APPLICATION OF GEOCELL REINFORCEMENT IN STABILISING RAILWAY TRACK SUBSTRUCTURES

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Abstract: Railway track settlement is a considerable problem in modern day railway engineering and has significant cost and time implications to the rail industry through maintenance operations, track renewals and line speed restrictions. One of the most recent stabilisation techniques used to try and increase the resistance of the track substructure to deformation is the use of geogrid and geocell reinforcement within the ballast layer of the track. However, due to the lack of research into track reinforcement with the geocell system, the potential for geocell reinforcement within rail tracks is somewhat lacking behind geogrid reinforcement.

This paper presents the preliminary results of on-going experimental research on track implemented with geocell reinforcement. A series of uniaxial compression tests carried out on granular materials confined by single cell geocells have been undertaken to determine the load-deformation characteristics of geocell reinforced granular soil. These tests enable the reinforcement potential of using geocell cellular confinement within railway tracks to be investigated. In order to examine the reinforcement mechanism of geocell reinforcement three different granular infill materials with varying quality have been used in this study to give an insight into the strength and stiffness variation of the geocell composites with quality of fill material used.

The experimental results illustrate the importance of the confinement mechanism of geocell reinforcement on the shear strength and load-deformation behaviour of reinforced granular soil, which is complimented by a mathematical description of the resilient behaviour. The potential for the use of geocell reinforcement on high speed tracks is shown via 3D finite element computer modelling and a description is given of the full-scale laboratory rail track testing facility, which is currently being constructed at Heriot – Watt University. This new test track will be used to conduct experiments in the next stage of the research program.

Keywords: geocell, cellular system, railway.

INTRODUCTION

The consequences of track deterioration are that ride quality decreases and dynamic loads increase, causing increased geometry degradation. The main cause of track deterioration is settlement of the substructure and while rail traffic can tolerate a certain degree of unevenness in the track, a point is eventually reached at which the track geometry has to be improved before differential track settlements give rise to faults in the vertical track geometry (Selig *et al*. 1994). These faults can cause serious problems to rail traffic and ultimately could result in derailment. Therefore, track settlement is a serious problem in modern day railway engineering and has considerable cost and time implications to the rail industry.

As a result, several well established polymer stabilisation techniques are being used to improve the mechanical properties of granular ballast and subballast layers in order to increase their resistance to deformation. These techniques can reduce the depth of the required granular layer and also reduce the frequency of the required maintenance. This paper is part of a wider research program that intends to study several of these polymer stabilisation techniques within a full-scale laboratory rail track testing facility. The results will quantify the benefits of the stabilisation in terms of reducing track settlement and illustrate if any significant cost savings to the rail network could be made in the long term. Some of the initial granular stabilisation techniques to be tested within the testing facility will be the geosynthetic reinforcement products known as geocell and geogrid reinforcement. These geosynthetic reinforcement materials use their tensile properties to confine the granular soil and resist strain and can be used to reinforce the ballast and subballast layers of rail track.

The reinforcing action of 2D planar geogrids is created through an interlock mechanism between the grid and granular material that it reinforces. This interlock creates a tensile restraining force in the geogrid and enables the grid to resist horizontal shear from the granular fill and thus, potentially restrain the granular material from lateral spread (Tensar International 2007). Comprehensive laboratory and field research (Brown *et al*. 2007a, 2007b, McDowell *et al*. 2006, Das *et al*. 2006 and Indraratna *et al*. 2006) conducted on geogrid reinforcement placed within the ballast layer of track substructures has shown that geogrid reinforcement over both weak and firm subgrades can help reduce the rate of permanent deformation associated with lateral ballast spreading. Although, a review of the published results suggests that this can be highly variable.

Research into the more recently developed geocell reinforcement system has shown that the pseudo-3D cellular confinement mechanism of geocell reinforcement retains desirable characteristics of 2D planar geogrid reinforcement and may offer an increased stability to the granular fill. The maximum load carrying capacity of an interconnected cellular mattress has been found to range from 27% (Dash *et al*. 2003) to 187% (Sitharam *et al*. 2005) greater than that of planar reinforcement. This again demonstrates the high variability of this type of reinforcement. Geocell reinforcement consists of interlocking cells integrated in a honeycomb structure into which granular materials are placed and compacted. Once filled, each cell acts in conjunction with adjacent cells to form a stabilised composite mattress that assists in dispersing load and lateral movement, and shear failure. The geocell cellular confinement mechanism improves the properties of granular material by restricting the lateral movement of soil, allowing a soil matrix to be developed as compacted granular fill can reach good compressive strength (Presto Products Company 2007). However, no substantial research has been conducted on geocell reinforcement within rail track, and although geocell reinforcement has been used to reinforce ballast in the UK on the East Coast main line (ECML) quantifiable benefits of the stabilisation in terms of reducing track settlement and ballast layer stresses is somewhat unknown.

Within this paper, a series of preliminary uniaxial compression tests carried out on granular materials confined by single cell geocells will be reported on. The main objective of these tests is to determine the load-deformation characteristics of geocell reinforced granular soil and thus, examine the potential of the geocell cellular confinement system to reinforce railway tracks. This paper will form the first stage of a wider research program into polymer reinforcement of railway tracks and only considers single geocell systems. A description of the full-scale laboratory rail track testing facility which is currently being constructed at Heriot – Watt University, and will be used to conduct the experiments on full geocell systems in the next stage of the research program, will be discussed in this paper along with a description of the resilient behaviour of reinforced granular soil.

MATERIALS AND EQUIPMENT

Granular materials

Three different granular infill materials with varying quality have been used in this study to give an insight into the strength and stiffness variation of the geocell composites with quality of fill material used and to help understand the reinforcement mechanism of geocell reinforcement. The granular materials include coarse angular gravel, coarse rounded gravel and fine gravel, which have all been tested in the geocell system at a relative density of 60% with the coarse angular gravel also being tested at a relative density of 40%. The three granular materials tested within the geocell system can all be described as relatively uniform in grading and can be classified as poorly graded gravels with no fines. The particle size distribution curve for the three granular materials is shown in Figure 1 along with the minimum specification for rail track ballast (Network Rail 2000). As shown in Figure 1 the granular materials used in this preliminary study are finer than the grading specification for rail track ballast in the UK. The quantification of the range of particles sizes and the properties of each material can be found in Table 1.

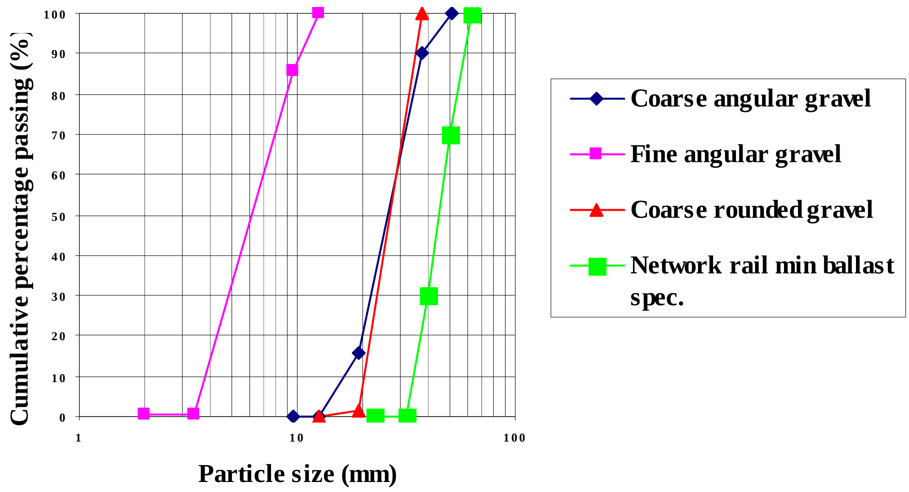

Figure 1. Particle size distribution graph

Table 1. Summary of geomechanical properties of fill materials

Granular infill material	D10 (mm)	Coefficient of uniformity–Cu	Max. Void ratio	Min. Void ratio	Max. dry density (Mg/m³)	Min. dry density (Mg/m³)	Specific gravity - Gs	Internal friction angle (°)
Coarse angular gravel	16.7	1.79	0.974	0.818	1.53	1.43	2.77	51.1
Coarse rounded gravel	20.4	1.47	0.745	0.684	1.65	1.55	2.65	48.4
Fine Gravel	4.10	1.83	0.869	0.666	1.47	1.38	2.48	38.3

Testing equipment

A 50 Tonne capacity Denison uniaxial compression machine at Heriot Watt University has been used to uniaxially load the geocell composites to destruction after each single perforated geocell was filled with the selected material. The single cell geocells used for this study were cut from a full geocell grid manufactured from high density polyethylene. The single cells have a depth of 200mm, length of approximately 250mm, width of approximately 200mm and have an average certified cell seam strength of 2840 N (Presto Products Company 2007). Prior to being placed in the loading equipment the geocells were filled in three equal layers by hand with the specific granular material at the required relative density. The relative densities of the materials were determined from mass-volume calculations as the volume of the cell to be filled was known. Consequently, the mass required for 40 and 60% relative density could be calculated. To replicate a stiff subgrade beneath the granular reinforced geocell composites and allow the cells to be filled outside the loading apparatus and then moved into position a thin wooden board of 3mm thickness was used in each test. The granular base/subgrade boundary was considered rigid.

To provide a level platform for the load to be applied uniformly across the geocell composite a metal plate of thickness 10mm was used over the top of the cell. Monotonic loading was applied to each composite structure by manually increasing the load in increments of around 1kN at a steady rate until the geocell membrane showed signs of failure. During the loading process the geocell composite compresses and expands circumferentially until eventually failing by bursting of the welded seam. Figures 2 and 3 illustrate the loading process and seam membrane failure respectively. All tests failed at the seam.

The vertical displacement of the geocells and applied load were measured from the vertical displacement dial gauge and digital output from the load cell on the Denison compression machine, respectively. The lateral displacement of the cells was measured from a linear variable differential transformer (LVDT) displacement transducer. Due to the nature of the monotonic loading (until failure) the settlement values presented are the accumulated permanent and resilient settlement values.

Figure 2. 200mm high geocell composite structure under vertical load

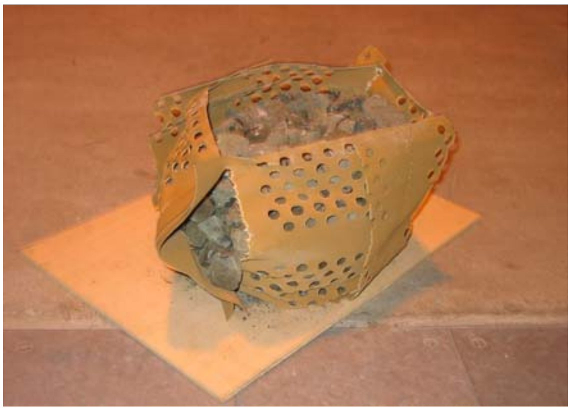

Figure 3. 200mm high by 250mm wide geocell composite structure after being loaded to failure

Limitations of testing equipment

The loading equipment used to conduct these tests and the rigid boundaries above and below the geocell composites obviously represent certain limitations on the results of this study. These rigid boundaries mean that the single geocell composites are effectively being vertically crushed during loading and the developed tensile membrane stresses are localised. As a result the tensile strength, passive resistance of adjacent cells, and anchorage mechanism of a full geocell system cannot develop and thus, the restriction to vertical settlement is limited. Therefore, the results in this paper are not indicative of how a full geocell system would operate if placed within the substructure of rail tracks. Nonetheless, the results provide important information regarding the load carrying capacity and the reinforcing characteristics of geocell reinforcement, which can be related to the potential of geocell reinforcement to stabilise rail track. It is thought that the failure process of the single soil composites upon the application of monotonic loading can be split into 3 stages:

- Initial vertical displacement of composite due to soil particle re-arrangement with a subsequent increase in density. The localised tensile membrane stresses in the walls of the geocells are relatively low.
- As the cell is vertically crushed and the lateral displacement of the composite increases due to increased particle re-arrangement the localised tensile membrane stresses in the walls of the geocells are increased. At large lateral strains these stresses cause a small increase in the resistance to vertical deformation until the seam is ruptured.
- Once the seam is ruptured the load is transferred back to the granular materials from the membrane as the membrane cell loses it strength. Hence, as the load is further increased it is simply crushing the granular material inside the cell resulting in particle breakage.

EXPERIMENTAL RESULTS

The results of monotonic loading of various geocell composites are shown in Figures 4 and 5 and Table 2. Relating Figures 4 and 5 to the assumed failure process it can be seen that after an applied load of around 2kN, with increased lateral displacement, the induced tensile membrane stresses in the walls of the cell composite reduce the rate of vertical deformation of the composites until the seam is ruptured, which is deemed the failure load. The axial stiffness values of the different geocell composites shown in Table 2 have been taken as the secant modulus.

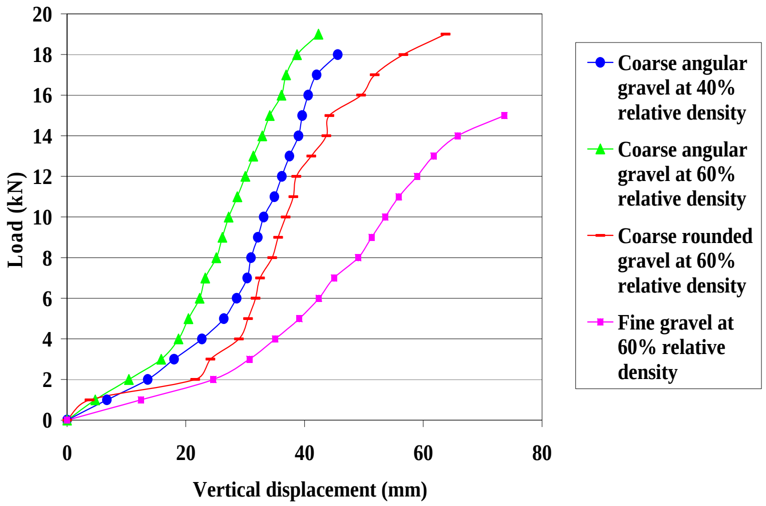

Figure 4. Plot of load versus vertical displacement for different fill materials and varying relative densities

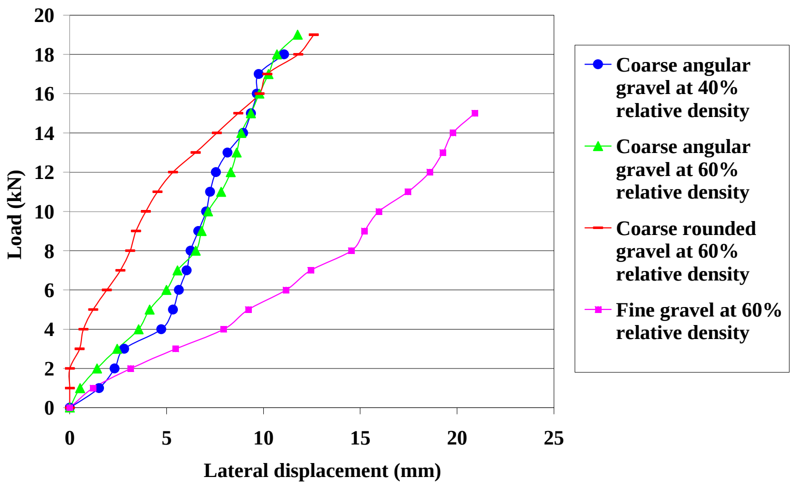

Figure 5. Plot of load versus lateral displacement for different fill materials and varying relative densities

Comparing the three different infill soils it is clear that the coarse angular gravel at 60% relative density produces the strongest and stiffest geocell soil composite structure while the fine gravel produces the weakest. The coarse rounded gravel composite fails at a similar stress level to the coarse angular soil, but exhibits more vertical displacement. This is believed to be due to the smooth rounded coarse gravel particles creating a reduced frictional interlock both within the infill and between the cell walls and the infill gravel, which reduces the resistance to vertical deformation.

Table 2. Failure, stiffness and cohesion values of different geocell composites

Geocell composite infill	Failure load (kN)	Stress at failure (kPa)	Axial strain at failure (%)	Apparent cohesion gained from geocell (kPa)
Coarse angular gravel at 40% relative density	18	821	23	145
Coarse angular gravel at 60% relative density	19	826	21	149
Coarse rounded gravel at 60% relative density	19	812	32	154
Fine gravel at 60% relative density	15	694	37	168

The fine gravel composite produces the most vertical and lateral displacement, which is understood to be due to a combination of high compressibility and poor frictional interaction between the soil and the cells walls. These factors are a function of the particle size, shape and strength. The high compressibility allows lateral displacement to develop at a steady rate while the poor frictional interaction restricts the resistance to vertical deformation and reduces the effectiveness of the composite membrane, which results in early failure at a stress of 694kPa. It is thought that a combination of both particle re-arrangement and particle breakage takes place during loading of the fine gravel composite.

Comparing the angular gravel soil composites prepared at varying relative densities it can be seen that the coarse gravel aggregate at 60% relative density produces the strongest and stiffest geocell soil composite structure. This is likely simply because of a greater frictional angle and lower compressibility at 60% relative density plus some dilation effects.

The enhanced strength of the infill soil due to geocell confinement can be described as an apparent cohesion (Bathurst *et al*. 1993, Rajagoapal *et al*. 1999). The values of the apparent cohesion gained for the different tests undertaken can be seen in Table 2. Comparing these apparent cohesion values to results from previous research indicates that these values are consistent with the measured values found in past experiments by Bathurst *et al*. (1993) and Rajagoapal *et al*. (1999).

RESILIENT BEHAVIOUR OF REINFORCED GRANULAR MATERIAL

The effect of reinforcement on granular soil can be analysed by considering the stress-strain state and the effects of shear stress and mean stress on the resilient modulus of granular materials. To consider both shear stress and mean stress on the resilient behaviour of granular soil Uzan (1985) introduced the universal model:

$$E_r = K_1 P_{atm} \left(\frac{3p}{P_{atm}} \right)^{K_2} \left(\frac{q}{P_{atm}} \right)^{K_3}$$

Where E_r is the resilient modulus, K_1, K_2 and K_3 are model parameters, P_{atm} is atmospheric pressure, p is mean stress and q is deviatoric stress. The resilient modulus of granular soil subjected to cyclic loading is governed by both the increase of secant modulus, with bulk stress, and the decrease of secant modulus with deviatoric stress, which can occur simultaneously. However, the increase of deviatoric stress does not always imply that a decrease in resilient stiffness will occur. Uzan (1985) reported a slight increase of resilient modulus with increasing deviatoric stress as long as shear failure was not reached. Furthermore, Werkmeister (2003) found that at low stress levels strain hardening is observed and strain softening is witnessed as the stress level approaches the failure state (in the universal model the strain hardening or softening effect of shear stress on the resilient modulus can be taken into consideration by assigning positive or negative values to k3 respectively). Generally, the level of shear stress/strain the granular soil is subjected to dictates whether strain hardening or softening is dominant. Figure 6 illustrates the stress-strain behaviour of granular soil.

Werkmeister (2003) explained that at low stress levels particles become more closely packed together into new interlocked positions as a result of deviatoric stress and such a particle rearrangement in dense granular soil in a restrained area can cause an increase in resilient modulus through dilation (Uzan 1985). Therefore, based on the experimental results reported in this paper and the universal model it can be concluded that the confinement mechanism of a geocell reinforced granular composite may cause an increase in resilient modulus with shear stress through the dilation induced load transfer from confined soil to geocell. Figure 6 shows that reinforced granular soil can be compared to soil at a low stress level.

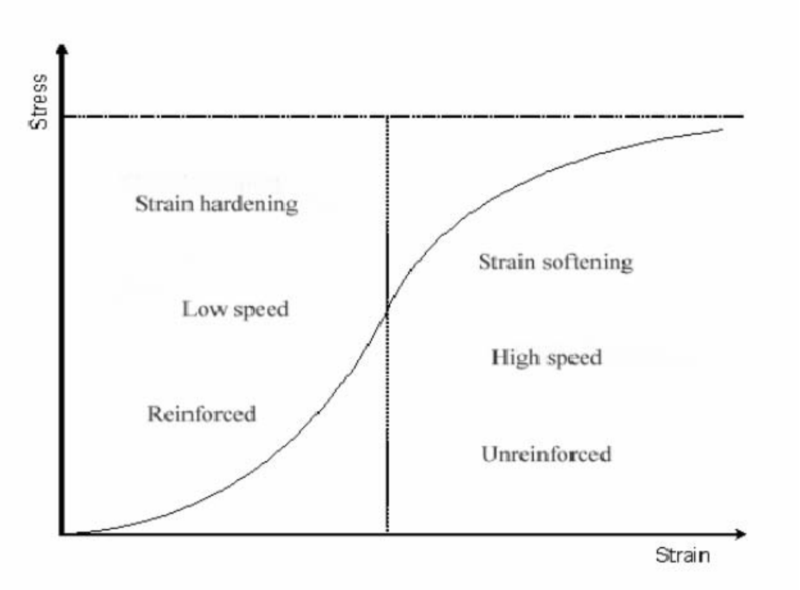

Figure 6. Stress-strain behaviour of granular soil (Werkmeister 2003)

The case for the application of geocell reinforcement in high speed train tracks can be made by considering the vertical stress level within ballast at high speed. Using a 3D finite element track model (Banimahd *et al*. 2007) the differences between the vertical stress level in ballast for a train travelling at 30m/s and a train travelling at 60m/s on soft soil have been investigated and are shown in Figures 7 and 8. It can be seen that by doubling the train speed the maximum level of vertical stress experienced within the ballast layer more than trebles for the particular case studied. The level of stress illustrated in these simulations is similar to the 71-196Kpa range quoted by Brought *et al*. (2003) which is expected within the substructure of railway tracks on a granular layer at 300mm depth below the underside of sleepers.

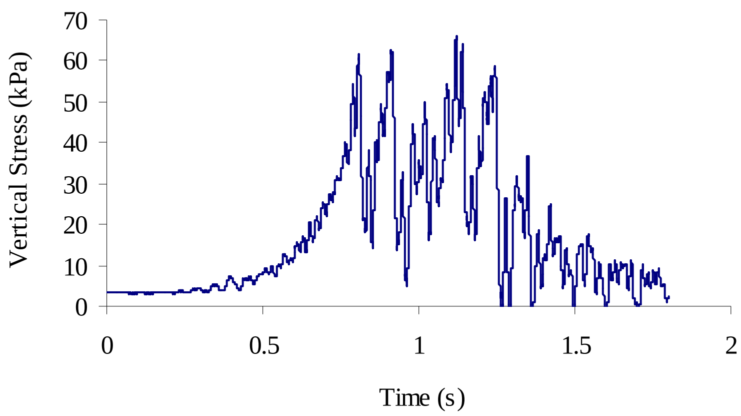

Figure 7. Vertical stress level within ballast for train travelling at 30m/s

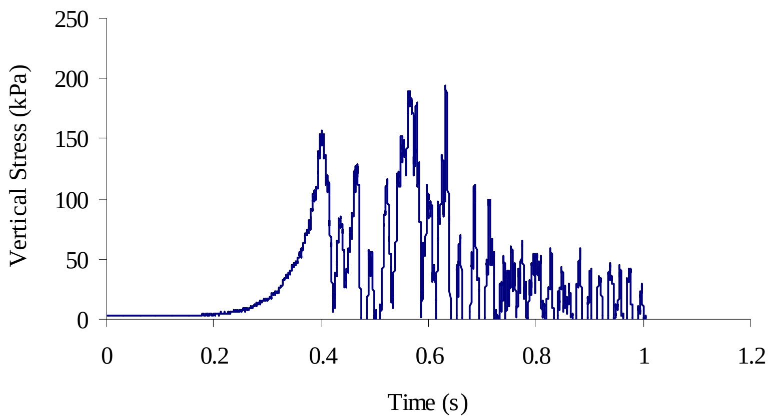

Figure 8. Vertical stress level within ballast for train travelling at 60m/s

At the high levels of stress predicted to exist in high speed track, strain softening may be predominant as shown in Figure 6. Thus, a decrease of resilient modulus with increasing deviatoric stress might be expected, resulting in increased geometry deterioration and required maintenance. Consequently, the potential for using the load carrying capacity of geocell reinforcement to reduce track deterioration in high speed tracks may exist. The load carrying capacity of geocell reinforcement is understood to be attributed to the confinement mechanism of geocell reinforced granular soil. Nonetheless, the long term behaviour of geocell reinforcement under cyclic loading needs to be examined and this resilient behaviour model needs to be developed and supplemented with experimental data.

FULL-SCALE LABORATORY RAILWAY TESTING FACILITY

The monotonic loading experiments reported on within this paper help to identify the reinforcement mechanism of geocell reinforcement and provide an indication of the maximum stress level that could be applied to a geocell system. However, these tests only form the first stage of a wider research program into polymer reinforcement of railway tracks and in order to research the full deformation characteristic of geocell reinforcement within a railway substructure under a large number of passing train wheels, full-scale cyclic load testing is required. Therefore, a full-scale rail testing facility is currently under construction at Heriot-Watt University and is due to be complete by April 2008.

The new test facility at Heriot-Watt University will consist of a trackbed constructed within a steel tank 1.2m x 3.0m x 1.5m high. The tank will be lined with a rubber based material to limit the lateral support to the substructure provided from the rigid walls of the steel tank and to provide lateral support similar to the horizontal residual support experienced in the field. The trackbed itself will consist of a 0.7m deep clay layer overlain by a 0.3m deep layer of ballast and 0.15m crib ballast surrounding the sleeper sections. Five sleeper sections 0.6m in length will be spaced at 0.65m centres. It is anticipated that constructing the trackbed with 5 sleepers will allow for sufficient anchoring of the reinforcement technologies to allow the full tensile strength of the reinforcement to develop. The 0.6m sleeper length replicates one half of a twin block sleeper used in the rail industry. The sleepers will be attached to a section of rail via rail clips to add to the authenticity of the facility.

The tank will be positioned under the cyclic hydraulic loading arm of the rig located in the heavy structures lab of Heriot-Watt University. The application of cyclic loads of up to 35 Tonnes (machine limit is 200 Tonnes) will be applied directly to the central sleeper via the rail section at rates up to 2 Hz. The extent and variation of applicable loads will enable both realistic static and dynamic loads of both typical passenger and freight traffic to be applied to the trackbed, which will generate realistic stress levels in the ballast and subgrade.

Several trackbed parameters will be monitored and analysed in response to the repeated loading through appropriate instrumentation within the proposed testing facility. LVDT’s will be located at either end of the centrally loaded sleeper section in order to measure sleeper settlement and large capacity load cells will be positioned so as to monitor the load distribution onto the sleepers from the applied load. Additional load cells and accelerometers will be placed within the ballast to measure the stress and vibration levels within the substructure respectively. The data gathered from the monitoring equipment will be collected on a data acquisition system and remote computer. In addition to the instrumentation data, load and displacement readings will also be recorded from the cyclic loading rig.

DISCUSSION AND CONCLUSION

The experimental tests described in this paper have provided useful data on the potential application of geocell reinforcement in railway tracks allowing more extensive and realistic full-scale experiments to be planned. The results indicate that the failure stress and axial stiffness of geocell composites increase with an increased frictional interaction of fill soil and cell wall, which is dependant on fill particle size, shape, strength and density. Overall, these experimental results have illustrated the importance of the confinement mechanism of geocell reinforcement and 3D finite element modelling has shown that there may be potential for using geocell reinforcement in high speed tracks to reduce track deterioration. However, track stiffness improvement may be very limited. The confinement mechanism is contributed to through the frictional interaction between cell wall and fill, the tensile membrane strength of the cell walls and the passive resistance of adjacent cells.

The restrictions caused by only being able to load single cells in the loading equipment has severely restricted the development of the confinement mechanism and even though the results have demonstrated that single geocell systems can tolerate a higher level of applied stress, high levels of vertical displacement have been found, which appear unreasonable for rail tracks. As only single cell composites have been loaded the anchorage mechanism, which increases the tensile membrane stress, cannot fully develop and there is no passive resistance developed from adjacent cells and thus, the restriction to vertical settlement is limited. Research on the confinement mechanism of geocell reinforcement has found that the passive resistance of adjacent cells can increase the failure load of geocell composite systems by 36%, on average, with corresponding reductions in the rate of vertical settlement (Kazerani 1986). Moreover, similar to the general findings of these experiments, Kazerani (1986) found that the total settlement of geocell systems filled with uncompacted fill was 29% higher than that of a geocell system filled with compacted fill. It follows that increasing the relative density from 60% could have a marked impact on the vertical settlement of the system. Other restrictions include undertaking monotonic loading as cyclic loading can lead to a considerable increase in material strength and stiffness (Suiker *et al*. 2005). Suiker *et al.* (2005) found that applying 1 million load cycles as opposed to monotonic loading increased the stiffness of subballast by a factor 7 and ballast by a factor of 3.5.

Therefore, although these experiments have been limited to monotonic loading of single cells the results have shown that even with single cell composites, parts of the confinement mechanism operate to increase the shear strength of granular material and increase the resistance to vertical deformation. Hence, it can be assumed that a full geocell system, with passive resistance of adjacent cells, filled at 100% relative density with a strong angular granular material (ballast) and loaded cyclically could have the potential to not only improve the strength of a subballast or ballast layer of rail track, but also improve the stiffness. However, this may be very difficult to achieve in the field. Improving the stiffness of the track has considerable cost saving implications to the rail industry through reducing the required maintenance and granular layer depth of the track. Despite that, in order to confirm the potential of geocell reinforcement in terms of reducing track settlement and directly compare it to unreinforced track and other rail track granular stabilisation techniques such as geogrid reinforcement, realistic full-scale cyclic load testing is required, which is the next stage in the wider rail track stabilisation research program at Heriot-Watt University.

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