SEISMIC STABILITY OF DAMAGED REINFORCED SOIL WALL WITH RESIDUAL STRENGTH OF BACKFILL SOIL

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ABSTRACT

Recent huge earthquakes have caused severe and small damage to a number of geogrid-reinforced soil walls. For proper repair or reconstruction, it is necessary to evaluate degree of damage of those structures. In this research, the pullout test of geogrid subjected to the unloading-reloading process was carried out to investigate its effects on the pullout resistance. The results were then used to evaluate the factor of safety and sliding surface of the damaged geogrid reinforced soil wall. GRSW models in centrifuge shaking and tilting table tests under 50G were performed. The two wedge method analysis was used to evaluate the stability of damaged GRSW using the both peak and residual strength of backfill soil. The results of experiments and theory were discussed.

Keywords: Geogrid reinforced soil wall, unloading-reloading, two-wedge, centrifuge test

INTRODUCTION

Geogrid reinforced soil walls (GRSW) are often used without considerable repair or reconstruction after simple inspection in many cases even after strong earthquakes if they are not damaged seriously. For the proper repair or reconstruction, it is necessary to evaluate damage of GRSW. 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, the crest settlement, and soil-geogrid interaction conditions. To evaluate the condition of GRSW which was suffered from a certain damage caused by temporary external load such as earthquake and heavy rain, the unloading-reloading process on the pullout resistance were applied then used to investigate its effects on the safety of GRSW. The effects of earthquake on geogrid in GRSW could be describes as the following process: At initial condition before earthquake at stage (1), overburden load affects geogrids. Under earthquake at stage (2), big pullout force affects geogrids temporarily with big deformation. After the earthquake at stage (3), the temporary load is released as shown in Fig. 1. Because after the big earthquake, the pullout resistance of geogrid and soil might reach residual part with some deformation, the next possible big events the pullout resistance of these geogrids might not reach to peak value. Therefore the unloading-reloading in pullout test is carried out beside the ordinary monotonic process to simulate all of this process. Based on the results of unloading-reloading effects on the pullout resistance, it was possible to evaluate the factor of safety for GRSW at peak, at peak in reloading after the unloading-reloading and at the residual parts.

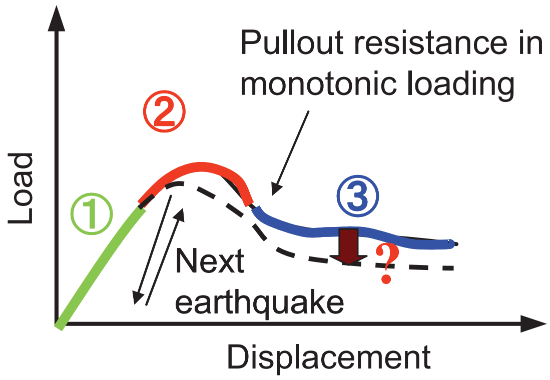

Fig. 1 Mechanism of pullout resistance of geogrids in GRSW under earthquake

There are many types of centrifuges and geotechnical centrifuge is one of them and it was used in this research. The special geotechnical modeling is to produce the soil behavior in terms of strength and stiffness. In the experimental container soil has free unstressed upper surface and the strength magnitude increases with depth and a rate related to soil density and the strength of the acceleration field. Centrifuge was used for the shaking table tests and tilting table tests. The special equipment was attached to model to prevent it from total collapse when it was subjected to dynamic loading by using the centrifuge shaking table tests. After the sliding was observed the model was moved to the centrifuge tilting table tests to apply unloading-reloading process and evaluate effects of the peak and residual pullout tests on damaged GRSW. There were two test series: Shaking – tilting table test series to investigate the damaged GRSW before peak value and tilting - tiling table test series to investigate the residual value of pullout resistance on the stability of damaged GRSW.

EFFECTS OF UNLOADING-RELOADING PROCESS ON FACTOR OF GRSW

The current GRSW design uses the peak pullout strength values. However, some researchers have proposed the use of residual pullout strength for design. The GRSW subjected to a large earthquake might experience some deformation, and geogrids inside the GRSW might show some displacement. This effect should be taken into account in the evaluation of stability of the damaged GRSW after the earthquake. In order to properly estimate pullout resistance of geogrid in the damaged structure, Giang et al. 2010 applied unloading-reloading process besides the ordinary monotonic pullout process. Figure 2 shows the effects of the unloading-reloading process on the pullout resistance of different geogrid.

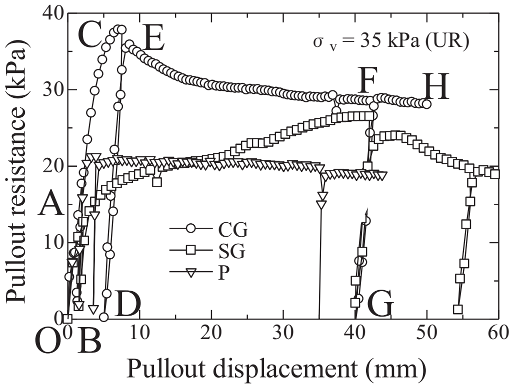

Fig. 2 Pullout resistance vs pullout displacement: Unloading-reloading process (Giang et al. 2010)

The unloading-reloading process reduces the pullout resistance at the peak and residual values but it does not affect the pullout resistance of geogrid before the peak. They found that after the peak value, at the residual part, the shear zone was formed very near the geogrid's surfaces and the unloading-reloading process does not considerably induce the horizontal displacements around the geogrid. Therefore, they concluded that the factor of safety of damaged GRSW may not reach the designed factor of safety using peak value if the geogrid pullout resistance in the damaged GRSW were already in the residual value.

TWO-WEDGE METHOD ANALYSIS

The pseudo-static two-wedge method (Ismeik and Güler 1998) to evaluate the factor of safety of GRSW against sliding and overturning was used to evaluate the static and seismic stability of the GRSW considering effects of unloading-reloading on pullout resistance of geogrid at peak and residual stage. This method has been studied by several researchers such as Jewell et al. (1984). Parameters obtained from pullout tests (Fig. 2) at peak and residual stages were used for Two-Wedge analysis of GRSW with 7.5 m height, five layers of 4.5 m length geogrids and 1.5 m interval. The backfill material was Toyoura sand. Figure 3 shows the relationship between the factor of safety against the sliding and the horizontal seismic coefficient at failure. It can be observed in Fig. 3 that when ϕ peak reduces to ϕ residual the factor of safety is also decreased for all the cases. For example, the SG case with $\phi_{peak} = 33.8^o$, the critical horizontal coefficient kh is 0.62. At the residual value when ϕ_{peak} decreased to $\phi residual = 27.6^o$, the critical horizontal coefficient kh is 0.54. This suggests that in a large earthquake, if the GRSW could resist the seismic activities and show some deformation and displacement of geogrids, the pullout resistance of geogrids in some deformed part of the damaged GRSW might work in residual condition. The unloading-reloading process of geogrid reduces the pullout resistance of geogrid in backfill soil resulting the factor of safety of the damaged GRSW reduces from factor of safety at peak to factor of safety at residual. In order to investigate this behavior of damaged GRSW, a series GRSW centrifuge shaking and tilting model tests were carried and the experimental results were compared with the predicted results of Two-wedge method.

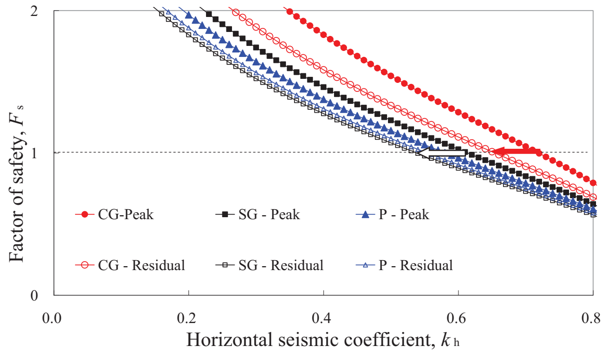

Fig. 3 Safety factor vs horizontal seismic coefficient at peak and residual values, against sliding

OUTLINE OF THE TEST

A series of centrifuge tilting and shaking table tests was carried out using Mark 3 centrifuge at Tokyo Institute of Technology. Toyoura sand with the relative density of 80 % was used as backfill material. Model geogrids were made of polycarbonate plates with 0.5 mm thickness. The shape of the model geogrid was the same in all cases as shown in Fig. 4. Figure 5 shows the schematic diagram of the model GRSW used in both centrifuge tilting and shaking table tests. Five layers of 90 mm long geogrids were laid in the backfill at 30 mm interval. Five pieces of plastic plates were used as a model wall and one geogrid was attached to one plate. Some optical targets were set on the surface of the transparent side wall for detailed observation of deformation. Both tilting and shaking table 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 achieved by tilting the model. On the other hand, in the centrifugal shaking table tests, cyclic loading as in the seismic events with frequency of 100Hz, which corresponds to 2Hz in prototype, were applied to the model. The parameters of geogrid pullout test at peak and residual stages in GRSW are shown in Table 1.

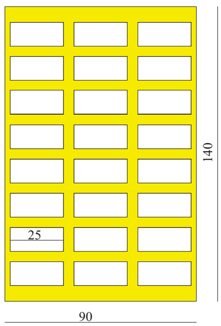

Fig. 4 Geogrid model for centrifuge tests

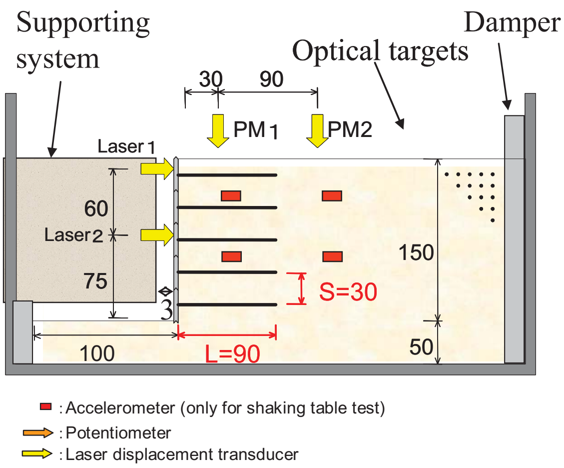

Fig. 5 Schematic view of the model GRSW

In 50G centrifuge condition, the GRSW model is equal to GRSW with height of 7.5 m. Using the above mentioned two-wedge method with parameters obtained from Table 1, the GRSW has horizontal coefficient at peak and at residual stages, k_h^p = 0.47, k_h^r =0.43, respectively. The reduction of the factor of safety of GRSW decreases when from ϕ_{peak} to $\phi_{residual}$. Factor of safety and failure surfaces of predicted results are shown in Fig. 6.

Table 1 Material and pullout resistance properties at peak and residual values

	peak	residual
c_{peak} (kPa)	0.93	-0.75
ϕ_{peak} (deg)	21.4	18.2
$\tan\phi_p/\tan\phi$	0.45	0.38

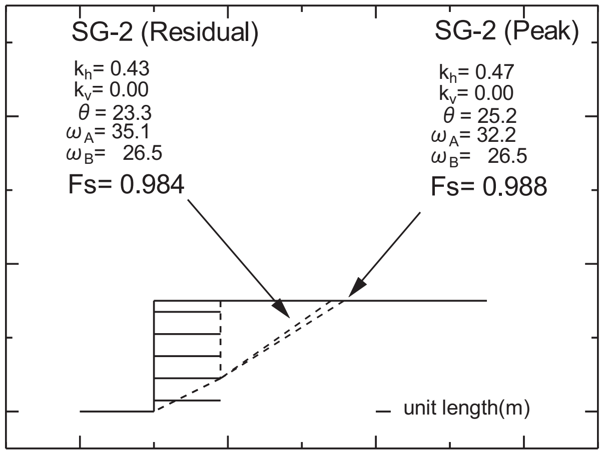

Fig. 6 Predicted two-wedge analysis failure of GRSW at peak and residual values

TESTING PROCEDURE

The displacement of wall facing of the GRSW was controlled by the supporting system as shown in Fig. 5. According to Izawa and Kuwano (2008), the damage of the GRSW would be evaluated from the surface deformation that is observed from the wall displacement or from the settlement of the crest. The supporting system in this model will prevent the GRSW from total collapse at peak and achieve the residual stage basing on the distance between the wall facing and the system.

There are two types of testing:

First type, Centrifuge Shaking-Tilting test: The GRSW was subjected to shaking in centrifuge test to achieve some deformation. Then the damaged GRSW was moved to tilting test and the tilting-untilting process was applied.

The centrifuge tilting - tilting test: The GRSW was subjected to tilting to achieve residual stage. The supporting system prevented the GRSW from total collapse and the GRSW was then un-tilted. The supporting system was then removed and the GRSW was tilted in centrifuge test again until the full collapse was obtained.

RESULTS AND DISCUSSIONS

This GRSW model test was collapsed at titling angle of 21° as reported by Izawa and Kuwano (2008). In the first test series, the GRSW showed some deformation however the pullout resistance of geogrids had not reached residual value. The GRSW was tilted and un-tilted causing the unloading-reloading process of geogrids in GRSW. In the geogrid pullout tests, the unloading-reloading process did not affect the pullout resistance before the peak value. In the GRSW shaking-tilting model tests, the tilting – untilting process also did not affect the stability of the GRSW. Even the GRSW showed some deformation, the tilting - untilting process with tilting angles η=5°, 15°, 20° did not cause the failure as shown in Fig. 8. Therefore, this agrees well with the results of the geogrid pullout test with unloading-reloading process.

In the second type of centrifuge tests, the GRSW showed deformation and the pullout resistance of geogrids had reached residual stage. After the first tilting, the supporting system was removed. The damaged GRSW was tilted again until full collapse. The damaged GRSW was then collapsed at tilting angle η=18.3° (shown in Fig. 7b). It was about 3° less than the critical tilting angle at peak η=21° as shown in Fig. 8. This agrees well with the results of geogrid pullout tests and the predicted behaviour by the two-wedge method that when in residual stage, the pullout resistance of geogrid can not reach peak after the unloading-reloading process and the factor of safety of GRSW decreases from ϕpeak to ϕresidual. The maximum shear strain and volumetric strain at the backfill of GRSW before failure are shown in Fig. 9a and 9b. The Fig. 9a shows that the shear strain concentrates behind the geogrid reinforcement and the failure surface has a two-wedge type.

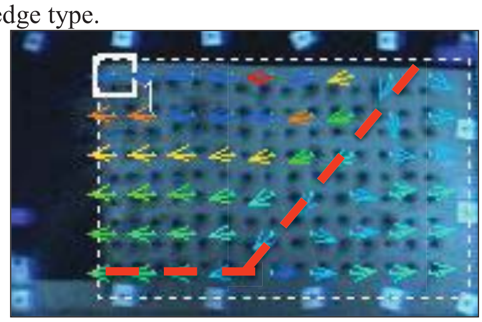

Fig. 7a Potential sliding surface before the collapse

Fig. 7b Two-wedge sliding surface

Even though both the predicted failure of peal value and residual value give higher critical horizontal coefficient than the experimental one but the predicted residual stage has closer critical horizontal value as well as failure surface with the experiment results in compare with the predicted peak value does. This could be explained that during the first tilting, some part of the GRSW had reached peak value of pullout resistance due to displacement and reduced to residual values while other parts were still working in peak value of the pullout resistance. The deformed plane was formed when the other part of potential failure was mobilized to a new failure plane. Thus, after the event, factor of safety and failure plane of GRSW could not reach to peak value. Therefore the residual value of pullout resistance is more suitable to use for re-evaluating the factor of safety of damaged GRSW when some part of GRSW has reached residual stage.

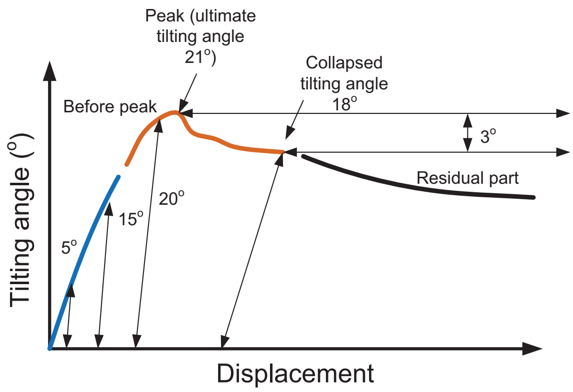

Fig. 8 Horizontal seismic coefficient (k_h) where GRSW was subjected to unloading-reloading process.

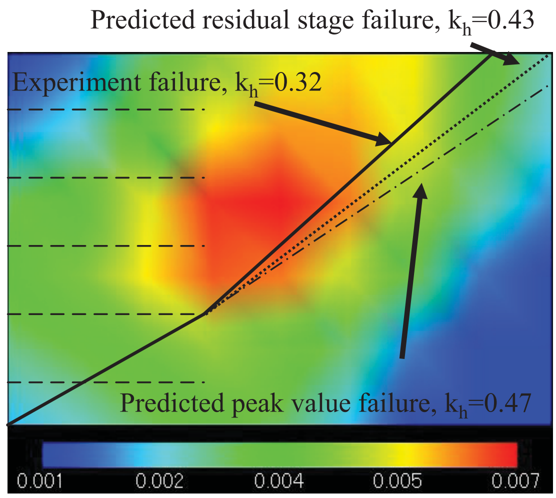

Fig. 9a Maximum shear strain

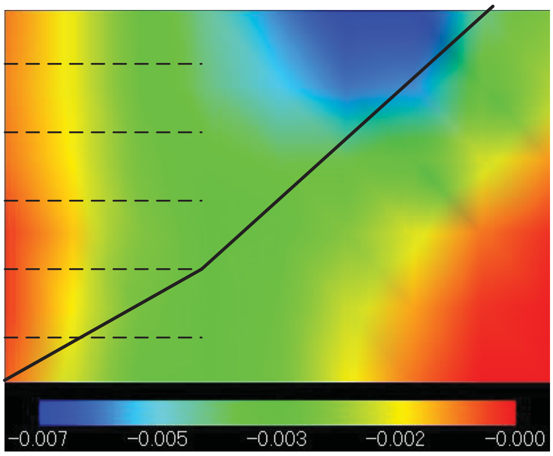

Fig. 9b Volumetric strain

CONCLUSIONS

Series of centrifuge GRSW shaking and tilting table tests were carried out to study the effect of unloading-reloading processes on factor of safety and failure surface of damaged GRSW. The two-wedge method analysis was used to predict stability of GRSW at peak and residual stage. The results were then compared with the experimental result. The following conclusions are achieved:

- The unloading-reloading process does not affect the stability of GRSW when the pullout resistance of geogrid is still before the peak.
- The GRSW was collapsed in two-wedge form suitable with the proposal two-wedge analysis.
- The residual value of pullout resistance should be used to re-evaluate the stability of damaged GRSW when part of it has reached residual stage

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