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DEFORMATION AND DEGRADATION OF CLAY FOULED BALLAST SUBJECTED TO MONOTONIC LOADING

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Railways offer an efficient and economic transport mode in many countries including Australia, China and USA. Conventionally, rail tracks are positioned on ballast due to several potential benefits, including economy (availability and abundance), rapid drainage and high load bearing capacity. However, the ballast becomes contaminated due to intrusion of pumped subgrade material (e.g. clay and silt). This is one of the primary reasons for rapid track deterioration. In severe circumstances, fouled ballast needs to be cleaned or replaced to maintain the desired track resiliency, load bearing capacity and the track alignment, all of which influence the level of safety. In Australia, massive amount of funds have been invested in track maintenance. By employing an effective maintenance program, both cost and the ballast quarrying can be reduced with significant favourable environmental implications and improved productivity. In order to identify the risk associated with fouling, it is important to accurately assess the amount of fouling. In this paper, the current methods commonly used for evaluating the degree of ballast fouling were critically examined and a new parameter, Void Contaminant Index (VCI) was proposed to capture the role of different fouling materials in terms of volume based air-voids reduction. A series of isotropically consolidated drained triaxial tests using a large scale cylindrical triaxial apparatus were conducted on both clean and fouled ballast with varying VCI to establish the relationship between the extent of fouling and the associated strength-deformation properties. Based on the laboratory findings, an empirical relationship between the peak deviator stress and VCI is proposed to assist the practitioners for preliminary track assessment and in the mitigation of the risk associated with ballast fouling. A non-linear shear strength envelope for clay fouled ballast is presented in a non-dimensional form, based on the proposed empirical equations.

Keywords: Deformation, Laboratory tests, Shear strength.

1. INTRODUCTION

When ballast is fouled due to intrusion of fines from external sources, significant changes in the pore structure of the ballast assembly occur resulting into reduced particle interlock (i.e.

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frictional resistance). Numerous studies on granular materials through discrete element methods (Huang *et al*. 2010, Huang and Tutumluer 2011, Lim and McDowell 2005, Lu and McDowell 2006) and on clean ballast using discrete and continuum mechanics approaches (Indraratna *et al*. 2011) were employed in the past. However, detrimental aspects of fouling on rail ballast have still not been assessed in detail. In this study, consolidated drained monotonic triaxial tests were conducted using large scale cylindrical triaxial apparatus to study the stress-deformation characteristics of clay fouled ballast.

Fouling material is defined as particles smaller than 9.5 mm accumulated in the ballast voids (Selig and Waters 1994). Commonly used fouling indices include the Fouling Index, *FI*, the Percentage Fouling (Selig and Waters 1994) and the Percentage Void Contamination, *PVC* (Feldman and Nissen 2002). In the former two indices, fouling materials that have significantly different specific gravities to parent rock (ballast) cannot be captured, leading to inaccurate volume estimations. *PVC*, which is a direct measure of percentage of voids occupied by fouling particles, provides better assessment of fouling. However, the volume of fouling material needs to be calculated after compacting (standard Proctor technique). This does not always represent the correct volume of fouling in the real track environment. In view of the above, a new parameter, *Void Contaminant Index* (*VCI*) is proposed that can capture the role of different fouling materials and the corresponding void reduction as a modification to the *PVC*.

$$VCI = \frac{V_f}{V_{\mathrm{vb}}} \tag{1}$$

where, V_f is actual volume of fouling material accumulated in the voids of fouled ballast and V_{vb} is the volume of voids in the clean ballast.

By substituting the relevant soil parameters, *VCI* can be expressed as:

$$VCI = \frac{(1+e_f)}{e_b} \times \frac{G_{s.b}}{G_{s.f}} \times \frac{M_f}{M_b} \times 100 \tag{2}$$

where,

e_b = void ratio of clean ballast
e_f = void ratio of fouling material
G_{sb} = specific gravity of the clean ballast
G_{sf} = specific gravity of the fouling material
M_b = mass of the clean ballast
M_f = mass of the fouling material

2. EXPERIMENTAL PROCEDURE

In order to understand the effect of clay fouling on the stress-strain and degradation behaviour of ballast, for different levels of fouling (0% to 80% *VCI*), a series of large scale monotonic triaxial tests were carried out for confining pressure in the range of 10–60 kPa that is representative of field conditions. Unlike conventional geo-materials such as sands and gravel, owing to the larger physical dimensions of ballast, a large-scale triaxial apparatus that could accommodate a specimen of 600 mm in height and 300 mm in diameter was designed and built at the University of Wollongong (Figure 1).

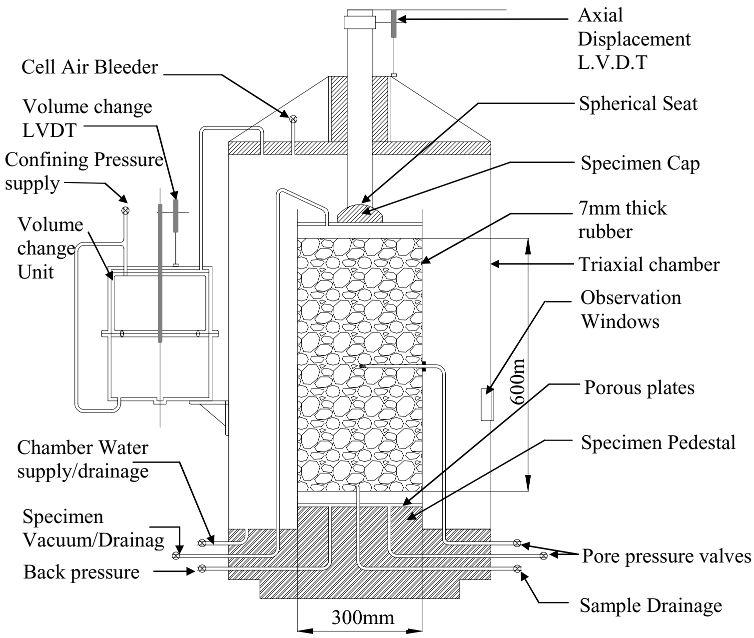

Figure 1. Schematic illustration of large-scale triaxial chamber (modified after Indraratna *et al.*, 1998).

A 7 mm thick cylindrical rubber membrane was used to prepare and confine the specimen. The Young's modulus of the membrane was determined to be 4300 kPa following the method described by ASTM D4767–04 and Bishop and Henkel (1962). The initial particle size distribution (*PSD)*, density and void ratio of ballast were kept almost identical in all specimens to capture realistic track conditions. It was pointed out in earlier studies that as the sample size ratio (i.e. diameter of the test specimen to the maximum particle size) exceeds 6, the sample size effects become increasingly insignificant (Marachi *et al*. 1972, Indraratna *et al*. 1993). The *PSD* of clean ballast used in this study is plotted in Figure 2 together with the recommended Australian Standards (AS 2758.7, 1996) where the maximum grain size falls between 50 and 60 mm. Commercial kaolin was used to simulate clay fouling.

Two specimen preparation methods were adopted for different levels of *VCI*. Ballast specimens were sieved and thoroughly mixed to ensure consistency of test specimens.

Method 1: Preparation of clean ballast specimens;

The clean ballast specimen was divided into four equal portions. Each portion was then placed inside the chamber and compacted using a vibrating plate to a height of 150 mm. A rubber pad underneath the vibrating plate was used to prevent particle breakage during placement. All layers were placed and compacted until the final height of 600 mm was attained. The specimen was then saturated from the base upwards.

Method 2: Clay fouled ballast with $10\% \leq VCI \leq 80\%$*;*

The amount of clay needed for predetermined *VCI* was calculated for each test specimen. Then a quarter of the clay mixture was mixed with a quarter portion of ballast using the

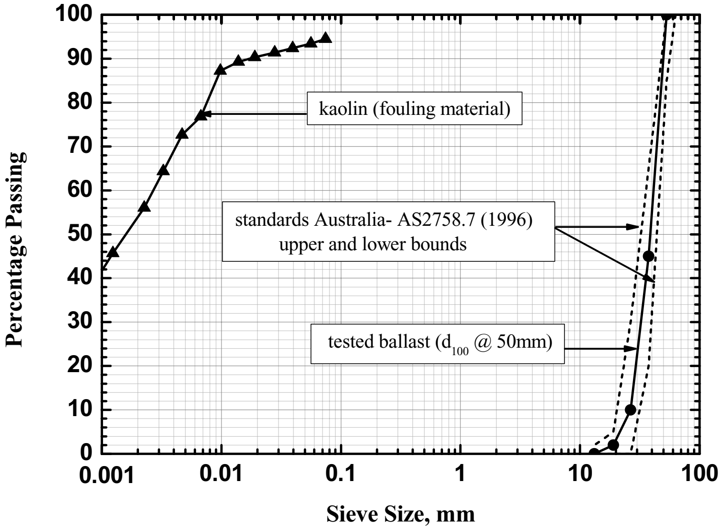

Figure 2. Particle size distribution of test materials.

concrete mixer, and then placed inside the upright cylindrical membrane in preparation mould. The moisture content of clay (52%) during mixing was slightly larger than the liquid limit. A vibrating plate was used to compact the specimen following the sequential procedure as explained before for the subsequent layers. Based on visual inspection, fouling material coating the entire surface area of ballast was ensured during and after the mixing process in the concrete mixer.

After preparing the test specimen, the outer cell chamber was placed and connected to the axial loading actuator. For all the tests, back pressure of 80 kPa was applied to obtain sample saturation with Skempton's B value approaching unity ($B > 0.98$). During testing, the required membrane correction was carried out according to ASTM D4767–04. Sieve analysis was carried out to measure the extent of particle breakage after each test.

3. RESULTS AND DISCUSSION

The upper plots of Figure 3 illustrate the stress-strain behaviour of fouled ballast (VCI = 10 & 80%) in contrast to fresh ballast (VCI = 0%) at increasing confining pressure. As expected when VCI increases, the peak deviator stress decreases significantly. The significant clay fouling (VCI = 80%) shows an increasingly more ductile post-peak response. The bottom plots of Figure 3 show the volumetric strain changes with the axial strain for varying levels of fouling and increasing confining pressure. In the compression zone (plotted as positive values), the increasing VCI generally shows a reduced compression of the fouled specimen as the voids between the ballast grains are occupied by clay acting as a void filler. Nevertheless, in the case of VCI = 10%, an exception is observed for all three specimens (at $\sigma'_3 = 10, 30, 60$ kPa) indicating a slightly increased compression compared to their fresh ballast counterparts. This may be attributed to the small amount of clay that is coating the ballast grains as a lubricant, thereby facilitating the specimens to attain a slightly higher

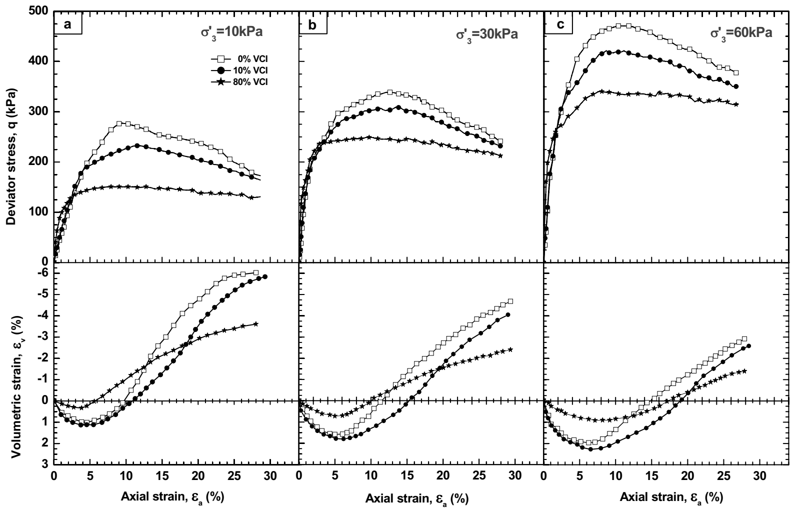

Figure 3. Stress-strain behaviour of clean and fouled ballast during isotropically consolidated drained tests at confining pressures (σ_3') of (a) 10 kPa, (b) 30 kPa and (c) 60 kPa, respectively.

Table 1. Variation of peak deviator stress ($q_{\mathrm{peak},f}$) with Void Contaminant Index for clay fouled ballast.

	peak deviator stress ($q_{\mathrm{peak},f}$), kPa at confining pressures σ_3'		
VCI,%	10 kPa	30 kPa	60 kPa
0	280	340	470
10	225	290	415
80	150	245	334

compression. With respect to dilation, the highly fouled specimens show a decrease in the rate and magnitude of dilation at axial strains exceeding @ 20%, while the increase in $\sigma'3$ from 10 to 60 kPa significantly suppresses dilation of all specimens. The addition of kaolin in sufficient quantities appears to contribute to a 'binding' effect that diminishes the tendency of the aggregates to dilate. Moreover, the specimens that are highly fouled (VCI = 80%) begin to dilate swiftly at a lower axial strain after showing a reduced compression initially compared to clean ballast.

Table 1 presents the peak deviator stress with *VCI*,

The following relationship that represents the normalized shear strength of clay fouled ballast may be used in the preliminary assessment of track conditions in view of track maintenance:

$$\frac{q_{\mathrm{peak},f}}{q_{\mathrm{peak},b}} = \frac{1}{1+\beta\sqrt{(VCI)}} \tag{3}$$

where, $q_{\mathrm{peak},b}$ and $q_{\mathrm{peak},f}$ are peak deviator stresses for fresh and fouled ballast respectively; β is an empirical parameter, whose magnitudes are 0.094, 0.047 and 0.05 for values of σ_3' 10, 30 and 60 kPa respectively.

Figure 4 shows the Mohr-Coulomb diagrams of the clay fouled ballast specimens, which exhibit a non-linear shear strength envelope similar to other rockfills (Indraratna *et al.*, 1993; 1998). It is seen that the peak friction angle (determined by the gradient of the envelope (i.e. $\tan^{-1} d\tau/d\sigma'$)) rapidly decreases when the effective confining pressures are in the range of 10–35 kPa. When VCI increases, the peak friction angle of clay fouled ballast also decreases.

A non-linear shear strength envelope for clay fouled ballast can be presented in a non-dimensional form;

$$\frac{\tau_f}{\sigma_c} = m\left(\frac{\sigma'_n}{\sigma_c}\right)^n \qquad (4)$$

where, τ, σ'_n and σ_c are shear stress, effective normal stress and uniaxial compressive strength of the parent rock (130 MPa). m and n are empirical coefficients which vary with *VCI*. The values of m and n in Eq. (4) are established by best fit (regression) analysis by the following expressions:

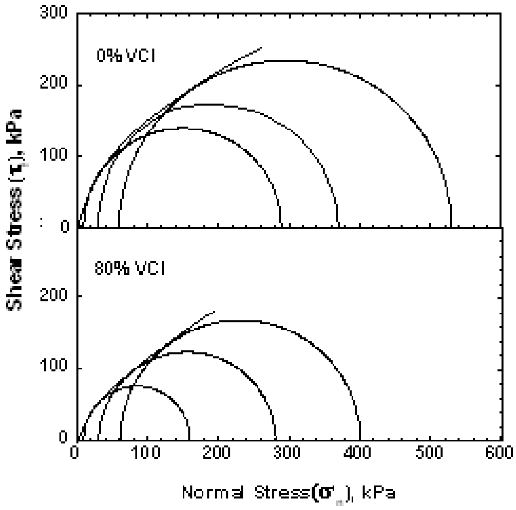

Figure 4. Mohr-Coulomb strength envelopes for clay fouled ballast.

$$m = 0.07[1 + \tan h(VCI/21.5)] \qquad (5)$$

$$n = 0.56[1 + 0.3 \tan h(VCI/21.5)] \qquad (6)$$

4. PRACTICAL IMPLICATIONS

From the results reported earlier, it is clear that clay fouling has significant implications on the performance of railway ballast. The peak deviator stress is an important parameter for ballast and it is influenced by the amount of fouling (*VCI*). For a given ballast gradation, if the appropriate reduced peak deviator stress is not carefully selected on the basis of the anticipated fouling levels, this may over-predict the track bearing capacity and stability. Therefore, an accurate assessment of the stress-strain-degradation characteristics of clay fouled ballast is highly beneficial for executing better maintenance and operation schemes of existing tracks and for the preliminary design of rehabilitated tracks.

5. CONCLUSIONS

Rail ballast becomes contaminated or fouled due to the infiltration of subgrade fines such as clay. Excessive fouling of ballast may cause differential settlements and rapid deterioration of the track demanding regular maintenance. Therefore, a proper understanding of the stress-strain-degradation characteristics of fouled ballast is pertinent for efficient maintenance and operation of tracks. In this paper, a series of isotropically consolidated drained monotonic triaxial tests using a large scale cylindrical triaxial apparatus were conducted on clay fouled ballast. A new parameter, *Void Contaminant Index* (*VCI*) that can adequately capture the extent of fouling in terms of volume based air-voids reduction was considered. Based on the laboratory test findings, a novel empirical relationship between the peak deviator stress and *VCI* is proposed with the aim of assisting the practitioner in the preliminary track assessment. A non-linear shear strength envelope for clay fouled ballast is introduced in a non-dimensional form, where the relevant shear strength coefficients could be conveniently evaluated as a function of *VCI*, based on the proposed empirical equations. The more complex aspects of clay fouling need to be carefully assessed through rigorous micro-mechanical studies in the future to predict performance of ballasted tracks under various levels of fouling.

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REFERENCES

1. ASTM (2002). Standard Test Method for Consolidated Undrained Triaxial Compression Test for Cohesive Soils., ASTM D4767-02.West Conshohocken, PA: ASTM International.
2. Australian Standard: AS2758.7 (1996). *Aggregates and Rock for Engineering Purposes; Part 7: Railway Ballast.*, Sydney, NSW, Australia.
3. Bishop A. W. and Henkel, D. J. (1962). *The Measurement of Soil Properties in the Triaxial Test*, Arnold, London.
4. Feldman, F. and Nissen, D. (2002). Alternative testing method for the measurement of ballast fouling, *Conference on Railway Engineering RTSA*, Wollongong NSW, Australia, 101–109.
5. Huang, H. and Tutumluer, E. (2011). Discrete Element Modeling for Fouled Railroad Ballast. *Const. and Building Materials.,* 25(8): 3306–3312.
6. Huang, H., Tutumluer, E., Hashash, Y. and Ghaboussi, J. (2010). Laboratory Validation of Coal Dust Fouled Ballast Discrete Element Model. *GeoShanghai 2010 Int. Conference,* 305–313.
7. Indraratna, B., Ionescu, D. and Christie, D. (1998). Shear Behaviour of Rail Ballast on Large Scale Triaxial Testing. *J. of Geotech. Geoenviron. Engng ASCE* 124(5): 439–449.
8. Indraratna, B., Lackenby, J. and Christie, D. (2005). Effect of Confining Pressure on the Gradation of Ballast under Cyclic Loading. *Geotechnique.,* 55(4): 325–328.
9. Indraratna, B., Wijewardena, L.S.S., and Balasubramaniam, A.S. (1993). Large-scale triaxial testing of greywacke rockfill. *Geotechnique* 43(1): 37–51.
10. Indraratna, B., Salim, W. and Rujikiatkamjorn, C. (2011). *Advanced Rail Geotechnology – Ballasted Track*: CRC Press/Balkema.
11. Lim, W. L. and McDowell, G. R. (2005). Discrete Element Modelling of Railway Ballast. *Granular Matter*, **7**(1): 19–29.
12. Lu, M. and McDowell, G. R. (2006). Discrete Element Modelling of Ballast Abrasion. *Geotechnique*, 56(9): 651–655.
13. Marachi, N. D., Chan, C. K. and Seed, H. B. (1972). Evaluation of Properties of Rockfill Materials. *J. of the Soil Mech. and Found. Div. ASCE* 98(1): 95–114.
14. Selig, E. T. and Waters, J. M. (1994). *Track Technology and Substructure Management*. Thomas Telford, London.