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Assessment of ballast fouling and its implications on track drainage

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ABSTRACT

Australian railways offer an efficient and economic mode for transporting freight and passengers across all States. Conventionally, rail tracks are positioned on ballast for reasons including economy (availability and abundance), rapid drainage, and high load bearing capacity. However, the ballast becomes fouled due to the intrusion of fines either from the subgrade or surface which impairs track drainage. In order to maintain serviceability, it is necessary to maintain adequate drainage capacity in the track. To identify the risk associated with fouling, it is important to understand the effects of the amount of fouling on drainage conditions. In this present study a critical assessment of different types of mass based fouling indices was carried out. A new parameter, the Void Contaminant Index, which considers variations in the specific gravity of ballast and fouling materials, is proposed to evaluate the amount of fouling. A series of large scale constant head hydraulic conductivity tests were conducted to establish the relationship between the extent of fouling and the associated hydraulic conductivity. Subsequently, a seepage analysis was carried out using finite element software to simulate a more realistic two-dimensional flow under actual track geometry to capture the drainage capacity of ballast. The drainage condition of the track was classified into different categories using the average rainfall in Australia. Finally, a maintenance schedule for practising engineers was provided based on the proposed drainage criteria.

Keywords: Ballast, Drainage, Fouling material, Hydraulic conductivity, Void Contaminant Index

1 INTRODUCTION

In order to sustain good performance it is essential to maintain proper drainage in the ballasted track. Railroad ballast usually contains uniformly graded material that creates a sufficiently large pore structure to facilitate rapid drainage. When it is degraded and aged, fine particles accumulate within the voids (ballast fouling) and decrease its drainage capacity.

There are numerous fouling indices available in literature to quantify ballast fouling. Selig and Waters (1994) have defined the Fouling Index as a summation of percentage (by weight) passing the 4.75mm (No.4) sieve and 0.075mm (No.200) sieve. This may lead to a misinterpretation of the actual quantity of fouling if the fouled material contains more than one type of material having considerably different specific gravities (e.g. coal and pulverised rock). Feldman and Nissen (2002) defined the Percentage Void Contamination (PVC) as the ratio of bulk volume of fouling material to the initial volume of ballast voids (i.e. when it was clean). The bulk volume needs to be calculated after the fouling material has been compacted (Feldmen and Nissen 2002) that does not always represent the actual volume of fouling accurately in a track environment. In view of the above, a new *Void Contaminant Index* (*VCI*) parameter that can capture the role of different fouling materials as a modification to the *PVC* is herewith proposed.

$$VCI = \frac{V_{f'}}{V_{vb}} \times 100 \qquad (1)$$

where $V_{f'}$ is the actual volume of fouling material within the ballast voids (V_{vb}). By substituting the relevant soil parameters, Equation (1) can be re-written as:

$$VCI = \frac{(1+e_f)}{e_b} \times \frac{G_{sb}}{G_{sf}} \times \frac{M_f}{M_b} \times 100 \quad (2)$$

where e_b = Void ratio of clean ballast, e_f = Void ratio of fouling material, G_{sb} = Specific gravity of clean ballast, G_{sf} = Specific gravity of fouling material, M_b = Dry mass of clean ballast, M_f = Dry mass of fouling material.

For example, a value of VCI = 50% indicates that half of the total ballast voids is occupied by the fouling material.

2 LARGE SCALE PERMEABILITY TEST

There are two distribution patterns of fouling material within the ballast voids that can be observed in a fouled ballasted track. Fouling material such as coal infiltrates from the top of the track and settles at the bottom (Indraratna et al. 2011), as shown in Figure 1(a) (non-uniformly distributed fouling). In the second case, fouling material accumulates within the voids of the ballast due to subgrade pumping, as shown in Figure 1(b) (uniformly distributed fouling e.g. clay fouling).

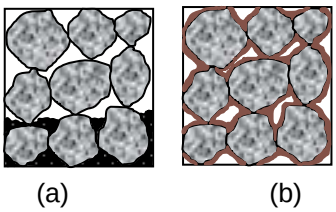

Figure 1: Schematic diagram of (a) non-uniform and (b) uniformly distributed fouled ballast

A large scale permeameter was used to measure the hydraulic conductivity associated with different levels of fouling (Tennakoon et al. 2012). This chamber could accommodate ballast specimens 500mm in diameter and 300-500mm high (Figure 2). In order to prevent the fine particles from washing out, a filter membrane was placed below the layer of ballast while still maintaining a free drainage boundary. The test specimen was placed above the filter membrane and compacted in four equal layers to represent a typical field density.

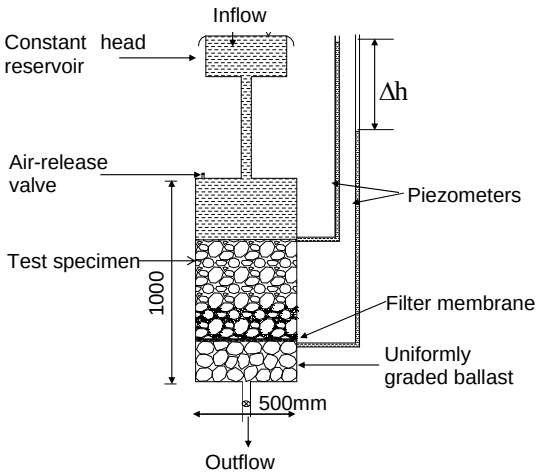

Figure 2: Schematic diagram of large scale permeability test apparatus

Both fouling patterns were simulated in the large scale permeability test. With the non-uniformly distributed fouling, the ballast layer was compacted first and then the fouling material was added from the top and allowed to infiltrate downwards with percolating water. To simulate uniformly distributed fouling, a given volume of kaolin was pre-mixed with the aggregates and then compacted in 5 layers. For 100% VCI, kaolin was placed at the bottom of the cell and then the ballast was placed on top of it and compacted using a vibrating plate until the required height was achieved for each layer and the excess kaolin was inevitably squeezed out to the top. The total volume, the weight of the ballast and its gradation, were kept constant for each test to maintain a similar initial porosity within the ballast.

2.1 Testing procedures

A series of large scale constant head permeability tests (AS: 1289.6.7.1) for different percentages of coal, fine clayey sand, and pure kaolin were conducted. It was reported by Parson (1990) that linear Darcy's law is still valid for fresh ballast at low hydraulic gradients (less than 4). Therefore, Darcy's law considering laminar flow was used in this study. The gradation of clean ballast obtained from Bellambi, NSW is illustrated in Figure 3 together with the gradation specified by AS 2758.7(1996). Fouling material having different gradation curves (Figure 3) was used. The fouled specimen was saturated for at least 24 hours. A number of constant head tests were conducted to investigate the effect of the percentage of fouling materials. These tests were conducted under steady state flow subjected to a 1.5m head of water using an adjustable overhead tank.

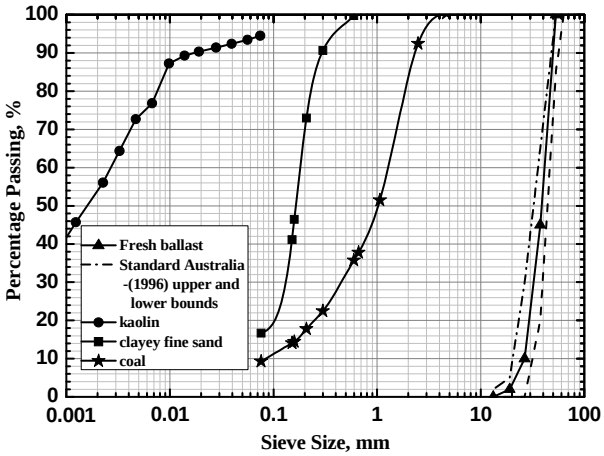

Figure 3: Gradations of clean ballast and fouling materials

2.2 Results and Discussions

Figure 4 shows hydraulic conductivity of coal-fouled and sand-fouled ballast. As expected, the overall hydraulic conductivity always decreased with an increase in VCI. The current test results showed that a 5% increase of VCI decreased the hydraulic conductivity by a factor of at least 200 and 1500 for ballast contaminated by coal and fine clayey sand, respectively. Beyond a VCI of 75%, any further reduction in hydraulic conductivity becomes marginal as it approaches the hydraulic conductivity of the fouling material itself. The above observations are also in line with the laboratory measurements of sand-gravel mixtures reported by Jones (1954), whereby a high percentage of sand in gravel would provide a hydraulic conductivity close to that of the sand itself.

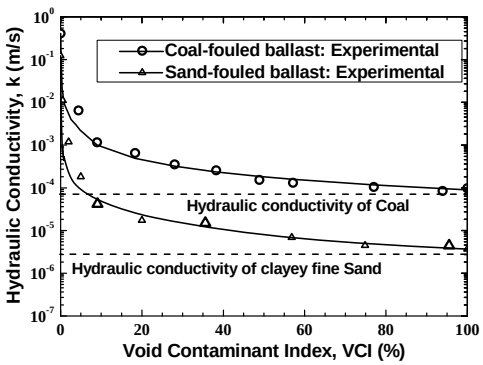

Figure 4: Variation of hydraulic conductivity with Void Contaminant Index for coal-fouled ballast and sand-fouled ballast (non-uniform distribution of fouling) (data sourced from Tennakoon et al. 2012)

Figure 5 shows the variation of hydraulic conductivity for clay-fouled ballast where the fouling material is distributed uniformly. At low values of VCI, the overall hydraulic conductivity of ballast was relatively unaffected, but beyond a VCI of about 90%, the overall permeability of fouled ballast was almost the same as kaolin clay.

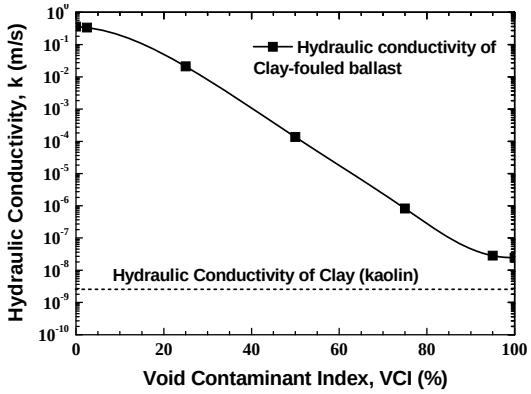

Figure 5: Variation of hydraulic conductivity with Void Contaminant Index for clay-fouled ballast (uniform distribution of fouling) (data sourced from Tennakoon et al. 2012)

3 DETERMINATION OF TRACK DRAINAGE CAPACITY USING A TWO-DIMENSIONAL SEEPAGE MODEL

As flow through the ballast track can occur in vertical and horizontal directions, a 2-D seepage analysis was conducted using the finite element software, SEEP-W (GeoStudio 2007), to determine the drainage capacity with respect to various fouling conditions for ballast fouled with clay. Hydraulic conductivity values corresponding to different VCI obtained from experimental results were used as input parameters in the analysis. A vertical cross section of a typical Australian track is shown in Figure 6.

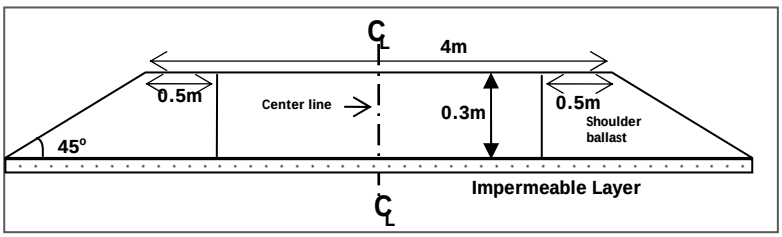

Figure 6: Vertical cross section of the typical ballast layer used in seepage analysis

Two types of boundary conditions were applied to the finite element model. While a free drainage boundary was used at the top surface of the shoulder ballast, along the centre line and at the bottom of the ballast bed (Figure 6), an impermeable boundary was used below the ballast bed. A hydraulic head equal to the height of the track was assumed at the top surface when calculating the steady state discharge (q). Any erosion of fouled materials was neglected in this simplified model.
In order to simulate two possible scenarios for track fouling, the following models were simulated for ballast fouled with clay.
Model 1: Newly constructed track: The track was divided into three equal horizontal layers (100mm each) and the hydraulic conductivity values corresponding to different VCI values were used.
Model 2: Track subjected to shoulder cleaning: The track was divided into four parts, shoulder ballast and three horizontal layers of ballast with different values of hydraulic conductivity.

3.1 Classification of the track drainage

As reported by Pilgrim (1997), the rainfall in Australia usually varies from 125mm/hr to 175mm/hr from one state to another. In this study a maximum rainfall intensity of 150mm/hr was used and corresponding flow rate named as critical flow rate (Q_c) is calculated to be 0.0002m^3/s over the unit length of the track. From the seepage analysis, the maximum drainage capacity (Q) of the ballast can be determined for various levels and conditions of fouling. When track drainage capacity is equal to or lower than what is required for a given rate of rainfall, then the fouled track drainage is classified as 'poor drainage'. In this context a ratio between the computed track drainage capacity and the critical

flow (Q/Q_c) was introduced as a dimensionless index to classify the drainage condition as stipulated in Table 1.

Table 1: Drainage capacity criteria

Drainage classification	Range
Free Drainage	$Q/Q_c>100$
Good drainage	$10<Q/Q_c<100$
Acceptable drainage	$1<Q/Q_c<10$
Poor Drainage	$0.1<Q/Q_c<1$
very Poor	$0.001<Q/Q_c<0.1$
Impervious	$Q/Q_c<0.001$

3.2 Seepage Data Interpretation

Figure 7 shows the track maintenance chart which is prepared based on results of seepage analysis of Track with and without shoulder ballast (Model 2 and 1 respectively). The various track drainage conditions ('acceptable drainage', 'poor drainage') as reported in Figure 7 are direct output of the numerical seepage analysis implemented using SEEP/W. Based on the seepage analysis of Model 1, it is found that as long as the top layer of ballast is clean (VCI ≤ 25%), the track can be classified either as 'free drainage' or as 'acceptable drainage'. In contrast, if the top layer is highly fouled (VCI ≥50%) and is underlain by a relatively clean layer of bottom ballast (VCI <=25%) then the drainage capacity can be considered as 'poor'. As expected, when all layers have a VCI ≥50%, then the track is considered to be 'very poor drainage' and therefore require maintenance. The results of this seepage analysis of Model 1 imply that it is not always mandatory to replace the entire volume of ballast unless the top layer of the track is highly fouled with a VCI exceeding 50%. In practice the common and convenient maintenance schemes include either cleaning the shoulder ballast or the top ballast (under cutting), or both. The results of seepage analysis of Model 2 clearly suggests that replacing or cleaning the ballast from the shoulder is more than adequate, when the top layer has a VCI that is less than 50%. When the VCI of shoulder ballast exceeds 50%, it acts as a flow barrier and the track drainage capacity decreases significantly to be categorised as 'poor drainage'. Moreover, the cleaning of the shoulder ballast alone will not be effective if the top layer of ballast is badly fouled (VCI ≥ 50 %). Under these circumstances, the ballast must be cleaned via undercutting or totally replaced by maintenance machinery. The analysis also showed that as long as there is at least 100mm thickness of clean ballast at any time, the overall track will have sufficient drainage.

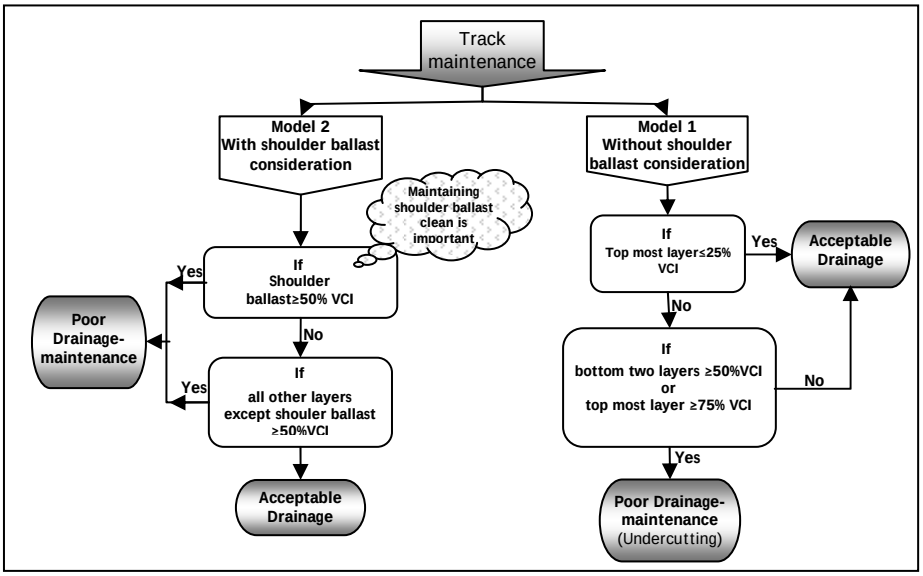

Figure 7: Track maintenance chart

4 CONCLUSIONS

In this study a new parameter called the Void Contaminant Index (VCI), incorporating the effects of void ratios, specific gravities, and gradations of both fouling material and ballast was presented. A series of large scale constant head permeability tests for different percentages of coal, fine clayey sand, and pure kaolin were conducted. Two distribution patterns of fouling viz. non-uniform (for clayey sand and coal) and uniform (for clay) were simulated. Test results indicated that even a small increase in the VCI leads to a significant decrease in the hydraulic conductivity of the fouled ballast. Beyond a certain limit of VCI (50% for ballast fouled with coal and 90% for ballast fouled with sand) the hydraulic conductivity of fouled ballast converged to that of the fouling materials itself.

Based on the hydraulic conductivity of ballast having different VCI, the drainage capacity of the track was determined using a two-dimensional, finite element seepage analysis applied to the actual track geometry. It was shown that both the location and extent of fouling played an important role when assessing the overall drainage capacity. Cleaning the ballast using the undercutting method is recommended when the VCI of the top portion (100mm thickness) of the ballast exceeded 50%. When the shoulder ballast was fouled by more than 50% VCI, the shoulder of the track should be cleaned or replaced to maintain an acceptable drainage capacity. If the shoulder ballast is badly fouled (i.e. VCI > 50 %), 'poor drainage' can still occur even if other layers of ballast are relatively clean.

The track maintenance chart developed on the basis of large scale laboratory testing and numerical analysis offers very useful guidelines for facilitating the decisions made by track engineers. Nevertheless, the contents of this paper were based on a limited number of divisions within the ballast bed with several conveniently selected levels of fouling.

5 ACKNOWLEDGEMENT

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