***, 8G	solution of
	Glass 4	82.6(%)**		30Hz,	methyl
	Fine sand	87.5(%)**		40cycles	cellulose (3cs)
08-00	Glass 4	89.9(%)**	15G	sin***, 8G	solution of
	Glass 5	89.9(%)**		30Hz,	methyl
	Glass 6	89.9(%)**		40cycles	cellulose (3cs)

* for the maximum density evaluated at compaction energy of about 550 kJ/m^3
** for the maximum density evaluated at compaction energy of about 2500 kJ/m^3
*** sin: sinusoidal

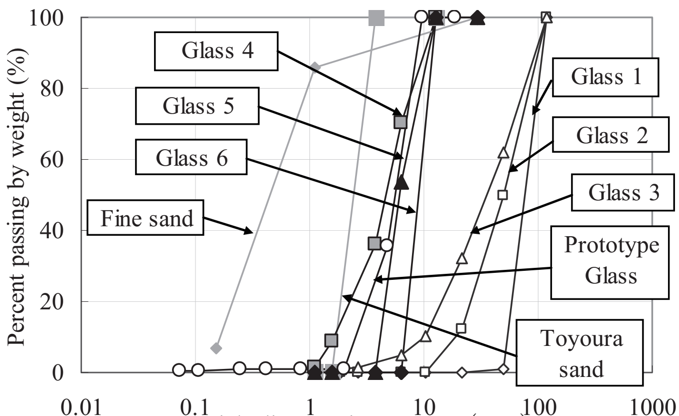
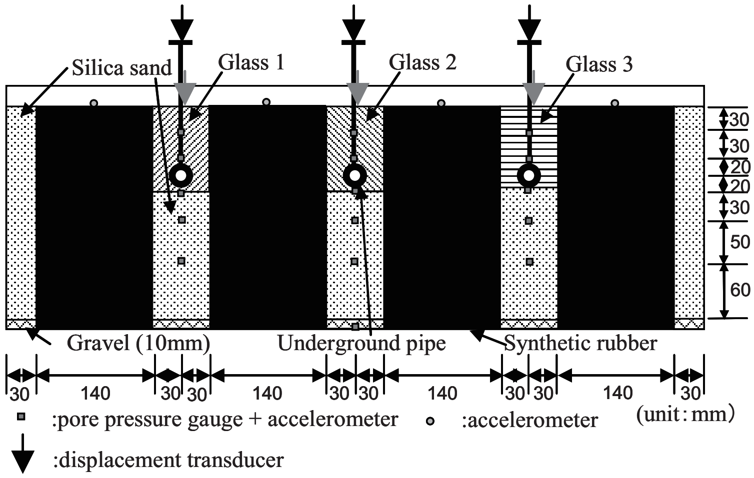


Figure 1. Particle size distributions

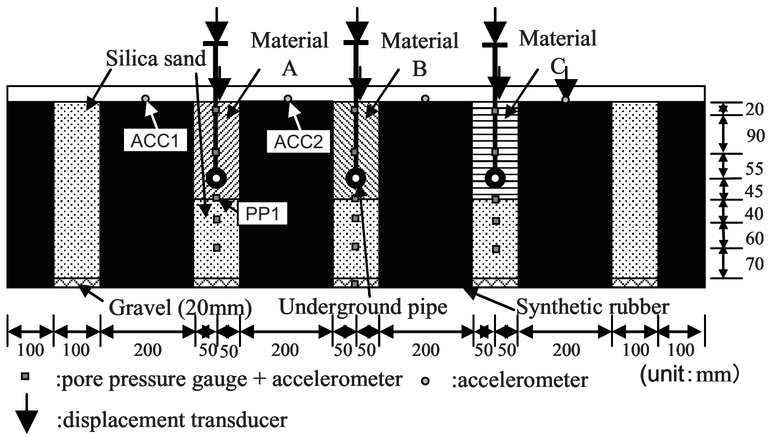
Figure 2 shows cross-sections of models in these tests. Synthetic rubber was used to model the original ground which was supposed to be soft ground like peat. Young's modulus of the synthetic rubber (=1.1 to 1.2 MN/m^2) was almost the same as that of typical peat ground. Its bottom was fixed to the base of the sand box. A gravel was placed below the original ground in order to make their saturation easily. In order to adjust the depth of the backfill layers, dense silica sand was placed between the backfill layers and the gravel layers.

In case 06-00, synthetic rubbers at both ends could not deform freely because these rubbers together with adjacent silica sand layers were constrained by the ends of the rigid sand box. Therefore, in cases 07-00 and 08-00, dummy backfill layers were added near the ends of the sand box in order to reduce the end restraint effect.

Underground pipe models used in these tests were 21 mm in diameter and 194.5 mm in length in case 06-00, and 30 mm in diameter and 295mm in length in cases 07-00 and 08-00. Apparent unit weight of these pipes was adjusted to 8 kN/m^3.



(a) Case 06-00



	Material A	Material B	Material C
Case 07-00	Toyoura sand	Glass 4	Fine sand
Case 08-00	Glass 4	Glass 5	Glass 6

(b) Case 07-00, 08-00

Figure 2. Cross-sections (Sugita et al., 2008)

Permeability tests on all of the backfill materials using water as pore fluid were conducted by the authors based on JIS A 1218. In addition, solutions of methyl cellulose with different viscosities were also used in permeability tests on Toyoura sand in order to evaluate the relationship between the viscosity of pore fluid and the permeability coefficient. Figure 3 shows the relationship between the viscosity of pore fluid and the permeability coefficient. These results revealed that the permeability coefficient was approximately in inverse proportion to the viscosity of pore fluid.

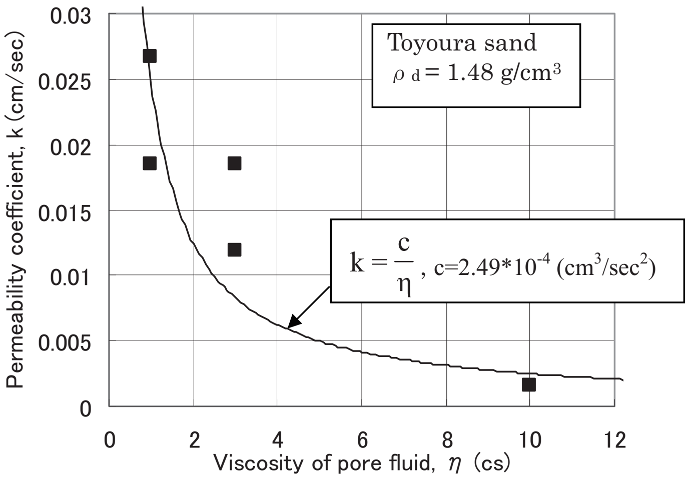


Figure 3. Relationship between permeability coefficient and viscosity of pore fluid

Table 2. Permeability coefficient in prototype

case	backfill material	Degree of compaction	permeability coefficient in prototype (cm/sec)
06-00	Glass 1	93.7(%)	$4.8*10^{-1}$
	Glass 2	92.5(%)	$4.0*10^{-1}$
	Glass 3	90.3(%)	$2.6*10^{-1}$
07-00	Toyoura sand	93.7(%)	$1.4*10^{-1}$
	Glass 4	80.1(%)	$1.2*10^{-1}$
	Fine sand	92.8(%)	$1.3*10^{-3}$
08-00	Glass 4	89.9(%)	$1.0*10^{-1}$
	Glass 5	89.9(%)	$6.0*10^{-1}$
	Glass 6	90.0(%)	$1.1*10^{0}$
Prototype Glass		92.2(%)	$0.3*10^{0}$

In the centrifugal model tests, the permeability in prototype as listed in Table 2 was evaluated using Eq. (1), which was derived based on the relationship shown in Figure 3.

$$k_p = k_{mw} \times \frac{\eta_w}{\eta} \times \frac{n_c}{n_g} \qquad (1)$$

in which k_p: permeability coefficient in prototype, k_{mw}: measured permeability coefficient of the material using water as pore fluid, η_w: viscosity of water, η: viscosity of pore fluid used in the centrifugal model test, n_c: centrifugal acceleration, and n_g: gravitational acceleration.

It should be noted that backfill material in cases 07-00 and 08-00 had smaller particle sizes than the prototype Glass. Therefore, less viscous pore fluid was used in these cases to compensate for the change in the measured permeability coefficient due to different gradations.

TEST RESULTS -UPLIFT OF UNDERGROUND PIPES-

Figure 4 shows the time histories of uplifting displacement of underground pipes in prototype.

In case 06-00, the pipe backfilled by Glass 3 uplifted a little by about 20 mm. Permeability coefficients of Glass 1, Glass 2 and Glass 3 were 0.48 cm/sec, 0.40 cm/sec and 0.26 cm/sec respectively. It could be inferred that uplift of underground pipes hardly occur under these conditions of permeability and compaction. On the other hand, as mentioned before, the particle size effect might be more predominant in this case.

In case 07-00, underground pipe in backfill of Glass 4 uplifted significantly by larger than 300 mm. The degree of compaction of Glass 4 was lower than that of Toyoura sand (Table 1), although the particle size distribution and permeability of Glass 4 were similar to those of Toyoura sand (Fig. 1 and Table 2). Therefore such severe uplifting displacement could be due to lower degree of compaction.

In case 08-00, the pipe in backfill of Glass4 uplifted a little by about 20 mm. The permeability of this material was lower than those of Glass 5 and Glass 6 (Table 2) because the particle size of this material was finer (Fig. 1). Therefore this small uplift could be due to lower permeability. The pipe in backfill of Fine sand in case 07-00 uplifted significantly by larger than 300mm. Such severe uplifting displacement could be also due to low permeability.

On the other hand, the pipe in the backfill of Glass 4 started uplifting during tapered excitation after the main excitation. In this case, 40 cycles were applied at a prototype frequency of 2Hz, while 20 cycles were applied at a prototype frequency of 1Hz in cases 06-00 and 07-00. Thus the total shaking duration in prototype in case 08-00 was the same as that in cases 06-00 and 07-00. Therefore the uplift of the pipe in the backfill of Glass 4 might be due to the effect of the larger number of cycles.

Relationships between the residual uplifting displacements of underground pipes in prototype and the permeability coefficients in prototype are shown in Fig. 5.

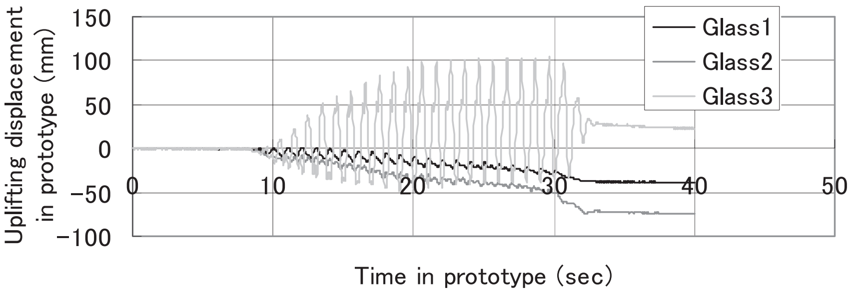
In case 07-00, the residual uplifting displacements of underground pipes could not be measured due to the overscaling of displacement transducers. Therefore, the residual uplifting displacements were evaluated as Eq.(2) in case 07-00. This evaluation could result into underestimation of the residual uplifting displacement, since settlements of underground pipes during the stage of reducing centrifugal acceleration was neglected. However, considering the possible error in the data measured with the displacement transducer due to inclination of its target, the accuracy of this evaluation was considered to be acceptable.

$$D_{res} = D_1 - D_2 \tag{2}$$

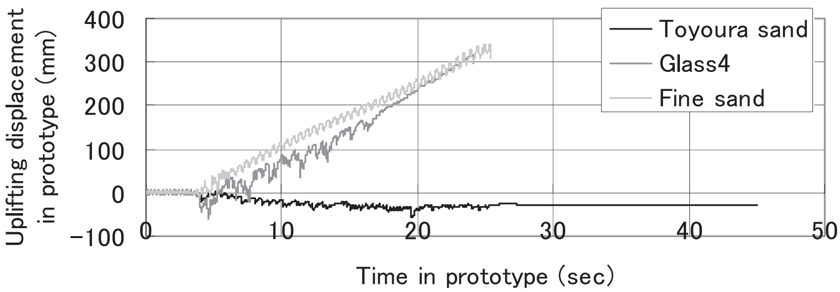
in which D_{res}: residual uplifting displacement, D_1: uplifting displacement measured by a ruler after the tests, and D_2: uplifting displacement (negative value) measured by displacement transducer during application of centrifugal acceleration and consolidation.

The test results using Glass 4 as the backfill material exhibited that employing enough compaction with the degree of compaction around 90% or more is effective in reducing the uplifting displacement.

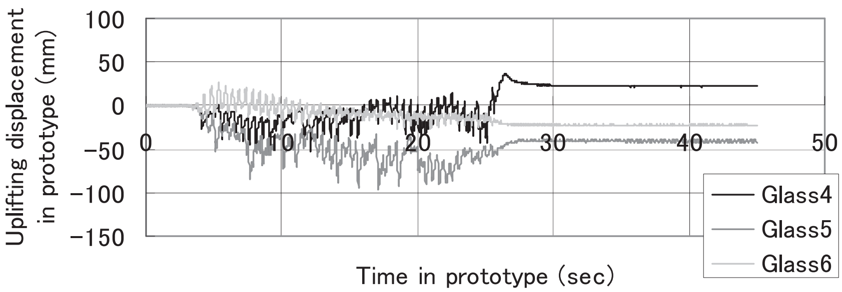
In cases where the degrees of compaction are around 90%, when the permeability coefficients exceeded about 0.1 cm/sec, uplift of underground pipes hardly occurred. Therefore the prototype Glass having diameters in the range of 5 to 10 mm, would not cause uplift of underground pipes under the backfill condition employed in these tests because the permeability coefficient of this material was about 0.3 cm/sec (Table 2). Moreover, it could be inferred that in cases where the degrees of compaction are around 90%, the relationship between the uplifting displacement and the permeability coefficient could be approximated by the broken curve as shown in Figure 5. Based on the curve, validity of use of granular materials as countermeasure against earthquake-induced uplift of underground pipes under the prototype backfill condition employed in these tests would be estimated.



(a) case 06-00



(b) case 07-00



(c) case 08-00

Figure 4. Time histories of uplifting displacement in prototype

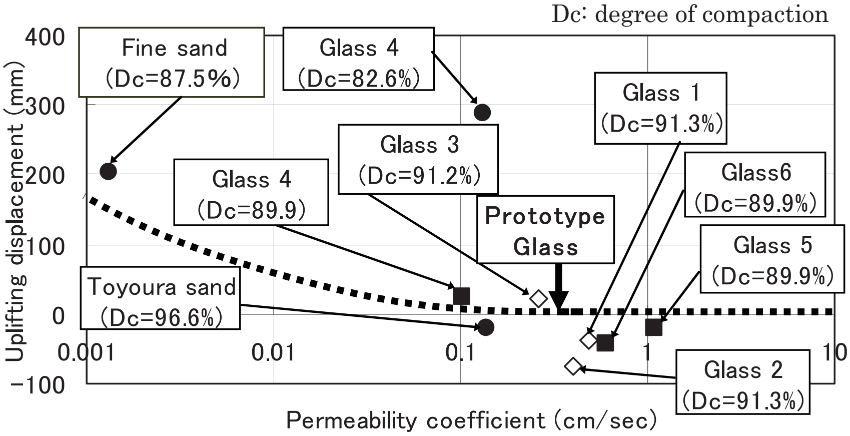


Figure 5. Relationship between uplifting displacement and permeability coefficient

TEST RESULTS -SETTLEMENTS OF GROUND SURFACE-

Figure 6 shows the time history of settlements of the ground surface in prototype in case 08-00.
The residual settlement of Glass 4 ground occurred hugely by about 700 mm. However, this value was possibly overestimated due to the movement of the target during shaking. In these tests, settlements at ground surface were displacements of targets set on ground surface measured by displacement transducers that were fixed to the top of the sand box. If the displacement transducers touch on the ground surface directly caused by the movement of targets, displacement transducer can stick into the ground easily. In Glass 4 ground, a dent due to the sticking of the displacement transducer was observed after the test.

On the other hand, residual settlements of Glass 5 and Glass 6 also occurred significantly by larger than 200 mm. Therefore, it is important to reduce not only earthquake-induced uplift of underground pipes but also settlements at ground surface in order to use granular materials as backfills of underground pipes.

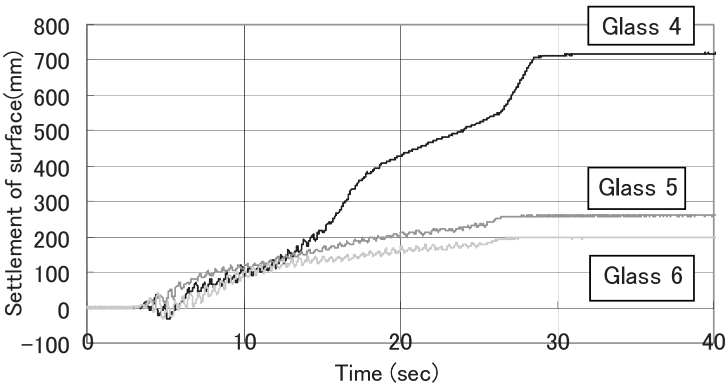


Figure 6. Time history of settlement at ground surface

TEST RESULTS -EXCESS PORE PRESSURE-

Figure 7 shows the time history of excess pore pressure measured at PP1 in case 08-00, Glass 4 (see Fig. 2 for the location of pore pressure gage). As typically shown in this figure, all of the time histories of measured pore pressure in the present model tests were with very spiky wave forms.

Dynamic pore fluid pressure in the backfill that was restricted by the synthetic rubbers could be generated during shaking. Therefore such dynamic pore fluid pressure might be one of the reasons for the spiky wave forms, while the amplitudes of the spikes were larger than those of the theoretical dynamic pore fluid pressures.

Figure 8 shows the time histories of response accelerations measured at ACC1 and ACC2 in case 08-00. They were different from each other. It could be due to the different degrees of end resistant effects. Therefore it could be inferred that horizontal cyclic loading was also applied on the backfill ground during shaking. Such horizontal cyclic loading might increase the amplitudes of the spikes of excess pore pressure.

In many of the model tests focusing on liquefaction, the degree of liquefaction has been evaluated based on excess pore pressure ratio. However, in the present model tests, the degree of liquefaction could not be properly evaluated due to the spiky wave forms as mentioned above. Therefore rational estimation techniques of degree of liquefaction should be studied more in the future.

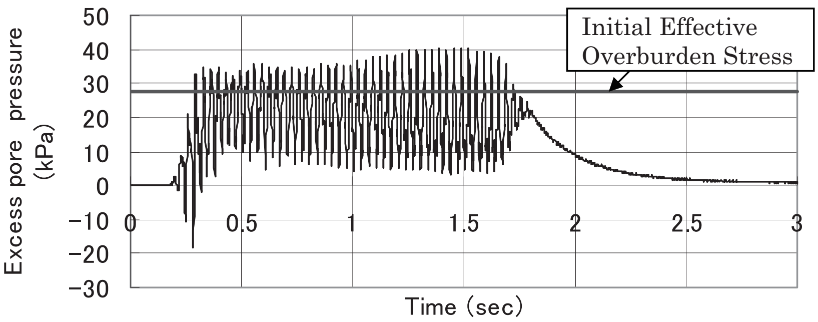


Figure 7. Time history of excess pore pressure (PP1, Glass 4, case 08-00)

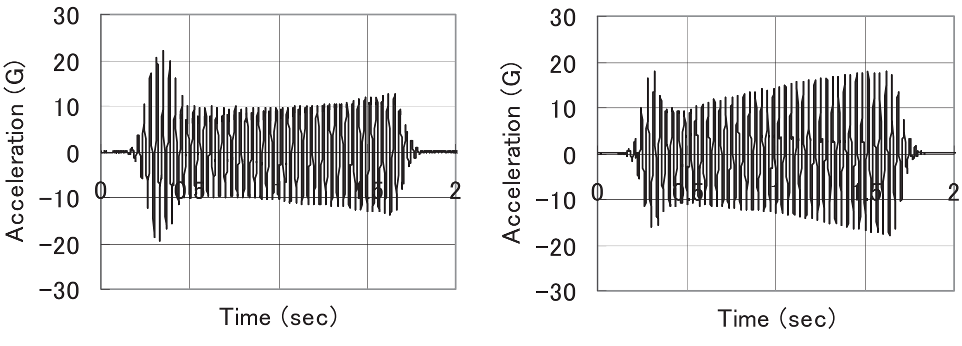


Figure 8. Time history of response acceleration of synthetic rubber (ACC1 and ACC2, case 08-00)

CONCLUSIONS

When the degree of compaction of backfill material was over 90% with permeability coefficient exceeding 0.1cm/sec, liquefaction did not occur under the conditions employed in the present model tests. Therefore the granular material made from recycled glass bottles having diameters in the range of 5 to 10 mm could be used as a countermeasure against earthquake-induced uplift of under ground pipes, because the permeability coefficient of this material is about 0.3 cm/sec.

Residual settlements of surfaces occurred severely in some model backfill ground. Therefore, not only resistance to earthquake-induced uplift of underground pipes but also resistance to settlements of surfaces should be secured in using granular materials as backfills of underground pipes.

ACKNOWLEDGEMENTS

The authors wish to thank Public Works Research Institute for providing the model test results that were analyzed in the present study

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