Enhancing Ballast Performance using Geocell Confinement

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ABSTRACT

A major issue in the enduring performance of embankments subjected to repeated loading is its progressive deformation and loss of strength over time. In particular, railroad ballast embankments are prone to a rapid loss of geometry under loading by heavy freight trains. This deterioration manifests itself with high rate of track geometry loss, costing many millions of dollars each year by requiring frequent maintenance that can disrupt train schedule. The objective of this work was to simulate repeated loading on a ballast embankment, exploring a promising methodology to slow the deterioration process. A series of 6 loading tests on idealized representations of railroad ballast embankments, unreinforced and reinforced with geocell were performed to study the impact of geocell on the strength and stability of confined ballast. Three test configurations (unreinforced, single-layer, double-layer) were used, each of which was loaded to failure under monotonic conditions, and separately loaded cyclically with stress amplitude of 140 kPa and 275kPa for unreinforced and reinforced configurations, respectively. Measurements show that the presence of geocell allowed for a significant increase in stiffness and strength while reducing permanent deformation implying that an optimized use of geocell reinforcement could lead to significant reduction in maintenance due to ballast degradation.

INTRODUCTION

Geocell was originally developed by the US Army Corps of Engineers in the 1970's as a means of improving poor roadway subgrades with cellular confinement (Webster and Alford, 1977). Many studies have shown that geocell is very effective at improving soil conditions through confinement; however, actual application to real-world projects is limited by a lack of design methodologies (Han et al., 2008). Earlier studies consisted mostly of reinforcement of unpaved roads in addition to a few studies on the effects on subgrades for paved roads. Studies also show that geosynthetic reinforcement can be an effective means of ballast subgrade stabilization. By using geosynthetics to confine ballast, vertical and lateral deformation of the track substructure were reduced (Indranatra et al., 2008).

The test setup used in this work is illustrated in Fig 1a. A series of six loading tests were performed on gravel composed of red granite (Poorly Graded, D_{50}=15.5mm, C_u=1.667, C_c=0.986). These tests consisted of constructing an embankment, with and without reinforcements, and studying its behavior under loading. The embankment rested on a ballast foundation, confined by a 10 cm wooden frame. The frame served as a consistent footprint for model preparation, providing a transition between the unconfined ballast and the rigid concrete floor at the testing facility. Overlying the foundation was the ballast embankment, a symmetrical prism in the shape of a truncated square pyramid – Fig. 1b. An ideal embankment is 2-D whereas here it was shaped as a prism. Hence, the modeling in this work, which compromises with limited resources, represents larger potential longitudinal displacements when compared with ideal embankment and in turn reflects more severe degradation. However, in the context of a comparative study of reinforcement layouts such modeling is instructive. Furthermore, it provides useful information for validating a general numerical model which later can be applied to simple 2-D embankments.

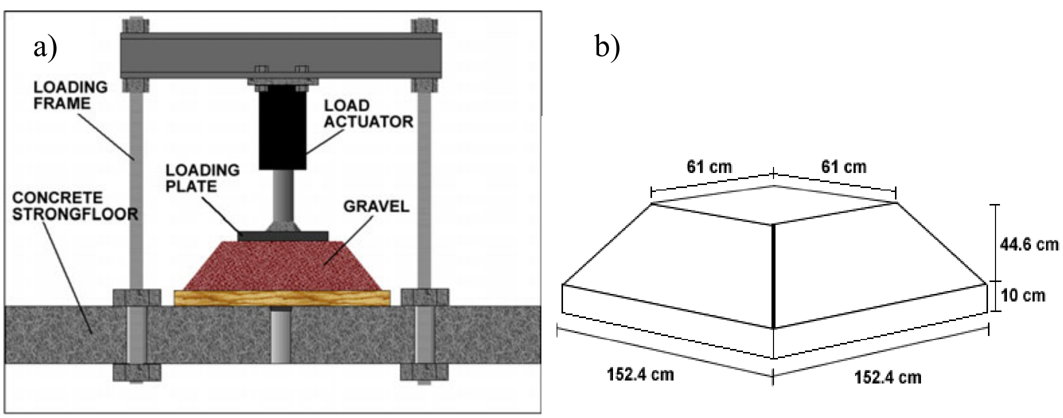

Figure 1. Schematic setup of a) loading frame and b) ballast model with 45° slope.

The reinforcement of choice was geocell made from a high density Polyethylene (HDPE) Alloy, which was found to have a tensile strength of approximately 37 kN/m. The reinforced model tests consisted of two different reinforcement layouts: a single, central layer and a double-layer reinforcement. Each layout was tested under two loading conditions: monotonic (static) and cyclic loading. An MTS hydraulic load actuator was used. It has a capacity of 450 kN, but the steel reaction frame was limited this capacity to 80 kN. The actuator applied load to the top of the embankment (Fig. 1a) using a centrically located 356x356 mm steel plate, 25 mm in thickness. The square loading plate was chosen because it closely matched the geometry of the model's crest, allowing symmetric loading within the limited space available. The reaction frame was connected to a 1 m thick concrete floor.

The behavior studied during each test included lateral spreading, vertical displacement under the "footing", global stiffness and strength of embankment, and reinforcement's strain. The lateral displacement was measured at 3 heights along each face of the ballast prism: 305 mm, 457 mm, and 546 mm from the floor. At the completion of loading, a grain size distribution analysis was performed to determine the degradation of the ballast due to the loading. The reinforcement was removed after testing and visually inspected for damage.

Prior to model testing, the ballast was characterized by a series of triaxial tests that were loaded monotonically or cyclically under a variety of confining pressures (60 - 95kPa). The triaxial specimens were 305 mm in diameter and 610 mm in height. The ballast was found to have a friction angle of 39° - 42° for confining pressures ranging from 60 kPa to 95kPa, respectively, with a min. dry unit weight of 13.05 kN/m^3 and a max. dry unit weight of 15.05 kN/m^3. The pump settings allowed the selected confining pressures to be easily attained.

UNREINFORCED MODEL TESTS

The control portion of the testing consisted of a model embankment that was constructed without reinforcement (Fig. 1). It consisted of a test monotonically loaded and another test that was cyclically loaded. The measured behavior was the load, displacement (laterally and vertically), and vertical stiffness (kPa/mm).

The unreinforced ballast embankment was first loaded monotonically at a displacement rate of 2.54 mm/min (0.1 in/min) so it would be manageable to record data. Loading was paused at every vertical displacement increment of 6.35 mm (0.25 inches) to enable data collection. This pause explains the "spikes" in the loading curve (Fig. 2a). Despite these jumps, the envelope defining the curve was unaffected, allowing an estimate of apparent stiffness of the deforming ballast foundation. It required about 4.5 kPa of vertical stress to cause 1 mm of vertical displacement in the initial, loading portion with a linear load-displacement relationship. The test was stopped when failure, manifested as uncontrolled displacement, developed. This occurred at an approximate vertical stress of 175 kPa. Lateral displacements, measured on each side relative to stationary benchmarks, were recorded as the test was in progress. Considerable lateral displacements occurred at all heights, but the largest spreading occurred at the crest of the embankment. The results of the test are summarized in Table 1.

Table 1: Summary of monotonically loaded embankments in all reinforcement setups.

	Test 1	Test 3	Test 5
	Unreinforced	Single-Layer	Double-Layer
Failure Stress / Load	175 kPa / 22 kN	575 kPa / 72.7 kN	625 kPa / 79.1 kN
Yield Vert. Disp.	65 mm	60 mm	53 mm
Apparent Stiffness	4.5 kPa/mm	10.9 kPa/mm	11.9 kPa/mm
Max. Lateral Spreading	72.78 % of Area (Top)	40.46 % of Area (Top)	13.38 % of Area (Top)

	Displacement (mm)			Percent Increase in Width[2]		
	Test 1	Test 3	Test 5	Test 1	Test 3	Test 5
Top, 54.6 cm[1]	108.0	63.5	22.2	31.48 %	18.52 %	6.48 %
Upper Middle, 45.7 cm[1]	30.0	12.2	13.6	6.56 %	3.00 %	3.35 %
Lower Middle, 30.5 cm[1]	20.1	10.2	10.2	3.04 %	1.82 %	1.83 %

[1]Height measured from concrete strongfloor.
[2]Percentage increase as compared to initial width.

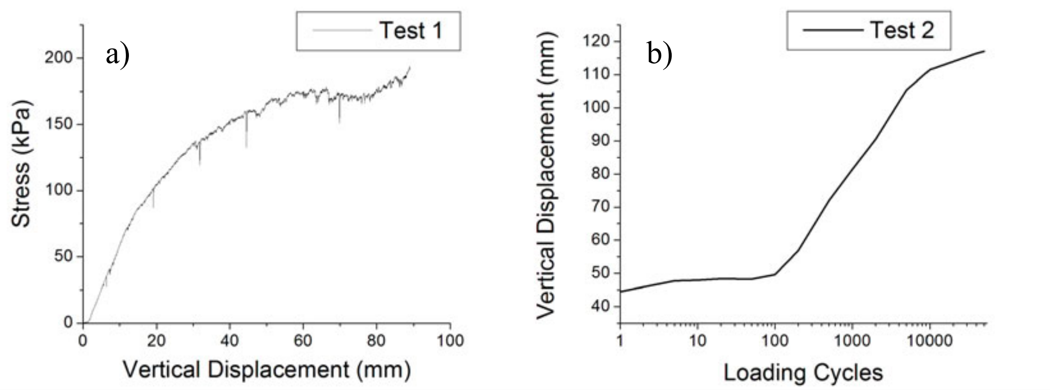

Figure 2. Loading curves for unreinforced embankment (a) monotonically loaded and (b) cyclically loaded.

A second, unreinforced ballast embankment was loaded cyclically at 5 Hz with loading amplitude between 35 and 175 kPa. Such frequency is assumed to reflect the loading rate exerted by medium to high speed trains. Measurements of displacements were taken at 0, 1000, 5000, 10000, 20000, 30000 and 50000 cycles – see Fig. 2b. The maximum load amplitude reflected the yield strength of the tested embankment setup, determined in the respective static test. For logistical reasons, the test was stopped at 50,000 loading cycles. A considerable amount of vertical displacement occurred, totaling 119 mm, which is very close to the maximum stroke allowed by the MTS load actuator. Much of the displacement accumulated during the initial few hundred cycles. Although the material did seem to stiffen up during the cyclic loading, vertical displacement was continuing significantly, indicating that the embankment was progressively failing under cyclic loading. As would be expected for such large vertical displacements occurring in ballast under low confinement, lateral spreading continued throughout the test considerably distorting the initial geometry 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 displacement at the crest. The results of the test are summarized in Table 2.

Table 2: Summary of cyclically loaded embankments in all reinforcement setups.

	Test 2	Test 4	Test 6
	Unreinforced	Single-Layer	Double-Layer
Final Vert. Disp.	118 mm	62 mm	57 mm
Cyclic Vert. Disp.	74 mm	36 mm	34 mm
Max. Lateral Spreading	25.69 % of Area (Upper Middle)	22.43 % of Area (Top)	15.36 % of Area (Top)

	Displacement (mm)			Percent Increase in Width[2]		
	Test 2	Test 4	Test 6	Test 2	Test 4	Test 6
Top, 54.6 cm[1]	36.1	36.5	25.4	10.52 %	10.65 %	7.41 %
Upper Middle, 45.7 cm[1]	55.3	13.3	10.2	12.11 %	3.27 %	2.52 %
Lower Middle, 30.5 cm[1]	23.4	7.0	4.9	3.54 %	1.25 %	0.88 %

[1]Height measured from concrete strongfloor.
[2]Percentage increase as compared to initial width.

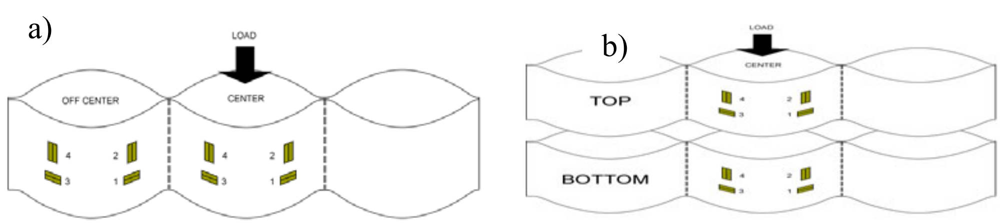

Figure 3. Strain gage schematic for tests (a) single-layer reinforced tests (tests 3,4) and (b) double-layer reinforced tests (tests 5,6).

REINFORCED MODEL TESTS: ONE LAYER OF GEOCELL

The model embankment using one layer of geocell is depicted in Fig. 4. Similar to the unreinforced case, it consisted of a monotonically loaded test and a cyclically loaded test. The measured behavior was the apparent stiffness, displacement (laterally and vertically), and failure load. The condition of the reinforcement was examined after testing. Vertical and lateral strain gages were attached to the central and off-center cells to monitor the geocell performance as well as to detect rupture, seam break, or excessive strains during the tests.

Figure 4. Single-layer reinforced test cross-section.

The embankment was first loaded monotonically at a displacement rate of 2.54 mm/min. Loading was paused every 6.35 mm (0.25 inches) to enable data collection. The pause caused 'spikes' in the loading curve – see Fig. 5a. Despite these jumps, the envelope defining the curve was unaffected, allowing an estimate of apparent stiffness of the deforming ballast foundation. It required about 10.9 kPa of vertical stress to cause 1 mm of vertical displacement in the initial loading portion before "yield" occurs. This apparent stiffness is 140% higher than the unreinforced model, as expected. Furthermore, the reinforced model was much stronger than the unreinforced (230%), likely due to the confinement and stiffening of the ballast from the geocell reinforcement. The test was stopped when the loading frame neared its allowable loading capacity at about 575 kPa. 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. Lateral displacements, measured on each side relative to stationary benchmarks, were recorded as the test was in progress. Lateral displacements were greatly reduced in this test, but still occurred at all heights. The largest spreading occurred at the crest of the model, where no reinforcement existed. The results are summarized in Tab. 1.

Although lateral spreading was reduced, significant damage occurred in part of the geocell. Strain gages placed on the geocell do not show large strain, yet suggest deformation events, like tearing or rupture (violent shifts between 0.007% in lateral tension to -0.008% in lateral compression). Upon dismantling the model, the geocell was examined visually for damage. All 4 of the seams beneath the loading plate were ruptured. This failure occurred under the higher monotonic loading, as there is a noticeable reduction in apparent stiffness near the end of the test – see Fig. 5a.

A second reinforced embankment was loaded cyclically at 5 Hz with a loading amplitude between 75 and 350 kPa. The reasoning behind the increased cyclic load (compared to the unreinforced case) is to demonstrate the increased capacity of the reinforced ballast in comparison to the standard dynamic loads encountered under the ties supporting freight trains (test 2). Displacements were measured at 0, 1000, 5000, 10000, 20000, 30000 and 50000 cycles – see Fig. 5b. The higher loading amplitude simulated realistic loading. 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 at 50,000 loading cycles. The final vertical displacement was 52% of that occurred in the unreinforced, cyclic test. This reduction would 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 displacement was greatly reduced (24% and 30% of original, unreinforced displacement results occurred in the upper middle section and lower middle sections, respectively) and mostly limited to the crest of the embankment, where no reinforcement existed (See summary in Table 2).

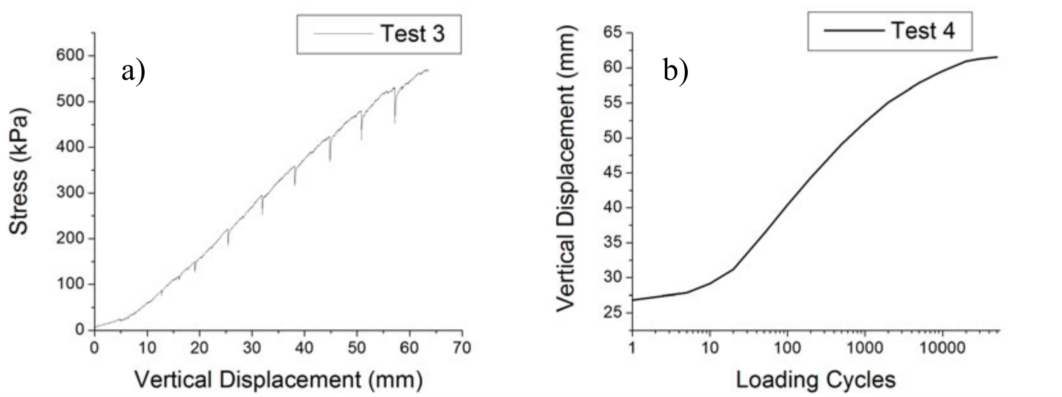

Figure 5. Loading curves for single-layer reinforced embankment (a) monotonically loaded and (b) cyclically loaded.

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 due to bending and compression of the top portion of the geocell walls. Lack of tearing is likely a result of a lower load than in the monotonic test. The strain gages show a relatively constant strain (the largest being about 0.025%) suggesting that no serious events occurred within the geocell during testing.

REINFORCED MODEL TESTS: TWO LAYERS OF GEOCELL

The reinforcement layout for the monotonic and cyclic loading is shown in Fig. 6. Essentially, the details regarding the testing measurements are the same as for the single layer reinforcement.

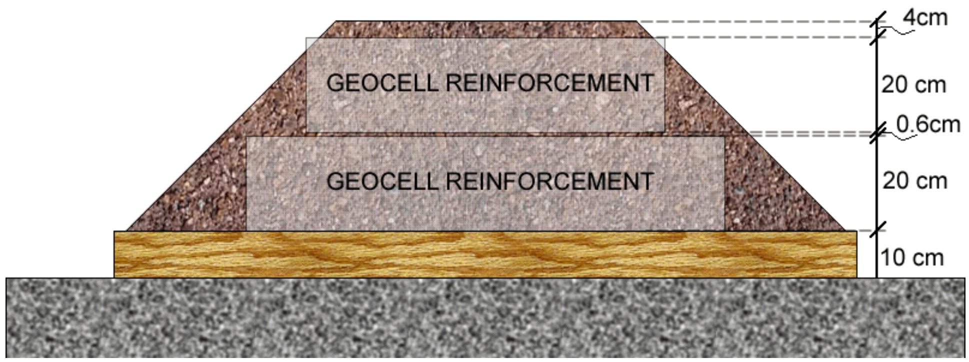

Figure 6. Double-layer reinforced test cross-section.

The loading curves for the monotonic and cyclic loading are presented in Figs. 7a and 7b, respectively. Similarly, Tabs. 1 and 2 show the test results for the monotonic and cyclic loading, respectively. It required about 11.9 kPa of vertical stress to cause 1 mm of vertical displacement in the initial loading portion before "yield" occurs. The apparent stiffness was 164% greater than the unreinforced case, as is expected. The stiffness was 10% greater than the single reinforced case. The double-reinforced configuration sustained 260% more load than the unreinforced case and 9% more load than the single-reinforced case at the stopping point. This apparent stiffness is higher by 164% than the unreinforced model. This increase in stiffness is expected as the whole model acts as a reinforced composite. The vertical displacement that occurred within the 175 kPa range of the double-reinforcement test was only 28% of displacement that occurred in the same range for the unreinforced, monotonically loaded test. Like the test with a single reinforcement, this test was stopped when the loading frame reached its allowable loading capacity of about 625 kPa, 260% greater than the unreinforced case. No significant damage in the geocell occurred and the ballast composite was significantly stiffer. The confinement of the double reinforcement layer was also very effective in the prevention of lateral spreading, limiting spreading at the crest to just 20% and 35% of what occurred in the unreinforced and central-reinforced cases, respectively.

Both layers of geocell were barely damaged during the monotonic loading of the model, 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 observed minor damage was slight bending and compression of the geocell walls. The strain gage data suggests that both layers of geocell encountered minute strains in the order of 0.02%.

The last stage of testing consisted of running a cyclic test under the same conditions as the single-reinforced test. The final vertical displacement was only 48% of displacement that occurred in the unreinforced, cyclic test. The lateral displacement was greatly reduced and mostly limited to the crest of the embankment, where only 70% of the lateral displacement occurred compared to the other setups. Most spreading occurred above the reinforcements. The vertical displacement in both the single- and double-reinforced cases were similar because much of the settlement occurred above the reinforcement.

Both layers of geocell were barely damaged by the cyclic loading. As expected, the lower layer encountered less lateral, tensile strain than the top layer (0.007% vs. 0.004%). The vertical, compressive strain was similar throughout the test (about 0.004%), suggesting that compressive stresses transferred evenly throughout, possibly due to the high stiffness of the confined ballast.

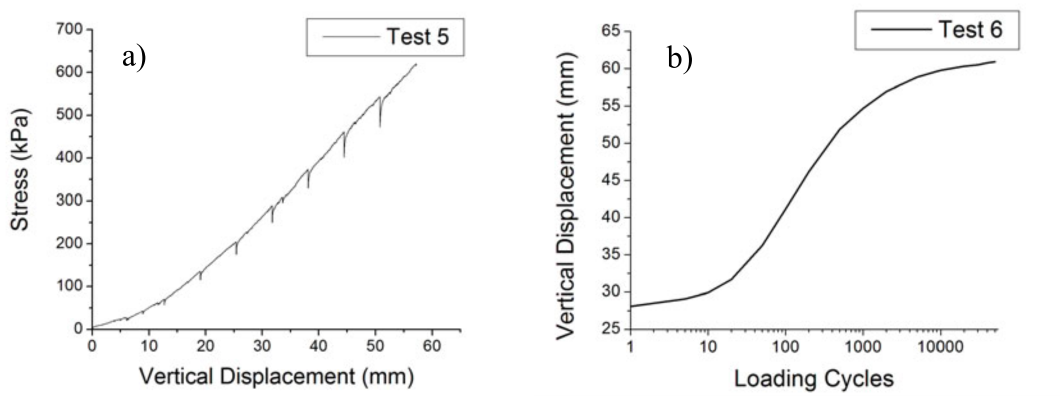

Figure 7. Loading curves for double-layer reinforced embankment (a) monotonically loaded and (b) cyclically loaded.

GRADATION ANALYSES

Gradation analyses performed before and after each model test suggested that the geocell had little impact on the degradation of the ballast due to loading. The grain size distribution of the ballast remained relatively constant throughout each of tests, although considerable dust was created as a by-product of abrasion between particles. Intuitively, confinement reduces relative movement of ballast particles, thus should reduce abrasion and particles break. However, it is likely that that the granite used for this testing is naturally resistant to deterioration. It is probable that the use of weaker ballast such as dolomite in combination with geocell confinement would significantly reduce ballast degradation thus enabling use of lower quality ballast if economical. Further studies should include the effects of a weaker ballast and/or larger amount of loading cycles.

CONCLUSION

It is important to consider that the 3-D nature of the tested model means that movement was allowed in both directions as opposed to the mainly transverse direction in a 2-D embankment. The implications of such a simulation are currently being studied although it is likely that the performance would be better for continuous case. However, the tests results clearly show that the geocell was effective in increasing the strength of the embankment while reducing its deformation under repeated loading. This observation is based on the comparison of unreinforced test with single geocell reinforcement. Layout with two geocell layers shows even greater improvement including lesser stress and degradation of the geocell itself. Such improvement implies that an optimal layout can be designed to ensure both significant improvement of the long-terms performance of both the embankment and of the geocell in a harsh environment.

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