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A LABORATORY STUDY OF RAILWAY BALLAST BEHAVIOUR UNDER VARIOUS FOULING DEGREE

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ABSTRACT

This paper presents a laboratory study of interface behavior between ballast and geogrid under various degree of fouling by coal fines. The stress-displacement behaviour of fresh and fouled ballast with geogrid was investigated through a series of large-scale direct shear tests where the fouling degree varied from 0% to 95% Void Contamination Index (VCI), at normal stresses ranging from 15kPa to 75kPa. The results showed that geogrid enhances the shear strength and increases apparent angle of shearing resistance, while only slightly reduces the vertical displacement of the composite geogrid-ballast system. However, when ballast was contaminated by coal fines, the influences of geogrid reinforcement decreased in proportion to the increasing level of fouling. A conceptual normalized shear strength model was introduced to calculate this decrease in peak shear stress and peak angle of shearing resistance caused by coal fouling.

Keywords: Ballast, fouling, geogrid, interface behaviour

INTRODUCTION

Ballast is a free draining granular material playing crucial role in transmitting and distributing the induced cyclic train loading to the underlying sub-ballast and subgrade at a reduced and acceptable stress level (Selig and Waters, 1994). Ballast normally consists of medium to coarse gravel sized particles (10-60mm) and a small percentage of cobber size aggregates. Upon repeated train loading, ballast material is free to spread laterally due to the inadequate confining pressure provided by the shoulder ballast (Indraratna et al., 2005). In addition, ballast deteriorates progressively and becomes fouled due to breakage and infiltration of external fine particles (e.g., coal fines, clay). Figure 1 depicts the main components of ballasted track embankment reinforced with geogrid. Given typical Australian coal freight tracks, (Feldman and Nissen, 2002) stated that dry coal fines are account for 70-95% of the fouling materials in ballasted rail tracks. Dombrow et al., (2009) conducted direct shear tests for coal-fouled ballast and presented that the shear strength steadily decreases with an increase level of fouling. Geogrids have been widely used to stabilise ballast and to increase duration of track serviceability (Bathurst and Raymond, 1987; Göbel et al., 1994; Raymond, 2002; Shin et al., 2002; Raymond and Ismail, 2003; Brown et al., 2006; Indraratna et al., 2006; Brown et al., 2007; Fernandes et al., 2008; Qian et al., 2010; Indraratna et al., 2011a; Indraratna et al., 2011b). The effectiveness of geogrid in providing lateral and vertical constraints to ballast has been emphasized as geogrid acting as a presumable non-horizontal displacement boundary that confines the surrounding ballast particles via the interlocking and frictional resistance between itself and the ballast aggregates. When ballast is fouled, the interaction between geogrid and ballast aggregates may change considerably as fine particles accumulate within voids of ballast and clog at the opening apertures of the geogrid resulting in reduced interlocking and friction between the geogrid and ballast. This paper
presents experimental study on the interaction between geogrid and fouled ballast at various levels of fouling subjected to direct shear loading.

Fig. 1  Schematic of main components of track structures (modified after Selig and Waters, 1994)

FOULING QUANTIFICATION

There are several existing methods to quantify the level of ballast fouling. Selig and Waters (1994) proposed the Fouling Index (FI) as a summation of percentage by weight passing the 4.75 mm sieve and 0.075 mm sieve. Feldman and Nissen (2002) defined the Percentage Void Contaminant (PVC) as the ratio between the bulk volume of fouling material and initial volume of fresh ballast voids. Recently, Indraratna et al. (2011) proposed the Void Contaminant Index (VCI) considering various fouling materials by incorporating their respective specific gravity to quantify ballast fouling, defined as follows:

\[
VCI = \frac{1+e_f}{e_b} \times \frac{G_{sb}}{G_{sf}} \times M_f \times M_b
\]

where: \( e_f \) = void ratio of fouling material, \( e_b \) = the void ratio of fresh ballast, \( G_{sb} \) = the specific gravity of ballast, \( G_{sf} \) = the specific gravity of fouling material, \( M_f \) = the dry mass of fouling material, \( M_b \) = the dry mass of fresh ballast.

MATERIALS TESTED

Ballast samples were collected from Bombo quarry, New South Wales, Australia, then cleaned and sieved following the Australia Standard (AS 2758.7, 1996). To eliminate boundary effects, a parallel gradation with maximum size of tested ballast of 40 mm was used in the study. Coal fines were provided by Queensland Rail and used as fouling material for the VCI of 20%, 40%, 70% and 95%, corresponding to 5%, 10%, 18% and 25% of the weight of fresh ballast, respectively. The engineering characteristics of coal fines are shown in Table 1. The grain size distributions of ballast, coal fines used in this study are presented in Fig. 2. Biaxial geogrid manufactured from polypropylene with aperture sizes of 40 mm x 40 mm provided by Polyfabric Australia Pty Ltd., that has been used commonly in Australian railway tracks, was used in this study.

Table 1  Engineering properties of coal fines

<table>
<thead>
<tr>
<th>No.</th>
<th>Specific gravity</th>
<th>Liquid limit (%</th>
<th>Plastic limit (%)</th>
<th>Maximum dry density (kg/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coal fines</td>
<td>1.28</td>
<td>91</td>
<td>50</td>
<td>874</td>
</tr>
</tbody>
</table>

Fig. 2  Particle size distributions of coal fines and ballast used in the study

LARGE-SCALE DIRECT SHEAR TEST

Large-scale direct shear apparatus used in this study consists of a 300 x 300mm square steel box, 200mm high, divided horizontally into two equal halves. Layers of 50 mm thick ballast was placed in the shear box and compacted to the field unit weight of 15.3 kN/m³. A sheet of geogrid was placed at the middle between the lower and upper half of shear box and secured to the apparatus by clamping blocks and nails. To simulate realistic fouling condition, specific amount of coal fines (equivalent to one-fourth of total weight of coal fines) was spread uniformly on top of each compacted ballast layer. These coal fines then migrated into voids of ballast upon vibration induced by compaction. Normal stress was applied via a rigid and free plate placed on the top of the shear box using a dead weight system attached to a lever arm. A displacement dial gauge was attached horizontally to lower section of the box and another dial gauge was attached to the center of the top plate to measure horizontal and vertical displacements, respectively. A load cell was attached to the shear box to measure the shear load. Tests were conducted at four normal stresses of 15, 27, 51 and 75kPa. The lower half of the shear box was forced to shear horizontally by an electric motor at a velocity of 2.5 mm/minute to a maximum displacement of 37 mm while the upper half of the box remained stationary. The schematic diagram of this test set up is illustrated in Fig. 3.
RESULT AND DISCUSSION

Figure 4 presents shear stress and vertical displacement versus horizontal displacement of fresh ballast at varying normal stresses, ranging from 15kPa to 75kPa. Results show that while the shear stress of geogrid-reinforced ballast is greater than that of unreinforced assembly, the dilation of reinforced ballast is somewhat lesser than unreinforced ballast. This is primarily attributed to the interlocking of ballast grains with geogrid apertures. All tests exhibited softening behavior as shear stress decreases after reaching its maximum value. These findings agree with the stress-strain behavior of rockfill reported by Marachi et al. (1972), De Mello (1977), Charles and Watts (1980), and Indraratna et al. (1993), among others. In addition, all test experienced a relative initial compression followed by dilation as ballast grains compressed to a threshold packing arrangement, subsequent shearing would initiate dilation associated with strain softening behavior.

The variations of shear stress-displacement of coal-fouled ballast at varying VCI (20%-95%) with and without geogrid inclusion are shown in Fig. 5. It is observed that coal fines significantly decrease peak shear stresses of both reinforced and unreinforced ballast assemblies. This is attributed to coal fines coating surfaces of ballast grains, inhibiting inter-particle friction and reducing the shearing resistance at the geogrid-ballast interface. At a given VCI, the geogrid generally increases the peak shear stress and decreases dilation compared to unreinforced ballast assembly. When voids of ballast are almost filled by coal fines (VCI=95%) the geogrid is unable to reduce dilation, because, coal fines inhibit the ballast from effectively interlocking with the geogrid. This also may have facilitated premature compression due to the ballast grains being rearranged and rotated prematurely.

Influence of Coal Fines on the Apparent Angle of Shearing Resistance

The variations of normalized peak shear stress ($\tau_\text{p}/\sigma_n$) and apparent angle of shearing resistance ($\phi$) with VCI of fouled ballast assemblies with and without geogrid reinforcement are presented in Fig. 6. Coal fines steadily decrease the peak shear stress of ballast assembly resulting in a decrease of the apparent angle of shearing resistance. The reduction of ($\tau_\text{p}/\sigma_n$) attributed to presence of coal fines is significant where the VCI is less than 70% and becomes marginal when VCI is beyond this value. The apparent friction angles obtained in this study vary from 46$^\circ$ to 65$^\circ$ depending on the applied normal stresses. These values are comparable to those measured from much larger triaxial apparatus of 350 mm in diameter and 700 mm in height reported by Indraratna et al. (1998). Therefore, the boundary effect of the shear box can be neglected.

Normalized shear strength reduction ($\Delta\tau_p/\sigma_n$) was proposed by the ratio between the decrease in peak shear stress ($\Delta\tau_p$) and normal stress ($\sigma_n$). The variations of normalized shear strength reduction with an increase of VCI is presented in Fig. 7. It is observed that the decrease in ($\Delta\tau_p/\sigma_n$) is more significant for unreinforced ballast than geogrid-reinforced ballast. These variations with respect to varying VCI can be defined by a hyperbolic equation adopted by Duncan and Chang (1970):
where $\Delta \tau_p$ = the shear strength reduction of ballast due to presence of coal fines; $\tau_n$ = normal stress; $VCI$ = Void Contaminant Index; $a$ and $b$ = hyperbolic constants.

PROPOSED SHEAR STRENGTH MODEL FOR FOULED BALLAST

Based on results obtained experimentally, it is concluded that the level of coal fines affects the shear strength of ballast assembly with and without geogrid reinforcement. The coal fines filling the voids of ballast decrease the inter-particle friction and consequently decrease interlocking between ballast and geogrid. Therefore, the shear strength of fouled ballast in relation to the shear strength of fresh ballast and the associated decrease in peak shear stress can be defined by:

$$\frac{(\tau_p)_{\text{Fouled Ballast}}}{(\tau_p)_{\text{Fresh Ballast}}} = 1 - \frac{\Delta \tau_p}{\tau_p}$$

(3)

Dividing Eq. 3 by the normal stress, $\tau_n$ gives:

$$\frac{(\tau_p)_{\text{Fouled Ballast}}}{\sigma_n} = \frac{(\tau_p)_{\text{Fresh Ballast}}}{\sigma_n} - \frac{\Delta \tau_p}{\sigma_n}$$

(4)

Combining Eq. 2 with Eq. 4 results in:

$$\frac{(\tau_p)_{\text{Fouled Ballast}}}{\sigma_n} = \frac{(\tau_p)_{\text{Fresh Ballast}}}{\sigma_n} - \frac{VCI}{100} \frac{a}{\sigma_n} + \frac{b}{\sigma_n}$$

(5)

where $(\tau_p)_{\text{Fresh Ballast}}$, $(\tau_p)_{\text{Fouled Ballast}}$ are peak shear stresses of fresh and fouled ballast; $\Delta \tau_p$ is shear strength reduction of ballast due to presence of coal fines; $\frac{\Delta \tau_p}{\sigma_n}$ is normalized drop in shear strength; $a$ and $b$ are hyperbolic constants depending on normal stress, type of geogrid and determined by plotting Eq. 2 in a transformed axes to represent the linear relationship as shown in Fig. 8.

Incorporating the Mohr-Coulomb envelop for granular material into Equation (5) results in:

$$\tan \phi_f = \tan \phi_0 - \frac{VCI}{100} \frac{a}{\sigma_n} + \frac{b}{\sigma_n}$$

(6)

where $\phi_0$ is peak angle of shearing resistance of fouled ballast; $\phi_f$ is peak angle of shearing resistance of fouled ballast.

The proposed Eq. 2 can be applied to predict the shear strength reduction of fouled ballast due to the presence of coal fine at a given $VCI$. As a result, the shear strength of fouled ballast at a specific $VCI$ can be predicted by using Eq. 5 after determining the shear strength of fresh ballast. In addition, the peak angle of shearing resistance of fouled ballast, $\phi_f$ at a specific $VCI$ can be obtained by applying Eq. 6 when the peak angle of shearing resistance of fresh ballast, $\phi_0$ is determined at a given normal stress.
Fig. 5  Stress-displacement behavior of fouled ballast with and without geogrid (a) 20%, (b) 40%, (c) 70% and (d) 95% (Indraratna, et al. 2011a)
Fig. 6  Effect of VCI on normalized peak shear strength and apparent angle of shearing resistance of ballast: (a) without geogrid and (b) with geogrid (Indraratna, et al. 2011a)

Fig. 7  Variations of normalized peak shear stress reduction for ballast with and without geogrid at varying VCI (Indraratna, et al. 2011a)
CONCLUSIONS

Large-scale direct shear tests were conducted to study the shear stress-displacement behavior of fresh and fouled ballast reinforced by geogrid. The Void Contaminant Index ($VCI$) that incorporates the specific gravity of ballast and fouling materials was utilized to quantify the degree of fouling. The results clearly stated that geogrid increases the shear strength and decreases the ballast dilation at a given $VCI$. This is justified by the interlocking between the geogrid and ballast grains occurring at the interface. Conversely, coal fines coat surfaces of ballast grains acting as lubricant which reduces the inter-particle friction and the shearing resistance of fouled ballast assembly. As a result, coal fines facilitate the movement of ballast grains during shearing, which leads to increased dilation. A conceptual normalized shear strength model was proposed to predict the shear strength of fouled ballast at a given $VCI$ for a specific normal stress. The proposed model can also be applied to predict the apparent angle of shearing resistance of fouled ballast at given level of fouling.

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