SEISMIC STABILITY OF SATURATED REINFORCED SOIL WALLS

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ABSTRACT

This paper studies the effect of saturation of backfill on the seismic stability of reinforced soil walls (RSWs) using centrifuge shaking table tests. For comparison, degradation of static stability and seismic stability of a RSW under unsaturated condition was also investigated. Test results showed that the RSW under saturated condition had enough static stability. However, seismic stability of saturated RSW significantly decreased as compared with that under unsaturated condition. The saturated model RSW did not collapse, though it showed large deformation. It maintained sufficient stability after shakings although a clear slip surface appeared in the backfill. Finally, it is discussed how to evaluate residual stability of RSWs damaged by earthquakes with test results and the simple evaluation method proposed by authors.

Key Words : Reinforced soil wall, Saturated, Seismic stability

1 INTRODUCTION

Many embankments and natural slopes were heavily damaged in 2004 Niigata-ken Chuetsu Earthquake probably due to high water content caused by Typhoon No. 23, which hit the shaken area a few days before the earthquake (JGS 2008). Reinforced soil walls (RSWs) were not exception and suffered large deformation, although it is well known that RSW can show very high seismic resistance. It is probably due to insufficient drainage works, which resulted in high water content in backfill. However, such damaged RSWs did not fully collapse, and maintained sufficient static stabilities. In such cases, it is necessary to evaluate residual seismic stability of the RSW and assess the necessity of repair work or reconstruction soon after the earthquake for quick recovery of infrastructures. Therefore, such assessment should be made usually based only on surface deformation, such as wall displacement or settlement at the crest without detailed investigation. This study investigated the effect of saturation in backfill of RSW on static and seismic stability of RSW with centrifuge model tests at first. Then, it is discussed how to evaluate residual seismic stability of RSW damaged by earthquake.

2 CENTRIFUGE MODEL TESTS

2.1 Model setup

Centrifuge tests were conducted using Tokyo Tech Mark 3 Centrifuge and Horizontal-Vertical 2D shaker (Takemura et al. 2002). Figure 1 shows a schematic view of the model reinforced soil wall used in the tests.

Backfill was made of dry Toyoura sand with relative density of 80%. Height of the RSW was 200 mm in model scale, which corresponded to 10 m in prototype in the operation centrifugal acceleration of 50 g. Similitude of RSW model test in centrifuge is described by Izawa and Kuwano (2010). The model RSW was reinforced with poly-carbonate plate with 0.5 mm thick and 9 mm wide, which modeled steel strip type reinforcement. The model RSW was designed based on Japanese standard (PWRC 2003). As shown in Figures 1 and 2, four reinforcements were attached to each divided facing wall panels, which was made of 3mm
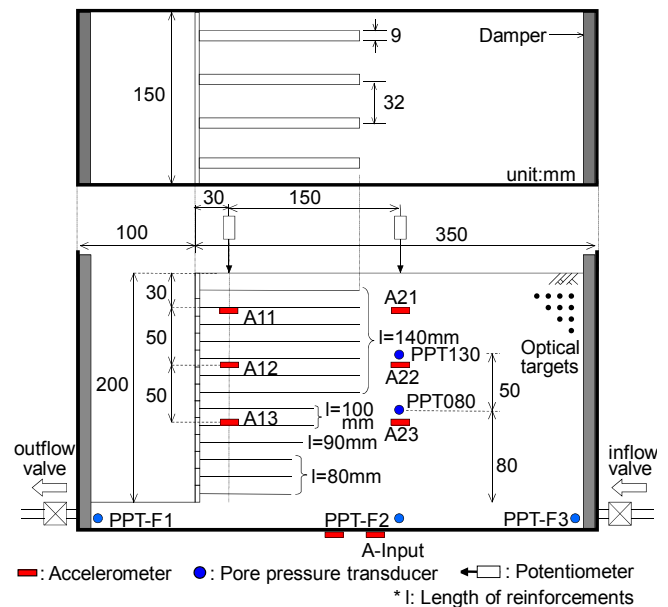

Figure 1. A schematic view of a model RSW.

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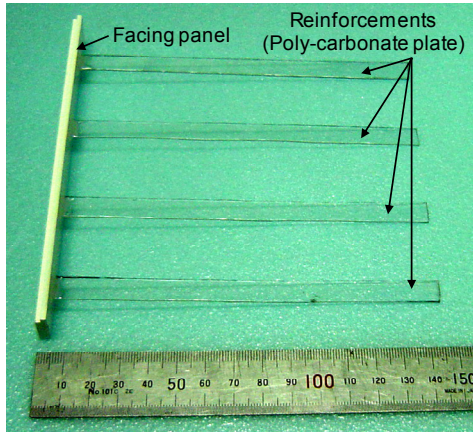
Figure 2. Model reinforcement and a facing panel.

Table 1. Properties of Toyoura sand (Dr=80%).

Average particle size	$: D_{50}$	0.19 mm
uniformity coefficient	$: U_c$	1.56
Permeability	$: k$	2.0×10^{-4} m/sec
Internal frictional angle	$: \phi'$	41.0 degree
Dry unit weight	$: \gamma_d$	15.4 kN/m^3
Saturated unit weight	$: \gamma_{sat}$	19.4 kN/m^3
Submerged unit weight	$: \gamma'$	9.59 kN/m^3

Table 2. Properties of the model reinforcements.

Tensile stiffness		506.8 (kN/m)
Pullout frictional angle	$: \phi_p$	12.9 (deg.)

thick acrylic plate. Table 1 and 2 summarize properties of Toyoura sand and model reinforcements, respectively. Frictional angle between Toyoura sand and Poly-carbonate plate was determined from the direct shear tests. Some optical targets were set in the front surface of the model in order to observe deformation in detail through the CCD-Camera. Displacement vectors and strain distributions were obtained from the displacements of the targets.

2.2 Test Procedure

Three kinds of tests, i.e. saturation test, shaking table tests for unsaturated model and saturated model, were conducted according to the test procedure shown in Table 3 using one model RSW. Details are described as follows.

2.2.1 Saturation test

This test was conducted to investigate instability of RSWs due to change in stress in backfill as a result of saturation. In this test, the water level was raised up to 20 mm above the upper surface of the RSW through the rotary joint and solenoid valve at a 50 g centrifugal acceleration. Figure 3 shows a conceptual diagram of the saturation test. Note that the front side of the RSW was also filled with water which is observed in the case of the RSW at the reservoir but not realistic in the case

Table 3. Test procedure.

1. Increase of centrifugal acceleration up to 50G
2. i) Raising the water table
       decrese the water table
   ii) Shaking table test for unsaturated model
3. Decrease of centrifugal acceleration up to 1G
4. Saturation of backfill at 1G
5. Increase of centrifugal acceleration up to 50G
6. Shaking table test for saturated model
7. Decrease of centrifugal acceleration up to 1G
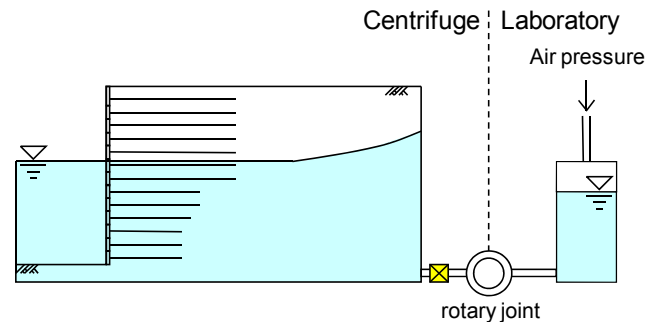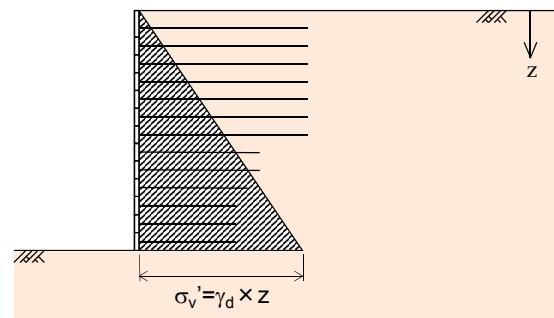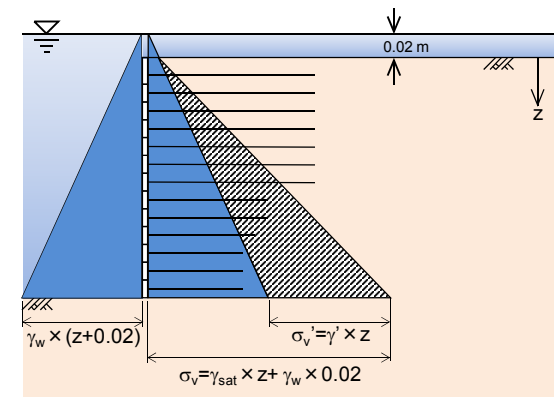

Figure 3. Model reinforcement and a facing panel.

(a) Dry conditions

(b) Saturated conditions

Figure 4. Vertical stress distributions in the RSW.

of embankment after heavy rain. Vertical stresses under dry and saturated conditions are schematically drawn in Figures 4a and b, respectively. It is thought that safety of the RSW was higher than under the real situation with unsaturated backfill because water pressure acting on the front wall provides resistance against the movement in the active direction of the RSW.
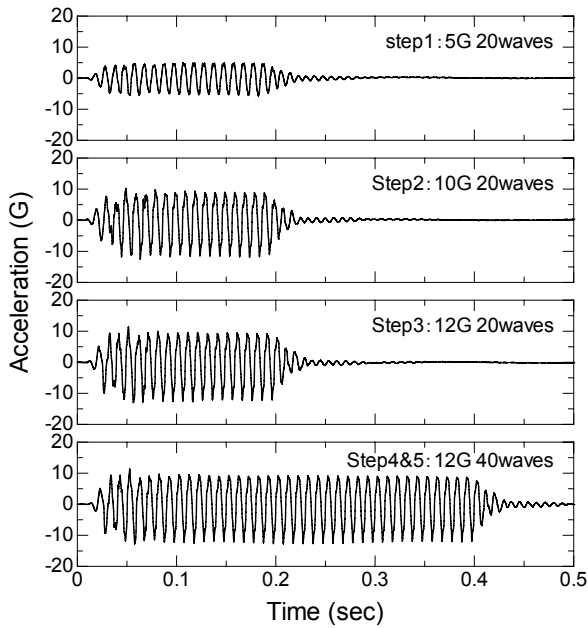
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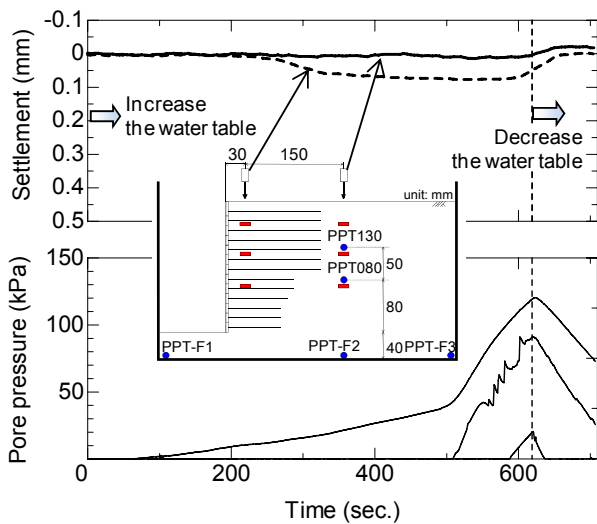Figure 5. Time histories of input accelerations.

Figure 6. Time histories of settlement due to saturation.

After raising the water table up to the prescribed level, water was drained away by opening the solenoid valve for outflow.

2.2.2 Shaking table test for the unsaturated model

After draining away water from the backfill, sinusoidal waves with frequency of 100 Hz were applied to the RSW at a centrifugal acceleration of 50 g. In this test, backfill of the RSW were under partly saturated condition as the water was not completely drained. Thus, shear stiffness and strength of backfill was expected to be higher than those under dry and saturated conditions. Figure 5 shows time histories of the sinusoidal waves applied to the model in the saturated test case. In the unsaturated case, only step 1~step 3 were applied. As described later, deformation of the model was little. Therefore, the same model
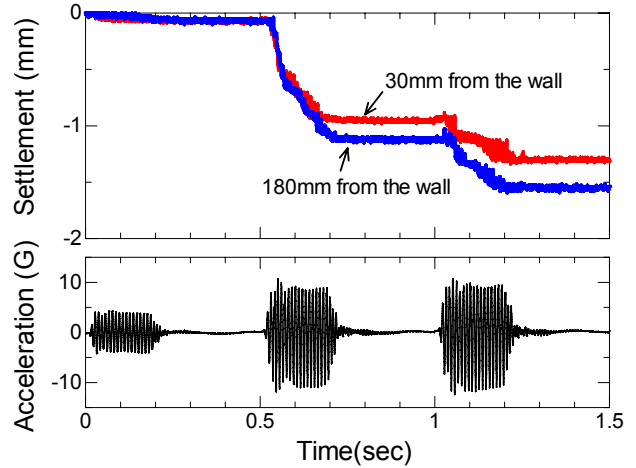

Figure 7. Time histories of settlement in the shaking table test with unsaturated backfill.

RSW was used in the shaking table test for the saturated model.

2.2.3 Shaking table test for the saturated model

After completing the shaking table test for the unsaturated model, centrifugal acceleration was decreased to 1 g once, and the model was filled with water in the 1 g field. Subsequently, shaking table tests were carried out under centrifugal acceleration of 50 g to know the effect of saturation on seismic stability of RSWs. Applied accelerations are indicated in Figure 5.

3 RESULTS AND DISCUSSIONS

3.1 Saturation test

Figure 6 shows time histories of settlement at the crest together with pore water pressure change at the base (PPT-F2) observed in the saturation test. Saturation of backfill led to degradation of stability of the RSW due to a decrease of effective stress. In this case, effective stress was reduced by about 38 % due to saturation, compared with dry conditions. This could cause decrease of frictional resistance between soil and reinforcement as well. However, the model RSW showed little deformation as shown in Figure 6, and maintained sufficient static stability.

3.2 Shaking table test for unsaturated model

Following the saturation test, the centrifuge shaking table test on the RSW under unsaturated condition was conducted. Time histories of settlements at the crest and input accelerations are shown in Figure 7. The settlements accumulated with shaking, but the RSW did not collapse and became stable again after shaking. In general, stiffness of soil decreases with increase in strain. However, settlement induced in step 3 was smaller than that in step 2, although almost the same input acceleration was applied to the model in both
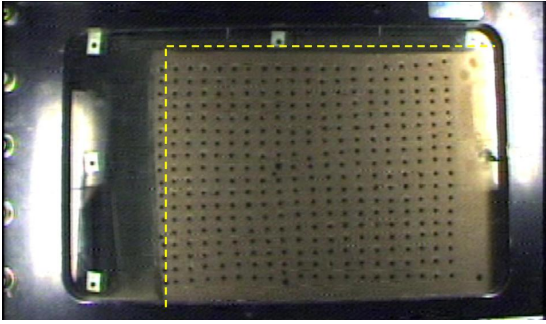
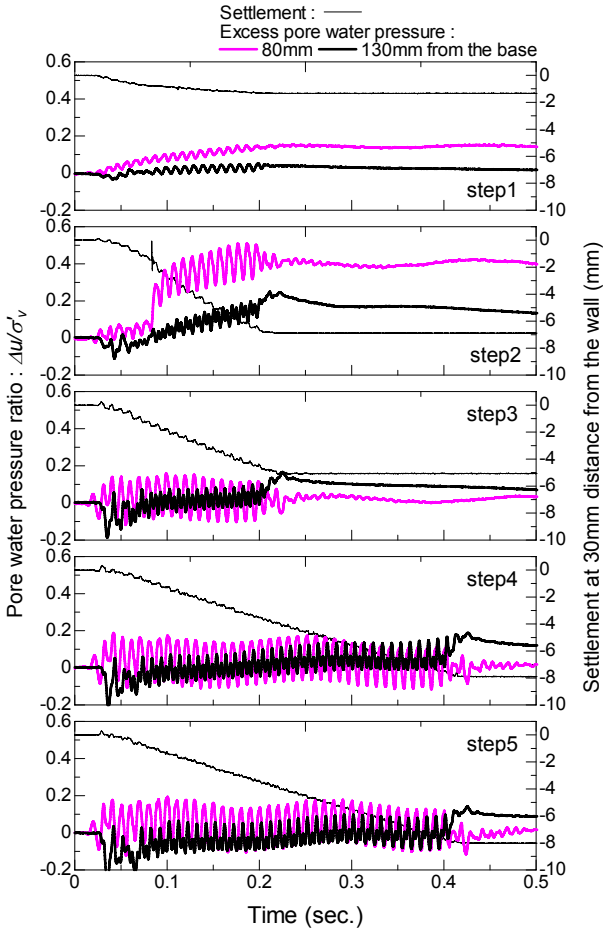Figure 8. Deformation of saturated RSW after shaking.

Figure 9. Time histories of excess pore water pressure and settlement in saturated case.

steps. The possible reason is that decrease of stiffness of the backfill could be prevented by tensile stress generated in reinforcements due to deformation of the RSW.

3.3 Shaking table test for saturated model

Finally, the centrifuge shaking table test on the RSW in saturated condition was made. Figure 8 is a picture of the deformed RSW after the 5th shaking step. Time histories of excess pore water pressure ratio, $r_u = \Delta u/\sigma_v'$, are given in Figure 9, where Δu and σ_v' indicate excess pore water pressure during shaking and the initial
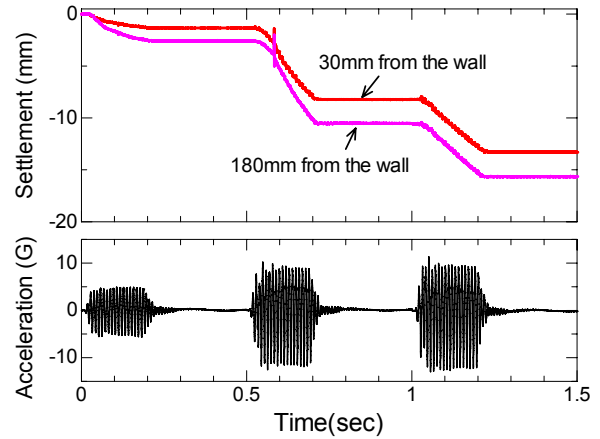

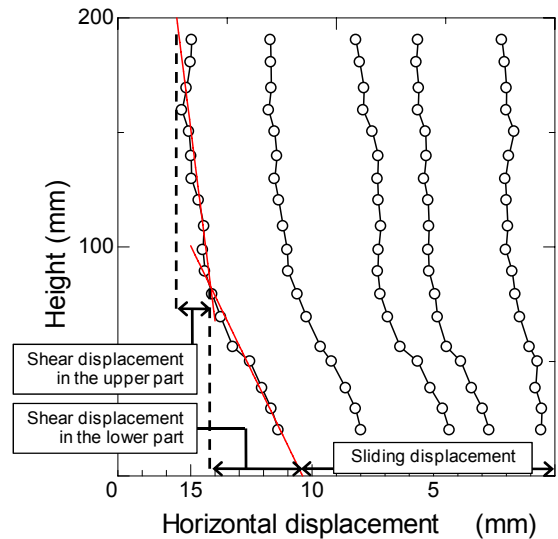Figure 10. Time histories of settlement in saturated case.

Figure 11. Vertical distribution of horizontal displacements at the facing in saturated case.

effective vertical stress, respectively. Obviously, r_u did not reach 1.0, that is, liquefaction did not occur during shaking in all steps. However, as shown in Figure 10, which indicates the time histories of settlements at the crest together with input accelerations, very large settlements were observed in the saturated case as compared with those in the unsaturated case indicated in Figure 7. As shown in Figure 9, dynamic amplitude of r_u was about 0.2, and it could lead to significant decrease of stability of the saturated RSW.

Vertical distributions of horizontal displacement of the wall are shown in Figure 11, which were obtained from the displacements of the optical targets set in the model. Horizontal displacement can be divided into three components, which are sliding displacement, shear displacements in the upper part and in the lower part, as shown in Figure 11. Each component after each shaking step is plotted in Figure 12.

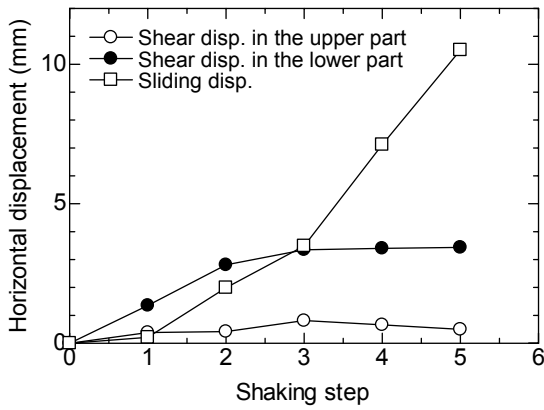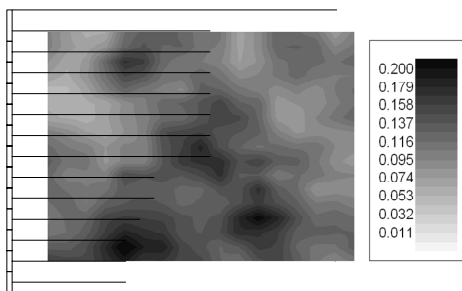Shear displacement in the upper part were smallest in all steps. Shear displacement in the lower part was
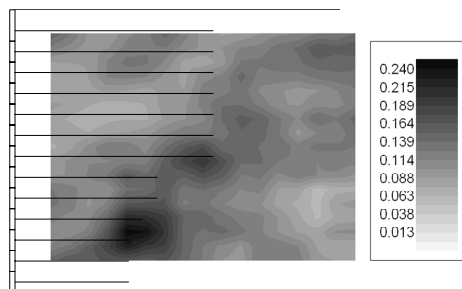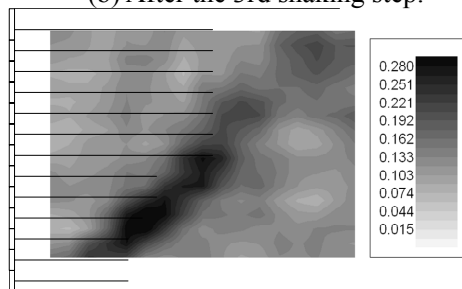
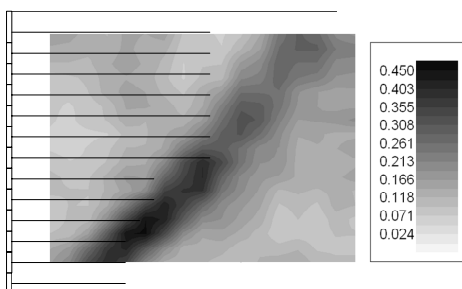Figure 12. Components of horizontal displacement.

(a) After the 2nd shaking step.

(b) After the 3rd shaking step.

(c) After the 4th shaking step.

(d) After the 5th shaking step.

Figure 13. Distribution of γ_{max} in saturated case.

dominant until the 2nd shaking step, and then stayed almost constant. Horizontal displacements due to sliding became significant after the 3rd step, although these began to increase from the 2nd shaking step.

Figure 13 shows distributions of maximum shear strain, γ_{max}, calculated from displacements of optical targets. In these figures, concentrated area of γ_{max} is considered to show a slip surface. Viewed in this light, a clear slip surface can be seen in and behind the reinforced area after the 4th shaking step. However, concentration of γ_{max} around the slip surface can be detected also after the 2nd and the 3rd shaking step, although they are not so clear. This means that the slip surface already began to form during the 2nd shaking step. Formation of the slip surface might trigger rapid increase of sliding displacement of soil wedge above the slip surface. However, sliding displacement increased after the 2nd shaking step, as shown in Figure 12.

These test results lead us to the following summary. RSWs can maintain their sufficient static stability even if the backfill is saturated with water. Seismic stability, however, may significantly decrease, and a clear slip surface will finally appear. RSWs without a slip surface show large shear deformation especially at upper part during shaking. After formation of a slip surface, sliding displacement became dominant. That is, the deformation mode of RSWs will change due to the formation of a slip surface and deformation of RSWs may rapidly increase. Therefore, for assessment of residual seismic stability of RSWs damaged in an earthquake, it is important to decide whether a slip surface has appeared in RSWs or not.

3.4 Formation of slip surfaces

As described above, formation of a slip surface is the important factor indicating residual seismic stability of RSWs damaged in an earthquake. Authors have proposed a simple method for evaluating the formation of a slip surface in geogrid reinforced soil walls using only inclination of the facing wall (Izawa and Kuwano, 2009 and 2010), as summarized below.

Firstly, the maximum shear strain of backfill, γ_{max}, is calculated using the following equation.

$$\gamma_{max} = 2\theta \qquad (1)$$

where θ indicates inclination of the facing wall. This equation was originally derived by Bransby and Milligan (1975) with simple plastic theory. Note that the effect of dilatancy angle is neglected in this study because effect of that on the calculation results is very small. It is expected that backfill soil in RSWs fails and a slip surface appears when the maximum shear strain in backfill reaches its peak strength state. Thus, if the maximum shear strain calculated by the Equation 1 exceeds the peak value of backfill soils, it can be expected that a slip surface has already appeared, and
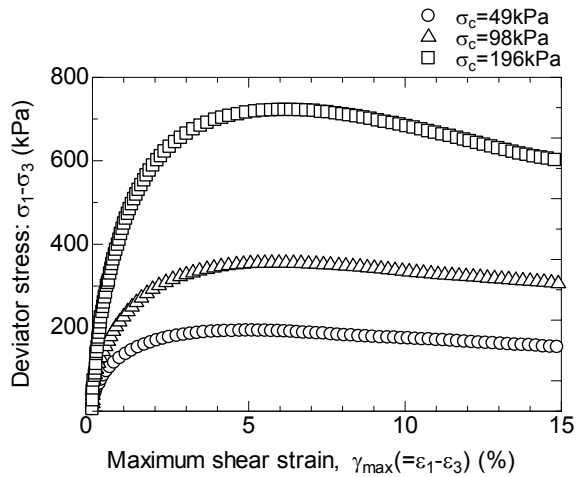
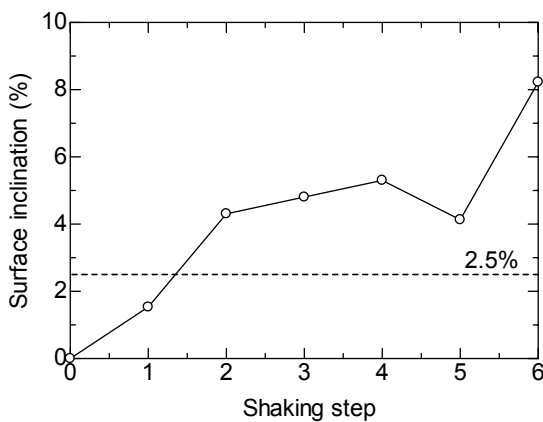Figure 14. Results of triaxial tests on Toyoura sand.

Figure 15. Facing inclination at the lower part after each shaking step.

large deformation may occur due to the coming earthquakes. Applicability of this method was confirmed with the results of centrifuge tilting and shaking table tests on geogrid reinforced soil walls having some kinds of dry backfill soils and geogrids (Izawa and Kuwano, 2009 and 2010). Applicability of this method to the RSW under saturated condition is discussed below.

Figure 14 shows relationships between deviator stress and maximum shear strain of Toyoura sand with relative density of 80%, which were obtained from drained triaxial tests under confining pressure of 49, 98 and 198 kPa. Note that the maximum shear strain was calculated. Toyoura sand develops a peak value of deviator stress at γ_{max} = 5.10%, 6.19% and 6.36% for confining pressures of 49, 98 and 198 kPa, respectively.

In the model RSW used in this study, effective stress at the base was about 58.9 kPa under static conditions. During shaking, however, it was probably smaller due to the excess pore water pressure generated. Thus, it is considered that effective stress condition in the lower part of the model RSW was similar to those in triaxial test specimen under a confining pressure of 49 kPa, where soil fails at the maximum shear strain of 5.1 %.

Using the proposed method, the critical inclination of the facing of the model RSW is expected to be about 2.5% using Equation 1 when a slip surface appears.

Figure 15 shows inclination of the facing in the lower part of the model RSW against the shaking step. Inclination of the facing exceeded 2.5% during the 2nd shaking step. That is, it is considered that a slip surface began to form during the 2nd shaking step. This result gives good agreement with test results although a slip surface was not so clear, as shown in Figure 13a. In general, formation of a slip surface in soil is delayed under saturated conditions compared with dry conditions. This is a possible reason why a slip surface was not clear, although the backfill had already failed. This result indicates that the proposed method is applicable to RSWs in saturated conditions.

4 CONCLUSIONS

In this study, effect of saturation of backfill on the seismic stability of reinforced soil walls (RSWs) was investigated through centrifuge model tests. In addition, applicability of the proposed method for detecting the formation of a slip surface to RSWs under saturated condition was discussed. As a result, the following conclusions were obtained.

1) RSWs can maintain sufficient static stability even if the backfill is fully saturated with water. However, seismic stability may significantly decrease and very large deformation may occur.

2) Shear deformation in the lower part of RSWs is dominant if a slip surface does not appear in the backfill. After formation of a slip surface, sliding deformation becomes dominant, and displacement may increase rapidly.

3) Formation of a slip surface in RSWs can be evaluated by a simple method proposed by the authors with only inclination of the facing panel.

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