Experimental study of embankments with different reinforcement materials and spacing between layers

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ABSTRACT

Worldwide, waste tires are being discarded in landfills at a huge environmental cost, therefore, their use as a three-dimensional reinforcement material is a wise solution to reduce their environmental impact, and fire risk in the case of shredded tires. In this research a series of experimental model tests of embankments reinforced with Geocell and tires were conducted to compare the performance of these types of reinforcement. The models tested had different Geocell embedment depths, number of Geocell layers, vertical spacing between Geocell layers and density or soil stiffness. Testing consisted of applying pressure at the crest of the embankment and monitoring the pressure distribution, as well as the vertical and horizontal deformations inside of the embankment. The results suggested that when compared with unreinforced embankments, reinforced embankments effectively improve the bearing capacity, thereby, reducing vertical and lateral displacements. This study also showed that an optimal embedment depth and spacing between Geocell reinforcement layers can further improve the slope performance. Comparisons between Geocell reinforced embankments and waste tire reinforced embankments, showed that waste tire reinforcement has a superior performance over the Geocell-reinforced embankments. This difference in performance between the two types of reinforcement is more apparent if the embankment backfill has lower stiffness. i.e. lower density.

Keywords

Geosynthetics, Soil Reinforcement, Geocell, Waste tires, Bearing capacity, Stress, Settlement, Model Test.

1.Introduction

Planar reinforcements (geogrid, geotextiles, wire mesh, etc.) are used to improve soil strength and reduce compressibility (Dash et al. 2007; Soude et al. 2013; Azzam and Nasr 2014; Cicek et al. 2015; Hegde and Sitharam 2015; Xiao and Liu 2016). In recent years research in three-dimensional reinforcement materials (Geocell and waste tires), has shown that this type of reinforcement has a better performance than planar reinforcement, particularly in the case of soft soils. Huang et al. (2001) compared the reinforcement effects of Geocell with those of single and double-layered geogrids, concluding that Geocell reinforcement has better results in terms of deformation mitigation. Latha et al. (2006) and Zhang et al. (2010) have shown that Geocell reinforced embankments have higher bearing capacity and lower settlements, whilst Sitharm et al. (2006) have shown that a foundation reinforced with a geogrid-Geocell composite can better diffuse additional stresses than the Geocell only reinforced foundation.

Worldwide, a significant number of waste tires are produced every year and usually sent to landfills at a significant environmental cost. Therefore, numerous researchers are exploring the possibility of using waste tires as reinforcement. Kamarudin et al. (2011) tested a solid tire from 1920s concluding that rubber is highly durable, particularly when not exposed to light and air. Keller (1990) described the use of tire faced retaining walls, which were used effectively to maintain forest roads. Garga and O’Shaughnessy (2000) showed that tire reinforcement can be used with frictional or cohesive soils, providing a satisfactory foundation for medium to light structures. Yoon et al. (2004) and Slack et al. (2008) found that waste tires gave significant improvements in slope stability and bearing capacity. Similar results were observed by

Yoon et al. (2008) with tires arranged in an “8” shape. Li et al. (2016) tested the performance of slopes reinforced by waste tires, showing that this type of reinforcement can effectively increase the stability of slopes, reducing deformations. These authors have also shown that the configuration of the tires within the slope is important and can be adjusted to maximize the outcomes.

Waste tires can be shredded into sizes of aggregates and used as alternative backfill material (Moghaddas Tafreshi and Norouzi, 2012). Foose et al (1996) have demonstrated that sands reinforced with shredded tires present much higher friction angles than the unreinforced counterpart. Despite the improvements in strength, shredded tires homogeneously mixed in the soil present a much greater combustion risk when used in slope stability than whole tires used as reinforcement layers (Humphrey 1996).

In this article the behavior of Geocell and waste tire reinforcement under two different backfill densities is compared, emphasizing the effect of the reinforcement on the same soil but with two different stiffnesses. The experimental program also considered factors such as the embedment depth of the Geocell layer, the number of Geocell layers, and Geocell vertical spacing.

2. Laboratory study

2.1. Methodology, Materials and Equipment

Plane strain model scale experiments were conducted inside of a stiff wooden paneled steel frame with plexiglass windows and dimensions of 200 cm (length) × 80 cm (width) × 76 cm (height), as shown on Figure 1. Although the results of these tests may be difficult to upscale, the size of the model would be representative of, for example, a strip foundation of a light structure where reinforcement is needed to better distribute the stresses on the soil below; this then avoids plastic deformations by maintaining the soil within the swelling line. Scale tests have many advantages, as they are relatively easy and simple to conduct. Therefore, they offer an excellent chance to test different reinforcement types and configurations, allowing conclusions to be drawn regarding the best options. The influence of the substrate soil was therefore eliminated by constructing the embankment over a stiff base.

A cross section of the soil embankment i.e. its dimensions and the arrangement of the instrumentation used are depicted in Figure 2. The angle of the embankment slopes was achieved using suction, by controlling the moisture content of the sand whilst building the embankment. The embankment was built in layers, carefully controlling the weight of wet soil to the volume required by the layer.

A number of steel balls are located adjacent to the plexiglass, at the points where letters represent lines and numbers represent the columns (Figure 2). The movement of these balls was tracked, allowing the measurement of the displacements within the soil mass.

A vertical load was applied to the embankment via a loading plate connected to an actuator, and the vertical stress distribution within the embankment was measured by six earth pressure cells located on positions B1, B3, C1, C3, D1, and D3.

Figure 1 - Test chamber

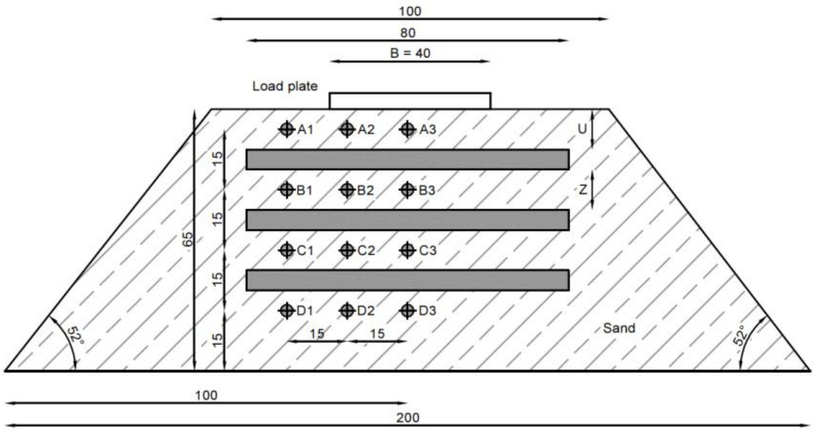

Figure 2 - Schematics of reinforced embankment systems

The materials used in this research include Geocell and waste tires from a local recycling station as reinforcement, and a clean river sand with no fine content. Figure 3 shows the particle size distribution curve of the sand used in the experiments. Figure 4 shows the pictures taken when the testing embankment was constructed and the reinforcement installed: (a) Geocell reinforcement and (b) waste tire reinforcement. The waste tires were mechanically fastened to each other by high strength friction grip bolts and wires. Tables 1 and 2 list the parameters determined in the laboratory for the sand, the waste tires and the Geocell reinforcement, respectively.

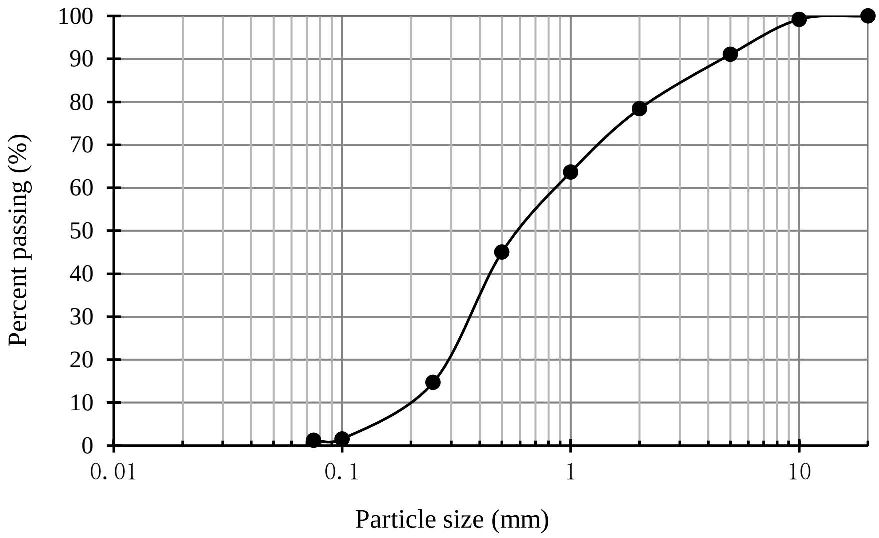

Figure 3 – Grain size distribution of the used sand

(b) Geocell **(c) Waste tires**

Figure 4 – Installation of the reinforcement on the testing embankments: (a) Geocell and (b) waste tires.

2.3. Experimental Program

The experimental program was developed to compare the efficiency of Geocell and waste tires as soil reinforcing agents. Parameters such as the distance between the top surface and the first layer of reinforcement, the distance between reinforcement layers, the number of layers and fill density were analyzed (Table 3).

Table 1 - Physical properties of the sand

Parameter	Value
Coefficient of uniformity, C_u	5.4
Coefficient of curvature, C_c	1.4
Maximum dry density (g/cm^3)	1.89
Minimum dry density (g/cm^3)	1.65
Specific gravity, G_s	2.67
Moisture content	6%
Internal angle of friction	35º

Table 2 – Parameters of the reinforcement

Tires	
Parameter	**Value**
Diameter (cm)	40
Thickness (cm)	1
Length of the tread (cm)	5
Width of tires sidewalls (cm)	4
Poisson's ratio	0.33
Elasticity modulus (MPa)	2.0×10^3
Geocell	
Height (cm)	5
Length of aperture side (cm)	40
Tensile yield strength (MPa)	24
Tensile modulus (MPa)	6.5
Aperture size (cm)	40 x 40

To reduce friction a thin layer of lubricant was applied to the lateral panels before assembling the fill, and each test consisted of the application of a static load to the top of the embankment via a rigid loading plate (790 mm × 400 mm). The load increments were equivalent to an increment in vertical stress of 0.5MPa. The experiments were terminated when significant settlement of the loading plate was observed.

Table 3 – Configuration and parameters of the model tests

Test No	**Reinforcement**	**Name**	***U* (cm)**	***Z* (cm)**	***N***	***Dr***	***Load (MPa)***
1	Unreinforced	Un11	-	-	0	0.11	0.8
2	Geocell	1G125L	0.125B	-	1	0.11	1.28
3	Geocell	1G250L	0.25B	-	1	0.11	1.5
4	Geocell	1G375L	0.375B	-	1	0.11	1.07
5	Geocell	2G125L	0.25B	0.125B	2	0.11	1.8
6	Geocell	2G250L	0.25B	0.25B	2	0.11	2
7	Geocell	2G375L	0.25B	0.375B	2	0.11	1.57
8	Geocell	3G250L	0.25B	0.25B	3	0.11	2.42
9	Unreinforced	Un45	-	-	0	0.45	2.45
10	Geocell	1G250D	0.25B	-	1	0.45	2.72
11	Waste tire	1T250D	0.25B	-	1	0.45	3.32
12	Waste tire	1T250L	0.25B	-	1	0.11	2.07

Note: ***U*:** Distance from the embankment crest to the first reinforcement layer; ***Z*:** vertical spacing between reinforcement layers; ***N*:** Number of reinforcement layers; ***D*r:** relative density of soil. ***Load*** is the load required for a vertical displacement s/B=3%. *U* and *Z* are illustrated in Figure 2. Name: Un – Unreinforced; G – Geocell; T – tire; D – denser (Dr=45%); L – loose (Dr=11%); 125, 250 and 375 – distance between the last layer and the surface of the embankment or the previous layer, equal to = 0.125B, 0.25B and 0.375B, respectively.

3. Test Results

3.1. Load versus settlement

Figure 5 shows the load-settlement curves (p-s curves) obtained from tests performed on the unreinforced embankment and Geocell reinforced embankments (Table 4, tests 1 to 8). As seen in the figure, the settlement of all the tested embankments increased with an increase in pressure. The settlement ratio also increased gradually with the load applied, generating larger and larger plastic strains at every increment of load. As the settlement of the embankment increased, cracks started appearing at the surfaces. For the case of the unreinforced embankment, cracks started appearing when the ratio between the settlement (s) and the width of the foundation or loading plate (B) was around 3% (s/B=0.03). The reinforced slopes showed cracks being formed once the settlement reached a larger value, 5% (s/B=0.05). Therefore, the load corresponding to a settlement of 3% was used for performance comparisons.

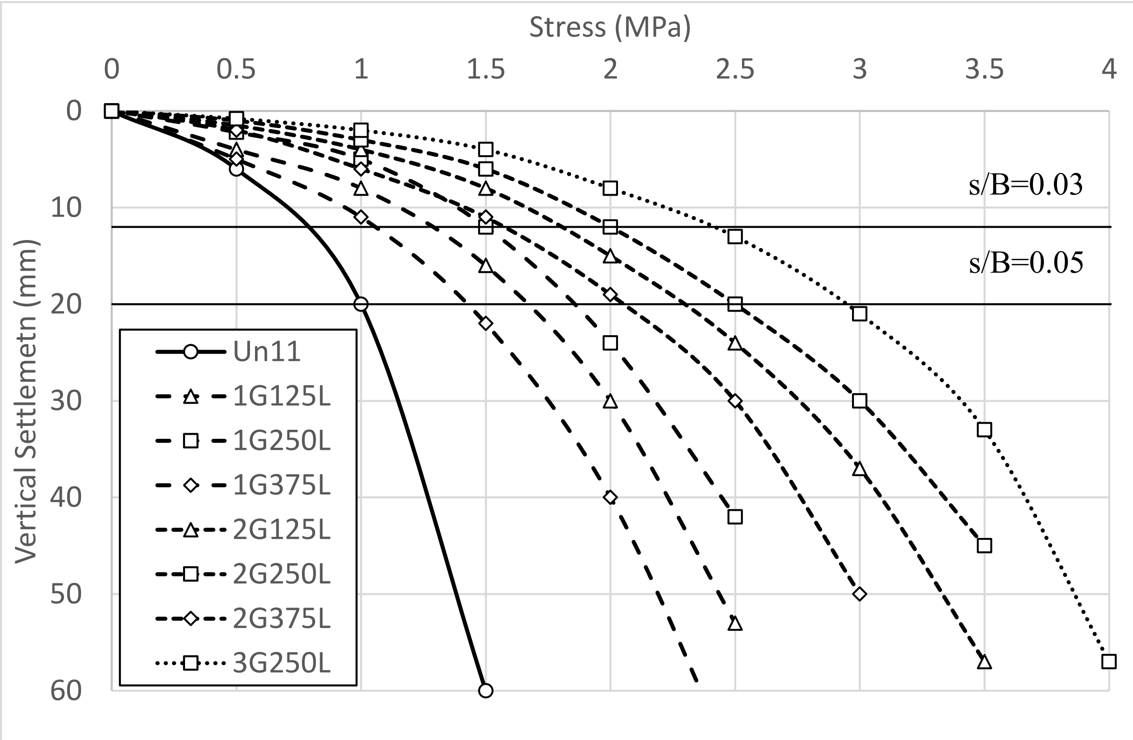

Figure 5 - Effect of reinforcement depth and the number of layers on the pressure-settlement curves for the slopes with a Dr=11%.

All reinforced slopes have shown a better performance than the unreinforced slope. The test results also show that there is an optimum depth for the location of the reinforcement layer: as the depth increases from 0.125B to 0.25B, the bearing capacity increases. However, when the depth is increased to 0.375B, the bearing capacity reduces, indicating that the optimum depth is located around 0.25B. A similar behavior can be seen for the embankment reinforced with 2 layers of Geocell, where the first layer was kept at 0.25B from the embankment surface. As the distance between the first and second layer increased from 0.125B to 0.25B, the stiffness and the ultimate load also increased. However, as this distance is increased from 0.25B to 0.375B, the stiffness and ultimate load reduced to values that are lower than the embankment with 0.125B between the first and the second layers.

The addition of a third reinforcement layer of Geocell yields a further improvement in stiffness and ultimate strength, however, the gain with respect to the embankment reinforced with two layers is reduced. At a value of s/B=3%, Un11 reached a vertical stress of around 0.77MPa and the embankment 1G250L a vertical stress of 1.5MPa. The addition of one layer of reinforcement was then seen to almost double the performance of the embankment. With the addition of a second layer of reinforcement at s/B=3%, the load increased to 2MPa, giving an improvement of 0.5MPa or 33%. With the addition of a 3rd layer, the load at s/B=3% further increased to 2.4MPa, yielding an increase of 20% when compared to the embankment reinforced with 2 layers.

The test results show clearly that there is an optimum depth for the location of every layer of reinforcement, and for the tests presented in Figure 5, at the lowest relative density this distance is 0.25B. These are likely to depend on the thickness and stiffness of the reinforcement, as well as on the friction and stiffness properties of the soil, or the density achieved during compaction.

The test results related to the best location of the first layer of Geocell reinforcement (0.25B in this study) are different than those obtained by Yoon et al. (2008) and Li et al. (2016) for tire reinforcement. These authors demonstrated that for tire reinforcement the location of the first layer should be as close as possible to the location of the loading application on the embankment.

In Figure 6 the load settlement curves of both unreinforced embankments, the Geocell reinforced embankments, and the tire reinforced embankments are plotted together (Table 4, tests 1, 3, 6, 8 and 9 to 11). These tests were performed based on the results of the previous tests, i.e. using the distance between layers that yielded the highest embankment strength or 0.25B. Un45 is an unreinforced embankment with a relative density of 45%, showing an initial behavior similar to test 3G250L up to a ratio s/B=3% and loosing strength quickly afterwards. The embankment reinforced with one layer of tires and a low relative density (1T250L) had a performance similar to the embankment reinforced with 2 layers of Geocell; this shows that tires offer a better alternative to the use of Geocell in terms of performance. The same behavior was observed when comparing the reinforced embankments using the densest configuration, where a layer of tire reinforcement offers better performance than the Geocell. In the tests performed the strength improvement against Geocell is around 23% (from 2.70 to 3.32MPa).

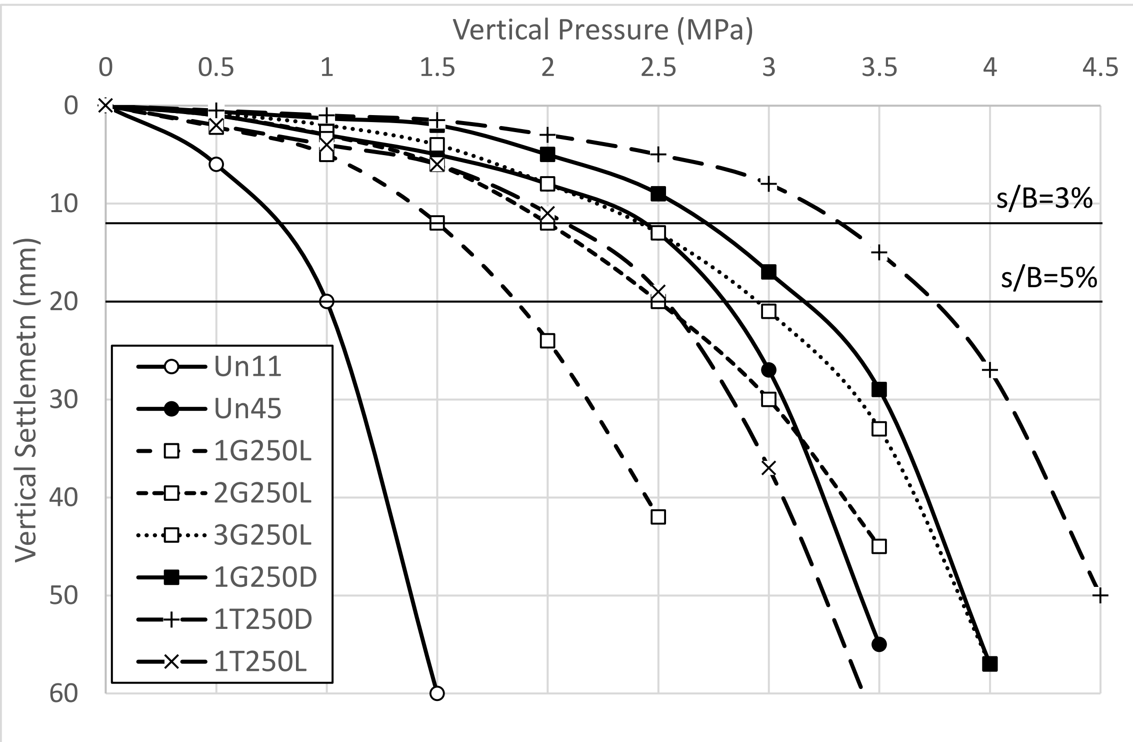

Figure 6 - Effect of the type of reinforcement and the Relative density on the pressure-settlement curves.

It is also noticeable that the improvement in performance amongst the denser embankments is not large when compared to the unreinforced soil. It is seen that one layer of Geocell improves the performance by around 10%, whilst a layer of tire reinforcement by 35%. Better improvement in the performance is seen when the soil is of a lower density (lower stiffness); where a performance increase of 87.5% for Geocell and 158% for tire reinforcement was measured. The improvement must, therefore, be related to the stiffness of the reinforcement. Therefore, the highest increase in strength is seen in the stiffer reinforcement of the tires, and as the stiffness of the soil increases with density, the effectiveness of the reinforcement is reduced.

3.2 Stress distribution

To understand the changes in stress distribution caused by the addition of reinforcement, the pressure values measured at positions B1 and B3 (Figure 2) were plotted in Figure 7 against the distance from the vertical axis, for a vertical pressure of 1.5MPa. Given the symmetry of the model embankment, the value at B3 was mirrored along the central axis of the embankment. Also represented in the figure is the loading plate, centered on the vertical axis. For all tests, the highest vertical pressure is measured at the vertical axis, reducing to much smaller values 30cm away (the loading plate only extends up to 20cm away from the axis), therefore, not all test results were plotted in the figure.

The unreinforced tests (Un11 and Un45) have the highest pressures at the axis center line for the density tested. However, the highest density (Un45) showed a lower value of vertical stress at the vertical axis of the embankment than the lowest density (Un11). The opposite was seen at 30cm from the axis where Un45 showed higher stresses than Un11; this is likely to be caused by a type of failure similar to a rigid punch, commonly seen on soft soils. The addition of reinforcement reduced the pressures measured at the center line, however, the highest reduction is seen for the tire reinforcement. At location B3 the values are inverted, i.e.: the highest stress is measured in the embankment reinforced with tires. This shows that the reinforcement is mobilizing soil strength further away from the influence of the loading plate, reducing the maximum stresses measured under the center axis, and spreading the stresses over large volumes of soil. The same can be seen for the reinforced embankments created with a relative density of 45%, where the highest reduction in vertical stress was seen along the central axis or point B1. Whilst at point B3, the tire reinforced slope caused the highest vertical stress measured, followed by the embankment reinforced with Geocell, indicating a more homogeneous stress distribution even further away from the edges of the load application plate.

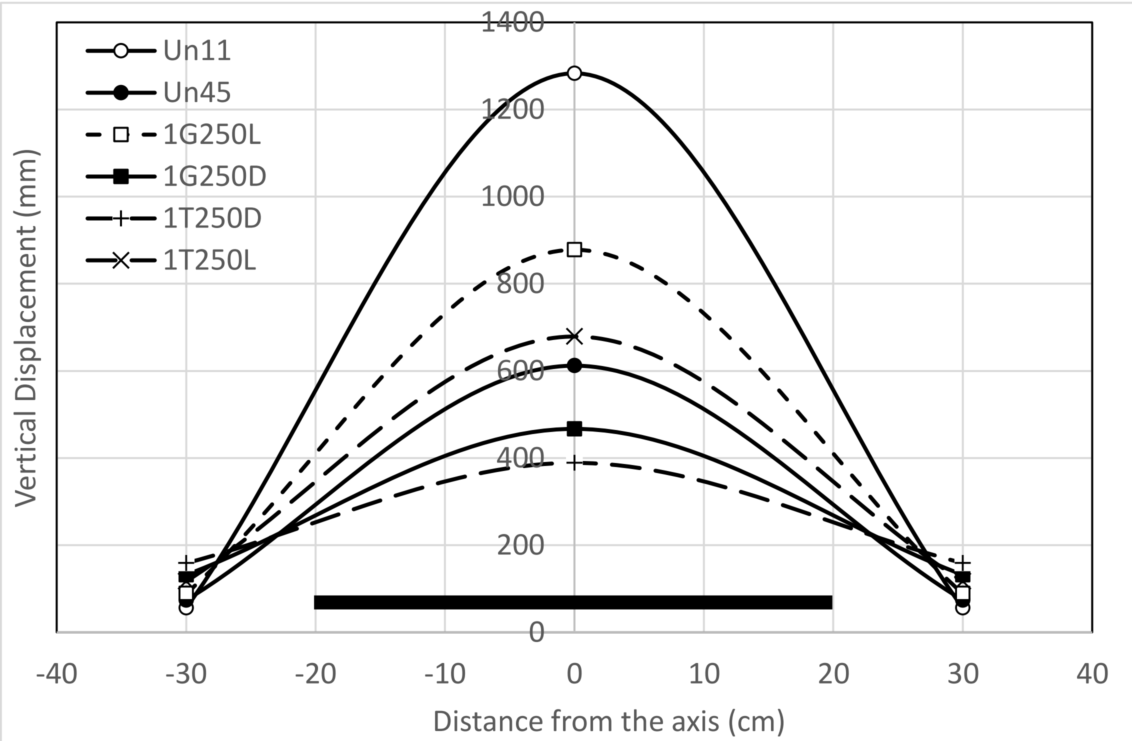

Figure 7 – Stress distribution at 20cm below the embankment surface for a 1.5MPa applied pressure, at the surface. The black line indicates the size and location of

the loading plate.

Again, this shows the effectiveness of the reinforcement in reducing the higher stresses acting in the soil mass, as well as the mobilization of strength in larger volumes of soil. The results are proportional to the overall stiffness of the reinforcement plus soil. The higher the overall stiffness, the more homogeneous the distribution of stresses in the soil; in these tests this is achieved by either the addition of the reinforcement or the compaction of the soil (density).

3.3 Vertical and horizontal Deformations

Figure 8 shows the settlement at locations B1, B2 and B3 for the same tests as Figure 7, however, the vertical load applied on the denser tests is of 3MPa. As before, given the symmetry, the results were mirrored to give a full plot of vertical displacements at the location mentioned above. Between the unreinforced embankments, as expected Un11 showed much higher vertical displacements than Un45, despite the load being applied at Un45 being twice of that at Un11. With the addition of reinforcement there is a reduction in the settlement level, and this reduction is larger for the lower density embankments. It is also possible to see that the vertical displacements of the embankments reinforced with tires present much lower vertical deformations than the Geocell reinforcement.

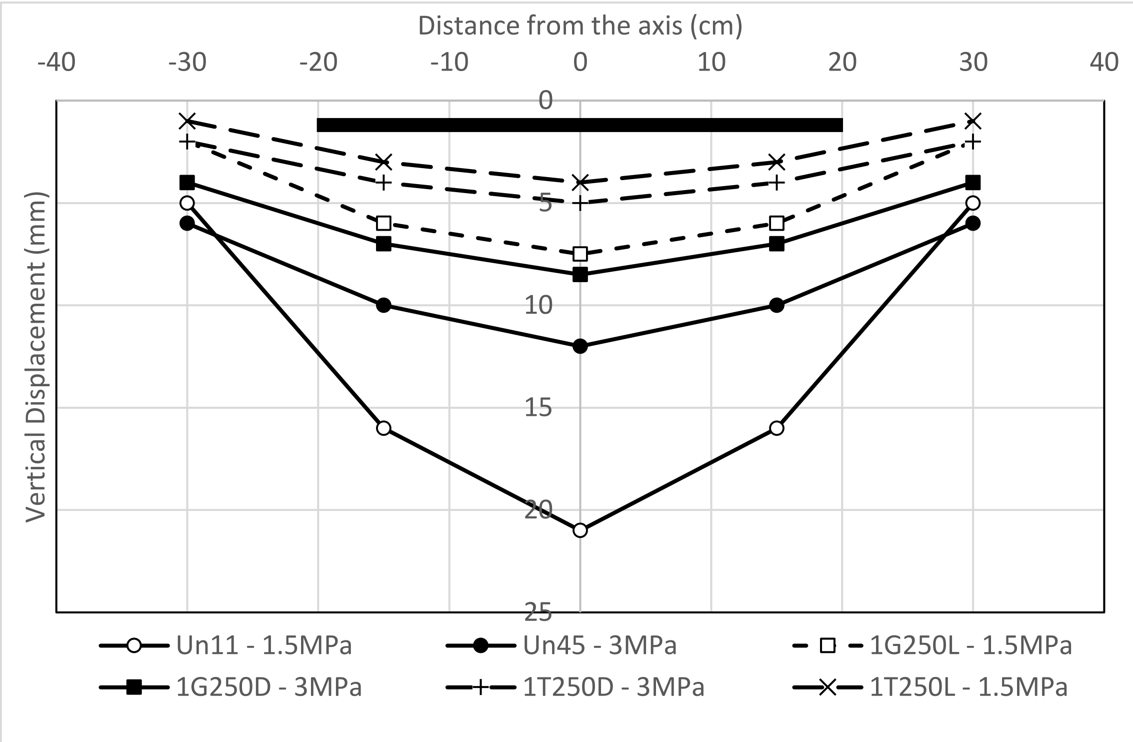

Figure 8 – Settlement distribution inside the embankment for a vertical pressure of 1.5MPa for the loose embankment and 3MPa for the dense embankment. Black line indicates the size and location of the loading plate.

The horizontal deformations of points A1, B1, C1, and D1were also measured and plotted in Figure 9 for the same tests. Again, for the denser embankment the horizontal deformations measured corresponded to a vertical stress of 1.5MPa, whilst the denser embankments were subjected to a vertical stress of 3MPa.

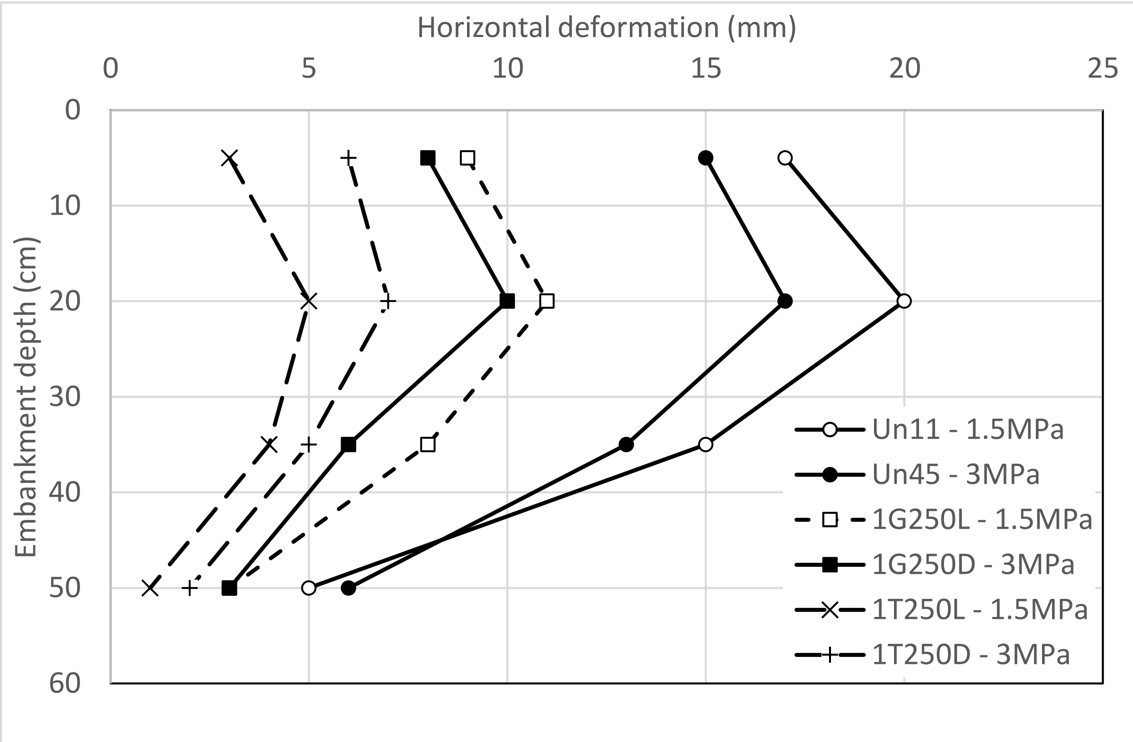

Figure 9 – Horizontal deformation of the embankment for a vertical pressure of 1.5MPa applied on the loose embankments (Dr=11%) and 3MPa on the dense embankments (Dr=45%).

Similar to what was seen before, the unreinforced slopes showed very large lateral deformations for the applied vertical stress. The larger lateral deformations were observed in the loose unreinforced embankment despite the load applied being only half of the one applied in the dense embankment. The addition of reinforcement drastically reduced the lateral deformation of the embankment, and the tire reinforcement showed better performance than the Geocell reinforcement.

The large change in behavior is seen for the maximum vertical deformation, where the use of Geocell reinforcement generated a vertical settlement of around 36% of the settlement of the unreinforced embankment. The use of tires however, generated around 19% of the settlement. For the densest embankment the values measured were around 71% and 42% respectively. The values obtained for the lateral displacement were somewhat similar, 55% for Geocell reinforcement and 25% using tire reinforcement on the loosest embankments, whilst the densest showed 59% and 41%, respectively.

4. Conclusions

The outlined experimental results were performed to analyze the effect of the depth of the reinforced layers on the mechanical properties of a model embankment. The performance of Geocell reinforcement to a more environmentally friendly alternative were also compared, and the results have shown that:

- The performance of the model embankment is dependent on the depth of the first reinforcement layer and the distance between reinforcement layers. The study of the Geocell reinforced embankment presented here has demonstrated that the optimum depth for the first layer is 0.25B, and that the distance between layers is also 0.25B.
- Increasing the number of reinforcement layers improves the mechanical properties of the model embankment, however, the improvement is reduced with the addition of each extra layer, alluding to the existence of a limited number of reinforcement layers.
- The reinforcement can be used to effectively reduce the maximum vertical stress seen on the embankments, as well as to create a more homogeneous stress distribution, that will in turn generate lower settlements and lower horizontal deformations.
- For loose embankments the improvements observed by using Geocell or waste tire reinforcement are better than the improvements observed in the densest

embankments. This confirms that the application of these types of reinforcement are best suited for soft or loose soils.

- For the configurations used in the experiments waste tire reinforcement has outperformed Geocell reinforcement in both stress and deformation reduction, it is also a more environmentally friendly alternative to reinforcement.

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