Cyclically Induced Deformations in Lightweight Cellular Concrete Backfilled Retaining Structures

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Abstract

Application of lightweight cellular concrete (LCC) materials are increasingly popular in major projects due to their multiple benefits including significantly low surcharge loads. While implementing agencies have shown their interest in using such materials in backfills of mechanically stabilized earth (MSE) retaining walls, the investigation is limited to the determination of the static properties. However, with the increased use of LCC retaining walls in seismically active regions, it is necessary to understand the seismic performance of these structures. In this study, a $1.8 \times 1.2 \times 1.2$ m block of LCC retaining wall with unit weight of approximately 4 kN/m^3, reinforced at the mid-height with a geo-grid layer, was subjected to seismic loading of different amplitudes and frequencies on a shake table to evaluate the response of the wall and geo-grid to seismic loading. Numerous accelerometers and strain gauges were installed at different heights to evaluate the deformation of the LCC block at different depths and relative to the geo-grid. To evaluate the effect of surcharge load and simulate different layers, the blocks were separately loaded seismically at the surcharge stresses equivalent to the surcharge load of 3 and 3.7 m, i.e., a total retaining wall height of 4.2 and 4.9 m, respectively. Specifically, the LCC retaining wall was subjected to a series of sinusoidal cyclic loads with amplitudes ranging from 0.1 to 0.2 g and frequencies of 2 and 3 Hz. Additionally, the ground motions recorded from the 1994 Northridge Earthquake were also applied to the model. Observations of the model during the shake table testing did not indicate the formation of any fractures within the LCC retaining wall. The results obtained from accelerometers and strain gauges indicated that the LCC retaining wall moved monolithically, meaning no observable differences were noted in the displacements of the LCC material relative to the geo-grid.

INTRODUCTION

Lightweight cellular concrete (LCC) offers a number of benefits including being highly durable, noncorrosive, having high freeze-thaw resististance and low permeability. These benefits combined with its low density has resulted in an increase in the use of LCC in major construction projects with LCC being used as lightweight pavements, to repair landslides, as fills in bridge approaches, and to provide shock absorption in tunnels and pipelines constructed in earthquake zones (Aberdeen Group 1963; LaVallee 1999; Tikalsky et al. 2004; and Maruyama and Camarini 2015). In order to form LCC, air voids are introduced into the water, aggregates and cement that is traditionally mixed to create concrete. The air voids are created within the mixture using either a protein-based or synthetic-based foaming agent, which traps the air by reacting both mechanically and chemically with the other components (LaVallee 1999; Tian 2011; Albayrak et al. 2007; Panesar 2013; Maruyama and Camarini 2015). The quantity of the foaming agent in the mixture will control the percent of air voids in the LCC and consequently, the unit weight of the material. LCC materials can have between 10% to 70% air voids (Panesar 2013), which results in unit weights as low as 3.1 kN/m^3 (Aberdeen Group 1963).

The static properties of LCC have been studied by several researchers. Specifically, Aberdeen Group (1963), Loudon (1979), and Neville (2002) presented the hydraulic conductivity of LCC. The drying shrinkage of these materials was reported by Aberdeen Group (1963) and Narayanan and Ramamurthy (2000), whereas the thermal expansion was studied by the Aberdeen Group (1963). Several studies including LaVallee (1999), Narayanan and Ramamurthy (2000) and Zaidi et al. (2008) also reported the values of the unconfined compressive strengths for LCC materials. Tiwari et al. (2017a) conducted laboratory soil tests on LCC materials with four different unit weights to determine their shear strength parameters, coefficients of permeability, and at-rest earth pressures. They related the LCC unit weight with the unconfined compressive strength and the undrained strength properties including the total friction angle and the cohesion intercept. Furthermore, they found that over the range of stresses tested, the effective friction angle and cohesion intercept were not dependent on the unit weight of LCC.

Unlike the static properties, the dynamic properties have been studied in considerably less detail with most studies suggesting that LCC materials have a good ability to absorb shock. However, Tiwari et al. (2017b) presented the results of cyclic simple shear tests conducted on the LCC with four different unit weights. During the testing, the LCC samples were subjected to four different consolidation pressures and a series of fifteen strain-controlled undrained sinusoidal cyclic loads with varying amplitudes. They found that an increase in the dry unit weight of the LCC and/or the consolidation pressure resulted in an increase in the maximum shear modulus. Additionally, Tiwari et al. (2017b) reported that the damping ratio decreased as the shear strain increased until a threshold shear strain level was achieved. Beyond this threshold shear strain level, they reported an increase in the damping ratio with an increase in shear strain.

Several implementing agencies have also demonstrated an interest in using this material in the backfill of mechanically stabilized earth (MSE) retaining walls. While the determination of the static properties are often included in the investigation of the potential use of these materials, the increased use of these structures in seismically active regions mandates the need to obtain an understanding of the seismic performance of MSE walls with LCC backfills. In this study, a LCC retaining wall reinforced with a geo-grid is tested on a shake table, where it is subjected to different amplitudes and frequencies of cyclic loading in order to examine its seismic performance.

MATERIALS AND METHODS

Two concurrent processes were used to cast the LCC. Elastizell Foam Concentrate and water are combined in a 1:40 ratio in the first of these processes. Elastizell Foam Concentrate is a protein-based biodegradable surfactant that is a by-product of the food industry. A foam is created by mechanically agitating the Elastizell Foam Concentrate and water mixture through a small nozzle. It is, then, subjected to high-pressure compressed air action. In the second of the concurrent processes, cement and water are mixed together, according to the design specifications, to form a neat cement slurry. A progressing cavity pump is coupled with a customized concrete mixer and used in this mixing process. The pre-formed foam is added to the neat cement slurry to produce the air-filled cellular concrete in a Proprietary Blending System.

The LCC retaining wall is cast using the air-filled neat cement slurry from the Proprietary Blending System. The LCC used in this study had a unit weight of approximately 4 kN/m^3. The compressive strength of the LCC material ranged from 265-1657 kPa. The static and dynamic properties of this LCC material were reported in Tiwari et al. (2017a) and Tiwari et al. (2017b), respectively. The slurry is poured into a wooden mold with dimensions of 1.8 m × 1.2 m × 1.2 m. The LCC retaining wall was reinforced with a geo-grid layer at mid-height. The LCC retaining wall was allowed to cure in the wooden mold for 25 days. On the 26th day after casting, the wooden molds were removed and the LCC retaining wall was allowed to air dry for at least three days prior to commencing of the shake table testing.

The LCC retaining wall model was placed on a shake table and surrounded by metal cage. The base of the model was fixed to the table using 6 steel rods. The metal cage was used as a safety precaution to ensure that the LCC retaining wall model would not slip off the shake table. However, the cage does not hinder the movement of the LCC retaining wall model and thus, ensures that the results were not hampered by its presence. A picture of the LCC retaining wall model and the shake table set-up is shown in Figure 1. The LCC retaining wall was instrumented with three accelerometers and four strain gauges at various depths. The locations of the instrumentation are presented in Figure 2. A surcharge stress equivalent to a surcharge load of 3 m thick LCC material was placed on top of the model. This is equivalent to a total retaining wall height of 4.2 m. The model was then subjected to a series of sinusoidal cyclic loads with

amplitudes of 0.1g and 0.2g and frequencies of 2 Hz and 3 Hz. The ground motions recorded during the 1994 Northridge earthquake were also applied to the LCC retaining wall model.

Following the testing of the LCC retaining wall model with a total wall height of 4.2 m, approximately 152 mm of LCC was removed from each side of the block resulting in a model with dimensions of 0.91 m by 1.5 m. A surcharge stress equivalent to a surcharge load of 3.7 m thick LCC material was added to this model resulting a total retaining wall height of 4.9 m. This model was also instrumented in a manner similar to that shown in Figure 2 and subjected to same cyclic loads as described previously.

Both LCC retaining wall models were carefully observed during the testing procedures to monitor the formation of cracks within the structure. However, no cracks were observed during any of the testing conducted.

Figure 1. Pictures of LCC retaining wall model on shake table with total equivalent wall height of 4.2 m (left) and 4.9 m (right).
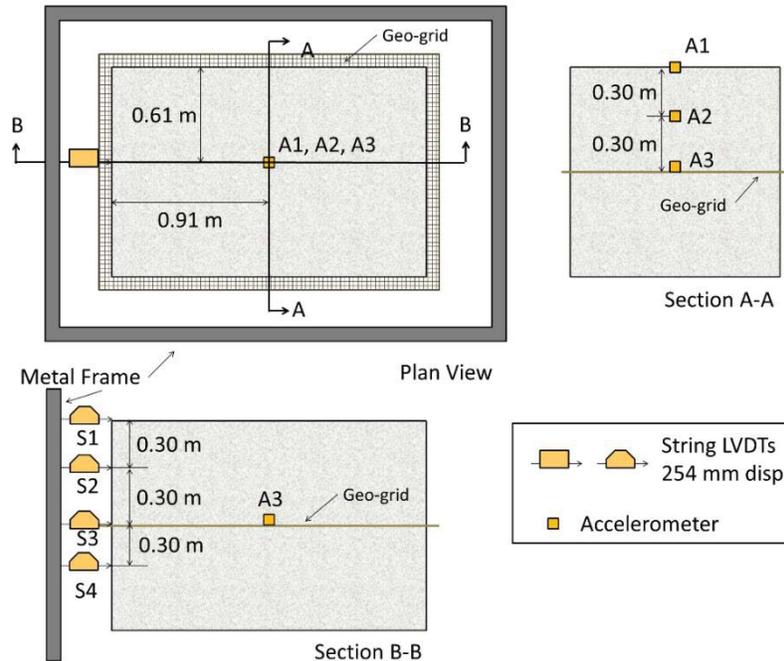
Figure 2. Location of accelerometers and strain gauges in LCC retaining wall model with a total equivalent wall height of 4.2 m; Locations are similar in model with total equivalent wall height of 4.9 m.

RESULTS AND DISCUSSION

Double integration of the acceleration time histories obtained from each of the accelerometer locations was performed to obtain the displacement time histories for each ground motion applied to the LCC retaining wall models. Figures 3 and 4 contain the typical results of displacement time histories obtained. The results in Figure 3 are from the LCC retaining wall with a total equivalent wall height of 4.2 m subjected to sinusoidal cyclic loads with an amplitude of 0.1g at a frequency of 2 Hz, whereas the results in Figure 4 are from the LCC retaining wall with a total equivalent wall height of 4.9 m subjected to the same sinusoidal cyclic motion. Only the results in the direction of shaking are included in this figure as the remaining two directions showed negligible displacements. The displacements shown in Figures 3 and 4 are the total displacements experienced by the accelerometer at the location indicated. Figures 3 and 4 show that there is negligible differences between the displacements recorded at the top surface (A1) of the LCC retaining wall model and at depths of 0.3 m (A2) and 0.6 m (A3) within the structure. Furthermore, as the readings at a depth of 0.6 m correspond to the location of the geo-grid installed, it is clear that there were no observable differences in displacement of the LCC material relative to the geo-grid.
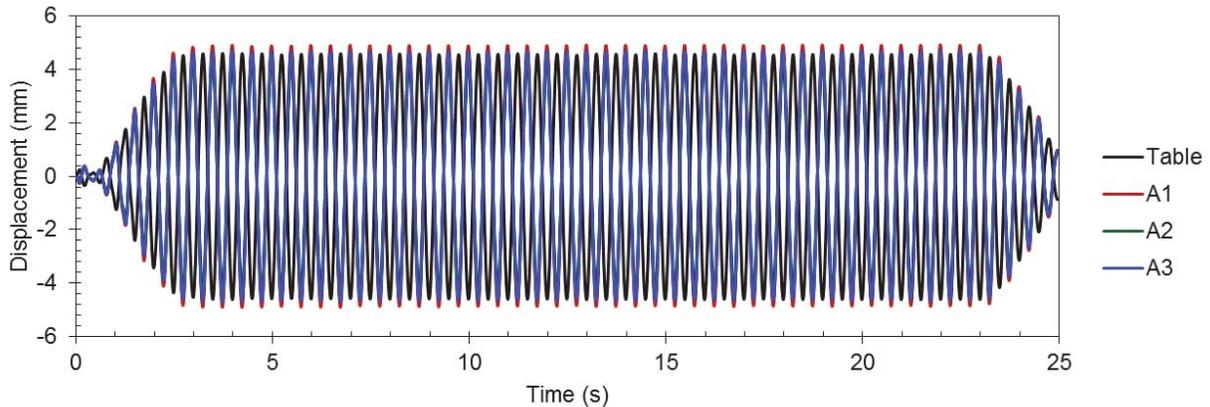
Figure 3. Displacement time histories in LCC retaining wall model with total equipment height of 4.2 m subjected to sinusoidal cyclic loads with an amplitude of 0.1g at a frequency of 2 Hz.
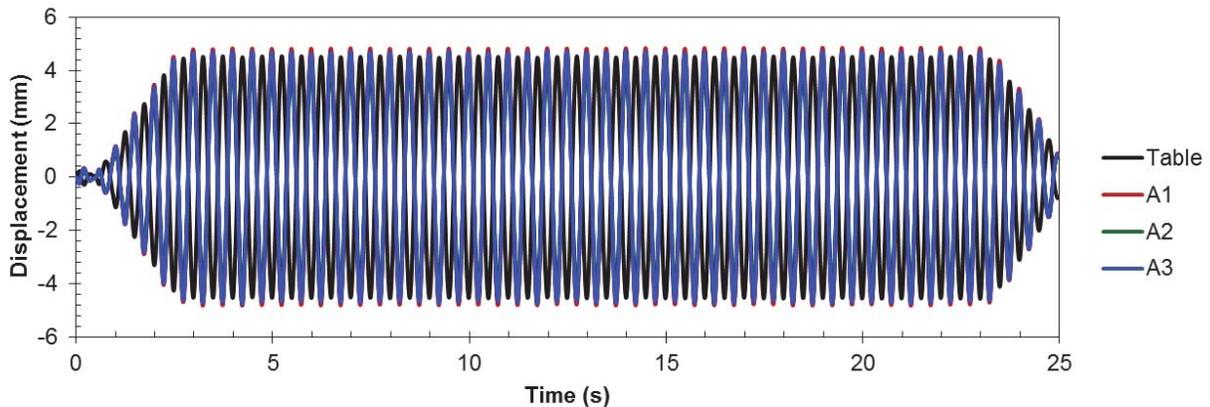

Figure 4. Displacement time histories in LCC retaining wall model with total equivalent height of 4.9 m subjected to sinusoidal cyclic loads with an amplitude of 0.1g at a frequency of 2 Hz.

The displacement time histories obtained from the strain gauges installed are shown in Figures 5 and 6. Unfortunately, the strain gauge located at 0.3 m from the top surface of the LCC retaining wall (labeled S2 in Figure 2) malfunctioned and thus, the data from that strain gauge is not presented here. The results presented in Figures 5 and 6 are from the application of sinusoidal cyclic loads with an amplitude of 0.1g at a frequency of 2 Hz on the LCC retaining wall model with a total equivalent wall height of 4.2 m. The results from the strain gauges represent the relative displacement between the LCC retaining wall model and the shake table. Although there is a slight increase in the displacement at the top surface of the LCC retaining wall model compared to the bottom, the magnitude of the differences can be considered negligible. Thus, in agreement with the results from the displacement time histories from the accelerometers, there is little relative displacement between the LCC material and the geotextile.

As such, the LCC retaining wall can be considered to be displacing monolithically under the applied cyclic loads.
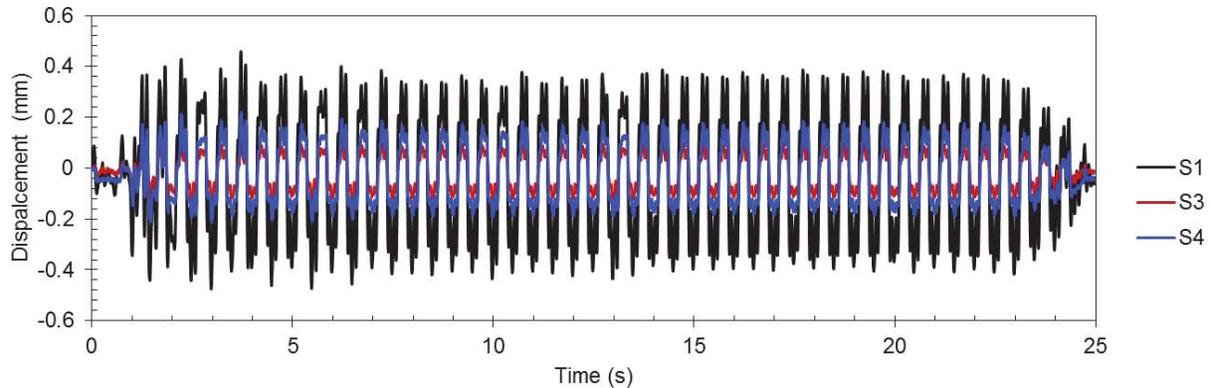
Figure 5. Displacement time histories obtained from strain gauges for LCC retaining wall model with a total equivalent wall height of 4.2 m subjected to sinusoidal cyclic loads with an amplitude of 0.1g at a frequency of 2 Hz.
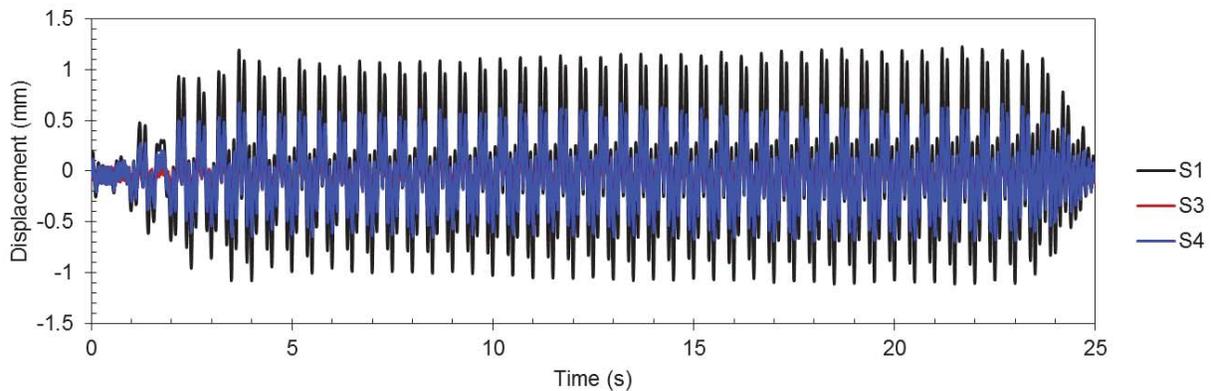
Figure 6. Displacement time histories obtained from strain gauges for LCC retaining wall model with a total equivalent wall height of 4.9 m subjected to sinusoidal cyclic loads with an amplitude of 0.1g at a frequency of 2 Hz.

The negligible magnitude of relative displacements between the geo-grid and the LCC material suggests that the geo-grid only acts to reduce crack propagation within the structure and to hold the facing material. However, the geo-grid is not acting as reinforcement within the LCC retaining wall. The results obtained from this study concur with the numerical analyses presented by Pradel and Tiwari (2017) on the displacement response of LCC retaining wall structures founded on soft clays subjected to cyclic loading. As such, the geo-grid used in the LCC may not be needed as soil reinforcement, but can help to reduce crack propagation in the LCC material.

CONCLUSIONS

Two LCC retaining wall models were tested in this study. The models were constructed using LCC material with a unit weight of approximately 4 kN/m^3. Both models were reinforced with a geo-grid layer located at mid-height. The first model was subjected to a surcharge stress that resulted in a surcharge load equivalent to 3 m thickness of LCC material, while the second model was subjected to surcharge equivalent to a surcharge load of 3.7 m thick LCC material. This corresponded to total retaining wall heights of 4.2 m and 4.9 m, respectively. The LCC retaining wall models were then subjected to a series of sinusoidal cyclic loads and the ground motion recorded from the 1994 Northridge earthquake. The results indicated that the LCC material experienced only negligible displacements relative to the geo-grid layer. This suggests that the LCC retaining wall model moved monolithically indicating that the geo-grid acted only to reduce crack propagation and to secure the facing material and does not provide reinforcement to the LCC material.

ACKNOWLEDGEMENTS

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