Evaluation for damage of geogrid reinforced soil walls subjected to earthquakes

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ABSTRACT: This study attempts to establish a simple method to evaluate the degree of damage to geogrid reinforced soil walls (GRSWs) subjected to earthquakes, using results of centrifuge model tests which especially focused on the effects of tensile stiffness of geogrid, pullout characteristics and backfill materials. As a result, it was found that GRSWs showed large shear deformation in the reinforced area during earthquakes and such deformation was influenced by tensile stiffness of geogrid, pullout resistance and deformation modulus of backfill material, and finally slip lines appeared. However, GRSWs maintained adequate seismic stability owing to pullout resistance of geogrid even after the formation of slip lines. It is considered that such slip lines appeared due to failure of backfill material. Since the maximum shear strain occurred in backfill can be approximately calculated using a simple plastic theory with inclination of the wall, it can be evaluated whether backfill has reached its peak state or not if stress-strain relation of backfill material is obtained. By the method described above, test results could be sufficiently simulated.

1 INTRODUCTION

It is well known that the geogrid reinforced soil walls (GRSWs) has high seismic stability and can be placed in service without considerable repair or reconstruction even after large earthquakes. However, GRSWs may show some deformation because reinforced effect can be obtained from deformation of GRSWs themselves. Thus, it is necessary to assess degree of damage of the GRSW for appropriate decision for necessity of repair. In addition, damage of the GRSW should be evaluated from surface deformation, such as wall displacement, settlement of the crest and so on. This paper describes how to evaluate degree of damage of GRSWs, based on results of centrifuge model tests.

2 CENTRIFUGE TILTING AND SHAKING TABLE TESTS

Authors conducted a series of centrifuge tilting and shaking table tests focusing on effect of tensile stiffness of geogrid and properties of backfill materials on seismic performance of GRSWs (Izawa et al., 2002; 2002; 2004). Test cases are summarized in Table 1. Three silica sands having different particle size were used with relative density of 80%. Model geogrids used were made of polycarbonate plates with 0.5 mm or 1mm thickness. Schematic diagrams of a model GRSW and a geogrid used in both centrifuge tilting and shaking table tests were indicated in Figure 1. Five layers of 90mm long geogrids were laid in the backfill at 30mm interval. Five pieces of aluminium plates were used as a model facing wall and each facing was rigidly attached to one geogrid. Some optical targets were set on the surface of the transparent side wall for visually detailed observation of deformation. All tests were conducted in the centrifugal acceleration of 50G. In the centrifuge tilting table tests, pseudo static horizontal loading usually used in the design was applied to the models

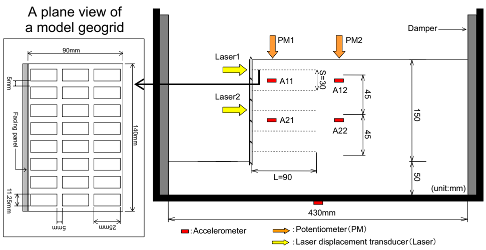


Figure 1 Schematic diagrams of a model GRSW

Table 1 Test cases and properties of the model geogrids and the backfills

	Geogrid			Backfill				Pullout characteristics		
Case	Type	Thickness (mm)	Tensile Stiffness (kN/m)	Type	D_{50}	γ_d (kN/m^3)	ϕ(°)	c_p (kN/m^2)	ϕ_p (°)	$\tan\phi_p/\tan\phi$
CS-T	CS	0.5	197	Toyoura	0.19	15.7	40.4	0.930	21.4	0.451
CS2-T				Toyoura	0.19	15.7	40.4	7.90	40.5	0.983
CS2-S5	CS2	1.0	557	Silica No. 5	0.52	14.5	45.0	16.7	44.5	0.949
CS2-S3				Silica No. 3	1.40	14.8	46.0	30.2	46.1	0.903

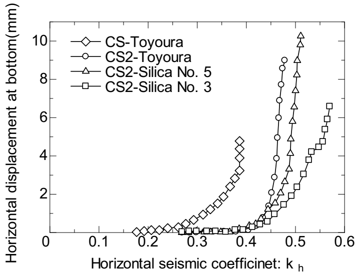


Figure 2. Horizontal displacements at bottom panel vs horizontal seismic coefficient

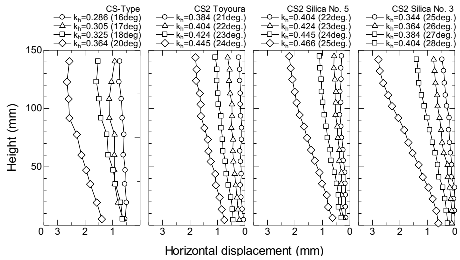


Figure 3. Vertical distributions of horizontal displacements of panels

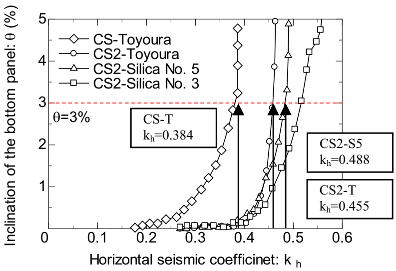


Figure 4. Inclinations of bottom panels vs horizontal seismic coefficient

by tilting the model. On the other hand, in the centrifugal shaking table tests, some sinusoidal seismic waves with frequency of 100Hz, which corresponds to 2Hz in prototype, were applied to the model with gradually increasing amplitude of acceleration.

3 INCLINATION OF THE WALL AT FAILURE SUBJECTED TO PSEUDO STATIC LOADING

Figure 2 shows relationships between horizontal displacement at the top of the GRSWs and horizontal seismic coefficient, k_h(=tanη), where η indicates tilting angle. In all cases, horizontal displacements increased gradually with tilting and finally the GRSWs failed suddenly due to sliding. However, overturning failure was observed only in CS2-S3. In addition, effect of tensile stiffness of geogrid and properties of backfill material can be seen. Figure 3 shows vertical distributions of horizontal displacements of the GRSWs. These were obtained from displacements of the optical targets set on side face of the models. In these figures, horizontal displacement at the bottom target and inclination indicate sliding displacement and shear deformation, respectively. From this point of view, these figures clearly show that shear deformation at lower part of the reinforced area was significant. Thus, inclinations of the bottom facing panel are plotted against horizontal seismic coefficient in Figure 4, together with horizontal seismic coefficients at failure. The inclination of the bottom panel "θ" is defined as $\theta = d_p/H_p$, where d_p and H_p indicate the horizontal displacement of the bottom facing panel and the height of the facing panel. This figure clearly shows that the GRSWs failed when the inclination of the bottom facing panel reached about 3.0%. Immediately before failure, clear slip lines appeared in the cases of CS-T, CS2-T and CS2-S5 as shown in Figure 5, where distributions of maximum shear strain before failure are indicated. On the other hand, the model of CS2-S3 did not show clear slip line.

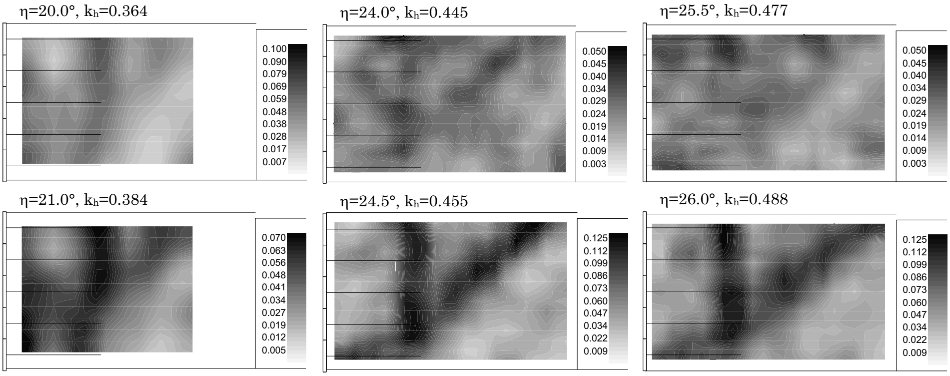
In summary, the model GRSWs subjected to pseudo static loading failed due to sliding immediately after the inclination of the wall at bottom reached about 3.0% and slip line generated. Additionally, such critical inclination didn't depend on tensile stiffness of geogrid since sliding failures were observed at almost the same wall inclination in CS-T and CS2-T, which had the same backfill but different geogrid. Thus, it is considered that such a slip line appeared when backfill in the reinforced area reaches its failure state.

4 EVALUATION FOR SLIP LINE FORMATION

Bransby et al.(1975) proposed relationship between inclination of sheet pile wall and maximum shear strain occurred in the backfill based on test results as follows.

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

where γ_{max}, θ and φ indicate maximum shear strain in backfill, inclination of sheet pile wall and dilatancy angle, respectively. Furthermore, it was reported that the proposed equation could give good agreement with test results. However, it is difficult to obtain the dilatancy angle. Figure 6 shows relationships between inclination of the wall and maximum shear strain in the backfill calculated by the proposed equation with different dilatancy angle. This figure clearly shows that the effect of dilatancy angle on maximum shear strain is small enough to be neglected. Thus, the proposed equation can be simplified as follows.



(a) CS-Toyoura (b)CS2-Toyoura (c)CS2-Silica sand No. 5

Figure 5. Distributions of maximum shear strain before failure in CS-T, CS2-T and CS2-S5

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

By using the equation (2), maximum shear strain occurred in reinforced area can be estimated with only inclination of the wall. As mentioned above, the slip lines appeared when the inclination of the facing of the GRSWs reached about 3.0%. That is, the maximum shear strain in backfill can be estimated to be about 6.0%.

Figure 7 shows relationships between deviator stress and maximum shear strain of Toyoura sand, Silica sand No. 5 and No. 3 obtained from drained tri axial compression tests at the confining pressure of 98kPa, which is almost the same pressure in the bottom reinforced area of the model under the centrifugal acceleration of 50G. Here, maximum shear strain was calculated, assuming that Poisson's ration of all sands is 0.2. As shown in this figure, the peak deviator stress could be obtained at the maximum shear strain of 6.2% and 5.7% for Toyoura sand and Silica sand No. 5, respectively. That is, it is clear that the backfill materials in the reinforced reached their failure value when the wall inclinations were about 3.0%. In addition, it is considered that this led to formations of slip lines. On the other hand, a clear peak value cannot be seen in Silica sand No. 3. This resulted in no formation of a slip line in CS2-S3.

In summary, maximum shear strain occurred in the backfill of GRSWs can be estimated by using equation (2). When the maximum shear strain reached to the peak value, slip line generates in the reinforced area and sliding failure occurred. Based on this relation, generation of the slip line can be evaluated using only horizontal displacement of facing.

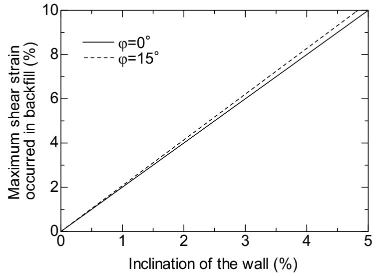


Figure 6. Effect of dilatancy angle on estimated maximum shear strain in backfill calculated by equation(1)

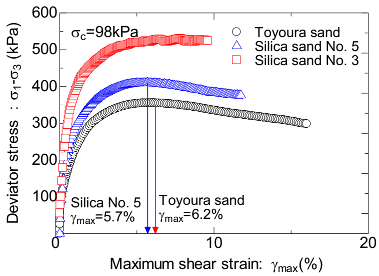


Figure 7. Results of tri axial tests under σ_3=98kPa

5 VALIDATION FOR RESULTS OF THE CENTRIFUGE SHAKING TABLE TESTS

In the centrifuge shaking table tests, the models showed almost the same deformation modes with those of the centrifuge tilting table tests. That is, shear deformation of lower part was significant. Figure 8 shows the relationships between the inclination of the bottom facing panel and cumulated acceleration power. Acceleration power can consider both acceleration and duration of shaking wave, and it is calculated by the following equation.

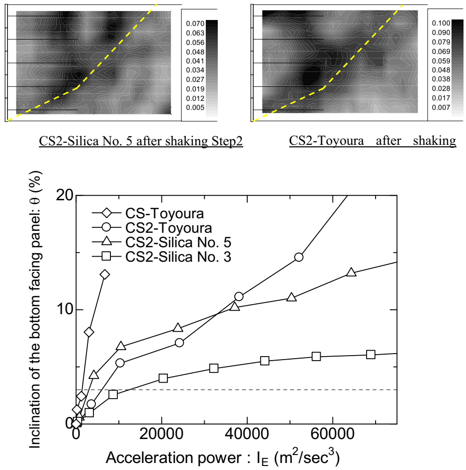


Figure 8. Inclination of the bottom facing panel vs cumulated acceleration power, together with maximum shear strain distributions at failure of CS2-T and CS2-S5

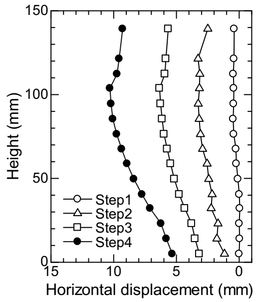


Figure 9. Vertical distributions of the horizontal displacement in the centrifuge shaking table test of CS2-T

$$I_E = \int_0^T a^2(t)dt \quad (3)$$

where T and a indicate shaking duration (sec) and input acceleration (m/s^2), respectively. In CS2-T and CS2-S5, the inclinations of the bottom facing panel exceeded 3.0% at the shaking step 3 and 2, respectively. Maximum shear strain distributions are also indicated in Figure 9. As shown in these figures, each slip line generated after the shaking step 3 and 2 although they were not so clear than those in the centrifuge tilting table tests. This result clearly shows that the criteria for evaluating formation of a slip line, as described in the previous chapter, can be applied to the GRSWs subjected to earthquake.

On the other hand, the GRSWs did not collapse even after the slip lines appeared in the centrifuge shaking table tests. Figure 9 shows vertical distributions of horizontal displacement of CS2-T, in which a slip line generated at the shaking step 3. As shown in this figure, sliding displacement was much larger than horizontal displacement due to shear deformation at the shaking step 4. This means that sliding displacement may become significant after formation of a slip line, although shear deformation was significant before formation of a slip line. Furthermore, it is clear that such sliding displacement depends on pullout resistance cutting through the slip line. Thus, the horizontal displacement in CS2-T was larger than that of CS2-S5 after the slip line appeared as shown in Figure 8, since pullout resistance of CS2-S5 was larger than that of CS2-T as indicated in Table 1.

6 CONCLUSIONS

This paper describes evaluation for degree of damage in geogrid reinforced soil walls with results of centrifuge tilting and shaking table tests. Especially, formation of a slip line in the reinforced area was focused on. As a result, it was found that slip lines appear in reinforced area when maximum shear strain in backfill reaches their peak values. In addition, a simple equation was proposed to determine the maximum shear strain occurred in the backfill using inclination of the wall. On the other hand, GRSWs can maintain its adequate stability against seismic loading due to pullout resistance of geogrid even after a slip line appears. However, after the formation of a slip line, sliding displacement along the slip line is getting significant. Additionally, such sliding displacement can be reduced by increasing pullout resistance between backfill and geogrid.

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