Summary of Reinforced Embankment Tests for PRS Mediterranean, Ltd.

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INTRODUCTION

A series of six (6) loading tests were performed on the previously studied Sandstone gravel. These tests consisted of constructing an embankment, with and without reinforcements, and studying its behavior under loading. The reinforcement of choice was PRS Neoweb Geocell. The reinforced model tests consisted of two different reinforcement configurations: a single, central reinforcement layer and a double-layer reinforcement. Each configuration was to be tested under two loading conditions: monotonic (static) and cyclic loading.

The behavior that was studied during each test included lateral spreading, vertical deformation under the “footing”, strength of embankment, and strain in the reinforcement. Afterwards, a grain size distribution analysis was performed to determine the degradation of the gravel due to the loading. The reinforcement was removed after testing and inspected for damage. After the tests were completed, data was compiled and analyzed.

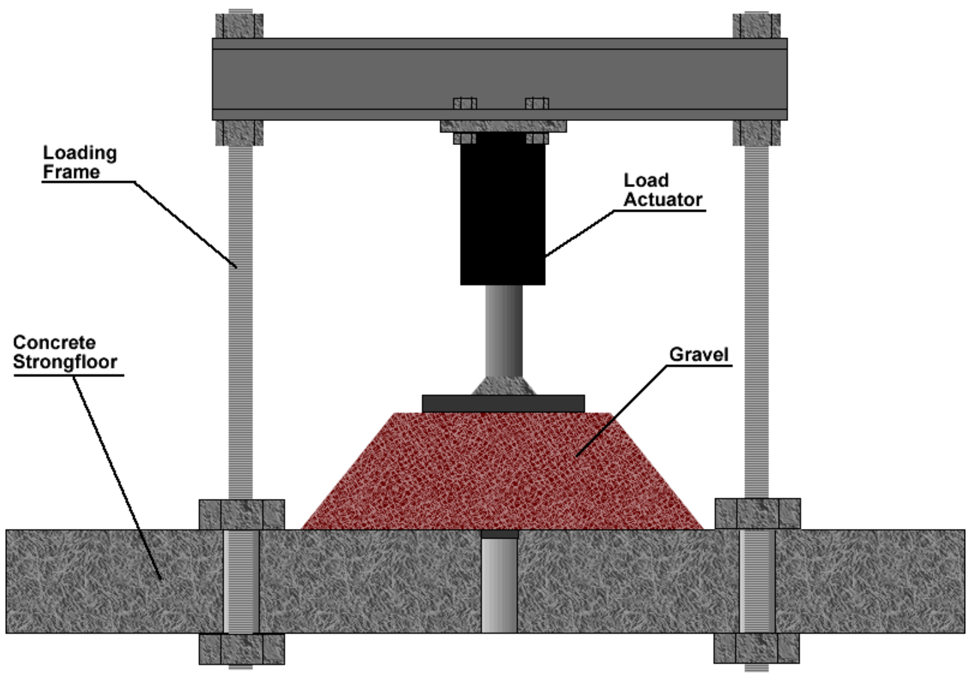

Figure A.1: Model Test Schematic.

UNREINFORCED MODEL TESTS:

The control portion of the testing consisted of a model embankment was constructed of the red sandstone without any type of reinforcement. This section of the experimentation consisted of two tests: one monotonically loaded test and one cyclically loaded test. These tests were used to observe the behavior and strength of the ballast model under different loading conditions. The behavior that was observed was the apparent stiffness, deformation (laterally and vertically), and failure load. Afterwards, a gradation analysis was performed and its strength was quantified.

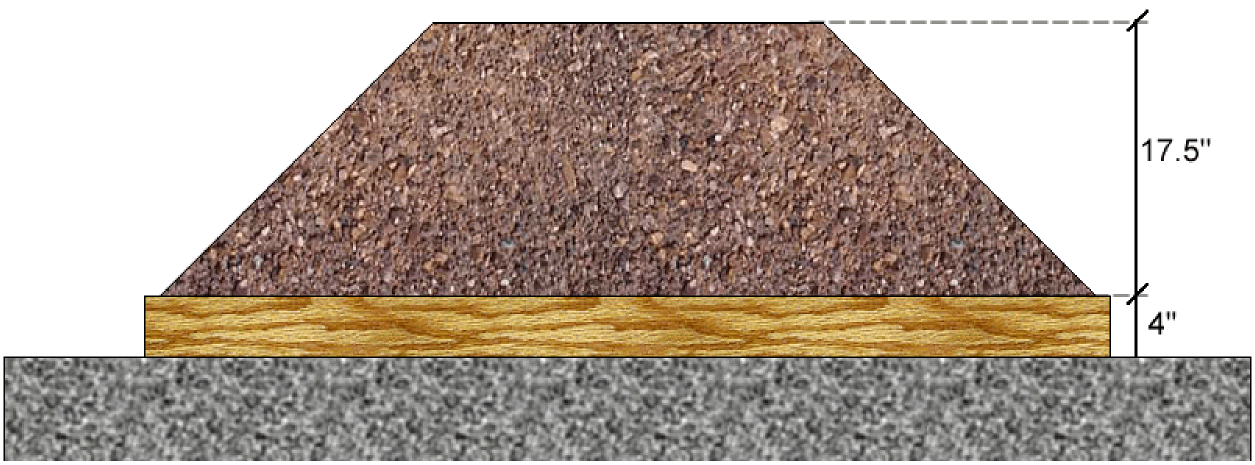

Figure 1.1: Schematic of embankment for tests 1 and 2.

Unreinforced, Monotonic Loading: Test 1

The unreinforced ballast embankment was loaded monotonically in displacement-control conditions. That is, a displacement rate was specified and the full loading was paused for every 0.25 inches (6.35mm) of vertical displacement so measurements and data could be collected. This explains the “spikes” or seeming discontinuities in the loading curve. Despite these jumps, the curve is rather unaffected, allowing an estimate of stiffness. It seemingly required about 4.5 kPa of vertical stress to cause 1 mm of vertical displacement in the initial, elastic portion before “yield” occurs.

The test was stopped when it was apparent that a constant load was still causing displacement, which is classified as failure. This occurred at an estimated vertical stress of 175 kPa.

Measurements of lateral deformation were made as the test was in progress. Considerable lateral deformations occurred at all heights, but the largest spreading occurred at the crest of the embankment. The increase in cross-sectional area at the recorded heights is as follows:

Height from Floor	Percent Increase in Cross-Sectional Area (%)
Top, 21.5” (54.6 cm)	72.78 %
Upper Middle, 18” (45.7 cm)	13.54 %
Lower Middle, 12” (30.5 cm)	6.17 %

Table 1.1: Lateral spreading of unreinforced, monotonically loaded embankment.

Summary of Test Results:

Failure Stress / Load	175 kPa (25.4 psi) / 22.1 kN (5000 lbf)
Yield Vertical Displacement	65 mm (2.56 in)
Elastic Stiffness	4.5 kPa/mm
Max. Lateral Spreading	72.78 % of Area (Top)

Table 1.2: Summary of notable test results.

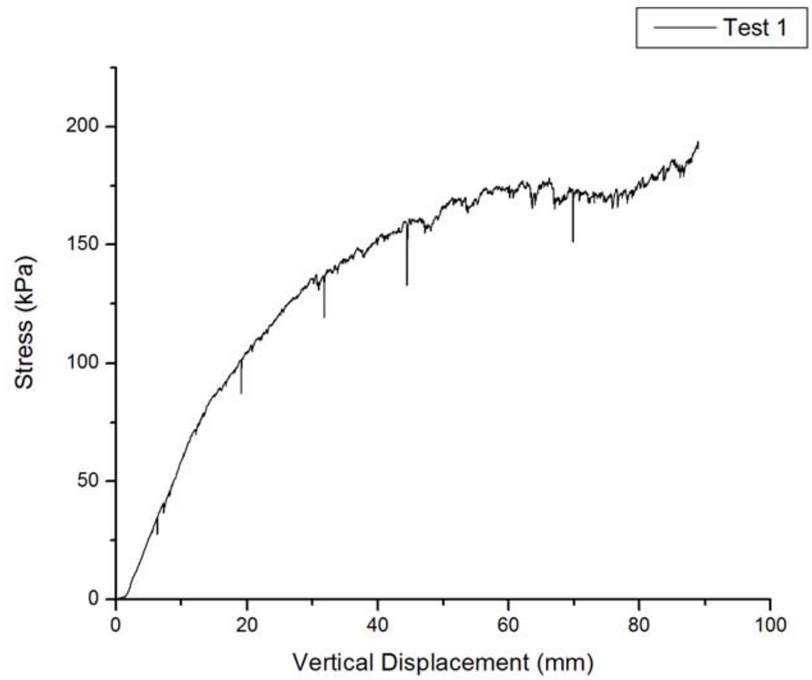

Figure 1.2: Load-Displacement Curve for unreinforced, monotonically loaded test.

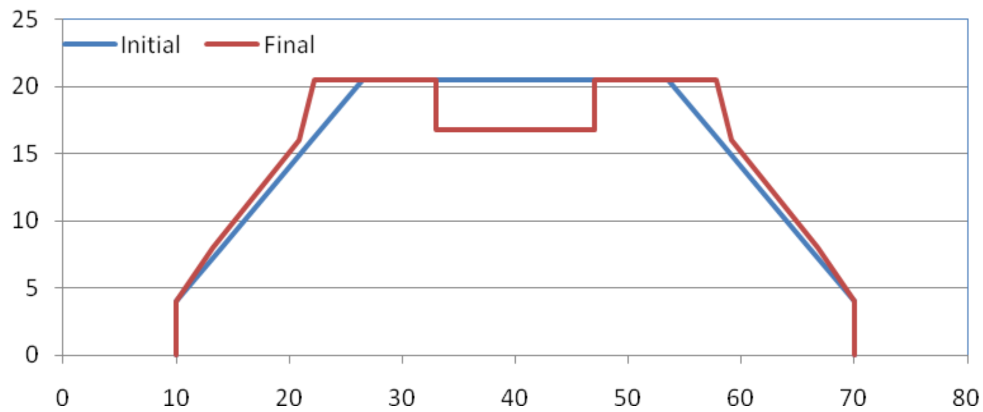

Figure 1.3: Schematic of initial shape and deformed shape of embankment after testing.

Unreinforced, Cyclic Loading: Test 2

The unreinforced ballast embankment was loaded cyclically in load-control conditions. That is, a loading amplitude between 35 and 175 kPa was specified and measurements of deformation were taken at 1000, 5000, 10000, 20000, 30000 and 50000 cycles.

The test was stopped when the load actuator reached its goal of 50,000 loading cycles. A considerable amount of vertical deformation occurred, totaling 4.7" (119 mm), which is very close to the maximum stroke allowed by the MTS actuator. Much of the significant deformation occurred in the initial few hundred cycles. Although the material did seem to stiffen up during the cyclic loading, vertical displacement was continuing significantly with every cycle, indicating that the embankment was failing under the cyclic loading.

As would be expected for such large vertical deformations, lateral spreading continued throughout the test and created a considerably different shape of the embankment. Some of the most significant lateral spreading occurred in the upper-middle portion of the embankment, although there was also a very large amount of deformation at the crest. The increase in cross-sectional area at the recorded heights was as follows:

Height from Floor	Percent Increase in Cross-Sectional Area (%)
Top, 21.5" (54.6 cm)	22.14 %
Upper Middle, 18" (45.7 cm)	25.69 %
Lower Middle, 12" (30.5 cm)	7.20 %

Table 1.3: Lateral spreading of unreinforced, cyclically loaded embankment.

Summary of Test Results:

Final Vertical Displacement	118 mm (4.65 in)
Vertical Displacement during Cyclic Loading	74 mm (2.91 in)
Max. Lateral Spreading	25.69 % of Area (Upper Middle)

Table 1.4: Summary of notable test results.

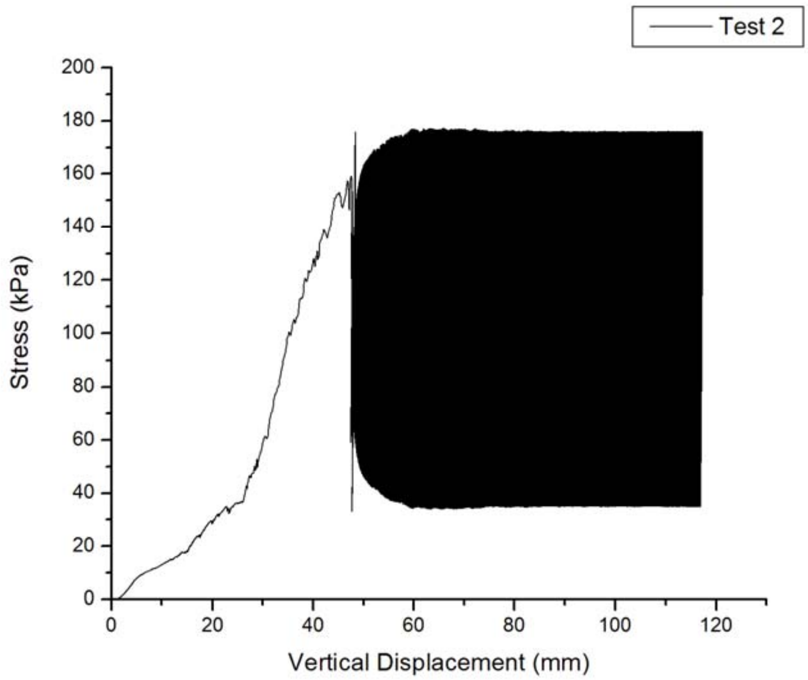

Figure 1.4: Load-Displacement Curve for unreinforced, cyclically loaded test.

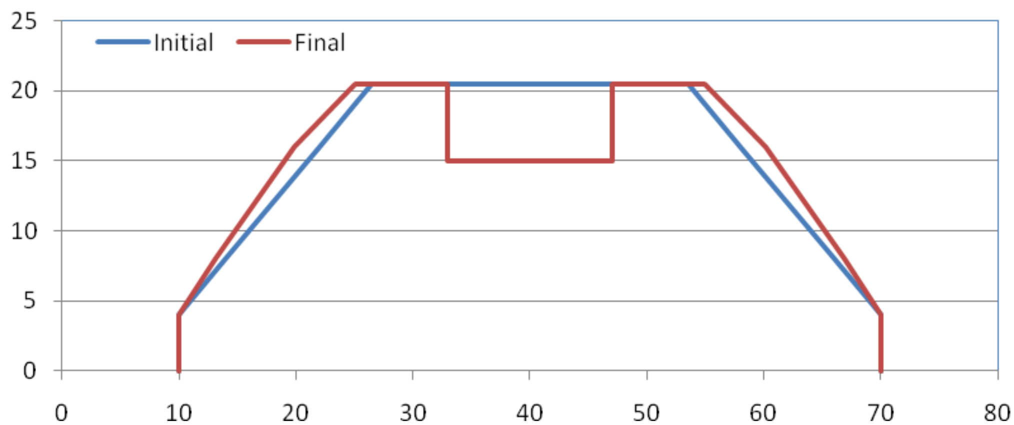

Figure 1.5: Schematic of initial shape and deformed shape of embankment after testing.

REINFORCED MODEL TESTS: ONE LAYER OF GEOCELL

The reinforced portion of the testing consisted of a model embankment constructed from sandstone, reinforced by a central layer of PRS Neoweb Geocell. This section of the experimentation consisted of two tests: one monotonically loaded test and one cyclically loaded test. These tests were used to observe the behavior and strength of the ballast model under different loading conditions. The behavior that was observed was the apparent stiffness, deformation (laterally and vertically), and failure load. Afterwards, a gradation analysis was performed and its strength was quantified.

Figure 2.1: Schematic of embankment for tests 3 and 4.

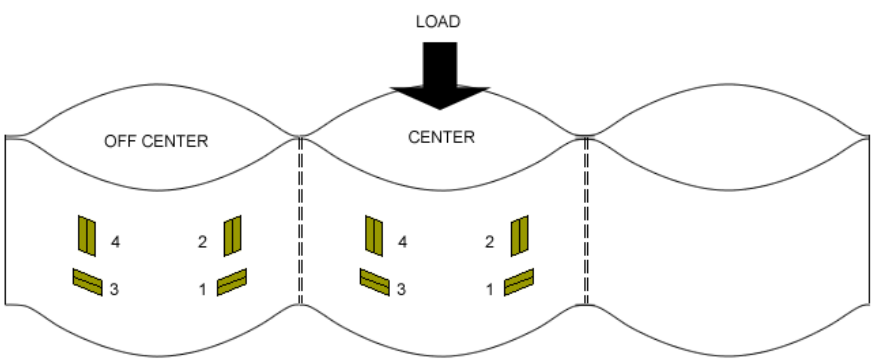

Figure 2.2: Schematic of strain gauge configuration in Geocell.

Reinforced, Monotonic Loading: Test 3

The reinforced ballast embankment was loaded monotonically in displacement-control conditions. That is, a displacement rate was specified and the full loading was paused for every 0.25 inches (6.35mm) of vertical displacement so measurements and data could be collected. This explains the “spikes” or seeming discontinuities in the loading curve. Despite these jumps, the curve is still rather linear, allowing an estimate of stiffness. It seemingly required about 10.9 kPa of vertical stress to cause 1 mm of vertical displacement. This apparent stiffness is higher than the unreinforced model, as expected.

In addition to a higher apparent stiffness, the reinforced model had much more strength than the unreinforced, likely due to the confinement and stiffening of the ballast from the Geocell reinforcement. The test was stopped when the MTS loading frame neared its allowable loading capacity (approximately 16,350 lbf, or 72.7 kN) of about 575 kPa. It seemed evident that the reinforced model could mobilize more strength before failure, but had already evidenced its effectiveness by doing more than tripling the carried load without excessive vertical deformation.

The confinement of the single reinforcement layer was also very effective in the prevention of lateral spreading. This lateral deformation was greatly reduced and mostly limited to the crest of the embankment, where no reinforcement existed. This is very evident from the results, which indicate very little lateral deformation from the level of the reinforcement and below. The increase in cross-sectional area at the recorded heights was effectively reduced by the Geocell confinement as follows:

Height from Floor	Percent Increase in Cross-Sectional Area (%)
Top, 21.5” (54.6 cm)	40.46 %
Upper Middle, 18” (45.7 cm)	6.09 %
Lower Middle, 12” (30.5 cm)	3.67 %

Table 2.1: Lateral spreading of single-reinforced, monotonically loaded embankment.

Summary of Test Results:

Final Stress / Load	575 kPa (83.4 psi) / 72.7 kN (16350 lbf)
Final Vertical Displacement	60 mm (2.36 in)
Elastic Stiffness	10.9 kPa/mm
Max. Lateral Spreading	40.46 % of Area (Top)

Table 2.2: Summary of notable test results.

The vertical displacement that occurred within the 175 kPa range of the single reinforcement test was 31% of displacement that occurred in the same range for the unreinforced, monotonically loaded test.

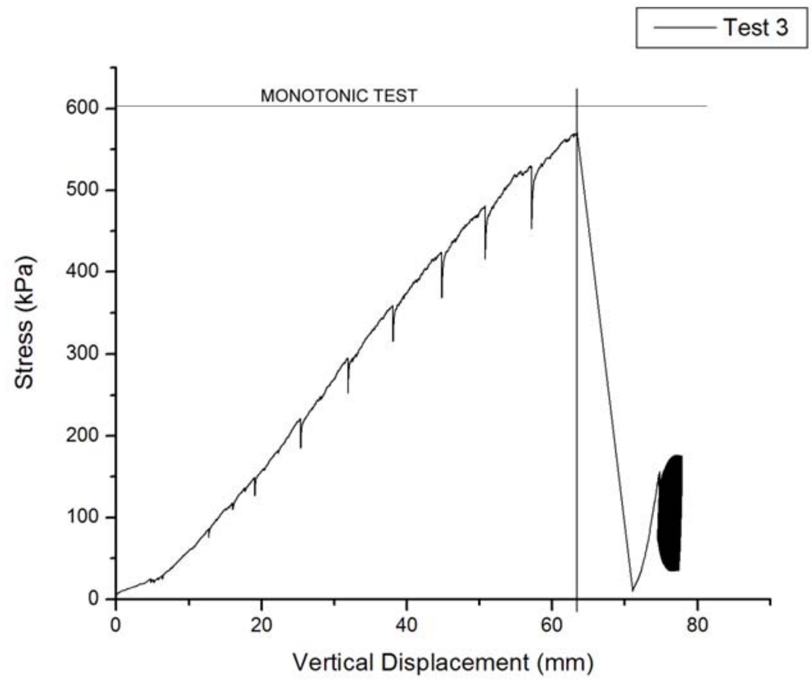

Figure 2.3: Load-Displacement Curve for single-reinforced, monotonically loaded test.

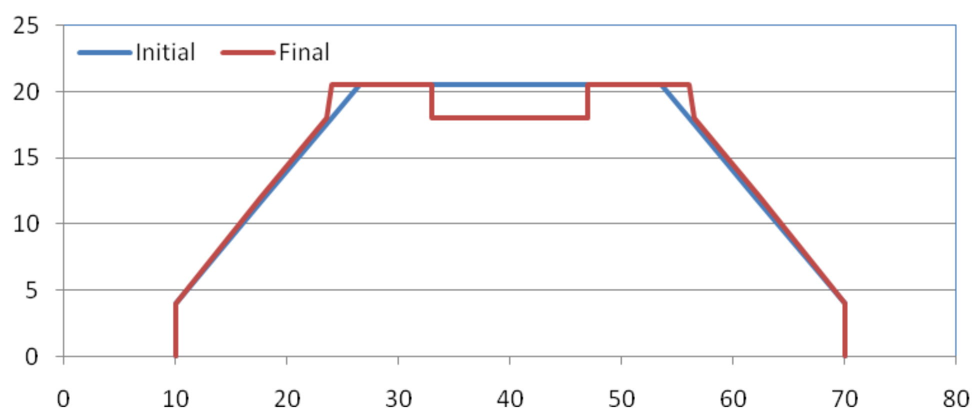

Figure 2.4: Schematic of initial shape and deformed shape of embankment after testing.

Durability and Behavior of Geocell during Test 3:

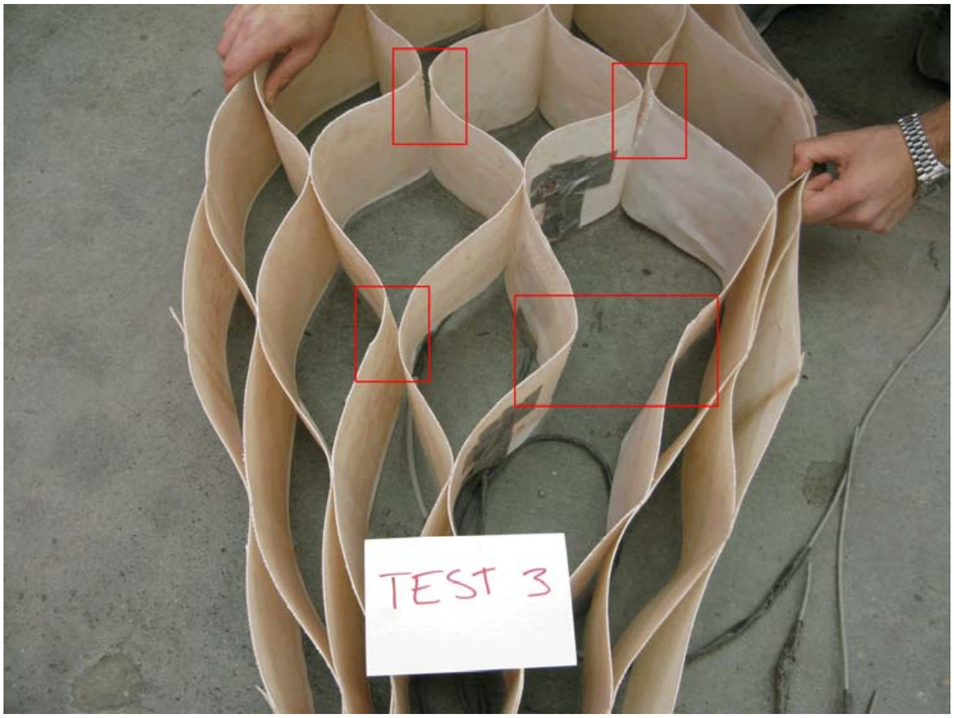

Figure 2.5: Damage in the Geocell after testing.

Despite the success in preventing lateral spreading, significant damage occurred to the Geocell at the seams under and around the center of the loading plate. Strain gauges placed on the Geocell seem to suggest excessive deformation and possible rupture due to sudden shifts between compression and tension.

Upon dismantling the model after it was run, the Geocell was examined for damage. It was clearly damaged significantly, with tearing and rupture at all 4 of the seams beneath the loading plate. Unfortunately, the strain gauge data beneath the center of the plate cuts off approximately 28 minutes into the test. This prevents any observation of sudden changes shifts or changes from compression to tension. These shifts are an effective means of determining any events within Geocell during the test.

The off-center strain gauges managed to capture data throughout the course of the test. It seems to imply that there was increasing tension laterally and compression vertically in the near off-center gauges (1 and 2) as the load was increased. The further off-center strain gauges showed little to no reaction from the load.

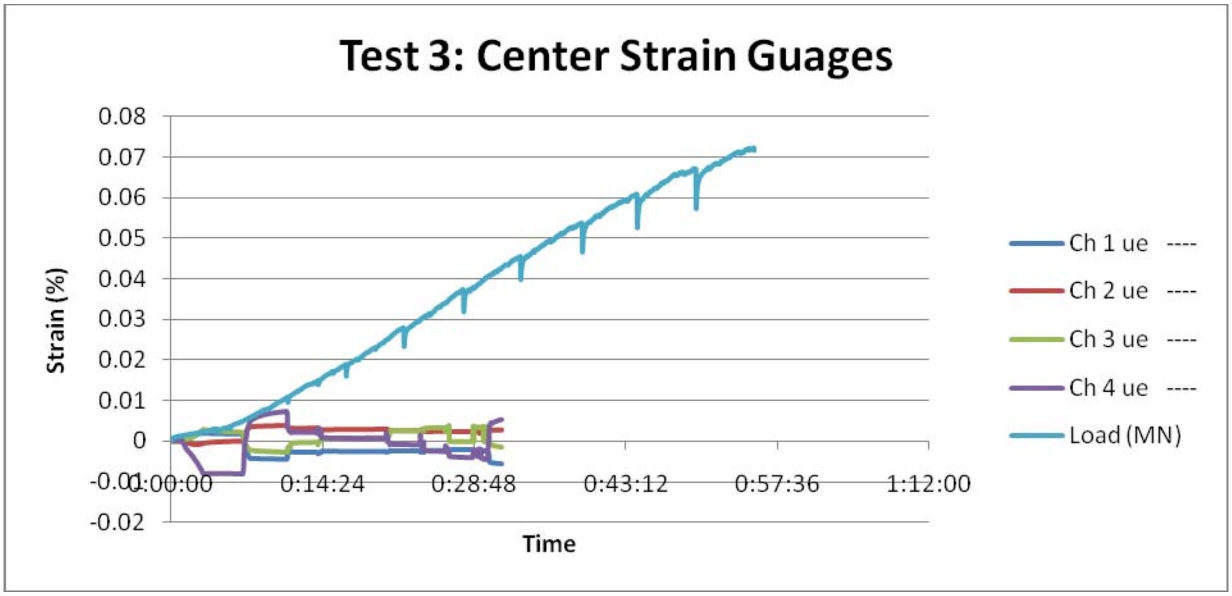

Figure 2.6: Limited strain data for on-center strain gauges.

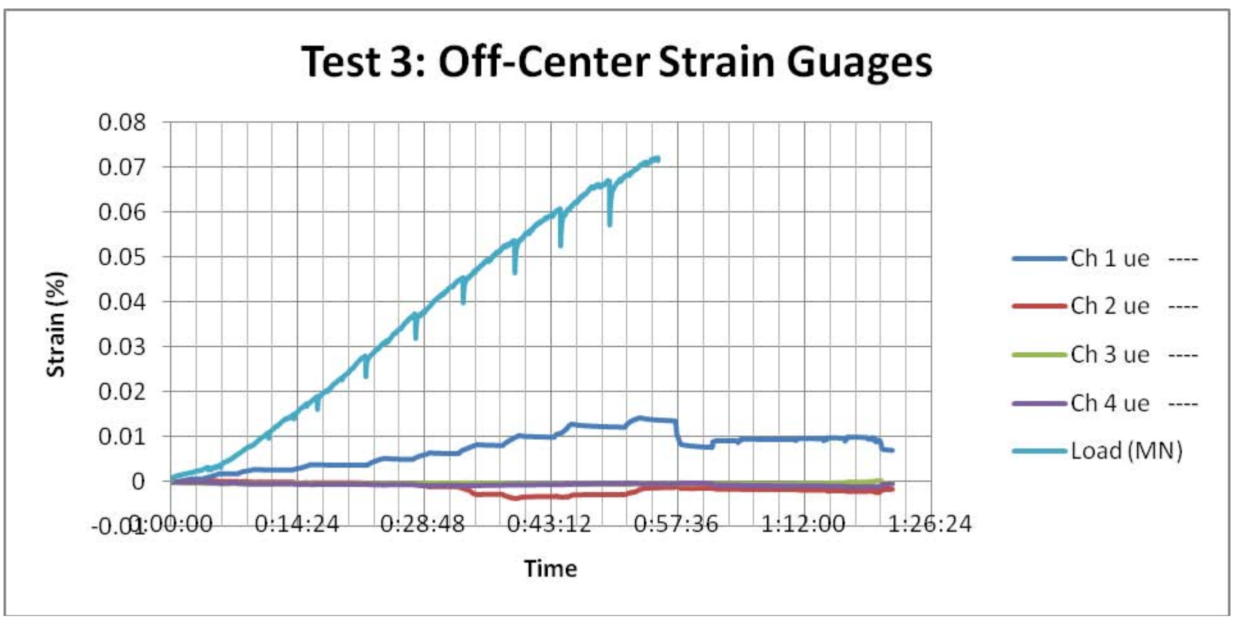

Figure 2.7: Full strain data for off-center strain gauges.

Reinforced, Cyclic Loading: Test 4

The reinforced ballast embankment was loaded cyclically in load-control conditions. That is, a loading amplitude between 75 and 350 kPa was specified and measurements of deformation were taken at 1000, 5000, 10000, 20000, 30000 and 50000 cycles.

The reinforced model had much more strength than the unreinforced, likely due to the confinement and stiffening of the ballast from the Geocell reinforcement. The test was stopped when the MTS reached its goal of 50,000 loading cycles. The test indicated that it prevented almost 60% of the total vertical deformation that would have occurred if the ballast had been unreinforced. This reduction could possibly have been much more if the cyclic amplitude for the reinforced test was the same as the lower loading amplitude used in the unreinforced test.

The confinement of the single reinforcement layer was also very effective in the prevention of lateral spreading. This lateral deformation was greatly reduced and mostly limited to the crest of the embankment, where no reinforcement existed. This is evident from the results, which indicate very little lateral deformation from the level of the reinforcement and below. The increase in cross-sectional area at the recorded heights was effectively reduced by the Geocell confinement as follows:

Height from Floor	Percent Increase in Cross-Sectional Area (%)
Top, 21.5” (54.6 cm)	22.43 %
Upper Middle, 18” (45.7 cm)	6.64 %
Lower Middle, 12” (30.5 cm)	2.52 %

Table 2.3: Lateral spreading of single-reinforced, cyclically loaded embankment.

Summary of Test Results:

Final Vertical Displacement	62 mm (2.44 in)
Vertical Displacement during Cyclic Loading	36 mm (1.41 in)
Max. Lateral Spreading	22.43 % of Area (Top)

Table 2.4: Summary of notable test results.

The final vertical displacement was 52% of displacement that occurred in the unreinforced, cyclic test.

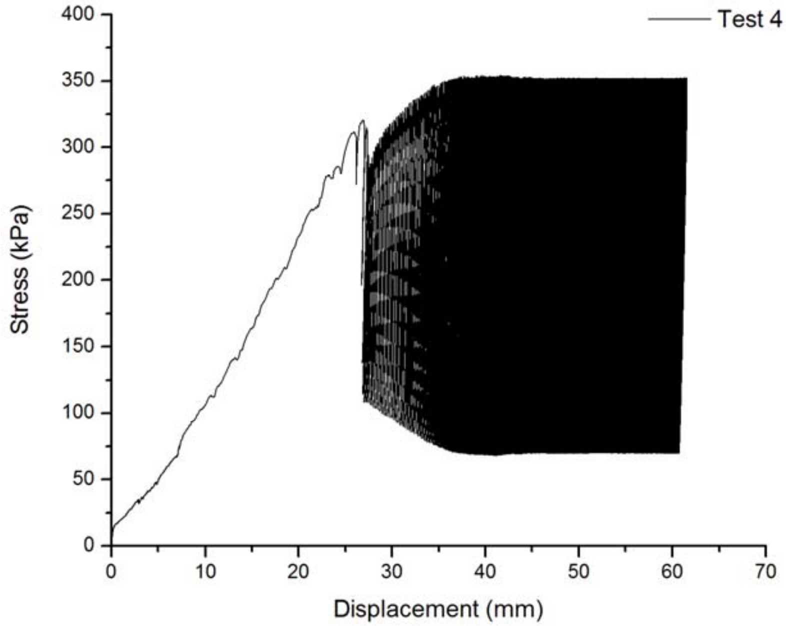

Figure 2.8: Load-Displacement Curve for single-reinforced, cyclically loaded test.

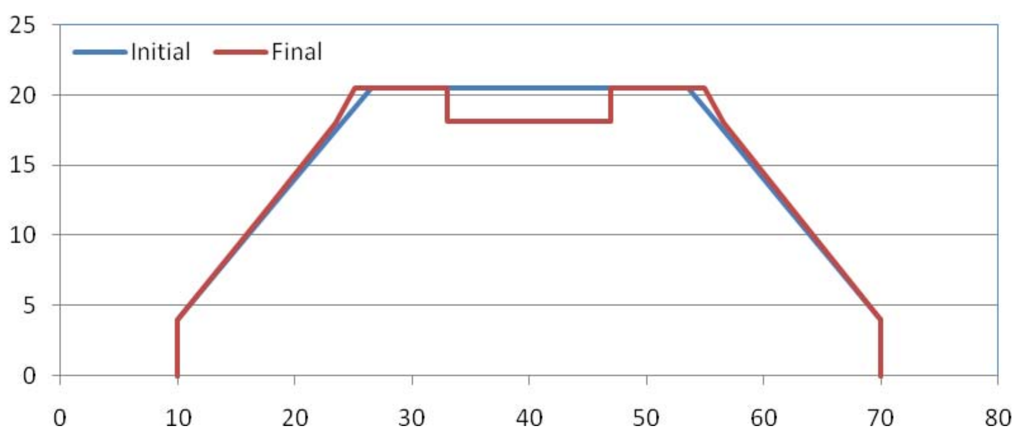

Figure 2.9: Schematic of initial shape and deformed shape of embankment after testing.

Durability and Behavior of Geocell during Test 4:

Figure 2.10: Condition of Geocell after test 4.

The Geocell encountered some damage during the cyclic loading test, but not nearly as much tearing at the seams as during the monotonic test. In fact, most of the damage occurred as bending and compression of the top portion of the Geocell walls. This lack of tearing could possibly be a result of the lower load amplitude.

More problems occurred with the on-center strain gauges, as they only started recording at about 2:20 into the test. However, there are no sudden shifts and the strain is relatively constant, suggesting that the previous data was likely similar. Further supporting this notion is the strain gauge data from the off-center cell. It shows a relatively constant strain throughout the test, suggesting that no serious failures or events occurred within the Geocell.

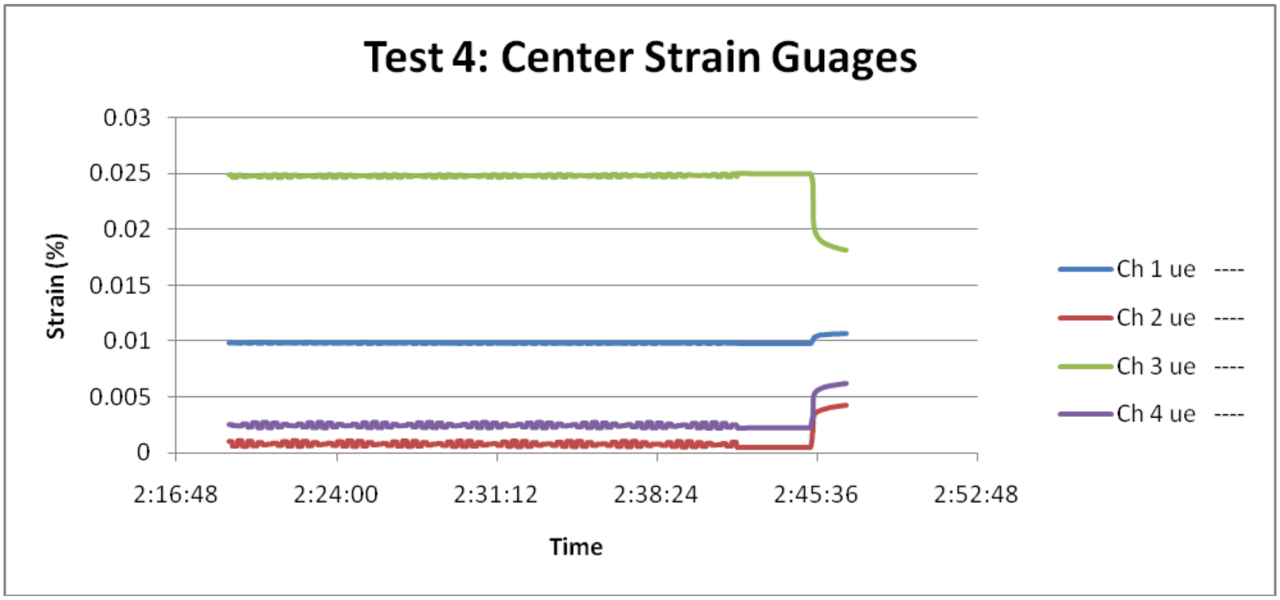

Figure 2.11: Limited strain data for on-center strain gauges.

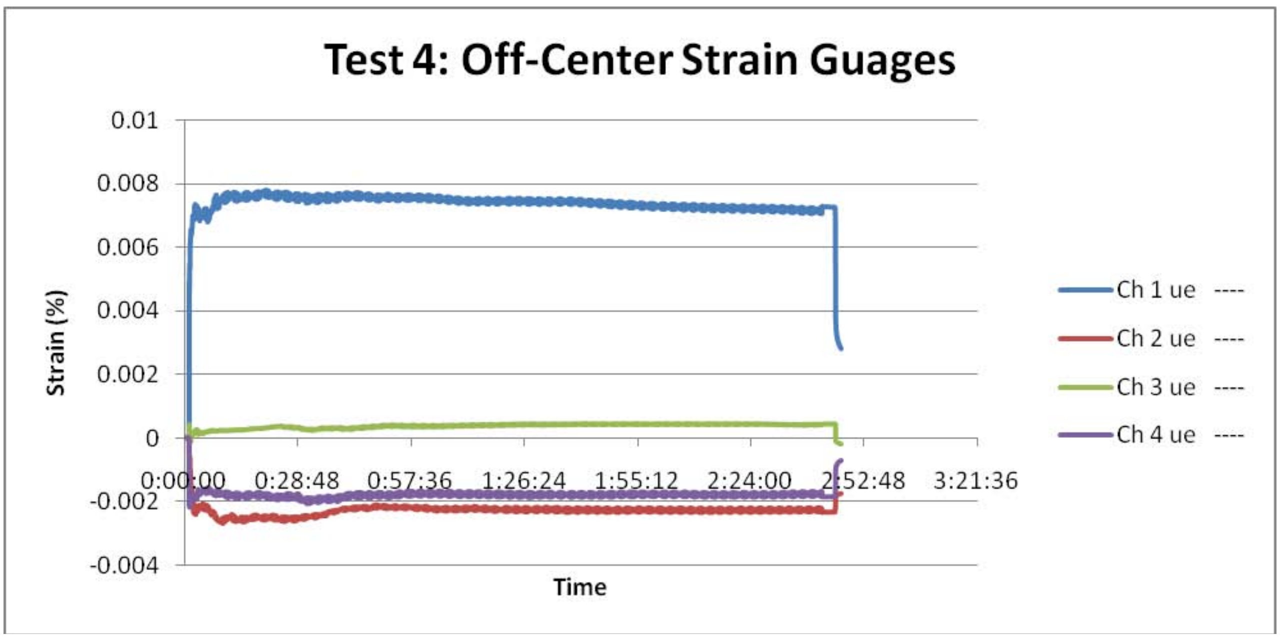

Figure 2.12: Full strain data for off-center strain gauges.

REINFORCED MODEL TESTS: TWO LAYERS OF GEOCELL

The reinforced portion of the testing consisted of a model embankment constructed from sandstone, reinforced by a two layers of PRS Neoweb Geocell: a top layer and a bottom layer. This section of the experimentation consisted of two tests: one monotonically loaded test and one cyclically loaded test. These tests were used to observe the behavior and strength of the ballast model under different loading conditions. The behavior that was observed was the apparent stiffness, deformation (laterally and vertically), and failure load. Afterwards, a gradation analysis was performed and its strength was quantified.

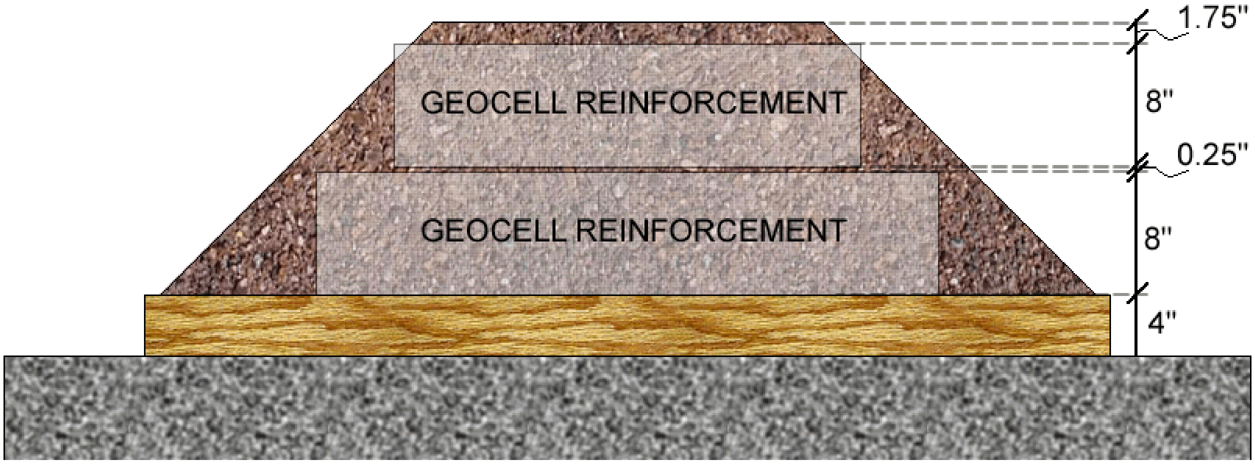

Figure 3.1: Schematic of embankment for tests 3 and 4.

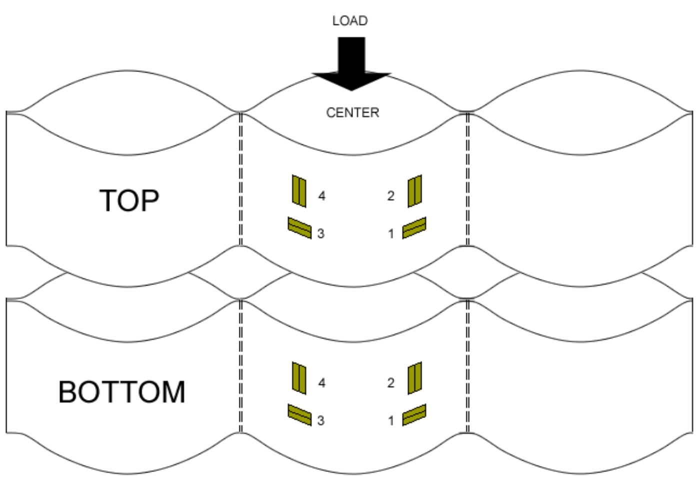

Figure 3.2: Schematic of strain gauge configuration in layers of Geocell.

Reinforced, Monotonic Loading: Test 5

The reinforced ballast embankment was loaded monotonically in displacement-control conditions. That is, a displacement rate was specified and the full loading was paused for every 0.25 inches (6.35mm) of vertical displacement so measurements and data could be collected. This explains the “spikes” or seeming discontinuities in the loading curve. Despite these jumps, the curve is still rather linear, allowing an estimate of stiffness. It seemingly required about 11.9 kPa of vertical stress to cause 1 mm of vertical displacement. This apparent stiffness is higher than the unreinforced model and the model with a central reinforcement layer. This increase in stiffness is expected as the whole model is a reinforced composite.

This model test was stronger than the unreinforced case, and possibly stronger than the case of just the central reinforcement. Like the test with a single reinforcement, this test was stopped when the MTS loading frame reached its allowable loading capacity (approximately 17,780 lbf, or 79.1 kN) of about 625 kPa. This test seemed stronger because no significant damage in the Geocell occurred and the composite model was significantly stiffer.

The confinement of the double reinforcement layer was also very effective in the prevention of lateral spreading. This lateral deformation was greatly reduced throughout the height of the model as the top layer of reinforcement prevented spreading at the crest. The increase in cross-sectional area at the recorded heights was effectively reduced by the Geocell confinement as follows:

Height from Floor	Percent Increase in Cross-Sectional Area (%)
Top, 21.5” (54.6 cm)	13.38 %
Upper Middle, 18” (45.7 cm)	6.82 %
Lower Middle, 12” (30.5 cm)	3.69 %

Table 3.1: Lateral spreading of double-reinforced, monotonically loaded embankment.

Summary of Test Results:

Final Stress / Load	625 kPa (90.7 psi) / 79.1 kN (17780 lbf)
Final Vertical Displacement	53 mm (2.08 in, calibrated)
Elastic Stiffness	11.9 kPa/mm
Max. Lateral Spreading	13.38 % of Area (Top)

Table 3.2: Summary of notable test results.

The vertical displacement that occurred within the 175 kPa range of the double-reinforcement test was 28% of displacement that occurred in the same range for the unreinforced, monotonically loaded test.

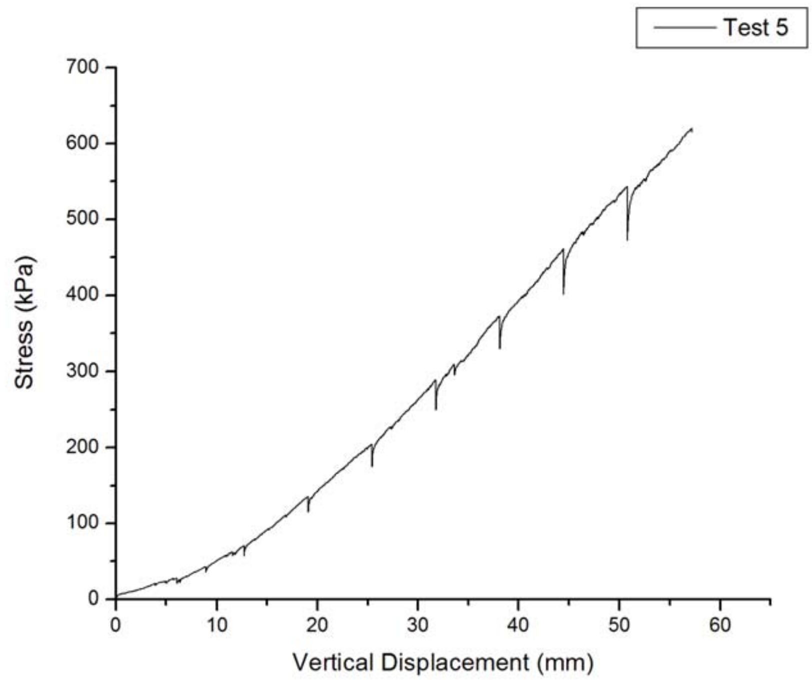

Figure 3.3: Load-Displacement Curve for double-reinforced, monotonically loaded test.

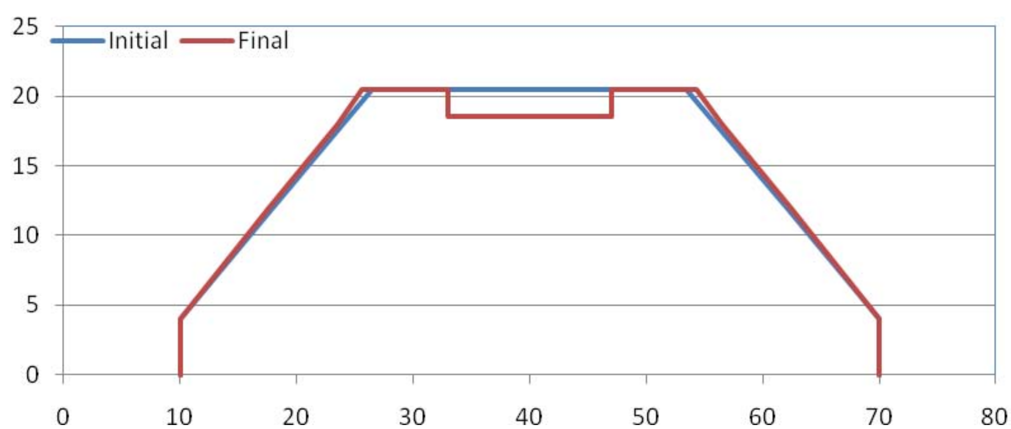

Figure 3.4: Schematic of initial shape and deformed shape of embankment after testing.

Durability and Behavior of Geocell during Test 5:

Figure 3.5: Condition of Geocell layers after test 5. They were relatively undamaged.

Both layers of Geocell were barely damaged from the monotonic loading of the model. Both encountered no tearing at the seams and joints, unlike in the single reinforcement layer test. This could likely be due to a higher stiffness of the embankment acting as a composite and in turn, a lower deformation of the Geocell. The only damage, which was negligible was slight bending and compression of the Geocell walls.

Further problems occurred with the strain gauges as no data was recorded in the bottom layer, but was not critical. Full data was available for the top layer, which indicated increasing strain correlating to each increasing load, as expected. The general return of the strains to the initial level after the test was completed suggests that strain was elastic and minimal damage (plastic strain) occurred.

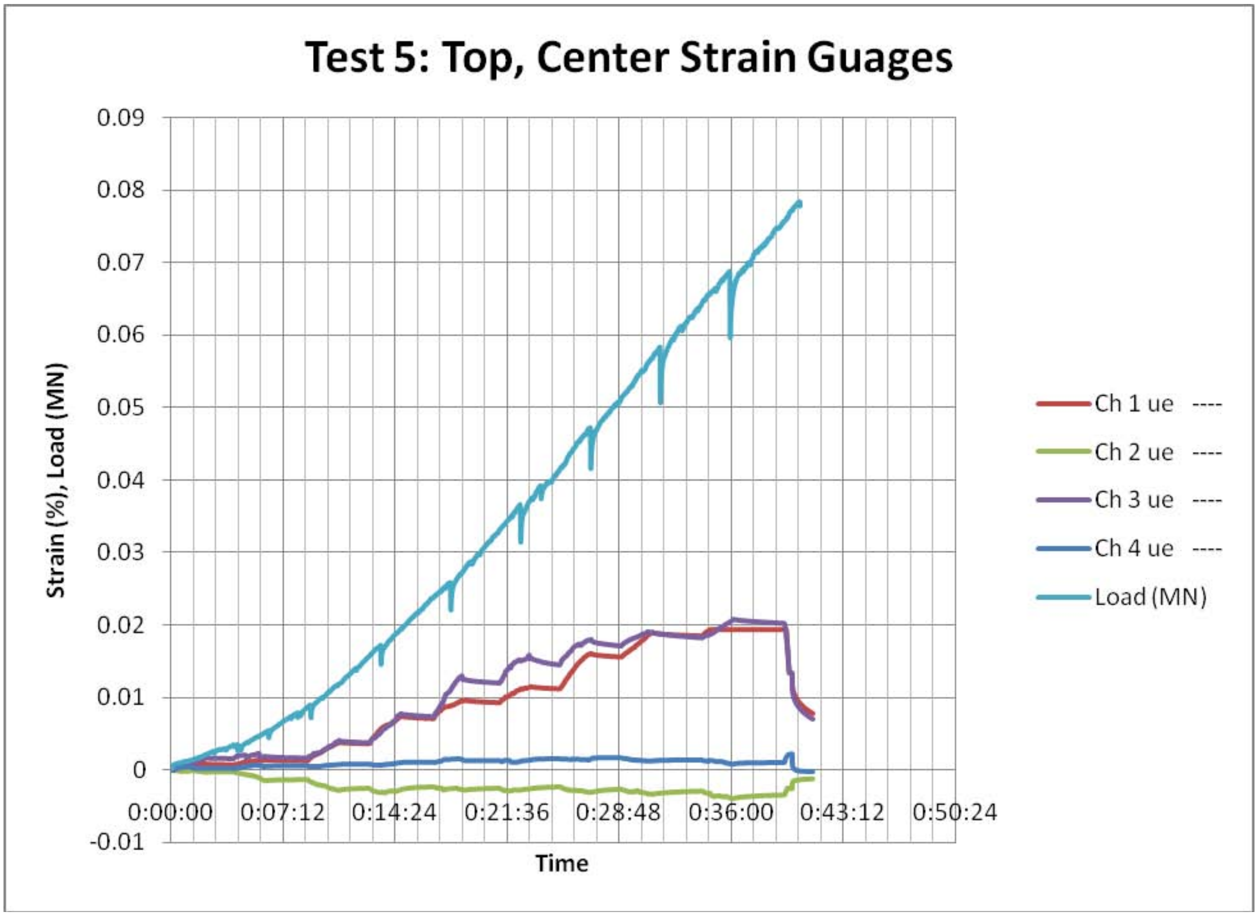

Figure 3.6: Full strain data for top, on-center strain gauges.

Reinforced, Cyclic Loading: Test 6

The double-reinforced ballast embankment was loaded cyclically in load-control conditions. That is, a loading amplitude between 75 and 350 kPa was specified and measurements of deformation were taken at 1000, 5000, 10000, 20000, 30000 and 50000 cycles.

The test was stopped when the MTS reached its goal of 50,000 loading cycles.

The confinement of the double-reinforcement layer was very effective in the prevention of lateral spreading. This lateral deformation was greatly reduced and mostly limited to the crest of the embankment, where no reinforcement existed. This is evident from the results, which indicate very little lateral deformation from the level of the reinforcement and below. The increase in cross-sectional area at the recorded heights was effectively reduced by the Geocell confinement as follows:

Height from Floor	Percent Increase in Cross-Sectional Area (%)
Top, 21.5” (54.6 cm)	15.36 %
Upper Middle, 18” (45.7 cm)	5.10 %
Lower Middle, 12” (30.5 cm)	1.76 %

Table 3.3: Lateral spreading of double-reinforced, cyclically loaded embankment.

Summary of Test Results:

Final Vertical Displacement	57 mm (2.24 in)
Vertical Displacement during Cyclic Loading	34 mm (1.34 in)
Max. Lateral Spreading	15.36 % of Area (Top)

Table 3.4: Summary of notable test results.

The final vertical displacement was 48% of displacement that occurred in the unreinforced, cyclic test.

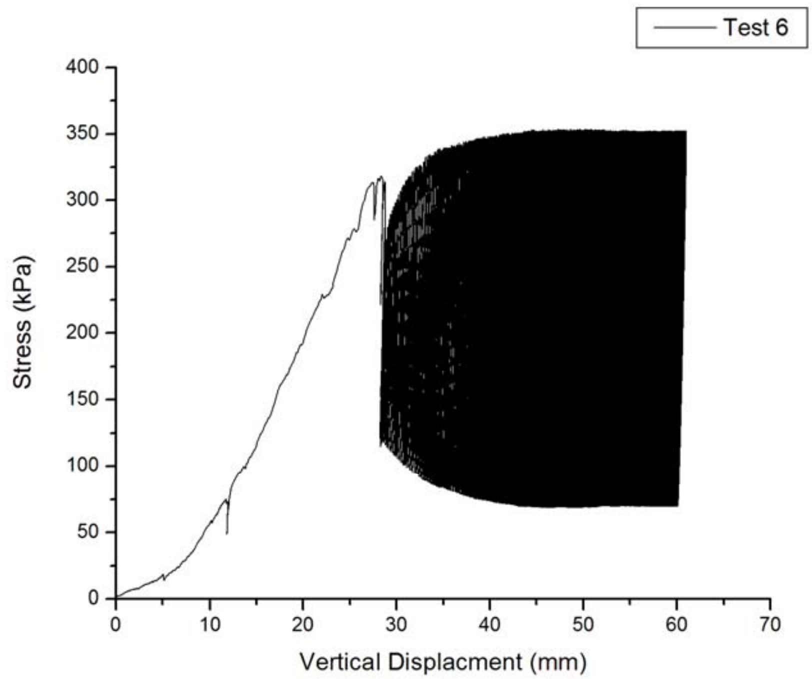

Figure 3.7: Load-Displacement Curve for double-reinforced, cyclically loaded test.

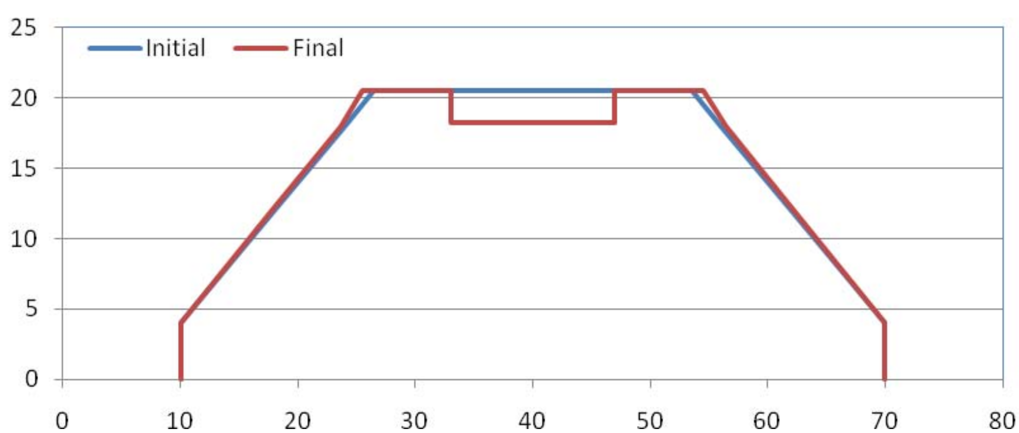

Figure 3.8: Schematic of initial shape and deformed shape of embankment after testing.

Durability and Behavior of Geocell during Test 6:

Figure 3.9: Condition of Geocell layers after test 6. They were relatively undamaged.

Both layers of Geocell were barely damaged from the cyclic loading of the model. Both encountered no tearing at the seams and joints.

To avoid some of the issues with the strain gauges that had been previously encountered, both data collection devices were connected to both layers for redundancy. As expected, one of the devices failed during the test, but the other collected data throughout, giving an accurate representation of what was occurring in both layers. As expected, the lower layer encountered less lateral, tensile strain than the top layer. However both were relatively constant throughout the test, suggesting that no events occurred. The vertical, compressive strain was rather similar throughout the test, suggesting that the compressive stressed were transferred rather evenly through the model, possibly due to the high stiffness of the model.

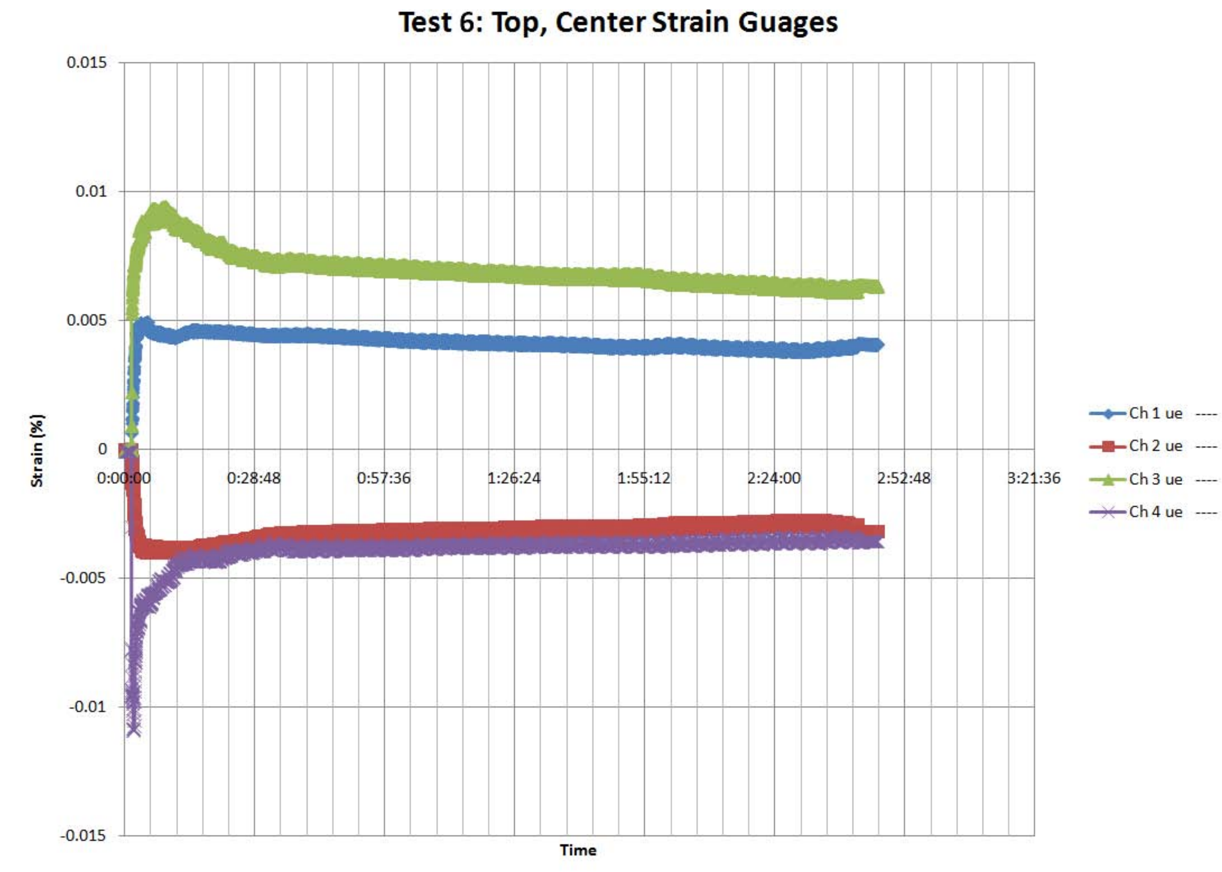

Figure 3.10: Full strain data for top and bottom, on-center strain gauges.

Gradation Analyses

Gradation analyses performed after each model test suggested that the Geocell had little impact on the degradation of the gravel due to loading. The grain size distribution of the gravel remained relatively constant throughout each of tests, although considerable dust was created as a by-product of abrasion between particles.

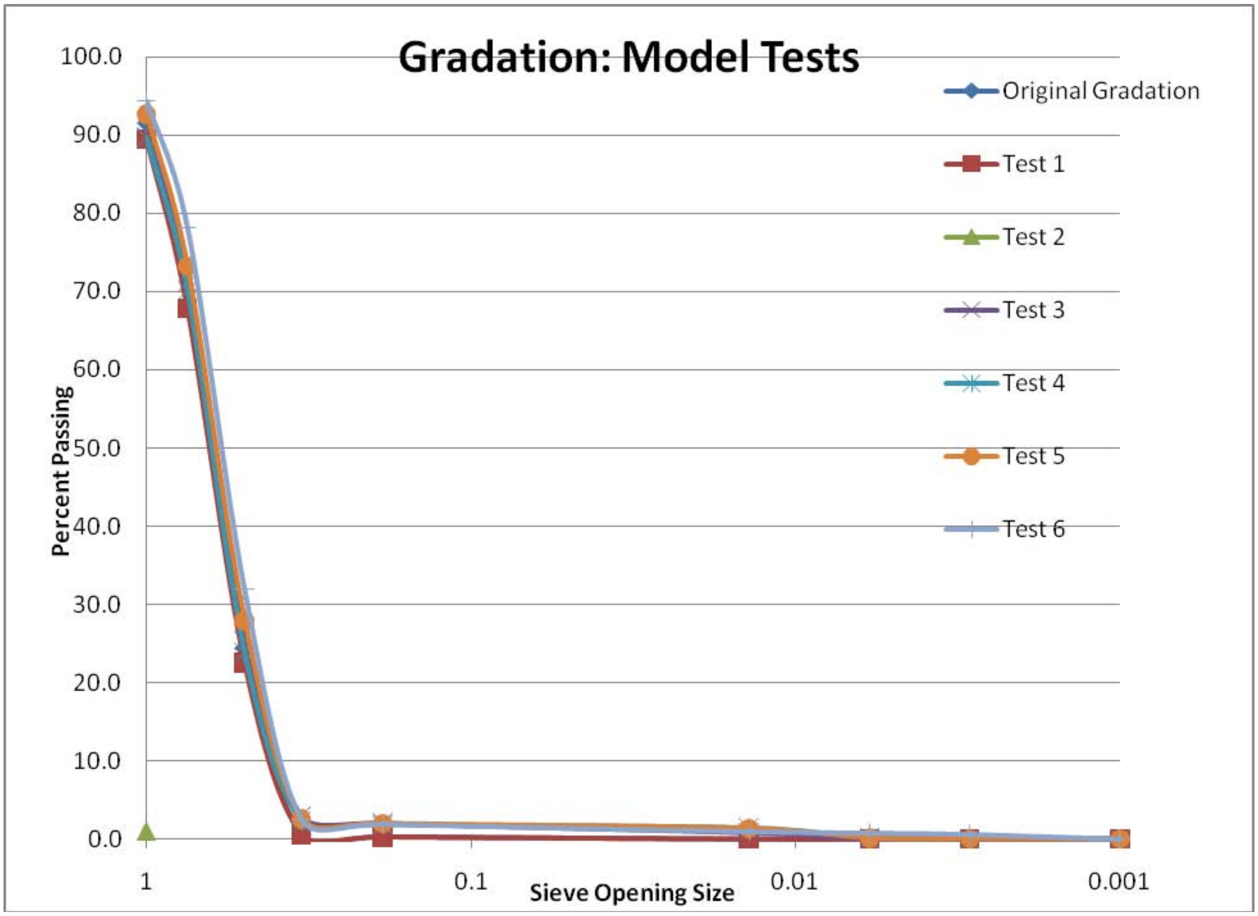

Figure 4.1: Comparison of gradation analyses for each test.

CONCLUSION

The Geocell was very successful in increasing strength and preventing excessive deformation in the foundation. Both configurations increased the stiffness and strength of the embankment, but expected load and design life are very important considerations before application. Long-term strength of the Geocell should be considered before design. Depending on loads and design life, Geocell could be an excellent tool in roadway subgrades, railroad ballasts, embankment construction, and even under footings in some cases. The confining nature of the cells and composite behavior as a mat make the Geocell an excellent idea for a cost-effective method of ground improvement. It is necessary, however, to consider working lateral loads that might occur within the Geocell, as damage can occur in the seams after large loads or repeated loading.

	Percent Increase in Cross-Sectional Area (%)					
Height from Floor	**Test 1**	**Test 2**	**Test 3**	**Test 4**	**Test 5**	**Test 6**
Top, 21.5” (54.6 cm)	72.78 %	22.14 %	40.46 %	22.43 %	13.38 %	15.36 %
Upper Middle, 18” (45.7 cm)	13.54 %	25.69 %	6.09 %	6.64 %	6.82 %	5.10 %
Lower Middle, 12” (30.5 cm)	6.17 %	7.20 %	3.67 %	2.52 %	3.69 %	1.76 %

Table 5.1: Comparison of lateral spreading in each loading and reinforcement configuration.

APPENDIX A: MATERIAL PROPERTIES

Red Sandstone	
Friction Angle, Φ	40°
Average Density	1433 kg/m^3

APPENDIX B: TEST SPECIFICATIONS

Loading Actuator: MTS 100 kip secondary actuator

Cyclic Testing Frequency	5 Hz
Data Collection Frequency	20Hz
Approximate Model Height	21.5”
Approximate Model Width (at crest)	24” x 24”
Aproximate Model Width (at base)	60” x 60”
Height of Confining Base Frame	4”
Lateral Spreading Data Collection Heights	
Top	21.5”
Upper Middle	18”
Lower Middle	12”

Loading Test, Before and After: Comparison of shapes before and after loading.

Acknowledgments

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