Effects of shaking histories and material properties on seismic performances of geogrid reinforced retaining walls and gravity type retaining walls

Effets des secousses et des histoires sur les propriétés sismiques performances de géogrille renforcée des murs de type et la gravité des murs

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ABSTRACT

A series of shaking table model tests on gravity type and reinforced soil retaining wall models was carried out so as to investigate into seismic behavior of retaining walls. In this study, seismic behaviors obtained from the step by step shaking tests were compared with the ones from the tests in which the models were subjected to large amplitude shaking from the beginning (i.e. no effects of the shaking history on seismic behavior). The test results revealed that the shaking histories had a significant effect on the seismic performance of the gravity type retaining walls, while it was not the case for the reinforced soil retaining walls. The former behavior is possibly affected by occurrence of local bearing capacity failure beneath the retaining walls. Effect of material properties of geogrid models (i.e. pullout resistance, rapture strength and tensile rigidity) on seismic performance of the reinforced soil retaining wall were also investigated in this study by using two diffrent types of geogrid models. Even though the material properties of the geogrid models were largely different, seismic performances of the retaining walls were almost equal to each other. This behavior can be explained by considering the difference in the pullout regidity between the two geogrid models which is not taken into account in the current design procedure.

RÉSUMÉ

Une série de secousses table essais sur modèle type et la gravité renforcée sol mur de modèles a été effectuée afin d'enquêter sur le comportement sismique de murs de soutènement. Dans cette étude, les comportements sismiques obtenues à partir de l'étape par étape, agitant des tests ont été comparés avec ceux de tests dans les modèles qui ont été soumis à des secousses de grande amplitude à partir du début. Les résultats des tests ont révélé que de secouer l'histoire a eu un effet significatif sur la performance sismique de la gravité de type murs, alors que ce n'était pas le cas pour le renforcement des murs de soutènement des sols. L'ancien comportement est susceptible d'être touché par la présence locale de la capacité portante échec sous les murs de soutènement. Effet des propriétés des matériaux de géogrille modèles sur la performance sismique des sols renforcés mur ont été également examinés dans cette étude en utilisant deux différents types de modèles géogrille. Même si les propriétés matérielles de l'géogrille modèles sont très différents, des spectacles de la sismique de murs de soutènement ont été à peu près égale à l'autre. Ce comportement peut être expliqué en considérant la différence dans le retrait regidity géogrille entre les deux modèles qui ne sont pas prises en compte dans la conception actuelle procédure.

Keywords : Shaking table model tests, Shaking history, Geogrid reinforced soil retaining wall, Gravity type retaining wall

1 BACKGROUND

In Japan, many studies on seismic behaviors of conventional type retaining walls (i.e. gravity type, leaning type and cantilever type retaining walls) subjected to large earthquake have been carried out so as to avoid severe damages to these retaining walls, which were typically caused by the 1995 Hyogo ken Nanbu-earthquake (Watanabe et. al., 2003, Kato et. al. 2002, and Nakamura, 2006). On the other hand, geosynthethics reinforced soil retaining walls (GRS walls) having a full-height rigid facing showed much higher seismic performance than the conventional ones, while the numbers of the constructions of the GRS walls have increased after the Hyogo ken Nanbu-earthquake (Tatsuoka et. al. 1998 and Koseki et. al. 2007).

Many studies on the seismic behaviors of GRS walls have been conducted so as to evaluate their ductile seismic behaviors properly. Based on the knowledge from these studies, a seismic design procedure has been developed and a procedure to evaluate seismic induced residual displacements has been also developed (Koseki et. al. 2004 and Horii et. al. 1999). However, effect of material properties of the geosynthetics reinforcement (e.g. rapture strength, tensile rigidity and pullout resistance etc.) has not yet been clarified.

A shaking table model test is widely conducted because it is one of the effective tools so as to investigate into the seismic behaviors of retaining wall (e.g. Bathurst et. al. 2002). In the shaking table model tests, a step by step shaking procedure in which the maximum input acceleration is gradually increased is frequently adopted as the shaking procedure although the cyclic loading has significant effect on the deformation characteristics of the granular geomaterials which are usually used as the backfill materials of the retaining wall. As far as the authors know, the effect of preceding shaking history on the seismic behaviors of the retaining wall has been investigated to limited

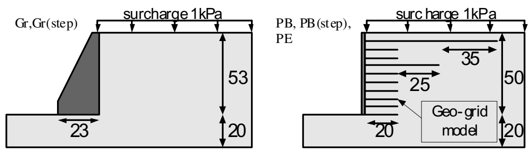

Fig. 1. Cross sections of model walls and ground (unit in cm)

Table 1. Summary for model test contitions

Test name	Type of wall	Reinforcement	Shaking condition	Ref.
Gr(step)	Gravity		0.1G～0.9G	Watanabe (2003)
Gr	Gravity		1G, two times	Watanabe (2007)
PB(step)	GRS	PB	0.1G～1.1G	Watanabe (2003)
PB	GRS	PB	0.9G～1.5G	Nakajima (2008)
PE	GRS	PE	0.9G～1.5G	Nakajima (2008)

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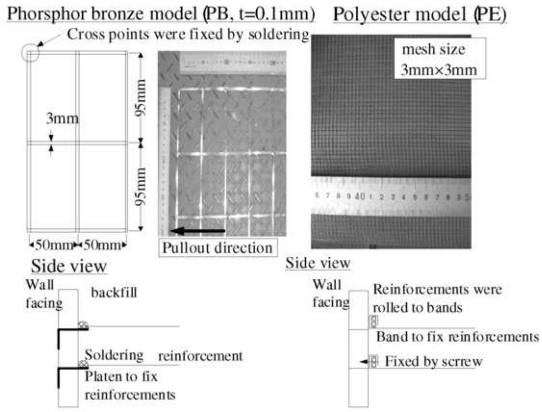

Fig. 2. Geogrid models (unit in mm)

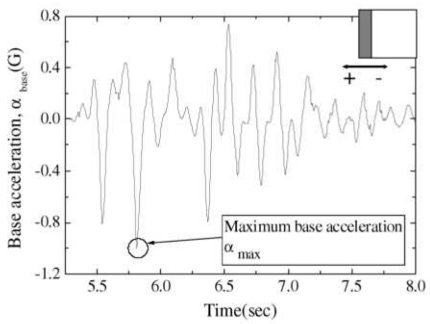

Fig. 3. Typical time history of irregular excitation

extents although the loading history seems to have significant effect on the seismic performance of the retaining wall.

Based on the above background, the effect of shaking history and material properties of the reinforcements for GRS walls on their seismic behavior are investigated in this study through the results from the shaking table model tests.

2 MODEL TEST PROCEDURE

Test conditions and the cross sections of the wall and ground model are summarized in Fig. 1 and Table 1, respectively. Test name in Table 1 will be used to refer each model test hereafter. As shown in Fig. 1, models of gravity type retaining wall and geogrid reinforced soil retaining wall with full height rigid facing are used in this study while the uppermost and middle reinforcements were extended to the unreinforced backfill in the model of GRS walls because this type of the arrangement showed good seismic performance as reported by Watanabe et. al.(2003). Two types of geogrid model were used in this study as shown in Fig. 2. One model was prepared by using lattice shaped phosphor bronze strips having a thickness of 0.1 mm and a width of 3 mm for each strip as also shown in Fig. 2, while the sand particles were pasted on the surface. Polyester mesh sheet were used for the other type of the geogrid model while the shapes and the procedure to fix the wall facing are also illustrated in Fig. 2.

Seismic load was applied by shaking the soil container horizontally using the irregular wave as typically shown in Fig. 3. In the case of tests Gr(step) and PB(step), the maximum input acceleration was gradually increased at an increment of about 0.1 G until the wall displaced largely. On the other hand, the models of test Gr, PB and PE were subjected to the large amplitude shaking (i.e. α_{max} in the first shaking was about 1.0 G for test Gr and 0.9 G for tests PB and PE) so as to simulate the real large earthquake. In tests PB and PE, the maximum acceleration was increased up to 1.5 G with an increment of about 0.3 G and in test Gr, the same amplitude shaking (i.e. 1.0 G) was applied twice.

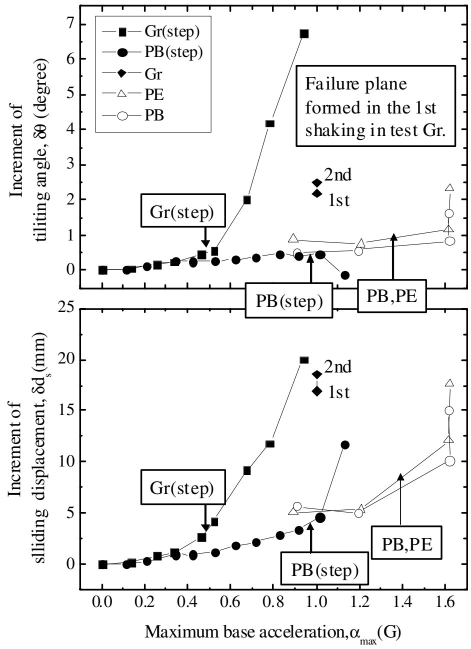

Fig. 4. Comparisons of residual displacement inclement

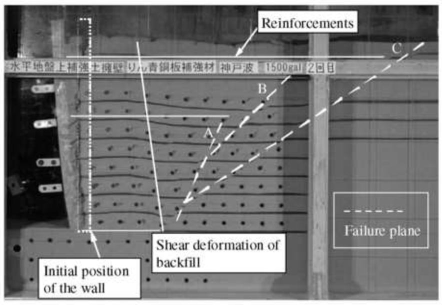

Fig. 5. Failure plane formation and backfill deformation (in test PB)

An air pluviation technique was used to prepare both subsoil and backfill layers with air-dried Toyoura sand at a relative density of about 90 %, which corresponds to the well compacted sands and gravels that are typically used for the backfill materials for the retaining wall. The details of model test procedures and geogrid models are reported in Watanabe et. al. (2003) and Nakajima et. al.(2008).

3 EFFECT OF SHAKING HISTORY ON SEISMIC BEHAVIOR

In the following discussions, the tests subjected to step by step shaking will be refferd as step shaking while the test subjected to the large amplitude shaking from the beginning will be called as large shaking. The increment of base sliding displacement and tilting angle, which are called as δd_s and $\delta\theta$ hereafter, are plotted versus the maximum base acceleration in Fig. 4. The timings of the failure plane formation in backfill layer, which is typically shown in Fig. 5, are also indicated by vertical arrows. As clearly shown in Fig. 4, GRS walls (tests PB, PE and PB(step)) showed higher seismic performance than the gravity wall (tests Gr and Gr(step)) regardless of the shaking history.

At low acceleration level (i.e. α_{max} is smaller than 0.4 G), the increment of the wall displacement in test Gr(step) was almost equal to the one in test PB(step) while drastic accumulation of the wall displacement was observed in case of test Gr(step) especially after the failure plane formation in the backfill layer at the shaking step of about 0.5 G. As compared with test Gr(step), in test PB(step), the failure plane did not form until higher acceleration level (i.e. at the shaking step of about 1.0 G) while rapid accumulation of the displacement increments was also observed after the failure plane formation. However, the displacement accumulation especially in tilting angle was rather gentle in tests PB(step) than that in test Gr(step). In the large shaking tests (Gr and PB), the same tendency with the step shaking was also observed in terms of the effects of the failure plane formation on the seismic behaviors.

The effects of the shaking history on the seismic behaviors of both GRS wall and gravity type retaining wall are discussed hereafter. In case of the GRS walls, the displacement increments in test PB and PB(step) were almost equal to each other at the shaking step of 0.9 G, which is the first shaking for test PB. This behavior indicates that the higher seismic performance of GRS walls was not lost even in case the preceding shakings were applied to the GRS wall. In test PB, the increment of the wall displacement during the shaking step of 1.2 G was almost equal to the ones in the shaking step of 0.9 G, while the increments of wall displacement in test PB were accumulated at the shaking steps of 1.0 G to 1.1 G because of the failure plane formation in the backfill at 1.0 G shaking step as indicated in Fig. 4.

Effect of shaking history on the seismic performance of gravity type retaining wall will be discussed hereafter. However, it should be noted that the maximum acceleration employed in test Gr(step) was about 0.9 G while that of test Gr was about 1.0 G. The value of δd_s in test Gr(step) was slightly larger than the one of test Gr at these shaking levels while the value of $\delta\theta$ in test Gr(step) was much larger than the one in test Gr. This behavior was possibly because of the effect of the local bearing capacity failure in the subsoil in test Gr(step). In test Gr(step), the preceding shaking induced the residual tilting displacement of the wall, which caused the local bearing capacity failure due to the stress concentration beneath the toe of the footing. As reported in Watanabe et. al. (2003), local bearing capacity failure in the subsoil caused the drastic increase of the wall displacement. Therefore, the discrepancy in terms of the amplitude of the tilting displacement increment between the tests Gr and Gr(step) was caused by the local bearing capacity failure due to the preceding tilting displacement in test Gr(step).

4 EFFECT OF MATERIAL PROPERTIES OF GEOGRID ON SEISMIC BEHAVIROS OF GRS WALLS

4.1 *Shaking table model tests*

Effect of material properties of geogrid reinforcements will be discussed by comparing the results of tests PB and PE. As shown in Fig. 4, the values of δd_s before the failure plane formation were almost equal to each other while the values of test PE became larger than the one in test PB after the failure plane formation. In contrast, the values of $\delta\theta$ in test PB were smaller than the ones in test PE during the whole shaking steps.

The photo taken after the second shaking step 1.5 G in test PB is shown in Fig. 5. Reinforced backfill, where the backfill reinforced with the geogrid reinforcements having a length of 20 cm was installed, was subjected to shear deformation. In case of the tests on GRS walls, the tilting displacement increments due to the subsoil deformation were not observed although such deformation were observed in case of the gravity type retaining wall, which is associated with the bearing capacity failure. Therefore, the shear deformation characteristics of the reinforced backfill shall be further investigated in evaluating earthquake-induced residual displacement of GRS walls.

It was also found from Fig. 4 and Fig. 5 that the wall displacement increased rapidly after the failure plane formed just outside of the uppermost reinforcement while the two failure planes (A and B in Fig. 5) formed before the final one (C) did not reach to the surface of the backfill because the uppermost reinforcement restricted their progressive formation.

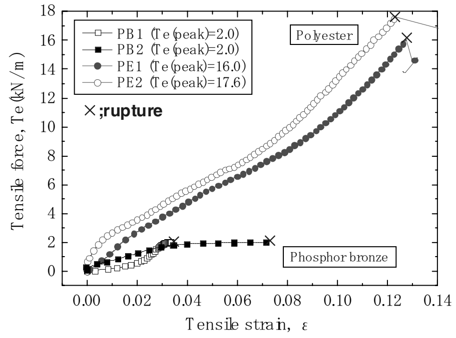

Fig. 6. Relationships between tensile force and tensile strain

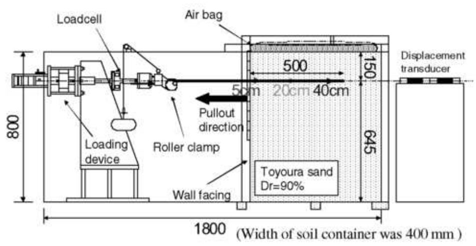

Fig. 7. Test apparatus for pullout test (unit in mm)

In additions to the restraint effect of the failure plane formation by the uppermost reinforcement, pullout resistance around the surface of the uppermost reinforcement, which improved the seismic performance of GRS walls effectively, was also mobilized when the reinforced backfill was subjected to the shear deformation. Based on the above discussions, material properties of geogrid models were also investigated so as to understand the model test results on PB and PE.

4.2 *Pullout tests and direct tension tests on geogrid models*

As shown in Fig. 4, the seismic performance of the GRS walls reinforced with different geogrid models was almost equal to each other although the shapes and rigidity of geogrid models used in this study were largely different. Therefore, direct tension tests and pullout tests on the geogrid models were carried out so as to investigate how the different material properties affected on the seismic performance of GRS walls.

Tensile force-strain relationships for both reinforcements PB and PE are summarized in Fig. 6 while the values of tensile force are converted to the values per unit width. As clearly shown in Fig. 6, the rapture strength of the reinforcement model PE was much larger than that of PE because the numbers of strips parallel to the tensile loading in model PE was larger than the ones of model PB as indicated in Fig. 2.

As mentioned above, the extended reinforcement could work effectively to improve seismic performance of the GRS walls because of the pullout resistances and the restraint effect of the failure plane formation. In this study, the pullout tests were also carried out so as to investigate into the effect of pullout resistances on the seismic behaviors of GRS walls.

The apparatus for pullout test is shown in Fig. 7. The reinforcement model was placed on the model ground consisting of air-dried Toyoura sand with relative density of about 90 %. Tests were conducted under the overburden pressure of about 5 and 10 kPa, which correspond to those of the middle and bottom depth of the backfill in the shaking table model tests.

In the series of the test, three types of the geogrid models were tested. The geogrid model PB2, which were made by the phosphor bronze strips with a thickness of 0.2 mm, was also tested as well as the models PB and PE which were the same geogrid models as used in the shaking table model tests. The relationships between pullout resistances and pullout displacement are shown in Fig. 8. In Fig. 8, test result using the

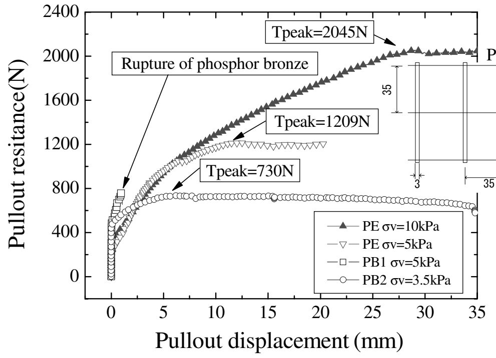

Fig. 8. Results obtained from pullout tests

other type of phosphor bronze geogrid model (PB2) is also indicated while the shapes of the geogrid models are also indicated in the figure (pullout test on the model PB2 was conducted by Nojiri et. al. 2007). As clearly shown in Fig. 8, the maximum pullout resistance of the reinforcement PE was larger than the ones of the reinforcements PB and PB2. In the case of test on reinforcement PB1, rapture of the reinforcement occurred although the mobilized resistance was higher than that of the reinforcement PE before the rapture of the strip.

In the test on reinforcement PB2, the rapture of the strip did not occur because the phosphor bronze strip was thicker than the reinforcement PB. As shown in Fig. 8, the maximum values of pullout resistance or rapture strength in the tests PB1 and PB2 were smaller than the ones of reinforcement PE while the larger resistances were mobilized especially at small pullout displacement level.

4.3 *Discussions*

Based on the test results on the material properties of geogrid models, the observed seismic behaviors in the shaking table model tests will be investigated. In the relevant design guideline for GRS walls (e.g. RTRI, 2007) the smaller value between rapture strength of the reinforcement and the maximum pullout resistance is adopted as the mobilized resistance by the reinforcement. However, the seismic behaviors observed in the tests PB and PE were not so largely different from each other although the material properties of geogrid models were quite different. In detail, higher seismic performance was observed in test PB, although both the rapture strength and the maximum pullout resistance were smaller than those of test PE. This behavior can not be explained by the above definition.

Mobilization of the pullout resistance before the rapture of the reinforcement shall be highlighted in these model tests because the rapture of the reinforcements was not observed. As discussed above, higher resistance was mobilized by the reinforcement PB than the reinforcement PE especially before the rapture of the reinforcement as shown in Fig. 9. Therefore, especially in terms of the tilting of the wall, the model wall PB showed higher seismic performance than the model wall PE because the pullout resistance mobilized by the uppermost reinforcement had significant effect in increasing the resistant moment against overturning of the wall.

This consideration indicates that the pullout rigidity of the reinforcement, which can be expressed by the slope of the pullout resistance-displacement relationship, shall be properly taken into account especially in the performance based design which typically evaluates the seismic performance of the GRS walls in terms of the residual displacements while the maximum values of pullout resistances or rapture strength are highlighted in most of the relevant design guidelines in Japan.

5 SUMMARY

The conclusions from this study can be summarized as follows;

a) Effect of shaking history on the seismic performance was not significant in the GRS walls in the case where the failure plane did not form in the backfill layer.
b) Effect of the shaking history was significant for the gravity type retaining wall because of the effect of the bearing capacity failure caused by the preceding tilting displacement of the wall.
c) Both the maximum pullout resistance and the rapture strength of the reinforcement PE were larger than the ones of the reinforcement PB although the seismic performances in the shaking table model tests were almost equal to each other.
d) The above behavior was possibly because of the mobilization of larger pullout resistance at small displacement levels of reinforcement PB than that of reinforcement PE even though such displacement dependant pullout resistance has been less highlighted.

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