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Shaking table test on seismic performance of geogrid reinforced soil wall

A.A. Ajuda & J. Kuwano
Saitama University, Saitama, Japan

S. Takamine
Kajima Corporation, Japan

K. Yasukawa
The Hiroshima Prefectural Office, Japan

ABSTRACT: This paper focuses on experimental study of reduced scale segmental GRS walls under seismic excitation using a shaking table and tilt test which simulated pseudo static condition. The influence of geogrid length, stiffness and wall inclination on seismic behavior was investigated. Facing displacement, backfill acceleration and formation of slip lines within the backfill were observed at different levels of vibration. Image analysis enable the slip lines to be identified within the soil mass. Test results showed that failure was predominantly due overturning with small amount of sliding. An increase in geogrid length and stiffness contributed to a decrease in wall horizontal displacement while wall inclination contributed to an increase in wall horizontal displacement. Slip lines appeared from the top of the wall and extended down to the lowest reinforcement layer in the reinforced area followed by inclined slip line in the retained area that propagated upwards to the backfill surface.

1 INTRODUCTION

Reinforced soil walls have been in use for over four decades due to satisfactory performance during earthquakes, low construction cost and rapid construction time comparing to conventional type retaining wall. Many conventional types of retaining wall were reported to suffer great damaged in previous earthquake events while reinforced soil wall revealed to have more resistance to earthquake damage as demonstrated in Kuwano et al. (2014) and Koseki et al. (2006). However, this exceptional characteristic made researchers to conduct laboratory experiments using shaking table and tilting test in order to improve the performance of geosynthetics reinforced soil walls during the earthquake. Watanabe et al. (2003) conducted test on a 500 mm high walls using a shaking table, cantilever and gravity type walls together with geosynthetics reinforced soil walls were compared to each other, parameter such as L/H ratio were investigated. It was observed that the wall moved to the outward direction and failure surfaces appeared in the backfill, one commencing from the back of the reinforced zone upwards to the retained soil and the second parallel to the wall moved down towards the bottom of the wall which stopped at the lowest reinforcement layer and no failure planes were observed at the bottom of the front wedge in the reinforced area suggesting that the reinforcement was effectively arranged. El-Emam & Bathurst (2007) conducted a series of shaking table test on a 1.0 meter wall using a sine wave with predominant frequency of 5 Hz. The amplification factor increased with increase reinforcement vertical spacing and decreased with reinforcement length. In the present experimental program, a series of shaking table and tilt test were conducted, parameters such as of reinforcement length (200mm and 300mm), geogrid reinforcement stiffness (low and high) and wall facing outward inclination (to simulate initial damage) were investigated. Global deformation within the backfill were investigated using optical targets and a CCD camera for later perform analysis in Move-Tr-2D software.

2 PHYSICAL MODELLING

2.1 *Shaking and tilting test*

A total of eight shaking and tilting table test were carried out on geogrid reinforced soil walls at Saitama University, Japan. The wall models were constructed in a 1300 mm long by 300 mm wide and 650 mm high container as illustrated in Figure 1. One of the sides was constructed with 15 mm thick transparent plexiglass so that the wall and backfill deformation behavior can be observed and captured by a CCD camera. Wall facing displacement and distribution of shear strain in the backfill were examined by changing model parameters such as geogrid length, stiffness and wall outward inclination, as summarized in Table 1. Tilting test can apply static horizontal body force to a model as assumed in pseudo static analysis, the geogrid reinforced soil walls were manually tilted using a crane system and tilting to the outward direction. The tilting velocity was approximately 1.0 degree per minute, the model walls were tilted until full collapse occurred. The horizontal seismic coefficient was calculated using Equation 1:

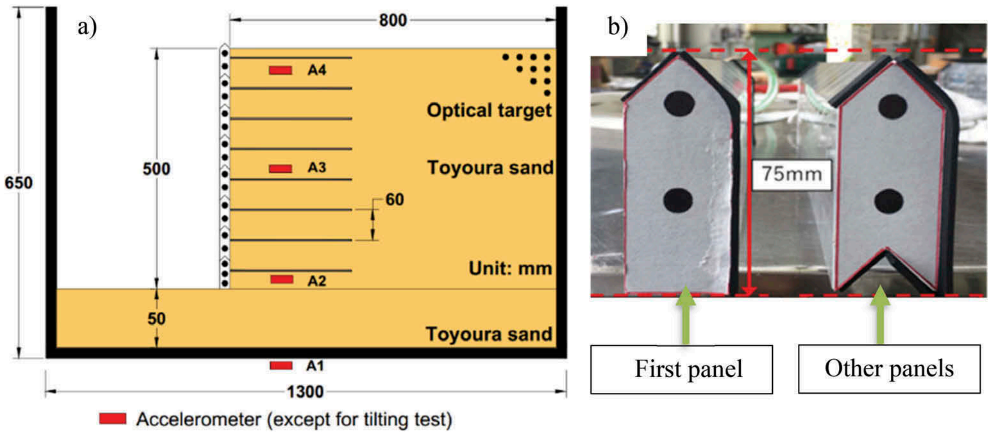

Figure 1. a) Model wall configuration b) Wall panels geometry

Table 1. Outline of the tests

Test name	Wall orientation	Geogrid length mm	Geogrid stiffness	Vertical spacing mm
Wall 1	Vertical	200	Low	
Wall 2	Vertical	200	High	
Wall 3	Vertical	300	Low	
Wall 4	Vertical	300	High	60
Wall 5	3 % Inclined	200	High	
Wall 6	3 % Inclined	200	Low	
Wall 7	3 % Inclined	300	Low	
Wall 8	3 % Inclined	300	High	

$$k_h = \tan\theta = a_{max}/g \quad (1)$$

Where θ = tilting angle; a_{max} = maximum acceleration; and g = gravity.

2.2 *Wall geometry*

All models in the present experimental tests were conducted using a 500 mm high wall. The wall was composed of eight acrylic panels, each with 30 mm thick, 297 mm wide and 75 mm high, as illustrated in Figure. 1b.

2.3 *Model construction*

Model geogrid reinforced soil walls were constructed in rigid container with 1300 mm long, 300 mm wide and 650 mm high as illustrated in Figure 1a. The wall facing was constructed from 8 acrylic segments of 75 mm high and 30 mm thick, the segments were placed on top of each other and no additional connection was made between the panels. Reinforcement connection made of 300 mm long and 30 mm wide steel was used to clamp the geogrid Figure 2b to ensure that slippage does not occur during the model testing and bolted to the wall panels as shown in Figure 2c. The backfill and soil foundation were constructed using dry Toyoura sand with the following properties: specific gravity = 2.648, e_{max}= 0.973, e_{min}= 0.609 and D_{50}= 0.19mm, air pluviation method was employed to achieve the desired relative density of 90%. The soil foundation was made of 50 mm layer Toyoura sand, the wall panels were inserted on top of the foundation layer and braced into the appropriate position and to prevent displacement of the wall during the backfill construction. Since the walls were placed in the sand the toe of the wall can be expected to slide freely to the horizontal direction. The backfill soil was then constructed in a 30 mm layer to allow optical targets to be placed in a 30 mm by 30 mm grid. After completing the backfill construction, unbracing stage started from the top towards the bottom as performed in real scale construction.

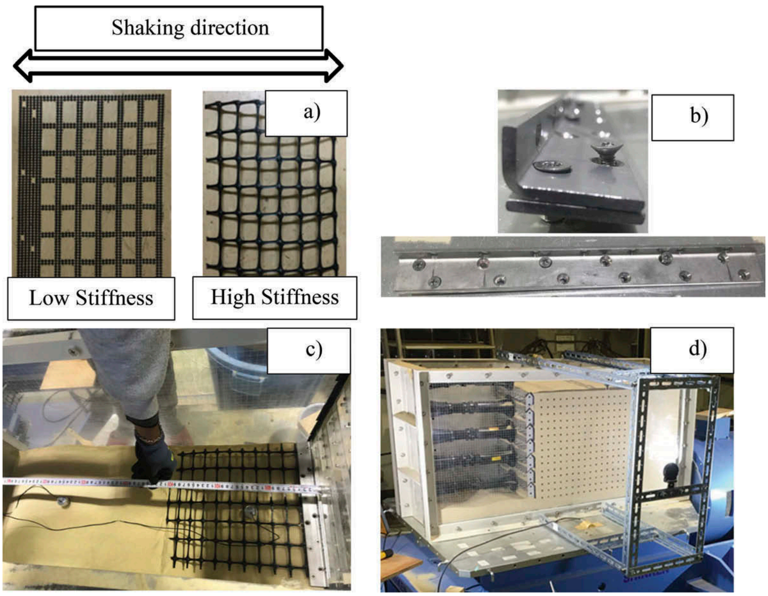

Figure 2. a) Model geogrid reinforcements b) Reinforcement connection detail c) placement of reinforcement and accelerometer and d) constructed geogrid reinforced soil wall.

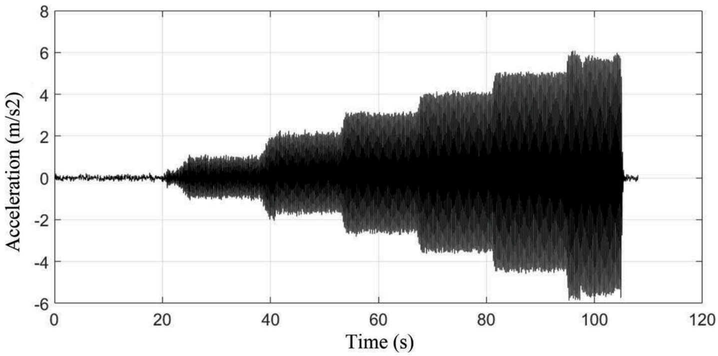

Figure 3. Input base acceleration measured from accelerometer A1

2.4 *Input motion*

The seismic motion was applied by the shaking table controller using a sinusoidal base input acceleration. The amplitude and duration were set so that the base input acceleration had a predominant frequency of 5 Hz. Sinusoidal motion contains more energy than an irregular time-history having same PGA and this type of motion allow comparison of results with other model studies conducted using this frequency Jackson & Bowman (2012). All models were subjected to several intensities of shaking from low to high, each shaking step was held for 10 seconds corresponding to 50 cycles, where the maximum initial horizontal acceleration was set to 1 m/s2 and with increments of 1 m/s2 for every stage until the models fully collapsed as shown in Figure 3. The first accelerometer A1 is fixed to the shaking table to monitor and record the base input acceleration and the others accelerometer A2 A3 A4 were placed at elevations 50, 250 and 480 mm respectively from the bottom of the container and at 150 mm from the facing. All accelerometer data were filtered and corrected using 6th order Butterworth filter with a cut-off frequency of 10 Hz to reduce noise in the acceleration data.

3 TEST RESULTS

3.1 *Wall displacement*

Figure 4 shows the relationship between wall top facing horizontal displacement with time and horizontal seismic coefficient in shaking and tilting test respectively. Generally, the top horizontal displacement increases with shaking time together with an increase in the base acceleration and with an increase in the tilting angle for all cases.

In the present research the slip lines in the backfill for all cases begin to be visible at 3% in shaking table test and 2.6% in tilt test of the wall height at this point the model walls top horizontal displacement increased rapidly after about 1.5 cm and 1.3 cm had been reached respectively. As for the varied parameters the following observation was made:

An increase in geogrid length by 50% from 200 mm to 300 mm produced a decrease in the amount of top horizontal displacement and it was able to sustain acceleration of about 1 m/s2 and slip lines begin to appear at late shaking time and tilting angle. Matsuo et al. (1998) conducted a series of experiment using 1.0 m high wall and they investigated the effects of length/height ratio. It was found that increasing the length/height ratio from 0.4 to 0.7 the wall shows a decrease in the horizontal displacement and an increase in the acceleration by which the models fail.

The effect of reinforcement stiffness on the wall horizontal displacement is also shown in Figure 4. Geogrid reinforced soil walls with higher geogrid stiffness produced a decrease in the horizontal wall top displacement in both shaking test and tilt test and slip lines begin to appear at relatively late shaking time and tilting angle.

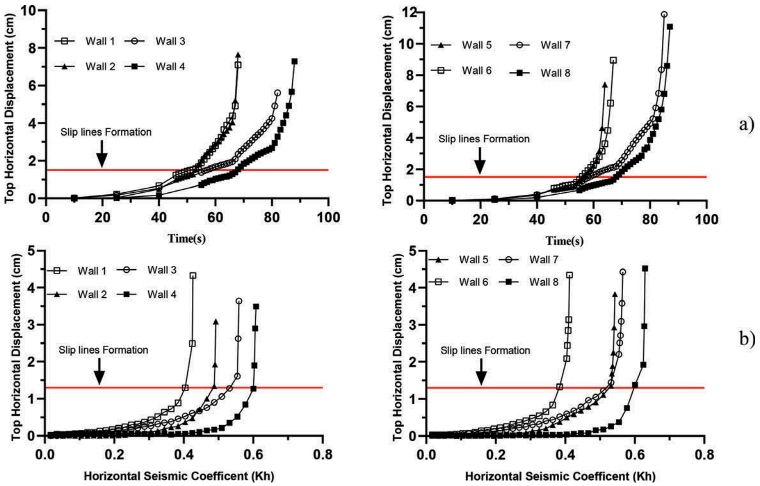

Figure 4. Top horizontal facing displacement in a) Shaking table test and b) Tilt test

Izawa & Kuwano (2011) presented a shear strain of 3% as a critical condition for initiation of slip lines using centrifuge test. This condition was used in the present experiment as a damaged condition of geogrid reinforced soil wall by inclining 3% the wall to the outward direction. As can be seen in Figure 4 similar deformation characteristics as the vertical walls can be observed, however, the inclined wall in all cases showed larger horizontal displacement, this could be attributed to the initial inclination which affects the overturning component leading to larger top horizontal displacement. Slip lines were formed at early stages in case of inclined walls compared to vertical walls, this suggests that a damaged wall without any repair may collapse in the next earthquake event at low shaking intensity, therefore, appropriate repair method should be decided right after the event.

3.2 *Deformation modes*

For all models, the major failure mode of the walls was overturning with tilting of the wall face toward the outward direction, possibly due to a reduction of confinement within the top reinforcement layers, therefore a reduction in resistance against overturning. A small amount of sliding along the base of the wall was also observed. From Figure 5b it is possible to notice four different colors which can be categorized as follow: red (displacement above 3 cm), blue (displacement between 2 and 3 cm), yellow (displacement between 1 and 2 cm) and green (displacement between 0 and 1 cm). The displacement vectors increased with an increase in shaking amplitude or time and with an increase in the tilting angle. The bottom part of the facing wall (last optical target) penetrated the soil foundation and the soil suffered small amount of heave which can be explained possible due to the existence of bearing capacity failure. During the increase of shaking amplitude and tilting angle, the wall face moved to the outward direction causing a collapse of the backfill with two wedge-shape geometry.

As shown in Figure 6, the formation of slip lines in the backfill for all cases can be summarized in the following stages:

Before the shaking or tilting started, no slip line was observed in the backfill, at this point the model are stable and the wall is under static loading prior to shaking;

During initial shaking or tilting, the stability of the wall started to slowly decrease for example at 3 m/s2 in shaking test and kh=0.466 in tilting test and slip line parallel to the wall begin to appear from the top of the backfill toward the bottom in the interface between reinforced and unreinforced area;

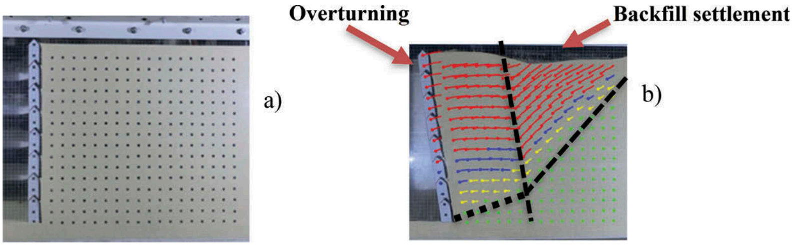

Figure 5. a) Before shaking and b) after shaking at 5 m/s2 which failure occurred for Wall 2.

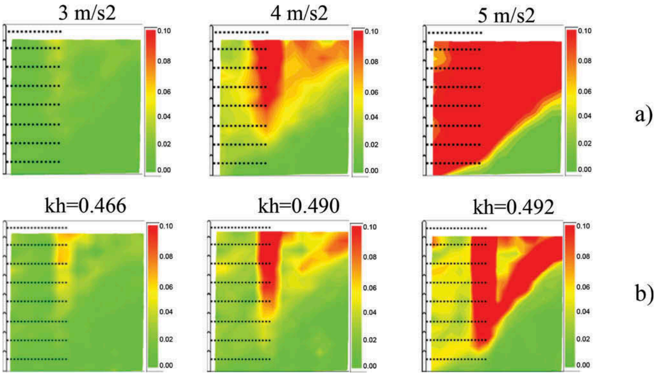

Figure 6. Slip lines formation a) shaking table test and b) Tilting test for wall 2

With further increase in shaking amplitude and tilting angle, clear slip lines started to be visible and continued to move towards the bottom until the second reinforcement layer (starting from the bottom) and inclined slip lines also started to appear together with an increase in the shear strain magnitude for example at 4 m/s2 and kh=0.490 in shaking test and tilt test respectively. It is possible to notice that shear strain tends to be concentrated at the end of the reinforcement layers in all cases, this could be attributed due to the difference in the stiffness between the reinforced area and unreinforced area Jackson & Bowman (2012);

When the shaking amplitude and tilt angle progresses further for example to 5 m/s2 and kh=0.492 in shaking table and tilt test respectively, the slip lines inclined from the toe of the wall upwards to the end of the first reinforcement layer and from this location the slip lines inclined upwards to the surface of the backfill allowing a creation of an active failure wedge which slides downward along the slip line into the back of wall, during this stage the model walls failed immediately and large settlement of the backfill surface was observed, similar behavior was reported by Sabermahani et. al (2009). Inclined slip lines that appeared in the bottom of reinforced zone could indicate that reinforcement arrangement was not sufficient enough to prevent such deformation. Differently, in Sabermahani et al. (2009) and Watanabe et al. (2003) the slip surface did not appear in the reinforced area, possibly due to the type of wall facing or good reinforcement arrangement respectively. In tilt test the active failure wedge developed and right after a slightly increase in the tilt angle the wall failed, while in shaking table the wall failed after continuously accumulating lateral deformation during the shaking as shown in Figure 6, similar characteristics was reported by Koseki et al. (1998);

Effect of geogrid length on backfill deformation can be seen in Figure 7a, c. The deformation shapes for vertical wall was similar even there was a 100 mm increase in reinforcement length from 200 mm to 300 mm. This increase in reinforcement length produced larger stability and the wall did not collapse at 5 m/s2 but around 6 m/s2. No clear slip line was observed in the bottom of reinforced area during 5 m/s2 and low magnitude of shear strain is observed,

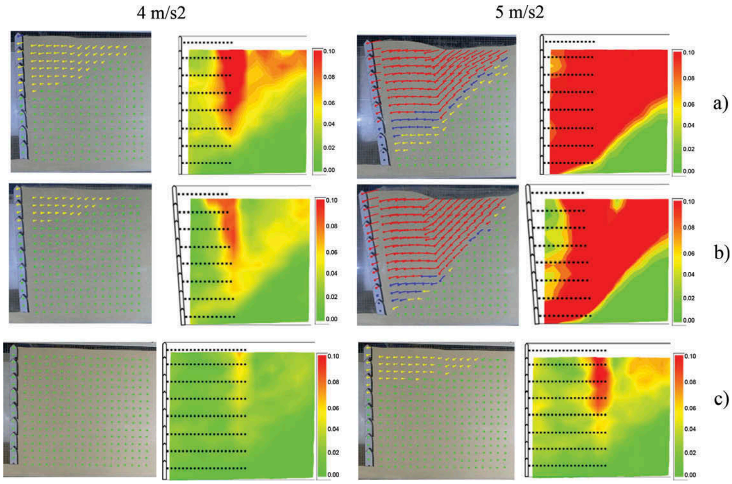

Figure 7. Deformation behavior and slip line formation of model geogrid reinforced soil walls in shaking table test at 4 m/s2 and 5 m/s2 a) Wall 2 b) Wall 5 c) Wall 4.

opposite behavior can be seen for wall 2, the angles of the slip lines formed at failure in Wall 2 at 5 m/s2 were steeper than the angle of slip lines formed in wall 4 at 6 m/s2 in the reinforced area approximately 24° compared to 11° respectively;

The deformation of the inclined walls can be observed in Figure 7b, until 4 m/s2 of shaking the deformation was mainly due to rotation of the wall and clear inclined slip lines were formed within the reinforced and unreinforced area together with a vertical slip line that stopped at the second reinforcement layer. However, the model wall 2 did not exhibit clear inclined slip lines within the reinforced area at the same stage, this behavior could indicate a decreased in stability due to the initial outward inclination of the wall 5.

3.3 *Backfill acceleration*

In this experimental test, FFT amplitude was calculated at different wall elevation in the reinforced area and then normalized with the base input FFT amplitude to obtain the amplification factor (AF), this method was also used by El-Emam & Bathurst (2004). It is possible to observe from Figure 8a that all accelerometer data are within the predominant frequency and from Figure 8b can be seen the comparison of (AF) along the height of the wall in the reinforced zone for wall 4. The maximum AF is within a value of 1.18 recorded at A3, while the accelerometer A4 the recorded amplification was smaller possible due to larger displacement state, similar observation has been reported by Matsuo et al. (1998) and Mirlatifi et al. (2007). Matsuo et al. (1998) reported AF of 1.3 and concluded that the fact that the model was vibrated at a base acceleration large enough to induce plastic deformation and the acceleration amplitude within the sliding block was smaller than the input acceleration.

4 CONCLUSION

Shaking table and tilt test of GRWS were investigated by varying the geogrid length, stiffness and wall inclination. The following is the summary of the test results:

- The amount of horizontal displacement of the walls decreased with increase in geogrid length and stiffness while wall inclination contributed to an increase in wall horizontal displacement;

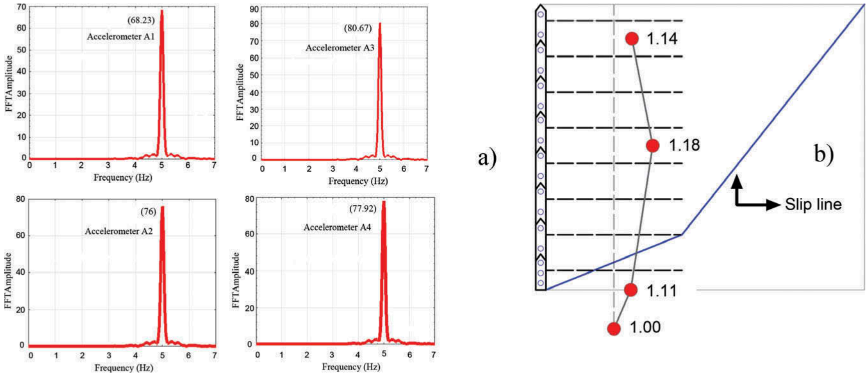

Figure 8. a) FFT in different elevation and b) amplification factor along the wall height in wall 4 (4 m/s2).

- Deformation modes were mainly due overturning accompanied with small sliding. Slip lines ran down into the backfill and into the lowest reinforcement layer of the reinforced area. The deformation mechanisms observed in the backfill agree with two-wedge model for all tested models;
- The amplification factor was found to be non-linear through the wall height, with a maximum amplification of 1.18 recorded at mid height of the wall. However, at the top of the backfill the amplification factor reduced, probably due to larger displacement state within the reinforced area since the amplitude of acceleration was smaller at the top of the reinforced area.

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