# Seismic behavior of geogrid-reinforced structure based on shear characteristics of reinforced soil

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ABSTRACT: Shear characteristics of reinforced soil are very important for the design of geosynthetics soil (GRS) structures. In particular, stress-strain relationship of reinforced soil characterizes a seismic behavior of reinforced area in GRS structures. Therefore, in order to investigate a seismic behavior of GRS structures, a large-scale 2.8 m high shaking table test on modular-block reinforced soil retaining wall was conducted. Moreover, to get better understanding of a seismic behavior of this shaking table test, large direct shear tests (LDST) have been conducted on unreinforced and reinforced specimens with cyclic-shearing. It was found that slippage did not occur in a reinforced area in shaking table test, and tensile strain of geogrid was increasing with wall displacement, and remained at passive phases. The results from LDST were also found to be consistent with the behavior observed in shaking table test.

# 1 INTRODUCTION

Earth structures are prone to catastrophic failure during the earthquakes. One of the reasons of collapse is the softening behavior of the soil, which results in accumulation of the strain energy in the shear bands during the earthquakes, and ultimately causes large displacements. On the other hand, geosyntheticsreinforced soil (GRS) structures are well known for their improved performance against induced seismic force. The high earthquake-resistance of GRS structures may be due to the absence of strain softening behavior of reinforced soil, which in turn can prevent the slippage/cracks in the backfill adjacent to the facing wall of GRS structure.

For the design of GRS structures, the reinforced area with geogrid can be assumed as a retaining wall. The concerned reinforced zone would be tough against failure, however flexible rather than stiff as in case of gravity retaining wall. Consequently, failure mode in GRS structure may change from (a) un-reinforced soil structure to (b) GRS structure as shown in Figure 1. In order to understand this phenomenon and also for rational evaluation of seismic behavior of GRS structure, the tensile force of geogrid and shear strength of soil needs to be investigated in detail in particular during cyclic shearing. In view of the above, largescale shaking table test on modular-block reinforced soil retaining wall and large-scale direct shear test on unreinforced and reinforced soil with cyclic loading were performed.



(a) Unreinforced soil structure
(b) GRS structure
Figure 1. Failure modes of unreinforced soil and GRS structures.

# 2 EXPERIMENTS

# 2.1 Shaking table test

Figure 2 shows the layout model of large-scale shaking table test on modular-block reinforced soil retaining walls with accelerometers, earth pressures, laser transducers and, strain gauges on geogrids. Shaking table test model was 2.8 m high and 2 m wide. A polyester (PET) geogrid was used in this test, which was frictionally connected to the facing blocks having a front lip. Table 1 and Figure 3 summarize the properties of the geogrid. Tokachi sand with about 10% water content ( $\rho_{\rm S} = 2.668 \text{ g/cm}^3$ ,  $D_{50} = 0.18$ mm, Uc = 1.8,  $e_{max} = 1.291$ ,  $e_{min} = 0.781$ ) was used. Relative density of backfill material was about 60% achieved by vibratory compactor. To observe slippage lines in backfill ground after shaking, color sands layers were installed at 200 mm intervals except geogrid layers. The North-South (NS) component of Kobe earthquake by the Japan Meteorological Agency



Figure 2. Layout of shaking table model test with sensors.

Table 1. Properties of geogrid.

	PET Geogrid	
Aperture size (mm)	$20 \times 20$	
E (kN/m)*	224	
Ultimate strength (kN/m)	30	

\*elongation at 5%



Figure 3. Tensile strain-stress relation.

was used. Two step shaking, respectively 400 gal and 800 gal of Kobe earthquakes were applied in this shaking table test. The details of the shaking table can be found in Ling et al. (2005).

#### 2.2 Large direct shear test (LDST)

Figure 4 shows the schematic diagram of LDST apparatus. The shear box was 600 mm high, 800 mm length, and 500 mm wide. Two reinforcements, 600 mm  $\times$  500 mm in cross section, were installed perpendicularly to the shear direction. Air-dried Toyoura sand ( $\rho_{\rm S} = 2.64$  g/cm<sup>3</sup>, D<sub>50</sub> = 0.21 mm, Uc = 1.2, e<sub>max</sub> = 0.98, e<sub>min</sub> = 0.62) was pluviated through multi sieves to achieve a relative density, Dr of about 75%. The top of upper shear box was maintained



Figure 4. Schematic diagram of large direct shear apparatus.

horizontally during shearing by adding a compensating balance moment applied by two sets of air cylinders. Reinforcements used in LDST were the same as used in the shaking table test, and strain gauges were fixed on it as shown in Figure 5. The shear rate was 0.23 mm/min and  $\sigma_v = 50$  kPa in all the tests. During cyclic loading, the unloading was performed at shear displacements of 1.5 mm, 3.0 mm, 5.0 mm, 8.0 mm, 12.0 mm, 20.0 mm, and 40.0 mm respectively, while reloading was started at a stress ratio of R = 0.05.

# 3 SEISMIC BEHAVIOR OF SHAKING TABLE TEST

# 3.1 Wall displacement response

Figure 6 shows phase between table velocity, calculated by integrating the acceleration measured at the base of the table, and wall displacements. Both displacements at the upper and lower part of walls correspond with table velocity, and block type wall rotate around the bottom.

# 3.2 Geogrid tensile strain response

Figure 7 shows phase between tensile strain of geogrid and table velocity. It was found that the tensile strain of geogrid corresponded well with table velocity, however the tensile strain still remained on the passive direction. This means that remaining tensile force of geogrid confines the soil around reinforcement during the shaking. Maximum strain, which could be recorded in this test, was about 1%.

	Position of gauges		
Y=500mm	Layer1	Layer2	Location, Y(mm
	S00	S10	Y=90
Y=435mm	S01	S11	Y=165
	S02	S12	Y=260
T=360mm	S03	S13	Y=260
Y=310mm	S04	S14	Y=310
Y=260mm	S05	S15	Y=310
	S06	S16	Y=360
Y=165mm	S07	S17	Y=360
	S08	S18	Y-435
Y=90mm	S09	S19	Y=500

Figure 5. Geogrid attached with strain gauges used in LDST.



Figure 6. Phase between table velocity and wall displacements.



Figure 7. Phase between tensile strain of geogrid and table velocity.

#### 3.3 Slippage

The slippage line based on observation is shown in Figure 8. It may be seen that continuous slippage lines occurred behind the reinforced area, while some of slippage lines occurred through the end of reinforcements. However no slippage line was observed in the reinforced area between wall and its mid point. Therefore, it seems that the slippage can be prevented by installation of geogrid-reinforcements. This reason will be explained later.

# 4 SHEAR CHARACTERISTICS OF EINFORCED SOIL

In order to understand shear characteristics of reinforced soil with active and passive seismic force, stress-strain behavior with reinforced soil was investigated during cyclic loading in LDST.

# 4.1 Conceptual shear deformation of unreinforced and reinforced soil

Figure 9 shows the conceptual deformation of unreinforced and reinforced soil during shearing. In unreinforced soil in Figure 9 (a), narrow shear zone would be formed due to concentration of shear strain in shear band after peak state. While, in reinforced soil in Figure 9 (b), tensile-reinforcing effect may prevent concentration of shear strain in shear zone, consequently results in formation of wider shear zone.

Figure 10 shows relation between shear displacement and ratio of incremental length in  $\gamma$  direction to shear zone ( $\Delta$ L/W). The relation indicates that, in case of no pullout between soil and reinforcement, tensile force of reinforcement is related with  $\Delta$ L/W.



Figure 8. Slippage line after 800 gal shaking.



Figure 9. Schematic formations of shear zone with unreinforced and reinforced soil.



Figure 10. Relation between shear displacement and incremental length in  $\gamma$  direction.

Therefore, shear zone in reinforced soil may be formed by equilibrium force between mobilized shear stress of soil and tensile force of reinforcement. Wider shear zone would bring higher mobilized shear stress of soil due to dispersion of shear strain, but incremental length decreases. This phenomenon will be discussed later.

#### 4.2 Shear strength characteristics

The results of LDST are shown in Figure 11. It was found that pre-post behaviors were almost same between reinforced and unreinforced soil specimens, but the softening behavior at about shear displacement of 8mm occurred in unreinforced soil specimen after peak state. To the contrary, the softening behavior disappeared in reinforced soil specimen. It was also found that reinforced soil specimen have more dilative behavior than unreinforced soil specimen after shear displacement of 45 mm. This means that shear zone with reinforced soil specimen is wider than with



Figure 11. Relation between shear displacement and stress ratio, vertical displacement.

unreinforced soil specimen. This inference is also supported by concept as described in section 4.1.

These results indicate that the reinforced area has nearly the same stiffness as with unreinforced soil before the pre-peak region, and they exhibit toughness after the peak state. This implies that the reinforced area would have flexibility due to dispersion of shear strain. Therefore, it is difficult to form shear bands (slippages) in the reinforced area.

# 4.3 Tensile force of geogrid with cyclic loading

Figure 12 shows relationship between shear displacement and tensile strain of geogrid. It was found that the tensile strains did not concentrate on the potential shear plane, rather distributed in 100 mm width, i.e., from S02 to S07. Therefore, it appears that the reinforcement prevents localization of shear deformation. This behaviour is also supported by the concept as described in section 4.1. Tensile strain of geogrid remained at unloading in figure 12(b). This elastic energy of tensile strain, which is accumulated with shear displacement, constrains soil around geogrid. On the other hand, in unreinforced soil specimen, accumulated shear strain energy of soil is almost un-recoverable due to plastic deformation. These two different behaviors may bring different deformation modes with cyclic seismic force to unreinforced soil and GRS structures. Specifically, it can be said that unreinforced soil structure easily deforms after peak state, and GRS structure starts to deform at high confinement level of soil by accumulated tensile force of geogrid. Similar behavior was also reported in Koseki et al (2004).

Likewise, in shaking table test, tensile strain of geogrid was remained by passive direction force as seen from Figure 7. At 20 mm shear displacement, which corresponds to 1% strain of geogrid and which is also the maximum recorded strain in the shaking table test, the reinforced soil specimen maintains high level strength after peak state in Figure 11. On the other hand, the unreinforced soil specimen achieves the residual strength at the same displacement resulting



Figure 12. Relation between shear displacement and tensile strain.

in the development of the shear bands. This inference is also supported by Figure 8, in which shear bands were observed only in the unreinforced area and not in the reinforced area.

# 5 CONCLUSIONS

In the present study, seismic behaviour of GRS can be better understood from results of LDST. The result of shaking table test showed that slippage did not occur in a reinforced area based on observation. Also, it was found that tensile strain of geogrid was increasing with wall displacement, and remaining at passive direction phase. This behavior may be supported by the following reasons obtained by result of LDST.

- Reinforced soil specimen has absence of softening behavior due to increase of a mobilized tensile force of geogrid with shear deformation, and increase of a confinement level of soil by accumulated tensile force of geogrid.
- Tensile strain of geogrid still remains at unreloading regions due to elastic material. Therefore, pre-stress effect, which constrains soil during unloading or passive seismic phase, makes GRS tough.
- 3. Geogrid may make shear zone wider due to equilibrium force. As a result, reinforced soil prevents concentration of shear strain.

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