Improved Performance of Subballast Stabilized Using Geocell for High Speed Train

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ARTICLE INFO

ABSTRACT

Rapid urbanization and growing industrial demand in many developing countries has led to frequent congestion of the transport infrastructure. Therefore, the expansion of high-speed rail (HSR) networks is crucial to meet this growing demand. Nevertheless, applying high cyclic stress causes significant lateral spreading and in turn excessive settlements of the track substructure. This problem becomes more crucial when the subballast layer is constructed using locally available poor quality granular material in order to keep the construction costs to minimum. The use of planar form of geosynthetics (geogrid, geotextile, geocomposite) to improve the performance of rail track is well established. Large-scale laboratory and full scale field studies conducted in the past at the Center for Geomechanics and Railway Engineering (CGRE) of the University of Wollongong, NSW, Australia, have shown that geogrids and geocomposites of appropriate technical specifications can effectively reduce track settlement. Recent studies have shown that cellular confinement, known as geocell mattress, can offer more confinement than planar geogrid for the infill material. By employing geocell as reinforcement in subballast layer, tensile strength mobilized as an additional confinement and arrests lateral spreading of infill material and help to maintain track geometry.

1. Introduction

Considering significant demand for urban rail service, increasing train speed is necessary to improve its efficiency compared to other transportation systems and to cater for substantial growth in capital cities in Australia and around the globe. The rapid expansion of high-speed rail (HSR) networks is therefore crucial to meet this growing demand. However, trains travelling with high speed exert high stresses, cause substantial differential settlement and lateral spread of granular media (ballast and subballast), leading to frequent and costly track maintenance. These problems become more severe in cities involving majority of population located in coastal areas, such as Sydney and Melbourne, where soil has relatively poor strength and the cost of transporting of required quality is high. The substantial improvements in railway substructure are necessary for commuting train with high speed. Among several techniques available, planar form of geosynthetics (geogrid, geotextile, geocomposite) have shown a promising approach for improving ballast performance, in terms of reducing axial and lateral deformations [1-4]. However, recent study shows that cellular confinement, known as geocell, can provide better performance than planar geogrid.

Geocells were developed originally by U.S. Army Corps of Engineers for improving mobility of army vehicles over soil with very low strength [5]. Since then, use of geocells has gained significant popularity in various applications (i.e. railway, runways and embankments) [6-8]. The improved
The effectiveness of the geocell mattress can be shown in terms of comparing the lateral spreading. Figure 2(a) shows the laboratory results of lateral spreading ($S_L$) in unreinforced and geocell-reinforced subballast at the given number of load cycles ($N = 500,000$ cycles) for different confining pressures ($\sigma_3 = 5, 10, 20$ kPa) and frequencies ($10 \leq f \leq 30$ Hz). As shown in Figure 2(a), unreinforced subballast experiences significant lateral deformation at relatively low confining pressure ($\sigma_3 = 5$ kPa). The magnitude of $S_L$ was reduced markedly by increasing $\sigma_3$ up to about 20 kPa. However, by using geocell mattress, lateral spreading of the specimen was reduced by about 30% for $\sigma_3 = 5$ kPa. This can be justified due to mobilized tensile strength acting as an additional confinement, applied through the three dimensional cellular mattress to the infill material. The effectiveness of geocell mattress was reduced by increasing confining pressure ($\sigma_3 \geq 20$ kPa). This indicates that a confinement of $\sigma_3 \geq 20$ kPa is sufficient to arrest excessive lateral spreading of subballast under cyclic loading exerted by the high speed trains. As shown in Figure 2(a), marginal improvement was observed in the performance of geocell-reinforced subballast at lower frequency ($f = 10$ Hz), while the magnitude of $S_L$ was more pronounced at higher frequency ($f > 10$ Hz).
This can be explained by the fact that at higher frequency, the magnitude of mobilized tensile strength in the geocell is markedly greater than that at lower frequency, which led to better performance of the reinforced layer. This highlights the influence of geocell mattress for arresting lateral spreading, at very low confining pressure and relatively higher train speed.

2.2. Vertical displacement

The beneficial influence of the geocell mattress is highlighted by comparing the axial deformation of unreinforced and geocell-reinforced subballast, as shown in Figure 2(b). At very low confinement ($\sigma_3 = 5$ kPa), unreinforced subballast underwent a substantial vertical displacement of about $S_V = 180$ mm. The magnitude of $S_V$ was found to be markedly reduced by increasing confining pressure ($\sigma_3 = 20$ kPa). Nevertheless, utilizing the geocell, helped to reduce vertical settlement of reinforced specimen by about 20-30%. This is because, subballast reinforced with geocell creates a semi-rigid mattress, which has higher stiffness. As a result, most of the applied cyclic loading is captured by the new geocomposite layer. Thereby, the stress level transferred to the lower soil layer is reduced notably, thus resulting into an improved performance of the specimen.

As shown in this figure, at the lower confining pressure ($\sigma_3 = 5$ kPa) and lower frequency ($f = 10$ Hz) geocell provided significant performance. Nevertheless, the influence of reinforcement was marginal at higher confining pressure ($\sigma_3 = 20$ kPa) and lower frequency ($f = 10$ Hz). The effectiveness of geocell reinforcement can be best illustrated by increasing frequency from 10 to 30 Hz. The vertical deformation was reduced to about 20-25% by utilising the geocell as reinforcement.

2.3. Mobilised friction and dilatancy angle

In the conventional practice, it is assumed that friction angle is constant for the specimen during the loading. Nevertheless, based on the laboratory results, it was found that internal friction angle and dilatancy angle changed at different confining pressures and frequencies of cyclic loading. The mobilised friction angle ($\phi_m$) and mobilised dilatancy angle ($\psi_m$) can be calculated by:

$$\sin \phi_m = \frac{\sigma_1^r - \sigma_3^r}{\sigma_1^r + \sigma_3^r}$$  \hspace{1cm} (1)

$$\sin \psi_m = \frac{d\epsilon_1^p + x d\epsilon_3^p}{d\epsilon_1^p - x d\epsilon_3^p} = \frac{d\epsilon_1^p}{d\epsilon_1^p} - \frac{d\epsilon_3^p}{d\epsilon_3^p}$$ \hspace{1cm} (2)

Figure 3(a) shows the variation of $\phi_m$ and $\psi_m$ at different $\sigma_3$ and $f$. By increasing confining pressure ($5 \leq \sigma_3 \leq 20$ kPa), the degree of $\phi_m$ and $\psi_m$ for both unreinforced and geocell-reinforced subballast are decreasing in the range of $39 \leq \phi_m \leq 44$ and $3 \leq \psi_m \leq 12$ degree.

Moreover, the rate of decreasing of $\phi_m$ in reinforced specimen was higher when the frequency was increased (Figure 3(a)). Considering higher $\psi_m$ for unreinforced subballast, it was found that the degree of mobilised dilatancy angle in the reinforced specimen was notably less than unreinforced specimen.

As a result, it can be concluded that in the reinforced specimen the mobilised dilatancy angle could be considerably suppressed (approaching to zero) at the higher rate than unreinforced subballast. This difference was more at higher frequency and confining pressure.

2.4. Resilient modulus

Another parameter that was found to be influenced by the geocell mattress was resilient modulus ($M_R = q_{cyc}/\epsilon'$) of reinforced layer. Figure 3(b) shows the resilient modulus obtained from experimental results for both unreinforced and geocell-reinforced specimens for different frequencies and confining pressures at the end of cyclic loading (i.e. $N = 500,000$ cycles). The magnitude of $M_R$, was increased by about 10%-20% by increasing both confining pressure levels ($\sigma_3 = 5-20$ kPa) and range of frequency ($f = 10-30$ Hz). This behaviour was observed for both unreinforced and reinforced specimens. This is due to the fact that cyclic loading causes particles rearrangement, lead to densification of specimen. Nevertheless, in the reinforced specimen the rate of increase of $M_R$ was greater than unreinforced one. This is because, the geocell mattress confines infill material and accelerated the rate of densification of infill.
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Figure 1. Large-scale process simulation prismoidal triaxial apparatus used in this study

Figure 2. (a) Lateral spreading and (b) Vertical deformation of unreinforced and geocell-reinforced subballast (data sourced from Indraratna et al. [17], with permission from ASCE).

(a)

(b)
material. As a result, rigidity of reinforced layer is increased, improving further the performance of reinforced soil layer.

The variation of $M_R$ at the confining pressure of 10 kPa and different number of cycles ($N$) is presented in Figure 4. Due to rapid densification, the magnitude of $M_R$ showed increase at the initial stage of cyclic loading and the rate of increase diminished at higher number of cycles ($N \geq 100,000$ cycles). It was found that the degree of densification was greater at higher frequency ($f = 30$ Hz). This figure also shows that by increasing number of cycles ($N \geq 200,000$ cycles), marginal improvement in $M_R$ is observed.

This is because, the specimen reached the stable zone (also known as shakedown zone), and no further volumetric change occurred.

3. Additional Confinement ($\Delta \sigma_3$)

The influence of geocell reinforcement can be best evaluated in terms of additional confining pressure ($\Delta \sigma_3$). The variation of resilient modulus ($M_R$) at different number of cycles ($N$) is presented in Figure 4. Due to rapid densification, the magnitude of $M_R$ showed increase at the initial stage of cyclic loading and the rate of increase diminished at higher number of cycles ($N \geq 100,000$ cycles). It was found that the degree of densification was greater at higher frequency ($f = 30$ Hz). This figure also shows that by increasing number of cycles ($N \geq 200,000$ cycles), marginal improvement in $M_R$ is observed.

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3. Additional Confinement ($\Delta \sigma_3$)

The influence of geocell reinforcement can be best evaluated in terms of additional confining pressure ($\Delta \sigma_3$) induced by the cellular confinement. There are several analytical models available in the literature, which can predict the additional confining pressure [15-16]. Nevertheless, they all fail to capture the actual $\Delta \sigma_3$ with respect to number of cycles, mobilized friction angle and dilatancy angle. By incorporating the elastic behaviour of geocell mattress and hoop tension theory [16], the degree of $\Delta \sigma_3$ can be determined by [17].

\[
\Delta \sigma_3 = \frac{2M_p}{D} \left[ \frac{1}{(1 + \nu_g)} \right] \left[ \frac{1}{(1 + 2\nu_g)} \right] \left( \frac{a}{N} + \frac{b}{N} \right) \left[ 1 + \sin \psi_m \right] \frac{dN}{\sin \psi_m}
\]

where, $D$ is diameter of an equivalent circular area of the geocell pocket, $M_p$ is the mobilized geocell modulus at a different number of cycles, $\psi_m$ is the mobilized dilation angle, $N_{lim}$ is number of cycles required to attain the stable zone, $a'$ and $b'$ are empirical coefficient parameters representing the stable and unstable zone, $\nu_g$ is the Poisson’s ratio of geocell and $k$ is the ratio of plastic circumferential strain ($\varepsilon'_p$) to plastic lateral strain ($\varepsilon'_d$). The value of $k$ is
Table 1. A summary of different factors ($R_S$, $I_R$ and $I_v$) obtained based on laboratory results

<table>
<thead>
<tr>
<th>Factor</th>
<th>Frequency $f$ (Hz)</th>
<th>Confining pressure, $\sigma'_3$ (kPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Settlement reduction factor, $R_S$ (%)</td>
<td>10</td>
<td>25.27, 22.88, 16.29</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>23.26, 19.18, 16.09</td>
</tr>
<tr>
<td></td>
<td>30</td>
<td>22.24, 17.36, 13.55</td>
</tr>
<tr>
<td>Resilient improvement Factor, $I_R$ (%)</td>
<td>10</td>
<td>18.37, 16.90, 14.43</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>17.88, 17.43, 15.37</td>
</tr>
<tr>
<td></td>
<td>30</td>
<td>17.92, 17.42, 15.82</td>
</tr>
<tr>
<td>Speed improvement factor, $I_v$ (%)</td>
<td>10</td>
<td>24.18, 20.40, 13.98</td>
</tr>
</tbody>
</table>

![Figure 5](image_url)  
(a) Figure 5. Variation of additional confinement of reinforced subballast with number of load cycles for (a) different confining pressures and (b) different frequencies (Indraratna et al. [17], with permission from ASCE).

considered as 0.45 in this study. The merit of the proposed model is its ability to capture the additional confining pressure at any desired number of load cycles and cyclic stress in terms of variation in mobilized friction angle, dilatancy angle and geocell modulus. The values of $\Delta\sigma'_3$ predicted using this proposed model are plotted for different apparent confining pressures at different frequencies for different number of cycles ($N$), as shown in Figure 5 (a & b). As shown in Figure 5(a), the degree of $\Delta\sigma'_3$ was increased by increasing number of cycles. Marginal improvement was observed after $N=100,000$ cycles, which is due to attainment of shakedown stage. At very low confining pressure of 5 kPa, the magnitude of $\Delta\sigma'_3$ was found to be maximum. The degree of $\Delta\sigma'_3$ was reduced remarkably by increasing confining pressure from 5 to 20 kPa. This is due to fact that increase in confining pressure lead to mobilization of lower tensile strength in the geocell. The results also confirm the
effectiveness of geocell, when it is used for specimen with very low confining pressure and relatively high frequency. Figure 5(b) shows that at given confining pressure ($\sigma_3 = 10$ kPa), the degree of $\Delta\sigma_3$ was increased by increasing frequency ($f$) to about 30 Hz.

Based on the laboratory results, different factors including the settlement reduction ($I_S$), resilient improvement ($I_R$) and speed improvement ($I_S$) factors for a given range of $\sigma_3$ and $f$ were defined and summarised in Table 1. Table 1 shows that the maximum effectiveness of the geocell mattress was at lower confining pressure and higher frequency. Considering the load frequency as a function of train speed and the distance between the wheels of bogies, the relevant train speeds for different range of frequencies can be calculated by using the relation viz. $v = \frac{\lambda}{2\pi_f}$, where $\lambda$ is the wavelength ($\lambda = 2.02$ m). Accordingly the influence of cellular confinement is shown for different confine pressures and frequencies. Accordingly the variation of train speed against vertical settlement (Figure 6). By utilizing the geocell reinforcement led to substantial reduction of vertical settlement of subballast ($S_V$).

4. Conclusions

The laboratory results presented in this paper showed that geocell can effectively improve subballast performance under high frequencies ($f = 10-30$ Hz) and at very low confining pressure increased resilient modulus of subballast. By increasing subballast rigidity due to use of geocells, axial settlements were markedly reduced. This implies that rail tracks can be subjected to higher cyclic stress from high speed trains to attain the same settlement as unreinforced subballast. This study proved that by employing geocell reinforcement reduces differential settlement, improves longevity of the ($\sigma_3 \leq 20$ kPa). Also, the use of geocell led to ballasted track, and thus curtails the track maintenance cost. The outcome of this study can be benefited by railway industry in rehabilitation schemes of existing tracks or construction of new tracks on subgrade with low shear strength.

Acknowledgments

The financial support received from the Cooperative Research Centre (CRC) for Rail Innovation to conduct this research is gratefully appreciated. The Author wishes to thank the Australia Research Council, CRC for Rail Innovation, Sydney Trains and Australian Rail Track Corporation for their continuous support. The assistance from Mr. Alan Grant (laboratory manager), Mr. Cameron Neilson (senior technical officer) and Mr. Ritchie McLean (technical officer) in the School of Civil, Mining, and Environmental Engineering at the University of Wollongong, is appreciated. A significant portion of the contents have been reproduced with kind permission from the Journal of Geotechnical and Geoenviromental Engineering ASCE.

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