A LABORATORY STUDY OF RAILWAY BALLAST BEHAVIOUR UNDER VARIOUS FOULING DEGREE

C. Rujikiatkamjorn[1], B. Indraratna[2], N. T. Ngo[3], and M. Coop[4]
[1]Senior Lecturer, Faculty of Engineering,
Centre for Geomechanics and Railway Engineering
University of Wollongong, Wollongong City, NSW 2522, Australia
Email: cholacha@uow.edu.au, Ph: +61 2 4221 5852 Fax: +61 2 4221 3238
[2] Professor of Civil Engineering, Faculty of Engineering,
Director, Centre for Geomechanics and Railway Engineering
University of Wollongong, Wollongong City, NSW 2522, Australia
Email: indra@uow.edu.au, Ph: +61 2 4221 3046 Fax: +61 2 4221 3238
[3]PhD Candidate, Faculty of Engineering,
Centre for Geomechanics and Railway Engineering
University of Wollongong, Wollongong City, NSW 2522, Australia
Email: ntn743@uowmail.edu.au, Ph: +61 2 4239 2359 Fax: +61 2 4221 3238
[4] Professor, Department of Civil and Architectural Engineering City University of Hong Kong, Tat Chee Avenue, Kowloon, Hong KongEmail: mrcoop@cityu.edu.hk, Ph: +8523442-6505 Fax: +852 3442 0427

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.

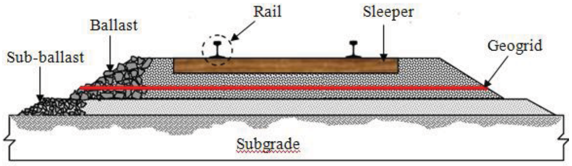

Fig. 1 Schematic of main components of track structures (modified after Selig and Waters, 1994)

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:

$$VCI = \frac{1+e_f}{e_b} \times \frac{G_{sb}}{G_{sf}} \times \qquad (1)$$

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 *VCIs* 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

No.	Specific gravity	Liquid limit (%)	Plastic limit (%)	Maximum dry density (kg/m^3)
Coal fines	1.28	91	50	874

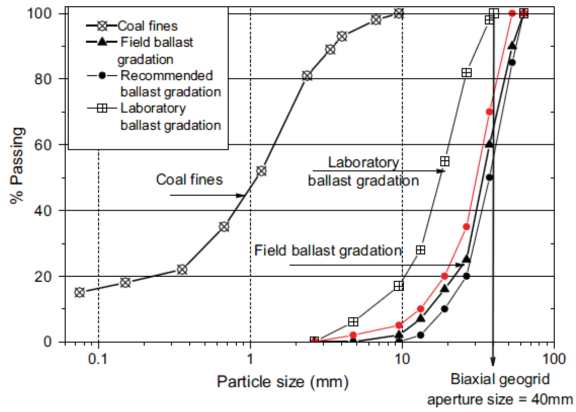

Fig. 2 Particle size distributions of coal fines and ballast used in the study

LARGE-SCALE DIRECT SHEAR TEST

Large-scale direct shear apparatus used in this study consists of a 300 x 300mm^{2}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/m^3. 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.

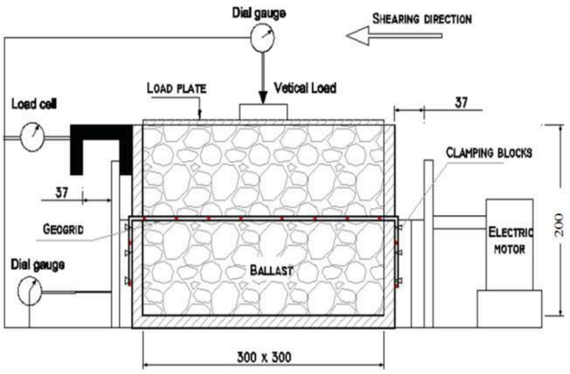

Fig. 3 Schematic diagram of the large-scale direct shear test set up (unit: mm) (Indraratna, et al. 2011a)

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 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 behaviour.

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.

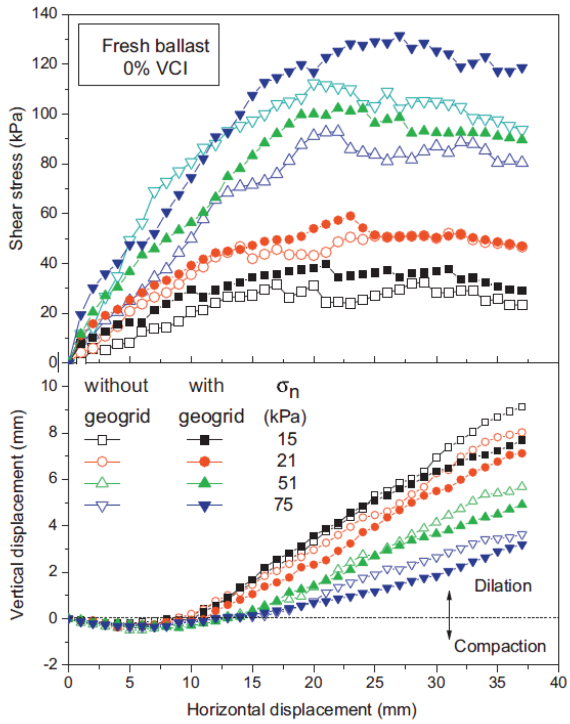

Fig. 4 Stress-displacement behavior of fresh ballast with and without geogrid (Indraratna, et al. 2011a)

Influence of Coal Fines on the Apparent Angle of Shearing Resistance

The variations of normalized peak shear stress (τ_p/σ_n) and apparent angle of shearing resistance (ϕ) 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 (τ_p/σ_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 46^0 to 65^0 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 (σ_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):

$$\frac{\Delta \tau_p}{\sigma_n} = \frac{VCI/100}{a \times VCI/100 + b} \quad (2)$$

where $\Delta \tau_p$ = the shear strength reduction of ballast due to presence of coal fines; σ_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:

$$(\tau_p)_{Fouled\ Ballast} = (\tau_p)_{Fresh\ Ballast} - \Delta \tau_p \quad (3)$$

Dividing Eq. 3 by the normal stress, σ_n gives:

$$\frac{(\tau_p)_{Fouled\_Ballast}}{\sigma_n} = \frac{(\tau_p)_{Fresh\_Ballast}}{\sigma_n} - \frac{\Delta \tau_p}{\sigma_n} \quad (4)$$

Combining Eq. 2 with Eq. 4 results in:

$$\frac{(\tau_p)_{Fouled\_Ballast}}{\sigma_n} = \frac{(\tau_p)_{Fresh\_Ballast}}{\sigma_n} - \frac{VCI\ /\ 100}{a \times VCI\ /\ 100 + b} \quad (5)$$

where $(\tau_p)_{Fresh\ Ballast}$, $(\tau_p)_{Fouled\ Ballast}$ 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:

$$\tan \phi_f = \tan \phi_0 - \frac{VCI\ /\ 100}{a \times VCI\ /\ 100 + b} \quad (6)$$

where ϕ_0 is peak angle of shearing resistance of fouled ballast; ϕ_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, ϕ_f at a specific *VCI* can be obtained by applying Eq. 6 when the peak angle of shearing resistance of fresh ballast, ϕ_0 is determined at a given normal stress.

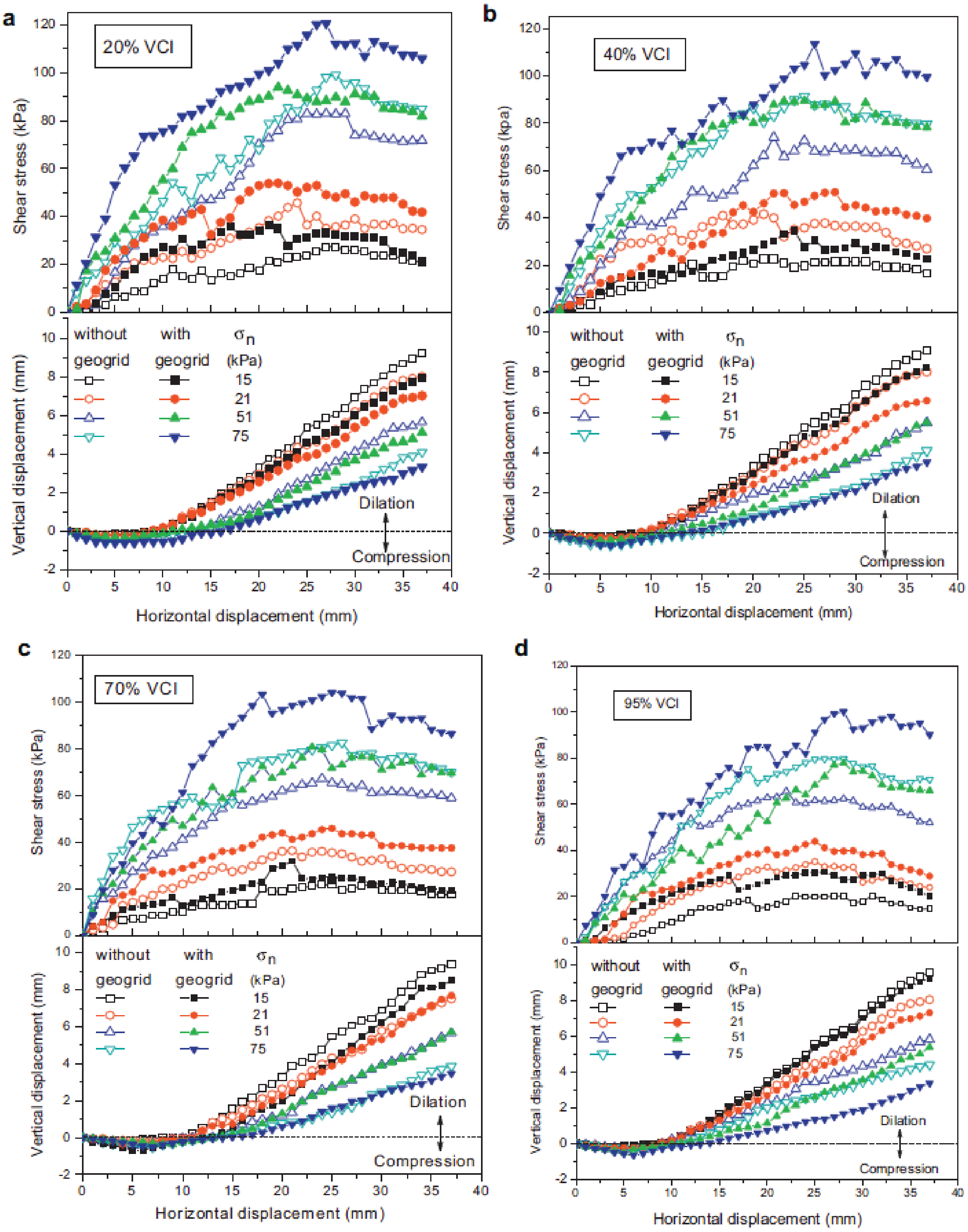

Fig. 5 Stress-displacement behavior of fouled ballast with and without geogrid (a) 20%. (b) 40%, (c) 70% and (d) 95% (Indraratna, et al. 2011a)

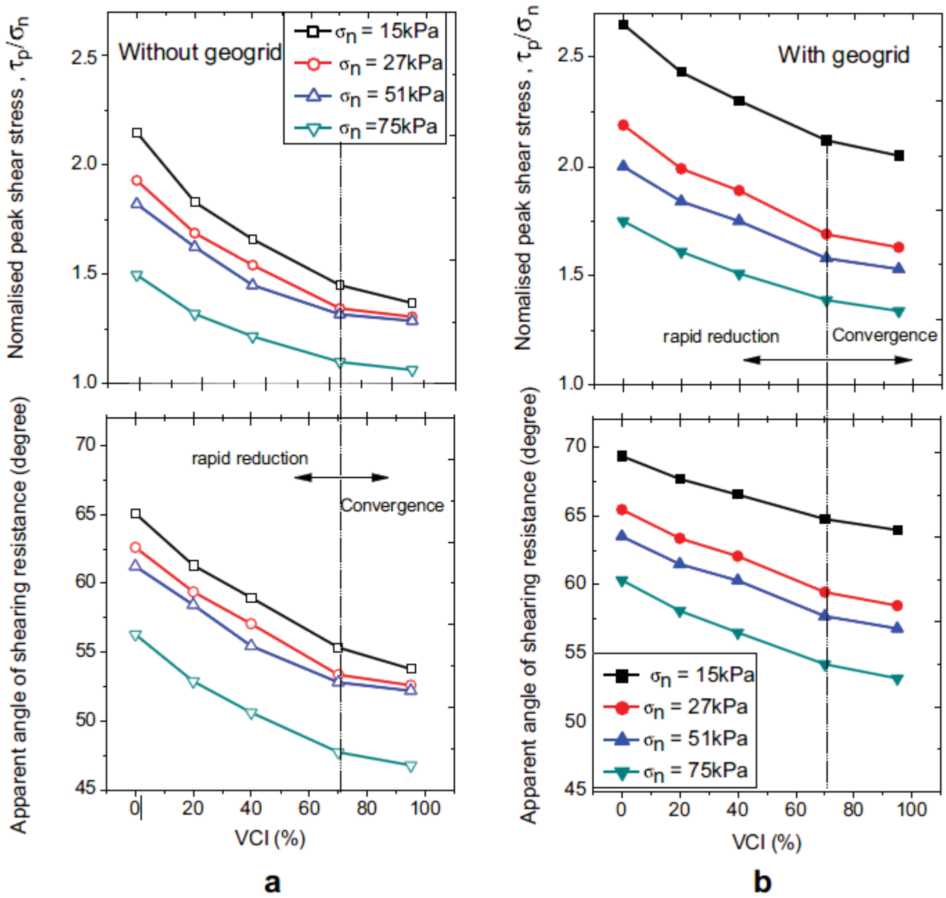

Fig. 6 Effect of VCI on normalized peak shear strength and apparent angle of shearing resistance of ballast: (a) without geogrid and (b) with geogrid (Indraratna, et al. 2011a)

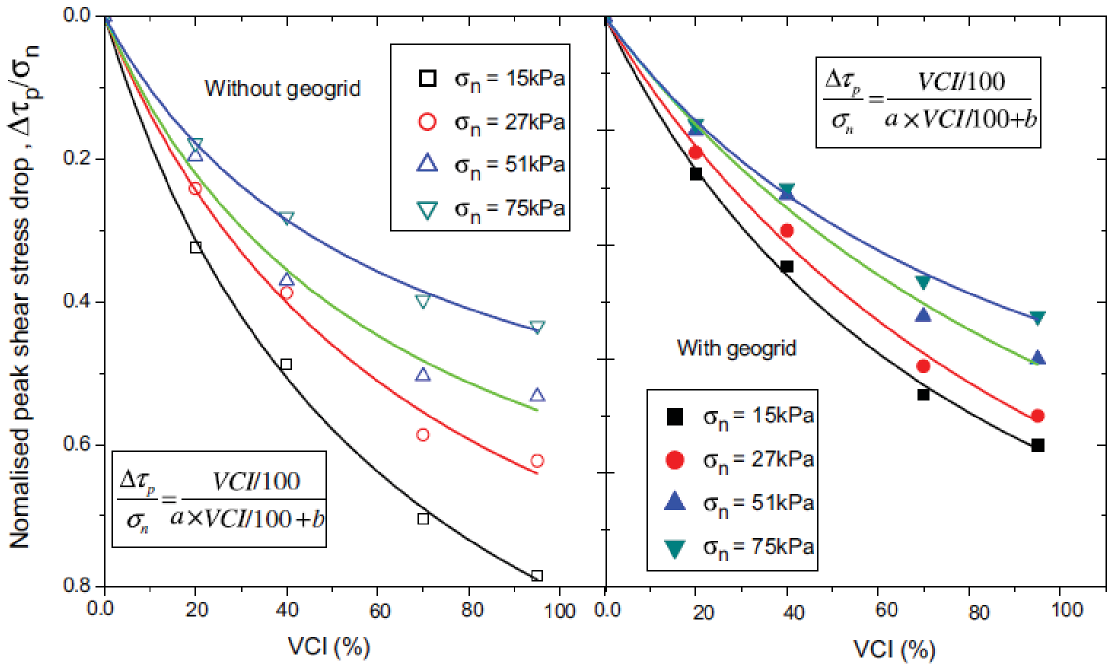

Fig. 7 Variations of normalized peak shear stress reduction for ballast with and without geogrid at varying *VCI* (Indraratna, et al. 2011a)

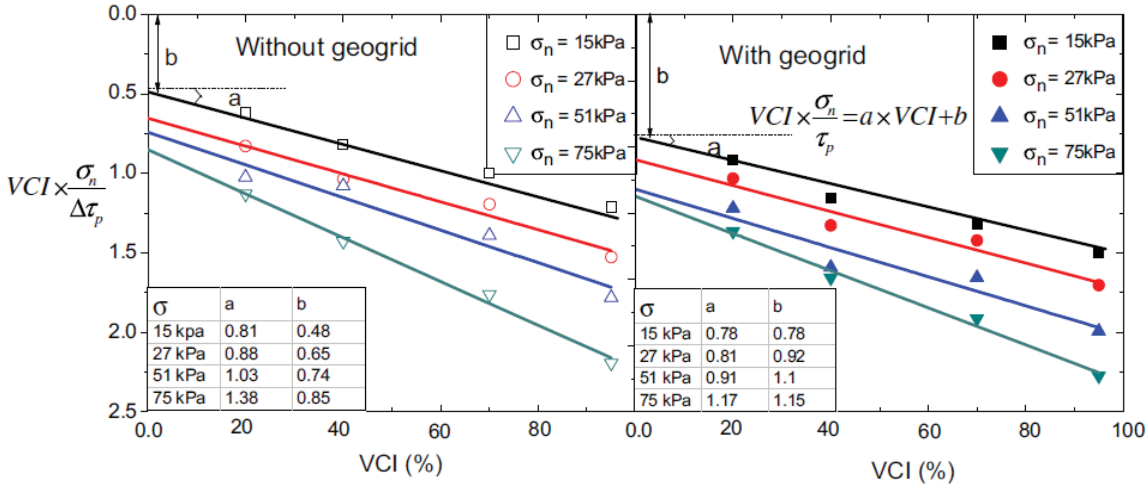

Fig. 8 Determination of hyperbolic constants *a* and *b* for ballast with and without geogrid reinforcement (Indraratna, et al. 2011a)

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.

ACKNOWLEDGEMENTS

The Authors are grateful for the financial support provided by Rail-CRC. The laboratory assistance from Mr. Alan Grant is also appreciated. Much of the contents in this paper are elaborated in Geotextile and Geomembranes. Selected contents from the article were reproduced with kind permission.

REFERENCES

Australian Standard: AS2758.7 (1996). Aggregates and Rock for Engineering Purposes; Part 7: Railway Ballast. Sydney, NSW, Australia

Bathurst, R. J. and Raymond, G. P. (1987). Geogrid reinforcement of ballasted track. Transportation Research Record. 1153:8-14.

Brown, S. F., Kwan, J. and Thom, N. H. (2007). Identifying the key parameters that influence geogrid reinforcement of railway ballast. Geotextiles and Geomembranes. 25(6):326-335.

Brown, S. F., Thom, N. H. and Kwan, J. (2006). Optimising the geogrid reinforcement of rail track ballast. Railfound Conference. Birmingham: 346-354.

Charles, J. A. and Watts, K. S. (1980). The influence of confining pressure on the shear strength of compacted rockfill. Geotechnique. 30(4):353-367.

De Mello, V. F. B. (1977). Reflection on design decisions of practicalc significance to embankment dams. Geotechnique. 27(3):279-355.

Dombrow, W., Huang, H. and Tutumluer, E. (2009). Comparison of coal dust fouled railroad ballast behavior- granite vs. limestone. Bearing Capacity of Roads, Railways and Airfields, Proc. of the 8th International Conference (BCR2A'09). Taylor and Francis Group.

Duncan, J. M. and Chang, C. S. (1970). Non-linear analysis of stress and strain in soils. Journal of Soils Mechanics Foundation Division, ASCE. 96(5):1629-1653.

Feldman, F. and Nissen, D. (2002). Alternative testing method for the measurement of ballast fouling. Proc. Conference on Railway Engineering. Wollongong, RTSA.

Fernandes, G., Palmeira, E. M. and Gomes, R. C. (2008). Performance of geosynthetic-reinforced alternative sub-ballast material in a railway track. Geosynthetics International. 15(5):311-321.

Göbel, C. H., Weisemann, U. C. and Kirschner, R. A. (1994). Effectiveness of a reinforcing geogrid in a railway subbase under dynamic loads. Geotextiles and Geomembranes. 13(2):91-99.

Indraratna, B., Wijewardena, L. S. S. and Balasubramaniam, A. S. (1993). Large-scale triaxial testing of greywacke rockfill.Géotechnique. 43(1):37-51

Indraratna, B., Ionescu, D. and Christie, D. (1998). Shear behaviour of railway ballast based on large scale triaxial testing. Journal of Geotechnical and Geoenvironmental Engineering. 124(5):439-449.

Indraratna, B. and Salim, W. (2005).Mechanics of Ballasted Rail Tracks - A Geotechnical Perspective.Taylor and Francis. Balkema, London, UK.

Indraratna, B., Khabbaz, H., Salim, W. and Christie, D. (2006). Geotechnical properties of ballast and the role of geosynthetics in rail track stabilisation Journal of Ground Improvement. 10(3): 91-102.

Indraratna, B., Ngo, N. T. and Rujikiatkamjorn, C. (2011a). Behavior of geogrid-reinforced ballast under various levels of fouling. Geotextiles and Geomembranes. 29(3): 313-322.

Indraratna, B., Salim, W. and Rujikiatkamjorn, C. (2011b). Advanced rail geotechnology - ballasted track. CRC Press, Taylor andFrancis Group

Marachi, N. D., Chan, C. K. and Seed, H. B. (1972). Evaluation of properties of rockfill materials. Soil Mechanics and Foundations Division: Proceedings of the American Society of Civil Engineers. 98(SM1): 95-115.

Qian, Y., Han, J., Pokharel, S. K. and Parsons, R. L. (2010). Experimental study on triaxial geogrid-reinforced bases over weak subgrade under cyclic loading. Proc. GeoFlorida 2010: Advances in Analysis, Modeling and Design (Geotechnical Special Publication, 199), ASCE:1208-1216.

Raymond, G. and Ismail, I. (2003). The effect of geogrid reinforcement on unbound aggregates. Geotextiles and Geomembranes. 21(6): 355-380.

Raymond, G. P. (2002). Reinforced ballast behaviour subjected to repeated load. Geotextiles and Geomembranes. 20(1): 39-61.

Selig, E. T. and Waters, J. M. (1994). Track geotechnology and substructure management. Thomas Telford, London.

Shin, E. C., Kim, D. H. and Das, B. M. (2002). Geogrid-reinforced railroad bed settlement due to cyclic load. Geotechnical and Geological Engineering. 20: 261-271.