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Seismic response of reduced-scale modular block and rigid faced reinforced walls through shaking table tests

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ABSTRACT

This paper focuses on understanding the seismic response of geosynthetic reinforced retaining walls through shaking table tests on models of modular block and rigid faced reinforced retaining walls. Reduced-scale models of retaining walls reinforced with geogrid layers were constructed in a laminar box mounted on a uniaxial shaking table and subjected to various levels of sinusoidal base shaking. Models were instrumented with ultrasonic displacement sensors, earth pressure sensors and accelerometers. Effects of backfill density, number of reinforcement layers and reinforcement type on the performance of rigid faced and modular block walls were studied through different series of model tests. Performances of the walls were assessed in terms of face deformations, crest settlement and acceleration amplification at different elevations and compared. Modular block walls performed better than the rigid faced walls for the same level of base shaking because of the additional support derived by stacking the blocks with an offset. Type and quantity of reinforcement has significant effect on the seismic performance of both the types of walls. Displacements are more sensitive to relative density of the backfill and decrease with increasing relative density, the effect being more pronounced in case of unreinforced walls compared to the reinforced ones. Acceleration amplifications are not affected by the wall facing and inclusion of reinforcement.

1. Introduction

Retaining walls reinforced with geosynthetics performed satisfactorily during strong earthquakes as observed by several researchers (Juran and Christopher, 1989; Kutter et al., 1990; Collin et al., 1992; Bathurst et al., 1993; Sandri, 1997; Tatsuoka et al., 1997; Ling et al., 2001). Collin et al. (1992) reported that Geosynthetic Reinforced Soil (GRS) walls survived the Loma Prieta earthquake of 1989 with estimated ground accelerations ranging from 0.3 to 0.7 g. White and Holtz (1997) conducted a survey of three geosynthetic reinforced walls and four geosynthetic reinforced slopes after Northridge earthquake of 1994 to show that these walls and slopes were not subjected to any visual distress after the earthquake. However, there are also many case studies of failures of geosynthetic reinforced retaining walls, a database of 171 of them documented by Koerner and Koerner (2013).

The use of Segmental or modular block Retaining Walls (SRW) that include dry-stacked concrete block units as the facia system together with extensible sheets of polymeric materials (geosynthetics) that internally reinforce the retained soils and anchor the facia has gained wide popularity in recent times. Studies on SRW in North America were reported by Bathurst and Simac (1994). Several other researchers (Cazzuffi and Rimoldi, 1994; Gourc et al., 1990; Knutson, 1990; Won, 1994) reported the use of these structures in Europe, Scandinavia and Australia. Use of modular block walls has tremendously increased all over the world during recent years. The distinguishing feature of these structures is the facing column that is constructed using mortarless modular concrete block units that are stacked to form a wall batter into the retained soils (typically 3–15° from vertical). Modular blocks of different shapes and sizes are available in market and are well explained by several researchers (Bathurst and Simac, 1994; Ehrlich and Mirmoradi, 2013).

Shaking table tests facilitate testing of relatively larger structures and model response can be physically observed in these tests along with measurements of response parameters. Most of the shaking table tests are conducted using reduced scale models in a

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1 g field (Bathurst et al., 2001; Koseki et al., 2003; Panah et al., 2015) that are possibly subjective to scale effects due to the influence of stress levels and the lack of reasonable scaling techniques. Most of the model studies on seismic behavior of GRS walls have been performed on very small-scale models where scale effects are expected to have a major influence on measured response. Some examples include: Wang et al. (2015), H (model wall height) = 0.7 m; Lo Grasso et al. (2005), H = 0.35 m; Watanabe et al. (2003); Kato et al. (2002) and Koseki et al. (1998), H = 0.5 m; Latha and Krishna (2008), H = 0.6 m. There are also some seismic tests on larger models: El Emam and Bathurst (2007), Matsuo et al. (1998) H = 1 m; Sakaguchi (1996), H = 1.5 m and Ling et al. (2005), H = 2.8 m. In the present study, height of the model walls is 0.6 m. Though scale effects prevail in these tests, relative performance of rigid faced and modular block walls at varying earthquake shaking conditions can be derived from the observations, providing insights to the effect of various parameters on the seismic performance of these walls.

Several studies on segmental retaining walls are available in literature. Yoo and Kim (2008) investigated the effect of surcharge loads on segmental retaining walls by carrying out a full-scale load test and a 3D finite element analysis on a two-tier, 5 m high, geosynthetic reinforced segmental retaining wall. Bathurst et al. (1997) presented full scale tests on geosynthetic reinforced retaining walls constructed with a column of dry-stacked modular concrete units and wrapped face. It was concluded that hard facing column is a structural element that acts to reduce the magnitude of strains that would otherwise develop in a wall with a flexible facing. Ramakrishnan et al. (1998) presented shaking table test results of geotextile wrap faced and geotextile-reinforced segmental model retaining walls. Segmental retaining wall was found to sustain approximately twice the critical acceleration of the wrap-faced wall. Huang et al. (2003) used multi-wedge method based on Newmark's sliding block theory to analyze four geosynthetic reinforced modular block walls in the 1999 chi–chi earthquake. Ling et al. (2005) presented shaking table tests on three large scale 2.8 m high modular-block geosynthetic-reinforced soil walls subjected to significant shaking using the Kobe earthquake motions. The reinforcements used were polymeric geogrids, which were frictionally connected to the facing blocks having a front lip. It was observed that the wall performance under earthquake shaking could be improved by increasing the length of the top reinforcement layer, reducing vertical reinforcement spacing, and grouting the top blocks to ensure firm connection to the reinforcement.

Koerner and Soong (2001) carried out extensive survey of existing geosynthetic reinforced segmental walls and reported major reasons for excessive deformations and collapse of some of these walls. Yoo and Jung (2006) investigated the case history of a failed geosynthetic reinforced segmental retaining wall in Korea. Finite element analysis of the wall and laboratory tests carried out on backfill and reinforcement revealed that the main reasons for failure were inappropriate design and low quality backfill, apart from the rainfall infiltration. Liu (2012) carried out extensive finite element analysis of geosynthetic reinforced segmental retaining walls and concluded that the deformation of reinforced soil zone was largely governed by reinforcement spacing and reinforcement stiffness, whereas the lateral displacement at the back of reinforced soil zone was governed by the reinforcement length.

To understand the performance of geosynthetic reinforced soil (GRS) walls during strong shaking, a series of shaking table tests on reinforced soil model walls with dry sand backfill are performed in the present study. This research effort had the goals of providing insight into the seismic response of geosynthetic reinforced soil walls under controlled dynamic base shaking, with the variation of parameters like type of facing, backfill relative density, reinforcement layers, and frequency of base motion.

Table 1
Properties of backfill sand.

D10	0.215 mm
D30	0.37 mm
D60	0.71 mm
Coefficient of uniformity C_u	3.30
Coefficient of curvature C_c	0.896
Specific gravity G	2.65
Maximum void ratio e_{max}	0.828
Minimum void ratio e_{min}	0.5022
Maximum unit weight γ_{dmax}	17.22 kN/m^3
Minimum unit weight γ_{dmin}	14.21 kN/m^3

2. Equipment and materials used in the experiments

This study presents the performance of rigid faced and modular block walls at varying earthquake shaking conditions, providing insights to the effect of various parameters on the seismic performance of these walls. To understand the performance of geosynthetic reinforced soil (GRS) walls during strong shaking, a series of shaking table tests on reinforced soil model walls with dry sand backfill are performed in the present study. This research effort had the goals of providing insight into the seismic response of geosynthetic reinforced soil walls under controlled dynamic base shaking, with the variation of parameters like type of facing, backfill relative density, reinforcement layers, and frequency of base motion.

2.1. Shaking table

A computer controlled servo hydraulic single axis shaking table with payload capacity of 1000 kg and foot print of up to 1000 mm × 1000 mm was used in this study. To minimize the boundary effects on model structures, a laminar box was designed and built for the shaking table facility. Laminar box is a large sized shear box consisting of several horizontal layers, built such that the friction between the layers is minimized. The layers move relative to one another in accordance with the deformation of the soil inside. The laminar box used in this study is rectangular in cross section with inside dimensions of 500 mm × 1000 mm and 800 mm deep made up of fifteen rectangular hollow layers machined from solid aluminum compose. The gap between the successive layers is 2 mm and the bottommost layer is rigidly connected to the solid aluminum base of dimensions 800 mm × 1200 mm and 15 mm thickness. The layers were separated by linear roller bearings arranged to permit relative movement between the layers with minimum friction. Accelerometers, soil pressure sensors and Ultrasonic Displacement Sensors (USDT) were used for instrumenting the model retaining walls.

2.2. Back fill material

Backfill material used for the model construction is locally available dry sand. The sand is classified as poorly graded (SP) according to the Unified Soil Classification System. Physical properties of the sand are reported in Table 1.

2.3. Reinforcement

Backfill sand is reinforced with two different types of geogrids, stronger biaxial geogrid (SG) and weaker biaxial geogrid (WG). These geogrids are made up of polypropylene, biaxially oriented integrally extruded geogrids with rigid junctions and stiff ribs. Properties of both the geogrids are presented in Table 2.