Evaluation of damage in geogrid reinforced soil walls based on wall displacement

Évaluation de dégât dans geogrid a renforcé des murs du sol basés sur déplacement du mur

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ABSTRACT
Geogrid reinforced soil walls (GRSW) have showed high seismic stability with limited deformation in the past earthquakes. GRSWs are often used without considerable repair or reconstruction after simple inspection in many cases even after strong earthquakes. For the proper repair or reconstruction, it is necessary to evaluate damage of GRSWs. As the restoration method of the structure should be decided right after the event, the damage must be evaluated by a simple index such as the wall displacement. Evaluation of damage in GRSWs subjected to earthquake is discussed in this paper based on results of centrifuge tests. The discussion is especially focused on the estimation of slip line formation by surface displacement. As a result, it was found that clear slip line may occur in reinforced area when inclination of the wall reaches to half of maximum shear strain of backfill material. However, the model GRSWs maintained adequate stability due to the pullout resistance of the geogrid even after the slip line generated. In addition, after the formation of the slip line, the sliding displacement along the slip line is getting significant. Such sliding displacement depends on the pullout resistance of the geogrid. Thus, it is necessary to know the appropriate pullout characteristics for evaluating the seismic stability of the GRSW having the slip line.

RÉSUMÉ
Geogrid a renforcé les murs du sol (GRSW) ont a affiché la haute stabilité sismique avec difformité limitée dans les tremblements de terre passés. GRSWs sont souvent utilisés sans réparation considérable ou reconstruction après inspection simple dans beaucoup de cas égalisez après forts tremblements de terre. Pour la réparation adéquate ou reconstruction, c'est nécessaire à évaluer dégât de GRSWs. Comme la méthode de la restauration de la structure devrait être décidé juste après l'événement, le dégât doit être évalué par un index simple tel que le déplacement du mur. Évaluation de dégât dans GRSWs a soumis à tremblement de terre est discuté dans ce papier basé sur résultats d'épreuves de la centrifugeuse. La discussion est concentrée surtout sur l'estimation de formation de la ligne de la fiche par déplacement de la surface. En conséquence, il a été trouvé que la ligne de la fiche claire peut se produire dans région renforcée lorsque l'inclination du mur atteint à la moitié de tension du ciseau maximale de matière du backfill. Cependant, le GRSWs modèle a maintenu la stabilité adéquate dû à la résistance du pullout du geogrid égalise après que la ligne de la fiche ait produit. De plus, le déplacement glissant le long de la ligne de la fiche devient considérable après la formation de la ligne de la fiche. Le tel déplacement glissant dépend de la résistance du pullout du geogrid. Donc, c'est nécessaire à savoir les caractéristiques du pullout appropriées pour évaluer la stabilité sismique du GRSW qui a la ligne de la fiche.

Keywords : centrifuge, geogrid, reinforced soil wall, seismic behaviour

1 INTRODUCTION

Geogrid reinforced soil walls (GRSW) showed very high seismic stability with limited deformation in past severe earthquakes. GRSWs have been used without considerable repair or reconstruction after simple inspection in many cases even after such earthquakes. For proper repair or reconstruction, it is necessary to evaluate damage of GRSWs properly. Since restoration method for structure should be decided right after earthquake, damage of them must be evaluated with a simple index such as wall displacement, crest settlement and others. Thus, evaluation for damage in GRSWs due to earthquake is discussed in this paper based on results of centrifuge tests. The discussion is especially focused on estimation of slip line formation by wall inclination.

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 soils 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.

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	CS2	1.0	557	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	CS2	1.0	557	Silica No. 3	1.40	14.8	46.0	30.2	46.1	0.903

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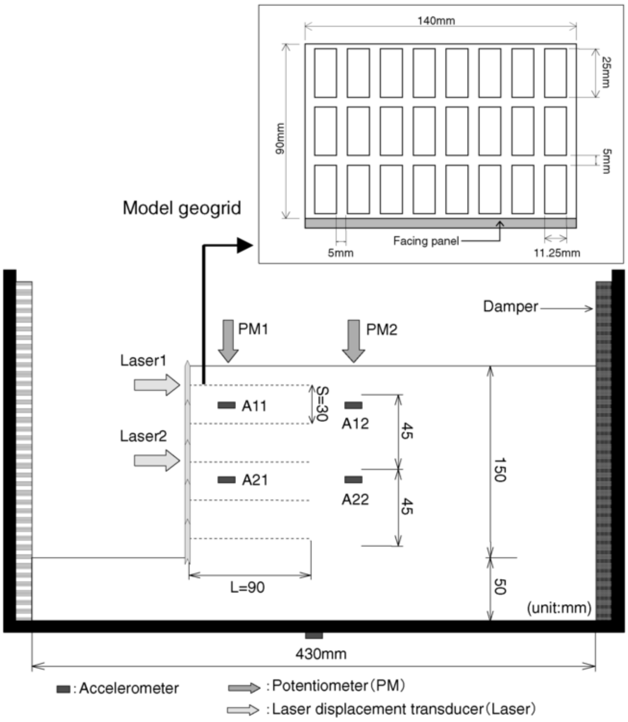


Figure 1. Schematic diagrams of a model GRSW and a geogrid

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 attached to one geogrid rigidly. 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 could be applied to the models 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 WALL INCLINATION AT FAILURE SUBJECTED TO PSEUDO STATIC LOADING

Figure 2 shows relationships between horizontal displacement at the top of the model GRSWs and horizontal seismic coefficient, $k_h=\tan\eta$, where η indicates tilting angle. In all cases, horizontal displacements increased gradually with tilting and finally the model GRSWs failed suddenly due to sliding. However, overturning failure was observed only in the case of CS2-S3. In addition, effect of tensile stiffness of geogrid and soil properties can be detected in deformation curves. Figure 3 shows vertical distributions of horizontal displacements of the model observed in centrifuge tilting table tests. 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 gradient 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. Here, 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 model GRSWs failed when the inclination of the bottom facing panel reached to about 3.0%. Immediately before that time, 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 and failed due to overturning.

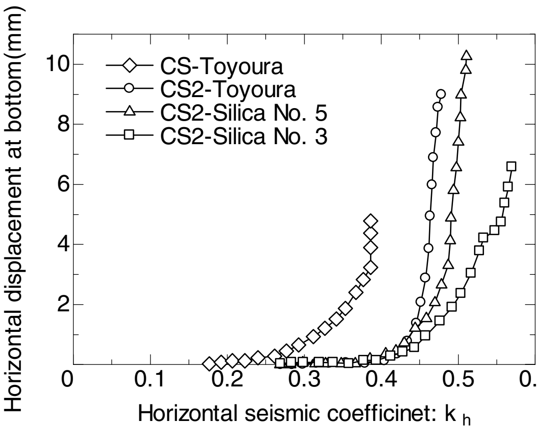


Figure 2. Horizontal displacements at bottom panel vs horizontal seismic coefficient

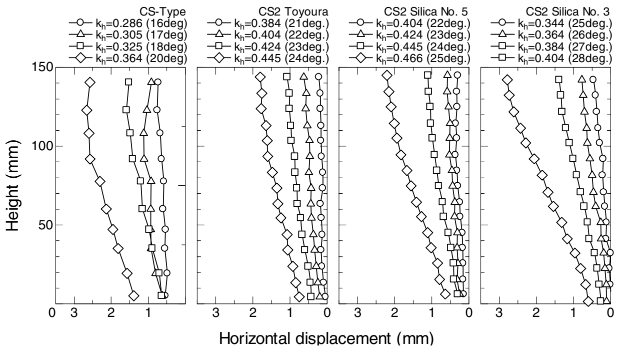


Figure 3. Vertical distributions of horizontal displacements of panels

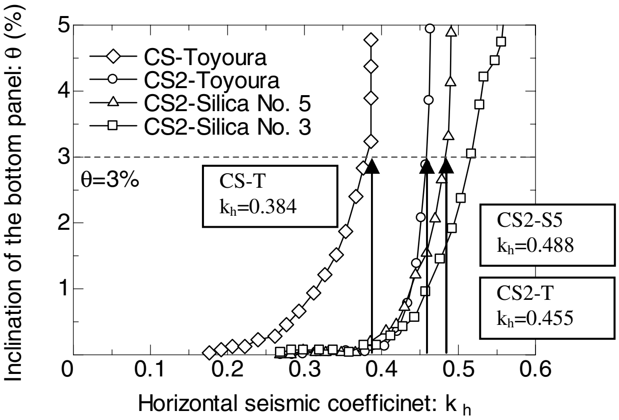
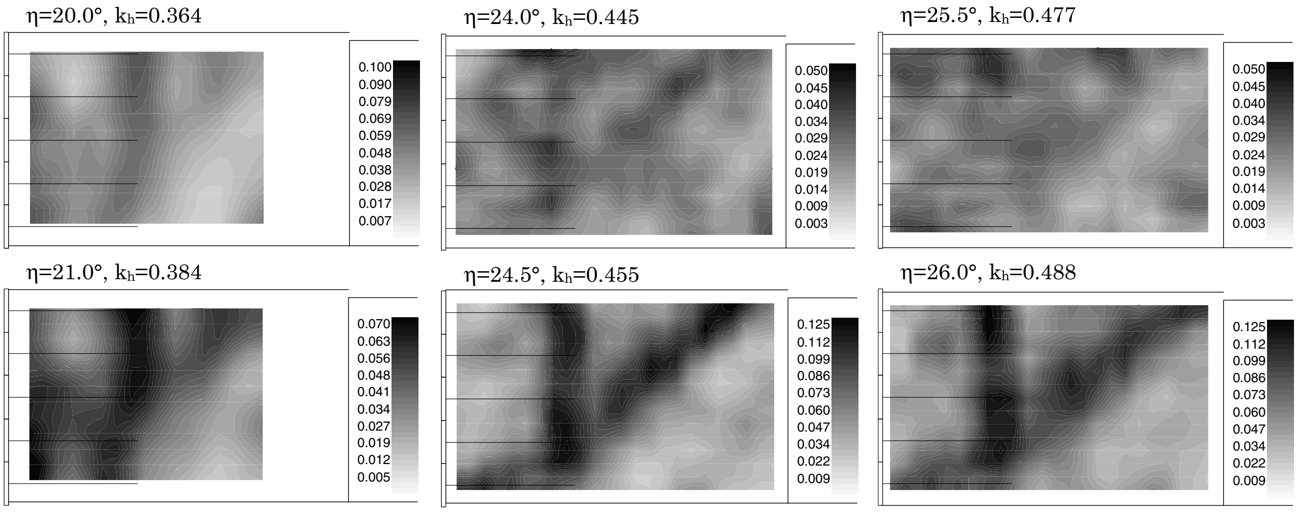


Figure 4. Inclinations of bottom panels vs horizontal seismic coefficient

In summary, the model GRSWs subjected to pseudo static loading failed due to sliding immediately after the inclination of the wall at bottom reached to the particular value 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 the cases of CS-T and CS2-T, where the same backfill material used but different model geogrids. Thus, it is considered that such slip line generated when backfill itself in reinforced area reaches to failure. Relationship between inclination of facing panel and strain in the backfill is discussed in next chapter.



(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

4 EVALUATION FOR GENERATION OF SLIP LINE

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.

$$\gamma_{max} = \frac{2\theta}{\cos\varphi} \tag{1}$$

where, γ_{max}: maximum shear strain occurred in backfill, θ: inclination of sheet pile wall and φ: dilatancy angle. Furthermore, it was reported that the proposed equation could give good agreement with test results. Here, it is not easy to obtain the dilatancy angle. Here, it is difficult to know the dilatancy angle easily. Figure 6 shows relationships between wall inclination and maximum shear strain occurred 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 negligible. Thus, the proposed equation can be simplified as follows.

$$\gamma_{max} = 2\theta \tag{2}$$

Above equation is equivalent to the Bolton's equation (Botlon, 1988), which was derived from test results focused on undrained behaviour of the sheet pile wall. By using equation (2), maximum shear strain occurred in reinforced area can be estimated with wall inclination. As mentioned above, the slip lines generated when the inclination of the facing of the model GRSW reached to about 3.0%. That is to say, it can be estimated that maximum shear strain about 6.0% occurred in the backfill of the model GRSWs.

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 GRSWs under the centrifugal acceleration of 50G. 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, the backfill materials in the reinforced reached to their failure value when the wall inclinations reached to about 3.0%. This led to formations of slip line. On the other hand, clear peak value is not shown in tri axial test result of Silica sand No. 3. This resulted in no formation of slip line in CS2-S3 and the model failed due to overturning.

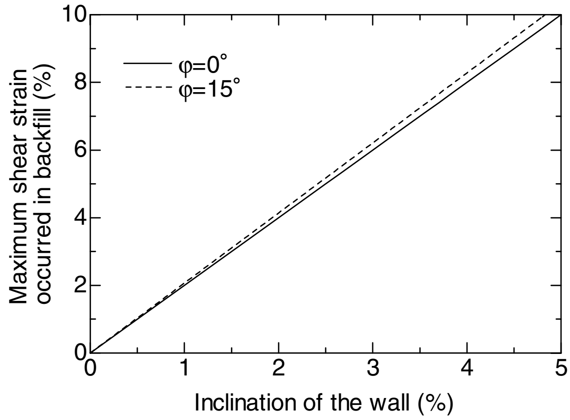


Figure 6. Effect of dilatancy angle on estimated maximum shear strain in backfill calculated by equation(1)

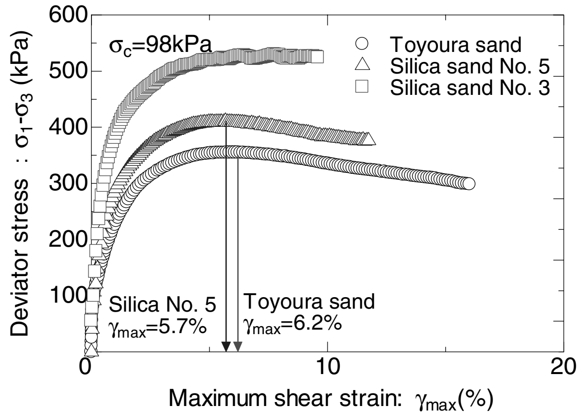


Figure 7. Results of tri axial tests under σ_3=98kPa

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.

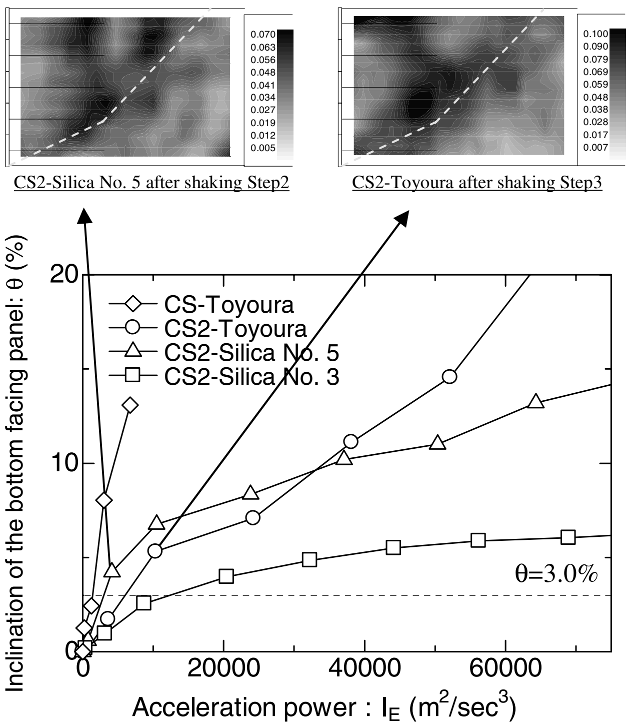


Figure 8. Inclination of the bottom facing panel vs cumulated acceleration power, together with maximum shear strain distributions at failure of CS2-T and CS2-S5

5 VALIDATION WITH RESULTS OF 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 to say, shear deformation of lower part in the reinforced area 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.

$$I_E = \int_0^T a^2(t)dt \tag{3}$$

where, T: Shaking duration (sec), a: Input acceleration (m/s^2). 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, slip lines 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 generation of slip line, as indicated in equation (2), can be applied to the GRSWs subjected to earthquake.

On the other hand, the model GRSWs did not collapse even after the slip lines occurred in the centrifuge shaking table tests. Figure 9 shows vertical distributions of horizontal displacement of CS2-T, in which 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

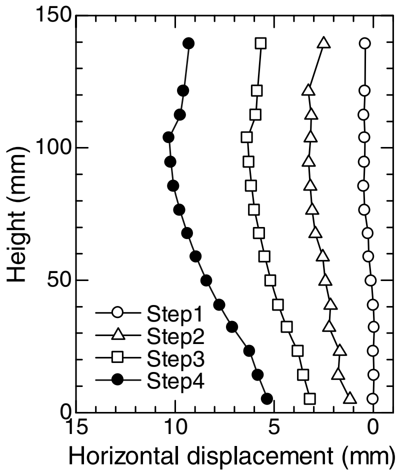


Figure 9. Vertical distributions of the horizontal displacement in the centrifuge shaking table test of CS2-T

step 4. This means that sliding displacement was significant after formation of slip line although shear deformation was dominant before formation of slip line. Amount of such sliding displacement may depend on pullout resistance of the geogrid cutting through the slip line. Thus, the horizontal displacement in CS2-T was larger than that of CS2-S5 after the slip line occurred as shown in Figure, since pullout resistance of CS2-S5 was larger than that of CS2-T as indicated in Table 1.

6 CONCLUSIONS

This paper describes evaluation of damage in geogrid reinforced soil walls based on results of centrifuge tilting and shaking table tests. In particular, authors focused on generation of slip line in the reinforced area was. Slip line generates in the reinforced area when the maximum shear strain of the backfill reaches to their peak value. The maximum shear strain occurred in the backfill can be estimated by the following equation.

Since inclination of bottom facing panel can be calculated by horizontal displacement, formation of slip line in reinforced area can be estimated using only the horizontal displacement of the facing. The GRSW maintains its adequate stability due to the pullout resistance of the geogrid after formation of slip line. However, after formation of slip line, sliding displacement along the slip line is getting significant. Such sliding displacement depends on pullout resistance of the geogrid.

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