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Dynamic Behavior of Geogrid Reinforced Segmental Block Walls under Earthquake Loads

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ABSTRACT: The results of an experimental study conducted on two 1/2 reduced-scale geogrid-reinforced soil retaining block walls are presented and discussed. The heights of the models were 1.9 m and El Centro, Izmit and Sakarya earthquakes were applied. The prototype design was taken from a design made for a real project. Therefore the geogrid reinforcement and facing blocks were scaled versions of the real wall. The geogrids are connected to the facing blocks only by friction. Again to simulate the real design, the walls were constructed with 6° inclined facings. Two different backfill materials were used. In the first model, coarse grained gravel and in the second model well graded sand was used and their effects on the measured parameters are investigated. The aim was also to see whether the wall designed according to current specifications would behave as it was designed under an earthquake loading condition. Accelerations and strains in the reinforcement layers were registered for a later complete evaluation. The test results showed that in both experiments the walls in fact behave almost elastically and the residual displacements observed on the front of the wall were very small under the design earthquake accelerations. The first most important conclusion drawn from the experimental work is that the designed Geosynthetic Reinforced Retaining Structures behaved very successfully even under extreme earthquake loading conditions. Although the connections between the facing blocks and geogrids are only frictional, they resisted even extreme seismic loads without any problem.

1 INTRODUCTION

When compared with the conventional gravity walls, Geosynthetic-Reinforced Soil Retaining Walls (GRS-RWs) offer cost-efficiency, higher performance, aesthetic appearance and much more durability. Because of these advantages, they are widely constructed in place of the conventional gravity walls (Koseki et. al., 2006). In practice, such walls are routinely designed using limit-equilibrium analysis and earthquake loads are considered using pseudo-static methods (AASHTO 1996; FHWA 1996). Shaking table tests were conducted by Ling et al (2005) and Leshchinsky et al. (2008). Leshchinsky demonstrates that although Limit Equilibrium analysis shows a FS≈1 for an acceleration of 0.39g, for a 2.8 m high geogrid reinforced slope having geocell facing and sand backfill, no failure was observed even for an acceleration of 0.8g.

The seismic design methodologies for GRS-RWs are largely based on the results of numerical modeling of reinforced structures constructed with inextensible reinforcement although the related empirical rules developed from these types of structures may not be applicable to nominal identical walls constructed with geosynthetic reinforcement. To help improve these kinds of inadequacies of the current seismic design methods and to gain a better insight into dynamic behavior of a Geosynthetic-Reinforced Soil Retaining wall (GRS-RW) under earthquake loads, a large number of numerical and experimental tests must be available.

This study presents initial results from two ½ reduced-scale Geogrid-Reinforced Soil Retaining Block Wall models that were tested on a shaking table. The model walls were constructed based on an original design made for a real project and loaded using the scaled El Centro earthquake (1940) and Izmit and Sakarya earthquake (1999) motions.

The constraints of the shaking table limit the weight of the model to be tested to 100 kN. Therefore in order to simulate a higher wall, scaled models are used. To evaluate the results obtained from model tests and link the results to its full size prototype, scaling laws are used. Scaling laws provided by the dimensional analysis is a compacting technique for reducing the number and complexity of experimental variables. Based on the scaling laws, similarity is achieved between the model and prototype.

In Table 1, the most common scale factors used in this study can be seen. These scale factors are in agreement with the ones proposed by Iai and Sugano (1999) and Jakrapiyanun and Ashford (2003). The details of the dimensional analysis and similarity between the model and prototype can be found in Guler and Enunlu (2009).

Table 1. Scaling factors used in this study

Quantity	Theoretical Ratio (Prototype/Model)	Study
Length	n	2
Density	1	1
Stress	n	2
Strain	1	1
Acceleration	1	1
Frequency	$n^{-0.5}$	$1/\sqrt{2}$
Time	$n^{0.5}$	$\sqrt{2}$

2 TEST SETUP, INSTRUMENTATION AND REINFORCEMENT LAYOUT

The shaking table tests were conducted in Kandilli Earthquake Research Center Laboratory of Bogazici University, Istanbul, Turkey. A steel container with dimensions of 2 m x 0,5 m x 2,8 m (height, width, length) is placed on the shaking table. Details of the testing device are given in Guler and Enunlu (2009).

In the first model, the container is filled with gravel and two different types of geogrid reinforcements were horizontally placed. The Huesker Fortrac 45/15-20 geogrid reinforcements were placed on the lower portion till mid-height of the wall. They have an L/H ratio of 0,8 (Length of the geogrid=1,5 m). They are placed with a vertical spacing of 0,2 m, in other words a reinforcement was placed for every two rows of model blocks. Huesker Fortrac 20/15-20 geogrid reinforcements were placed on from the mid-height till the upper portion of the wall and they have an L/H ratio of 0,7 (Length of the geogrid=1,3 m). Both model geogrids used have ca. half the strength and the same strains as the prototypes acc. to the scale factors. The vertical spacing of reinforcement is again 0,2 m. A schematic of the wall is given in Fig. 1 and a photograph of the facing is given in Fig. 2. No intermediate reinforcement layers were placed during the experiments. The interconnection between the facing blocks and geogrid reinforcement was purely frictional as can be seen in Fig. 3. In the second model, all the parameters regarding the reinforced wall were the same as the first model except the backfill material, which was selected as well-graded sand. When placing the backfill, both gravel and sand were compacted at each 100 mm.

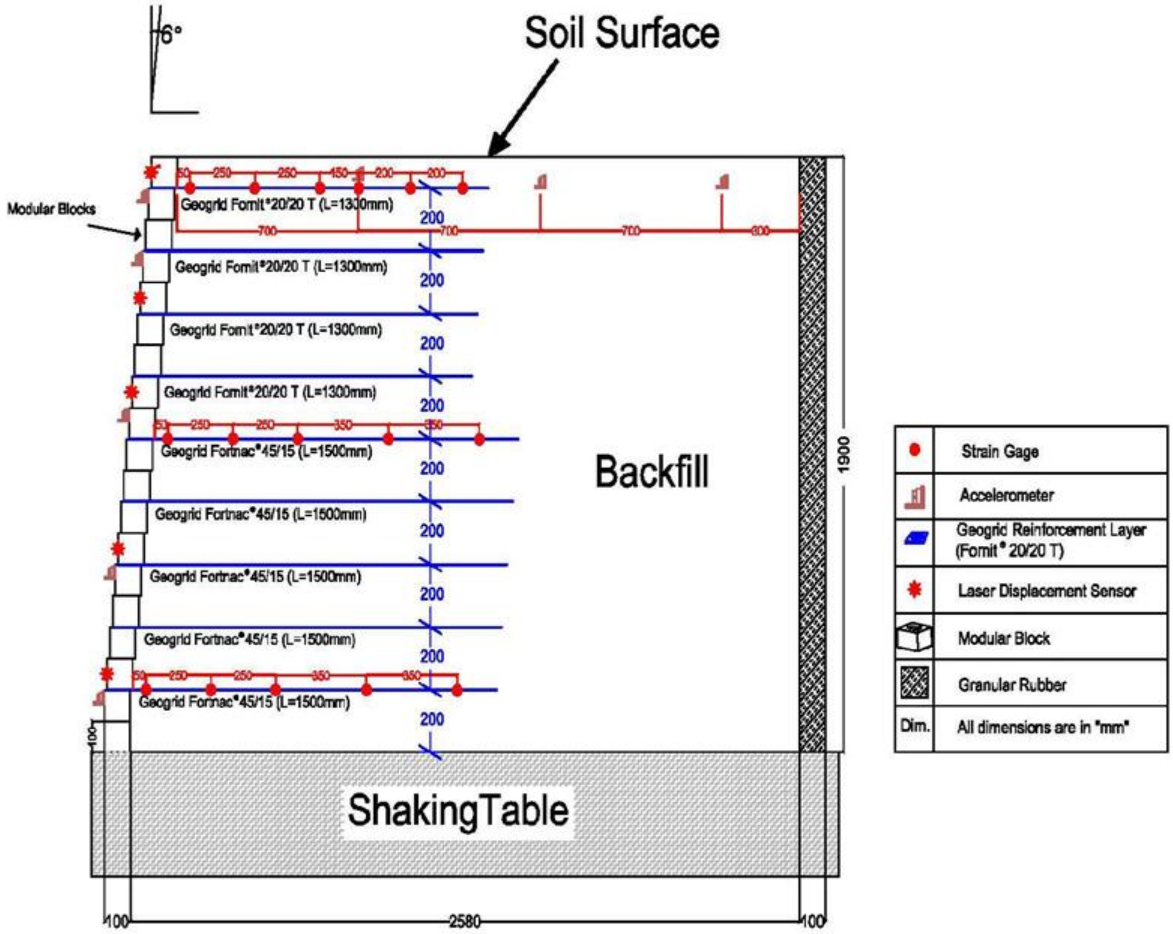

Figure 1. Schematic view of the model wall and locations of instrumentations.

Since the side boundaries of the steel container and backfill materials are prone to friction, rubber sheets were utilized on the side boundaries. Those rubber sheets were not only helpful on eliminating the side effects of the friction phenomena but also the rubber sheet would follow the deformation of the backfill without significant resistance.

In order to simulate segmental retaining structures, hollow concrete facing blocks are placed vertically on the facing with an inclination of 6° from the vertical to simulate the original design. As facing blocks, scaled versions of hollow blocks used by Geoduvar in Turkey were used. The dimensions of these model blocks were 100 mm x 100 mm x 200 mm (height, depth, width).

10 cm thick granular rubber fill was placed between backfill and the back of the steel container in order to prevent reflection of the earthquake waves (Fig. 1).

A total number of 16 strain gages are installed on three different geogrid reinforcement layers (at the bottom layer, at mid height layer and top layer) to measure the strain behavior under dynamic conditions. The strain gages are installed on the middle section of the geogrids which can be seen in Fig. 4. The strain gage cables were passed through polymer flexible pipes so as not to effect the measurements. The strain gages are installed on geogrids using special kind of adhesive and connected to a 16 channel TDG Aib8 data acquisition system.

Figure 2. An overall view of the model wall with accelerometers and strain gages mounted

Figure 3. Installation of geogrids with frictional connection to the facing blocks.

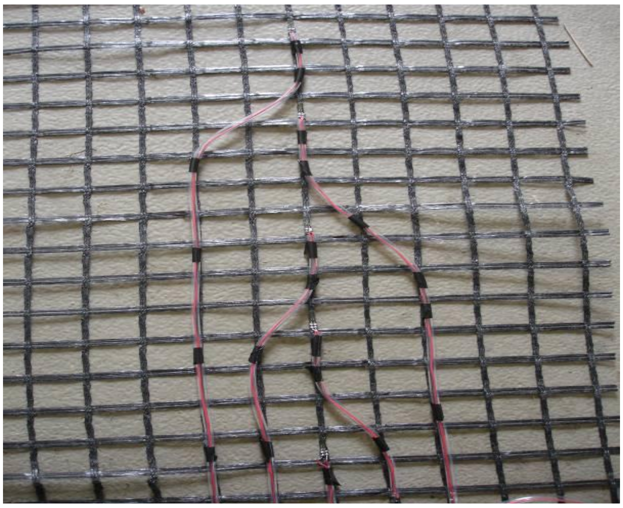

Figure 4. Strain gage setup on geogrid.

The instrumentation also consisted of nine accelerometers which were installed on the facing elements of the wall, top of the backfill and one accelerometer on the shaking table. One of the accelerometers mounted on the wall can be seen in Fig. 5

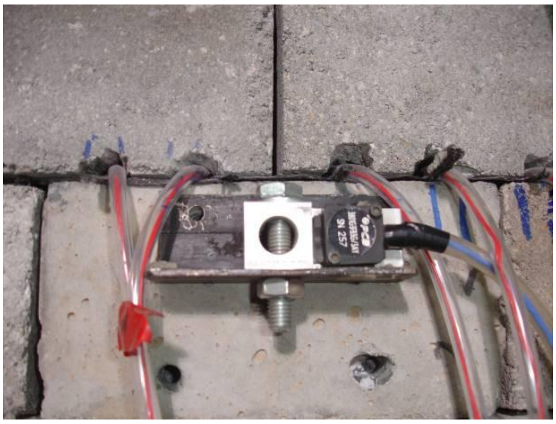

Figure 5. One of the accelerometers mounted on block facing and strain gage cables.

Six laser displacement sensors measuring the displacement of the wall face are installed (with a distance of 25 cm away from the facing elements) in a glass covered steel cell. This glass covered steel framed cell was mounted on the steel container and made the same displacement as steel container in earthquake motion. By this way, only the relative displacement values are measured.

3 SHAKING SEQUENCE

Three different recorded earthquake motions (El Centro, Izmit and Sakarya Earthquakes) were applied on each model. Since the model is a 1:2 scaled model, the natural periods are decreased by $1/\sqrt{2}$. The period of the motion for each earthquake lasted 18.75 seconds for El-Centro, 28 seconds for Izmit and 20 seconds for Sakarya in which the peak accelerations were 0.3 g for El Centro and lower peak accelerations for the other two earthquakes. As an example, the acceleration record used for the El-Centro Earthquake is given in Fig. 6. On later stages of the experiment the peak acceleration values were doubled and tripled meaning that almost 1 g peak acceleration values are applied on the models. Vertical acceleration is not applied on the models.

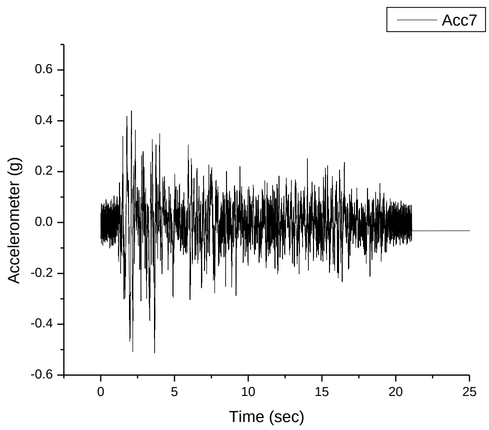

Figure 6. The 100% El-Centro Earthquake Record.

4 DEFORMATIONS

4.1 General

The results indicated that geogrid reinforced retaining structures designed according to the specifications show good resistance to earthquake loading conditions. Both gravel and sand backfilled models behaved successfully under earthquake loading with peak acceleration values of up to 1 g. One of the most interesting facts registered is that although the connections blocks to geogrids are only frictional they resisted even extreme seismic loads. Although significant facing displacement and vertical settlement at top is observed at peak horizontal acceleration values of 1 g, the reinforced walls did not fail.

The maximum peak and residual displacements of the (critical) top block row of walls 1 and 2 for 100% and 250% of the El Centro earthquake loading are given in Table 2. The maximum displacements were measured during the earthquake loading and the residual displacements are the displacements remaining after the earthquake. The maximum displacement is of concern for example if the block wall is in the near vicinity of another structure, or carries a structure upon itself. The residual displacement is of concern because of immediate usability or with a minimum remediation.

Table 2. Horizontal Displacements Measured on Top Modular Block (mm)

	Gravel (Peak)	Gravel (Residual)	Sand (Peak)	Sand (Residual)
100% El Cento	1,9	0,5	2,5	0,8
250% El Cento	26,3	6,8	31,9	5,0

As can be seen from the table no significant permanent displacement occurred for 100% El-Centro Earthquake. When peak deformations under the extreme loading condition of 250% El-Centro are considered, it was observed that even under these extreme accelerations the residual displacements remained minimal. None of the walls 1 (gravel backfill) and 2 (sand backfill) failed in spite of the application of three different earthquakes including the use of artificially high accelerations of up to nearly 1 g. The deformations of all the facing of blocks were within acceptable limits.

The Wall 1 (gravel backfill) tend to behave a bit better (in terms of horizontal displacements) than the Wall 2 (sand backfill), but the differences are surprisingly small, less than one would expect in general due to the difference in the mechanical behavior of gravel/sand. For 100% El Centro earthquake both the peak, as well as the residual displacement are virtually equal. For 250% El Centro the maximum displacement in Wall 1 is by only 8% "better" in the residual displacement even worse, or possibly the same if one tenth of a millimeter is within measurement precision.

This means that at least in this respect (displacements), the fill soil properties does not play a significant role (Figure 7), and that the behavior is dominated more by the other resistance component, the geogrids.

The tested systems exhibit not only high resistance in the sense of stability and deformation during the earthquake, but the residual deformations are also surprisingly good after the earthquake. This fact is tried to be illustrated in Table 3. It is evident that under a "normal" intensity earthquake (100%) only ¼ of the maximum displacement remains as residual displacement. At the extreme earthquake exposure (250%) the same order of magnitude is valid, or it can be stated that the sand backfilled wall behaves even better.

It is also evident that similar to the absolute values of the deformation as given in Table 2 also the ratio of maximum to residual displacement there is hardly any difference in the behavior of walls with gravel and sand backfill. It is likely that here also the "resilience" is determined more by the presence of the geogrid, rather than the backfill.

A significant difference was observed in the subsidence of the surface behind the reinforced zone. Namely at an acceleration of approximately 1 g two rows of cracks were observed on the backfill behind the reinforced zone. Its depth is unknown; the width is in the range of a few millimeters (Figure 8). In the wall with gravel backfill there was no visually detectable crack.

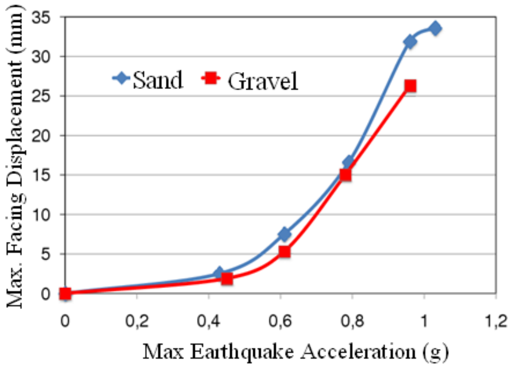

Figure 7. Maximum horizontal facing displacements vs. maximum seismic accelerations.

Tabel 3: Ratio of residual to maximum displacement of the top block row in %

Earthquake Intensity	„Wall 1“ (Gravel)	„Wall 2“ (Sand)
100 % El Centro	26	32
250 % El Centro	26	15
Average	26	23

5.2 Distribution of deformation along the wall height

The distribution of the deformation changes with the amplitude of the earthquake. Under a normal earthquake intensity (100% El Centro), the deformations are very small and fairly independent of the level for both the gravel backfill (Figure 9a) and sand backfill (Figure 9b). Above 200% of the original acceleration, the deformation does not only increase with increasing height, but also start becoming slightly higher at greater heights. This relation for gravel can be seen in Figure 9a. The distribution of deformation of 200% and 250% El Centro earthquake indicate clearly a shear deformation. But if one imagines that the whole wall is sheared, the shear deformations remains even under these extreme accelerations at less than 2%. The same observation can be made for sand backfilled model from Figure 9b.

Generally one can say that compacted granular soils reach plastic shear deformation limit at 3 to 4% shear strain. Thus, the measured deformations indicate, that the system still remains in the elastic range. This also explains why the residual deformations are so small.

Figure 8. Tensile cracks observed in sand backfill behind the reinforced zone.

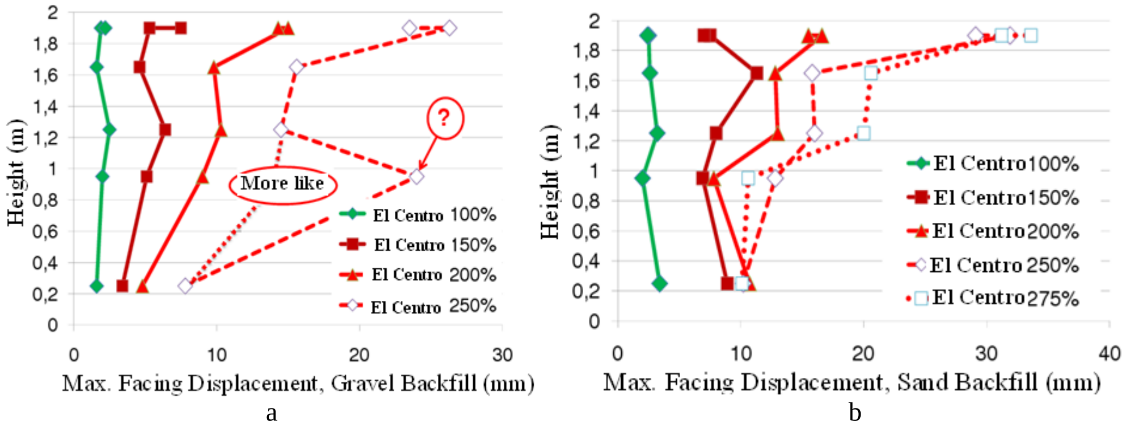

Figure 9. Facing displacement along the height of Walls under El Centro Earthquake with different intensities: a. Wall 1 (Gravel), b. Wall 2 (Sand).

5 CONCLUSIONS

The geogrid reinforced segmental block walls designed according to current specifications showed a very good resistance to earthquake loading conditions. The test results showed that in both experiments the walls behaved almost completely elastically under the design earthquake accelerations. As a consequence the residual displacements observed on the front of the wall were very small.

It was observed that the whole fill underwent a shear deformation and the amount of the calculated shear deformation indicated that the system remained within the elastic zone even under extreme earthquake loading conditions. This fact also explains the reason of the good behavior in terms of displacement and stability.

The tested walls remained stable even under extreme lateral accelerations. Both gravel and sand backfill showed very successful behavior. The Geogrid Reinforced Segmental Block Walls showed minimal residual deformations and acceptable maximum deformations under extreme lateral earthquake accelerations. One of the most interesting facts registered is that although the connections blocks to geogrids are only frictional they resisted even extreme seismic loads.

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