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Performance Assessment of Geocell-Reinforced Subballast: Modeling and Design Implications

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Abstract

This paper presents a study of the load-deformation behavior of geocell-stabilised subballast subjected to cyclic loads using a large-scale track process simulation apparatus and numerical modelling. The tests and numerical simulations were conducted to mimic the actual track conditions. Subjected to a given frequency and cyclic loads the predicted load-deformation behavior of the subballast with and without geocell inclusions match reasonably with those measured in the laboratory, and show that geocell could effectively decrease the lateral and axial deformations of the reinforced subballast. The results also provide an insight to design of rail tracks capturing the roles of geocell in decreasing lateral deformation of subballast. Additionally, the numerical modelling carried out in this study can be applied in the preliminary design of track substructure where a wide range of subballast aggregates and geocell mattresses with varying strengths and stiffness can be considered.

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Performance Assessment of Geocell-reinforced Subballast: Modeling and Design Implications

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ABSTRACT

This paper presents a study of the load-deformation behavior of geocell-stabilised subballast subjected to cyclic loads using a large-scale track process simulation apparatus and numerical modelling. The tests and numerical simulations were conducted to mimic the actual track conditions. Subjected to a given frequency and cyclic loads the predicted load-deformation behavior of the subballast with and without geocell inclusions match reasonably with those measured in the laboratory, and show that geocell could effectively decrease the lateral and axial deformations of the reinforced subballast. The results also provide an insight to design of rail tracks capturing the roles of geocell in decreasing lateral deformation of subballast. Additionally, the numerical modelling carried out in this study can be applied in the preliminary design of track substructure where a wide range of subballast aggregates and geocell mattresses with varying strengths and stiffness can be considered.

INTRODUCTION

Railway networks are one of the major transport systems used for carrying passengers, and transporting freight and bulk commodities between major mines and ports in many countries worldwide. In recent years, traditional railway foundations have become overloaded due to an increasing demand for heavier and faster trains; this has accelerated the deterioration of track substructure and increased maintenance costs (Indraratna et al. 2013; Ngo et al. 2016a). Upon repeated train loading, ballast and subballast subject to significant lateral spreading that results in substantial vertical settlements owing to insufficient confinement. To compete with other transportation modes and meet the ever growing demand for public and freight transport, the railway industry will face challenges to improve the track operational efficiency and decrease maintenance and infrastructure costs (Rujikiatkamjorn et al. 2012; Indraratna et al. 2011; Ngo et al. 2016b-c). The foundation of a conventional ballasted track consists of granular material layers that help to transmit and distribute induced cyclic load to the underlying subgrade at an acceptable and controlled stress level (Selig and Waters 1994; Indraratna et al. 2014; Biabani *et al.* 2016a). Reinforcing track substructure using a planar reinforcement (e.g. geogrids, geocomposites) has been increasingly adopted as it can decrease the axial and lateral deformation of ballast and subballast layers, and to improve the stability of track substructure under cyclic train loading (Ngo et al. 2014; Tutumluer et al. 2012; Indraratna et al. 2016). Past research have indicated that cellular reinforcement can provide much better lateral confinement to infill granular soils than planar reinforcement (Indraratna et al. 2015, Biabani et al. 2016b; McDowell et al. 2006). Subjected to induced loads, additional confinement is mobilized in the geocell that helps to prevent infilled granular aggregates from spreading laterally. By increasing the infill rigidity, geocells also improve the load-carrying capacity of track embankments, which in turn enhances track performance. Understanding the performance of geocell reinforcement under cyclic loading is therefore essential, which is needed for its design and application in ballasted rail tracks.

LARGE-SCALE LABORATORY TESTING

A large-scale track process simulation apparatus (TPSA) was designed and built at the University of Wollongong (Figure 1), and it was used to study the load-deformation behavior of the unreinforced and geocell-reinforced subballast subjected to cyclic loading (Indratna et al. 2015; Biabani et al. 2016a). The area of the test specimen in the TPSA was chosen following to Australian standard gauge for heavy haul track with an approximate plan area of 800mm × 600mm, and 600 mm height. The subballast material (crushed basalt) was selected from Bombo quarry near Wollongong, New South Wales, Australia. The particle size distribution of subballast was within the Australian rail industry specified range (D_{50} = 3.3 mm, D_{max} = 19 mm, D_{min} = 0.075 mm, C_u = 16.3, C_c = 1.3, unit weight, γ= 18.5 kN/m^3, void ratio of 0.65), as shown in Figure 2. Subballast aggregates had a total depth of 450 mm, of which the upper 150mm was reinforced by geocell. A geocell mattress made from polyethylene materials, that was bonded at joints to form a three-dimensional cellular form (i.e. depth = 150 mm, ultimate tensile strength = 9.5 kN/m, thickness = 1.3 mm, density = 950 kg/m3) was used in this study. A predetermined weight of sub-ballast was placed inside the TPSA in several layers and compacted using a vibratory hammer to achieve a relative density (D_R) of about 77%, which is representative of the density of subballast in the field. A geocell mattress was placed onto the surface of the sub-ballast. All specimens were prepared until the layer of sub-ballast reached a final height of 450 mm. Ten strain gauges were firmly bonded to the geocell strips and were connected to data loggers to measure the circumferential and vertical strains during the tests.

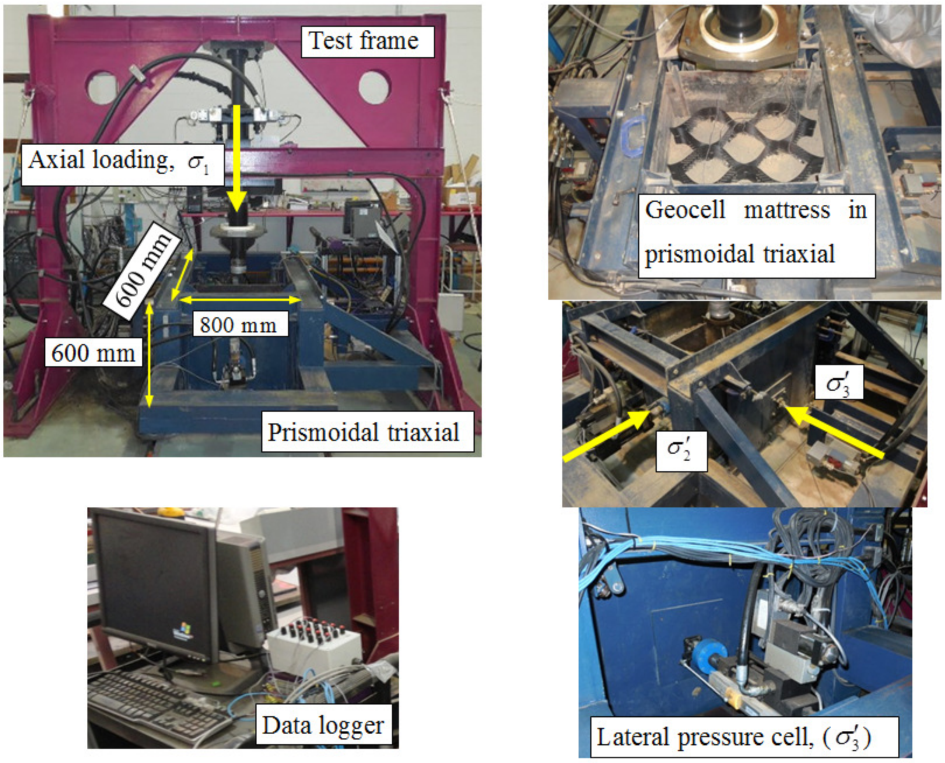

Figure 1. Schematic illustration of cyclic loading.

All tests were carried out under a plane strain condition, where any lateral movement in the longitudinal direction (parallel to the track) was prevented (ε_2=0). Walls were allowed to displace laterally in the direction parallel to the sleeper simulating a long straight section of track. Laboratory tests were conducted in a strain-controlled manner at an initial state, followed by a stress-controlled manner, where the magnitudes of the cyclic stresses are given in Figure 3. To study the influences of confining pressures on the load-deformation of sub-ballast, cyclic tests were carried out at different confining pressures of, σ_3 = 5, 10, 15, 20, 30 kPa and frequencies of f =10, 20, 30 Hz. All tests were conducted up to 500,000 load cycles.

Experimental data indicated that the confining pressure (σ_3) and frequency (f) induce a significant influence on the load-deformation responses of the subballast subjected to cyclic loads. Laboratory results showed that under cyclic loading, geocell mattress can offer additional confinement ($\Delta\sigma_3$) to the infill material (i.e. other than the confining pressure available from sleepers and shoulder ballast), and help to reduce axial strains (Figure 4). The results also showed that using geocells had markedly decreased the strain rates of specimens tested at lower confining pressure ($\sigma_3' \leq$ 15 kPa), but had diminishing returns at higher confining pressures (σ_3'= 20-30 kPa). Undoubtedly, the inclusion of geocell reinforcement certainly improved the performance of subballast (Indraratna et al. 2015). The geocell-reinforced subballast approached shakedown (i.e. stable state) at a lower number of cycles than unreinforced subballast. As a result of the geocell confinement, the lateral spreading of infilled subballast is minimized with increased stiffness thereby creating a quasi-rigid mattress.

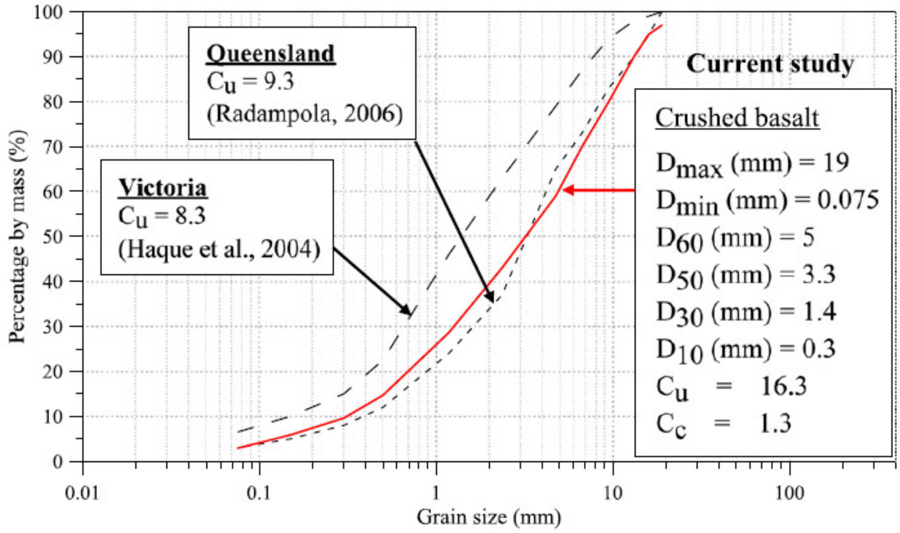

Figure 2. Particle size distribution of subballast tested in compared with typical materials used in track in various states in Australia

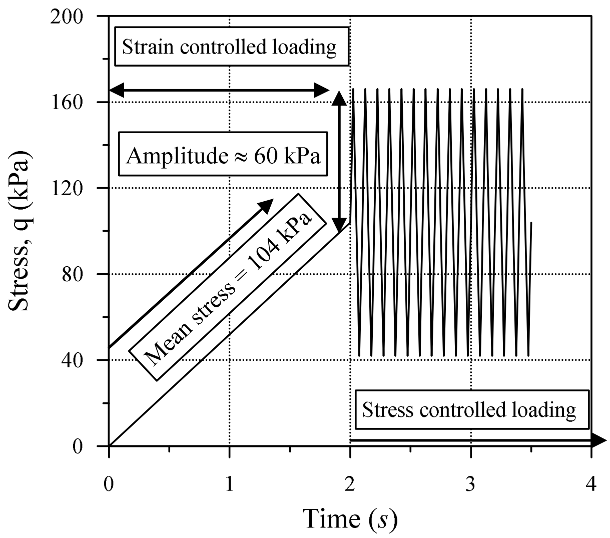

Figure 3. Schematic illustration of cyclic loading.

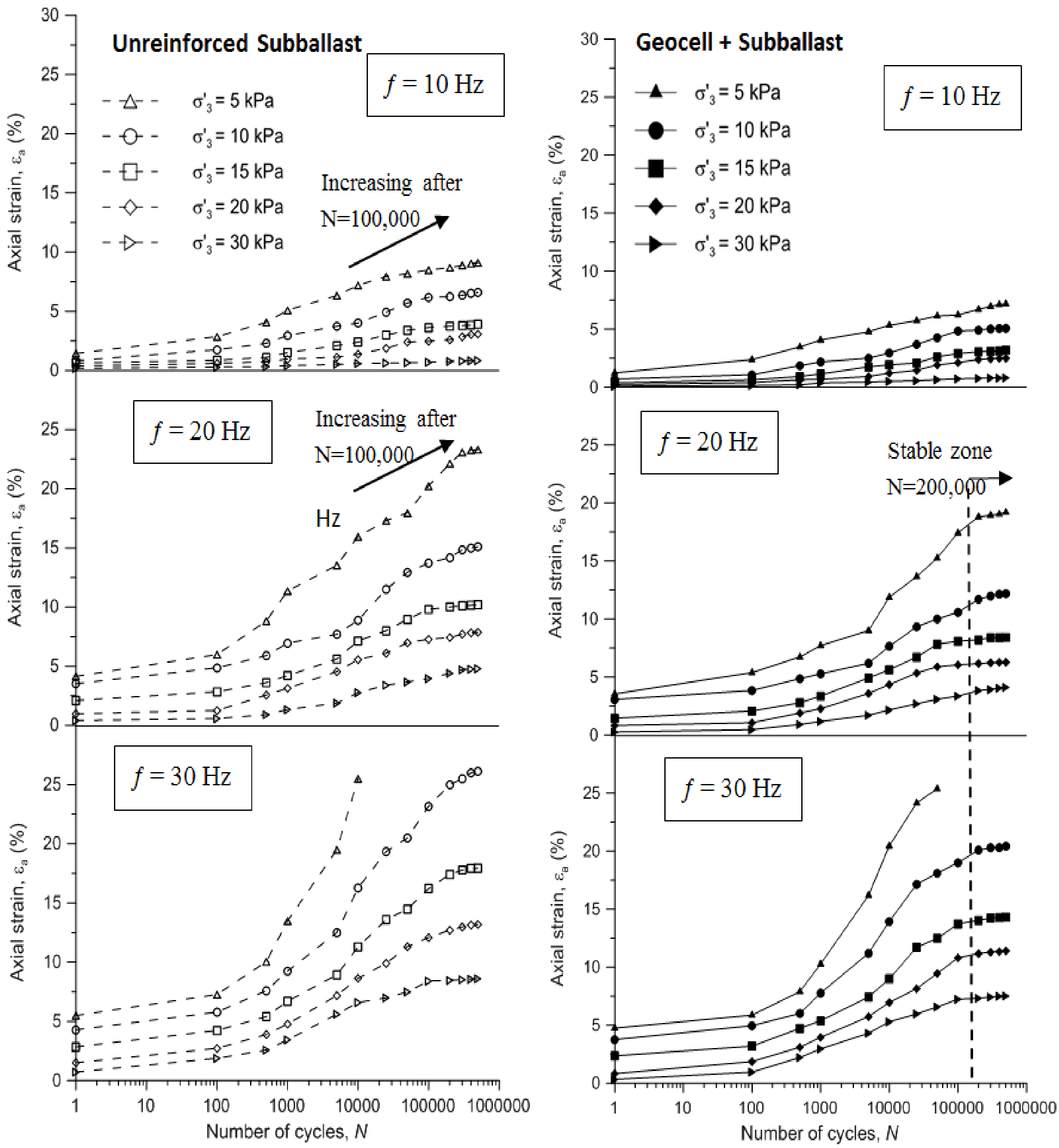

Figure 4.Variations of axial strain versus number of cycles (a) unreinforced subballast; (b) reinforced subballast (modified after Indraratna et al. 2015)

COMPUTATIONAL MODELING

Finite element method (FEM) was used to simulate the TPSA where the material properties obtained from laboratory tests and model geometry followed the TPSA carried out in the laboratory (800 mm × 600 mm × 450 mm), as illustrated in Figure 5. Cyclic loads exerted beneath the ballast, was loaded directly onto the subballast surface, where the loading characteristics were identical to those applied in the laboratory. Elasto-plastic constitutive model with non-associative behavior was adopted to simulate subballast in the analysis. Drucker-Prager yield criterion was also used to capture the elasto-plastic behavior of subballast. Model parameters (i.e., ϕ, ψ) were determined in the laboratory using triaxial equipment (i.e. friction angle ϕ=39^0, angle of dilation ψ=9^0, cohesion yied stress =2 kPa, Poisson's ratio ν= 0.3) . A geocell was modeled as a linear elastic-perfectly plastic material was used to model the geocell mattress. A hexagonal shape was adopted to model the geometry of the geocell pockets, as it is similar to the actual shape of the geocell carried out in the laboratory. Input parameters used to model geocell are given as: density = 950 (kg/m^3), secant modulus (3% strain) = 0.3-5 (GPa), Poisson's ratio = 0.3. The contact between the subballast - geocell interface was modelled as interface elements with a fixed angles of shearing resistance of 26^0 (2/3ϕ). Due to high computation time required to simulate a cyclic model, in this study all simulations were conducted up to 10,000 cycles, where most of the subballast deformation had already occurred, as observed in the laboratory. Cyclic loading and dynamic behavior of subballast and geocell were modelled using defined sinusoidal functional loading and considering dynamic amplification factor of 1.45.

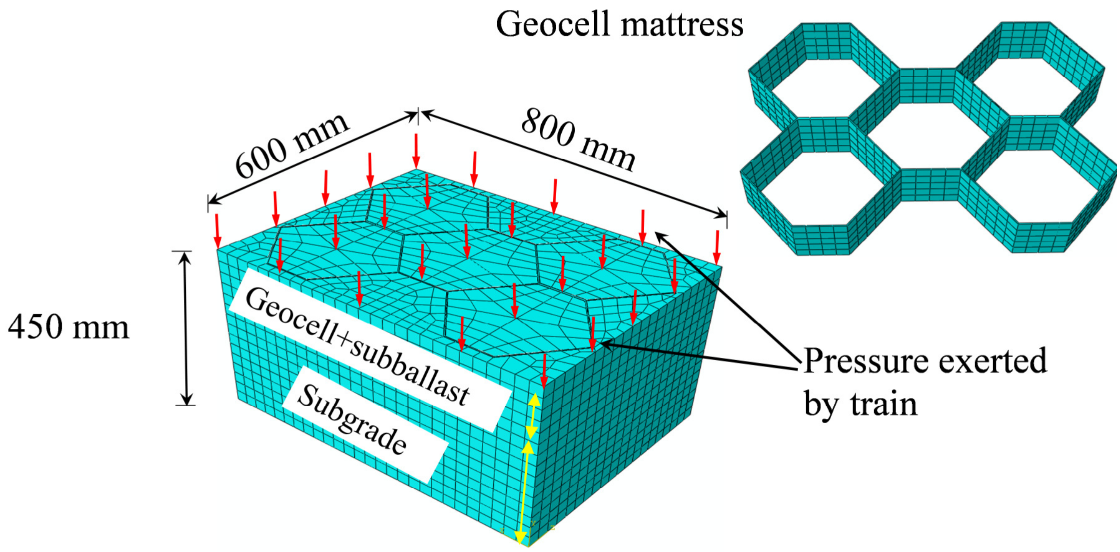

Figure 5. Finite element modeling for geocell-reinforced subballast (modified after Biabani et al. 2016a)

Figure 6 shows the lateral deformation with the depth of geocell-reinforced subballast under a confining pressure of σ_3= 10 kPa at varying load cycles. Contours of lateral spreading of subballast are presented in Figure 6a where maximum lateral spreading is observed in the subbalalst beneath the geocell. As expected, lateral movements increase with an increase in number of cycles (N) and the lateral spreading beneath the geocell-reinforced layer also increases.

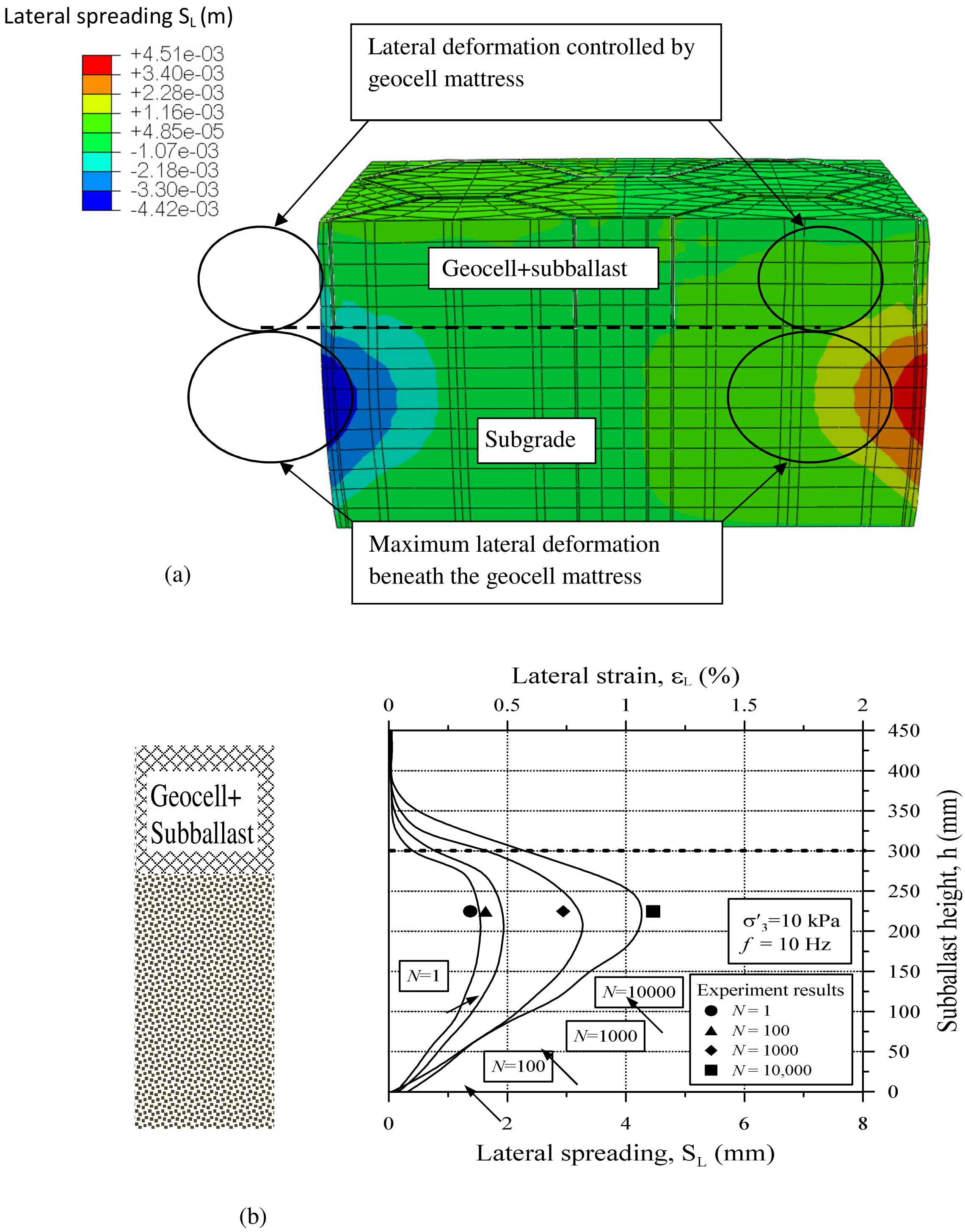

Figure 6. Typical lateral deformation profile of reinforced geocell-reinforced subballast (a) predicted by FEM and (b) at different depth and number of cycles (modified after Biabani et al. 2016a).

The value of lateral spreading (S_L) reaches a maximum at a depth of approximately subballast height of h = 200-250 mm. Figure 6b indicates that at a given number of load cycles there is only limited lateral displacement of subballast within the zone of geocell inclusion due to the additional confinement provided by the geocell.

The tensile strength of geocell is an essential property, governing the performance of geocell-reinforced subballast, where it is commonly considered to be unchanged in conventional design practices (Indraratna et al. 2015; Leshchinsky and Ling 2013). However, data captured from this study shows that during cyclic loading, the mobilized tensile stress of geocell changes considerably, as shown in Figure 7. It is seen that during the loading stage, maximum tensile stress is mobilized in the geocell to prevent the infill subballast from excessive lateral displacement. Tensile stresses developed non-uniformly across the geocell where the middle of the geocell strip (e.g. point A) exhibited the highest degree of mobilized tensile stress. Figure 7 also shows that minimum tensile stress occurs in the direction parallel to the intermediate principal stress (e.g. point C), where the geocell mattress was prevented from moving in this direction (i.e. plane strain condition).

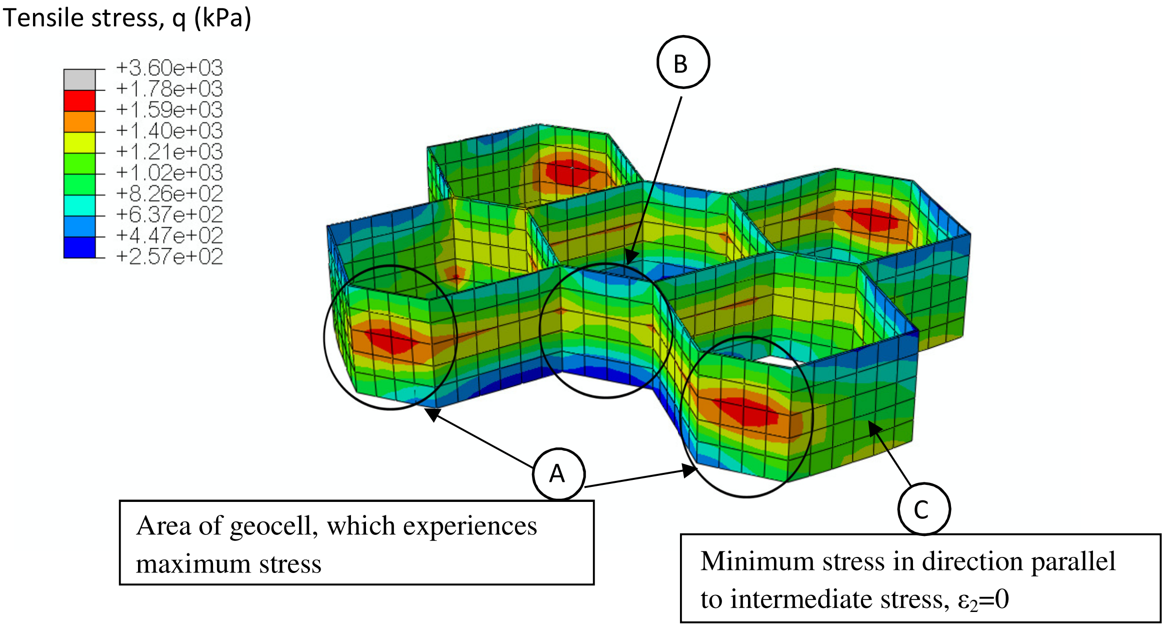

Figure 7. Tensile stress mobilized in geocell mattress subjected to cyclic loading (modified after Biabani et al. 2016a).

CONCLUSION

The load-deformation responses of subballast reinforced by a geocell subjected to cyclic loading were studied using a series of large-scale track process simulation apparatus and finite element modelling. The results obtained from FEM model was compared with the laboratory data and a reasonably good agreement was achieved. The proposed FEM model can be effectively used to predict the performance of subballast reinforced with a geocell mattress. The performance of subballast enhanced considerably with the inclusion of a geocell. At a given confining pressure and load cycle, measured axial strains in reinforced assembly were considerably less than those in unreinforced assemblies. The FEM simulations also showed that a maximum lateral spreading occurred beneath the geocell. This study found that mobilized tensile stresses in the geocell were distributed non-uniformly across the geocell where the maximum stress occurred in the direction parallel to the intermediate principal stress during the loading stage. Based on results obtained from this study, it can be seen that the use of geocell in the subballast layer will reduce excessive axial and lateral deformation.

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