

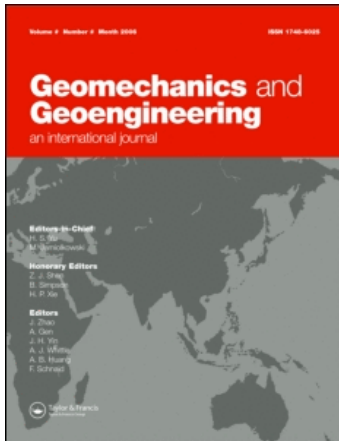
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Using a seismic survey to measure the shear modulus of clean and fouled ballast

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In this paper a first time attempt has been made to measure the low strain shear modulus of clean and fouled ballast using a seismic survey of Multi-channel Analysis of Surface Wave (MASW). A model rail track was built with nine sub-sections, each having different fouling characteristics. MASW survey was performed in the top of each section of ballast and shear wave velocity was measured. The shear modulus of ballast fouled by pulverized rock, clayey sand and coal was calculated by using shear wave velocities and densities of each section and presented. The optimum and critical fouling points are defined considering the shear stiffness and drainage criteria for ballast fouled by clayey sand and coal. In both cases the shear stiffness increased to a maximum and then decreased as the percentage of fouling increased. The degree of fouling corresponding to the maximum shear wave velocity is defined as the optimum fouling point. After a particular degree of fouling the shear stiffness decreased less than clean ballast and the corresponding drainage condition become unacceptable. This point is defined as the critical fouling point. The results obtained from the model track were compared with the field data.

Keywords: Ballast; fouling; MASW; shear stiffness; optimum fouling; critical fouling

Introduction

Inspecting or mapping the sub-surface will assist in measuring its properties and understanding the behaviour of the stratum. The characteristics of railway ballast beds are normally discovered by digging trenches at evenly spaced intervals, a process that requires a lot of resources. Various geophysical investigative methods are available for studying the ballast bed, including radar, infrared imaging, seismic refraction, and electrical resistivity among others. Various studies have been carried out using non-destructive testing with Ground Penetration Radar (GPR) to map the sub-surface of ballast sections. GPR is a tool of modern geophysical approach which can provide information about the formation of the track-bed interface (Gallagher *et al.* 1999). Most GPR results depend on a visual interpretation and are qualitative in nature. However, a railway engineer still needs quantitative numbers to establish an appropriate design and maintenance program. GPR can be used to obtain information on fouling but cannot clearly define the degree or type of fouling. Fouling by sub-grade or coal fines is a routine problem in soft soil regions and track used to transport coal. Fouling needs to be clearly identified in a timely manner to ensure that the rail network functions effectively. It can be measured in terms of a fouling index, percentage of fouling, Percentage Void Contamination (PVC) and Relative Ballast Fouling Ratio (RBF) (Selig and Waters 1994, Feldman and Nissen 2002).

A Multi-channel Analysis of Surface Wave (MASW) is - geophysical (seismic refraction) method that is widely used for sub-surface characterisation. However, only limited studies to measure the shear modulus of ballasted tracks under different fouling conditions have been conducted with this method. In this study a typical model track with fouled and clean ballast above the capping and sub-grade layers for different track conditions has been set up in the laboratory. An attempt was made to measure the shear modulus of ballast using MASW in relation to fouling indices, from which two new terms, the optimum fouling point (OFP) and the critical fouling point, (CFP) were defined with respect to the shear stiffness and drainage.

A Multi-channel Analysis of Surface Waves

A number of geophysical methods for near-surface characterisation and measurement of shear wave velocity using a wide variety of testing configurations, processing techniques, and inversion algorithms have been proposed. The most widely used are spectral analysis of surface waves (SASW) and MASW. The SASW method has been used for sub-surface investigation for several decades (e.g., Nazarian *et al.* 1983, Al-Hunaidi 1992, Stokoe *et al.* 1994, Tokimatsu 1995, Ganji *et al.* 1997). With the SASW method, the spectral analysis of a surface wave generated by an impulsive source and recorded by a pair of receivers is used. MASW is a new and improved technique that incorporates a MASW using active sources

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(Park *et al.* 1999, Xu *et al.* 2006). The MASW method is more efficient at unravelling shallow sub-surface properties (Park *et al.* 1999, Xia *et al.* 1999, Zhang *et al.* 2004, Anbazhagan and Sitharam 2008a). MASW is increasingly being applied to earthquake geotechnical engineering for seismic microzonation and site response studies (Anbazhagan and Sitharam 2008b, 2008c, Sitharam and Anbazhagan 2008a, Anbazhagan *et al.* 2009). In particular, MASW is used in geotechnical engineering to measure the shear wave velocity and dynamic properties (Sitharam and Anbazhagan 2008b), and identify the sub-surface material boundaries and spatial variations of shear wave velocity (Anbazhagan and Sitharam 2009). MASW can also be used for the geotechnical characterisation of near surface materials (Park *et al.* 1999, 2005, Xia *et al.* 1999, Miller *et al.* 1999, Kanli *et al.* 2006, Anbazhagan and Sitharam 2008a, 2008c, Anbazhagan *et al.* 2009).

MASW generates a shear-wave velocity (V_s) profile (i.e. V_s versus depth) by analysing Raleigh-type surface waves on a multi-channel record. In this investigation the MASW system consisted of a 24-channel SmartSeis seismograph with twelve 10-Hz geophones was used. The seismic waves were created by a 1-kg sledge hammer and a 70 × 70-mm aluminium plate with a number of shots. These waves were received by the geophones/receivers and further analysed using SurfSeis software.

Experimental setup and properties

The percentage of fouling (% fouling) is the ratio of the dry weight of material passing through a 9.5-mm sieve to the total dry weight of the sample. It is noted that the percentage of

fouling may not be applicable for all types of fouling due to the limited materials used for fouling in this empirical development. Care should be taken when evaluating ballast fouled with materials whose specific gravity differs from the ballast. The authors recommended new parameters considering specific gravity that the Relative Ballast Fouling Ratio (R_{bf}) is a weighted ratio of the dry weight of fouling particles passing through a 9.5-mm sieve to the dry weight of ballast, i.e. particles retained on by a 9.5-mm sieve.

The relative ballast fouling ratio (R_{bf}) can be defined as:

$$R_{bf} = \frac{M_f \times \frac{G_{sb}}{G_{sf}}}{M_b} \times 100\% \quad (1)$$

Where M_f and M_b , and G_{sf} and G_{sb} are the mass and specific gravities of fouling materials and ballast, respectively.

A model rail track 3.5 × 5.4 × 0.57 (width × length × height) was built to represent a typical Australian rail track (Figure 1). Figure 2 represents the vertical cross-section of this model track. The materials used in its construction are clean ballast (CB), fine ballast/pulverized rock (FB), coal (C), and clayey sand (SC). The fines used to construct the fouled ballast section having the water content of about 3%. Figure 3 shows the gradation of materials used, and the upper and lower gradations (UG and LG) specified by AS 2758.7 (1996). At the bottom of the track a 0.15-m thick layer of silty clay sub-grade was compacted and a 0.15-m thick layer was placed on top. From this, nine sub-sections with different fouling conditions were built (Table 1). The fouled sections were built by considering the percentage of fouling and the Relative Ballast Fouling Ratio.

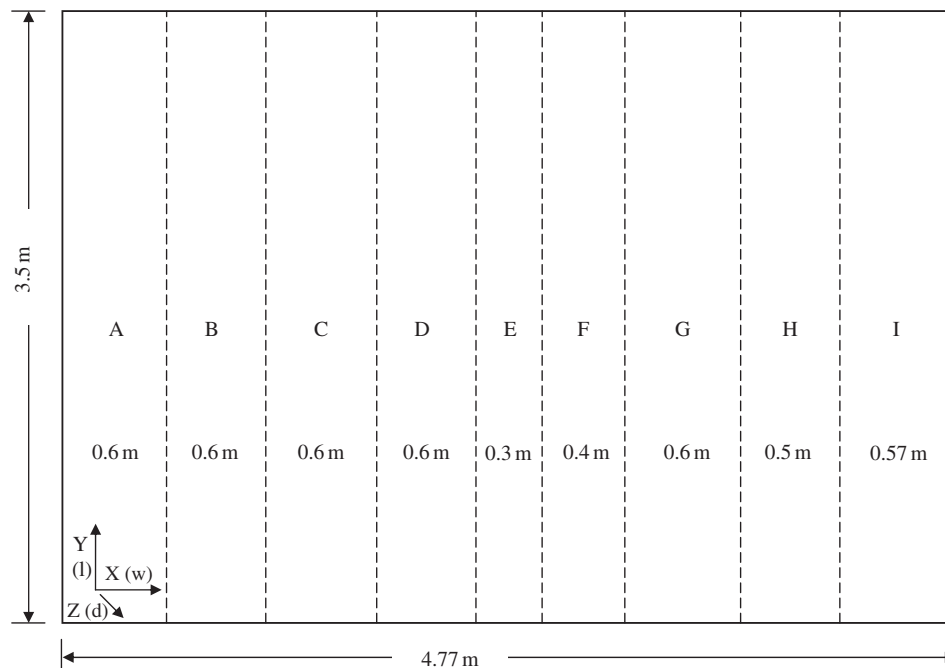


Figure 1. Plan view of the model track.

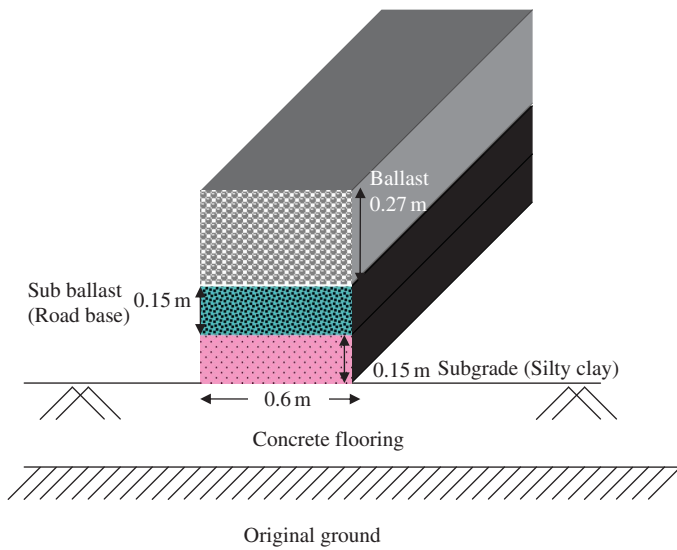


Figure 2. Plan view of laboratory setup of ballast section.

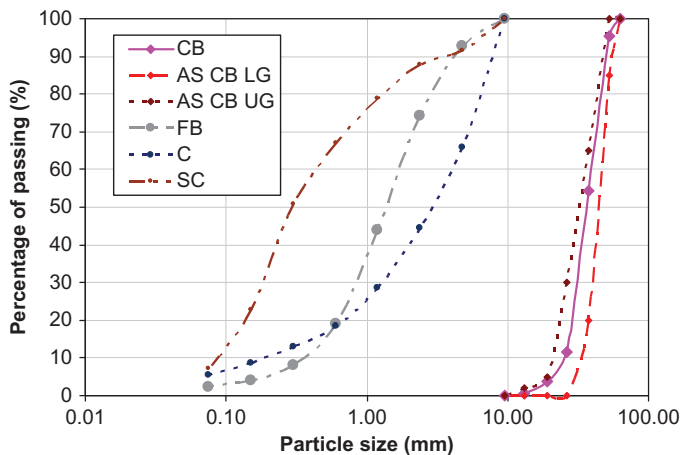


Figure 3. Gradation of materials used in the model track with Australian standard upper and lower gradation.

Table 1. Sectional detail with degree of fouling and densities of model track.

Section	Description	Relative ballast fouling ratio	Fouling percentage	Density (ton/m ³)
A	Ballast + Coal	10	4.94	1.675
B	Ballast + Coal	25	11.51	1.807
C	Ballast + Fine Ballast	25	20	2.017
D	Ballast + Clayey sand	25	19.35	2.096
E	Ballast + Clayey sand	10	8.76	1.753
F	Clean Ballast-I	0	0	1.587
G	Ballast + Clayey sand	50	32.43	1.899
H	Clean Ballast-II	0	0	1.636
I	Ballast + Coal	50	20.64	1.770

Clean sections of ballast (F and H) were built by compacting equal layers using a hand held vibrating plate. The dense clean ballast (DCB) in section H was built by using more layers than in section F. The fouled sections of A, B, C, D and E were built by placing the clean ballast and spreading the fouling materials (coal, clayey sand and pulverized rock) above the layer of clean ballast and then compacting them with the vibration plate. The ratio between the weight of clean ballast and fouling materials was chosen to result in an R_{bf} of 10% (% fouling of 4.94 and 8.75 for coal and clayey sand), 25% (% fouling of 11.5, 19.35 and 20 for coal, clayey sand and fine ballast), and 50% (% fouling of 20.64 and 32.43 for coal and clayey sand). The fouled ballast for sections G and I were obtained by mixing the fouling materials and clean ballast in a small concrete mixer. This is used to build the sections G and I by compacting as equal layers using the vibration plate. Figure 4 shows the combined gradation of clean and fouled ballast blended with pulverized rock, coal, and clayey sand. Here ballast fouled with coal has less fines than ballast fouled with clayey sand. Nine sections were formed and separated using a geo-textile. Nine sub-sections degrees of fouling and densities are given in Table 1. Figures 5a and 5b show the variation in density for different degrees of fouling. Those sections of ballast fouled by coal are lower in density than those fouled with clayey sand. Figure 5a shows a variation in the density pattern for ballast fouled by coal and clayey sand which may be attributed to the percentage of fouling where the specific gravity of fouling material was not considered. The specific gravity of coal generally varies from 1.05 to 1.4 and from 2.5 to 2.8 for ballast and clayey sand. Figure 5b shows a similar variation in the density pattern because R_{bf} considers the specific gravity of fouling materials. For the same R_{bf} , the density of ballast fouled by coal is lower than ballast fouled by clayey sand. The density of the fouled section of fine ballast is similar to the ballast fouled by clayey sand which may be attributed by the similar range of specific gravities for clayey sand and fine ballast, although their particle gradation curves are different.

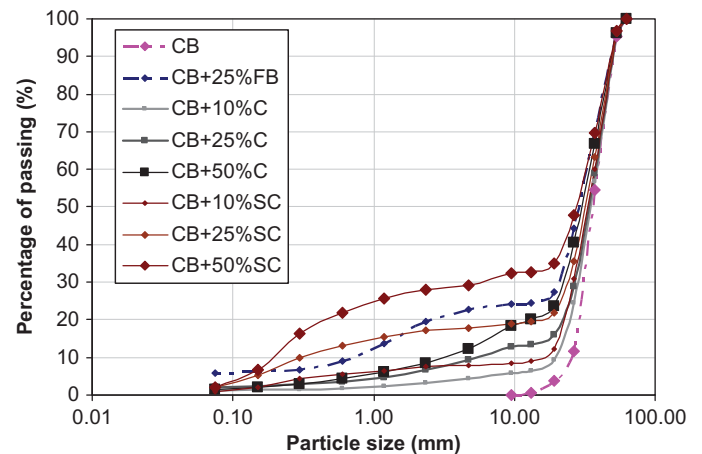


Figure 4. Gradation of clean and fouled ballast with respective relative fouling values.

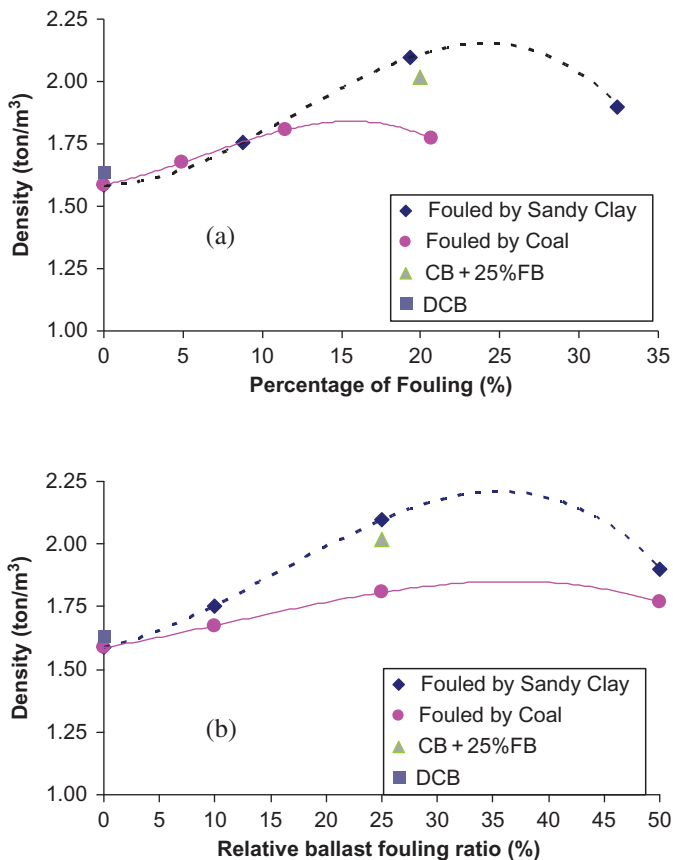


Figure 5. Density variation of model track sections with respect to degree of fouling (a) density versus % of fouling and (b) density versus relative ballast fouling ratio.

MASW survey

The MASW survey was carried out by placing 12 geophones parallel to the y axis along the line A- I (see Figure 1). It was found that the strongest signal from the source to the receiver occurred when the geophones were placed 0.25 m (Δx) apart, and the distance between the source to the first receiver was 0.5 m (x). This set up was similar to configuration used for the hard martial (pavement) mapping field (Anbazhagan and Sitharam 2008d) and was used to survey every section. A typical testing arrangement is shown in Figure 6. Each section was surveyed three times and the seismic signals were recorded every 0.125 ms at a length of 256 ms.

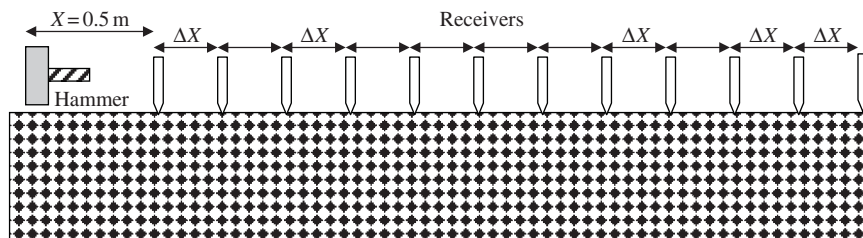


Figure 6. Typical geophone and source arrangement along y-y direction.

The generation of a dispersion curve is a critical step in the MASW method. It is generally displayed as a function of phase velocity versus frequency. Phase velocity can be calculated from the linear slope of each component on the swept-frequency record. The accuracy of a dispersion curve can be enhanced by the analysis and removal of noise on data. High frequency seismic signals are used to get a dispersion curve of sections of ballast with a high signal to noise ratio. The frequencies varied from 25 to 60 Hz and had a signal to noise ratio of 80 and above (see Figure 8). A typical dispersion curve for a section of ballast is shown in Figure 7. An inversion analysis must be carried out by an iterative inversion process that requires the dispersion data to profile the shear wave velocity (V_s) of the medium. A least squares approach allows the process to be automated (Xia *et al.* 1999) and V_s is updated after each iteration, with Poisson's ratio, density, and model thickness remaining unchanged throughout the inversion. An initial V_s profile should be defined such that V_s at a depth D_f is 1.09 times the measured phase velocity C_f at the frequency where the wavelength λ_f satisfies the following relationship (Stokoe *et al.* 1994).

$$D_f = a\lambda_f \quad (2)$$

where a is a coefficient that only changes slightly with frequency (Park *et al.* 1999). A typical shear wave velocity profile obtained for section H is shown in Figure 8 and the interpretation of this figure is presented in the following section.

Shear properties of clean and fouled ballast

Seismic surveys are widely used to estimate the *in-situ* shear modulus by measuring the *in-situ* density and shear wave velocity (Schneider *et al.* 1999). Shear modulus from seismic survey is widely used for site response and seismic microzonation studies. Shear modulus of soil layers are correlated with field standard penetration test (SPT) N values (Anbazhagan and Sitharam 2010). In this study the shear wave velocity for each section was determined by averaging three sets of data having a standard deviation of less than 9. Only four points are available for two type of fouling materials, these points are connected using second order polynomial having R^2 value of 0.9 and above for the further discussion. The study shows that the average shear wave velocity of clean ballast (section F and H) varies from 125 to 155 m/s for a density ranging from 1.59 to 1.66 ton/m³, which are similar to the ballast shear wave

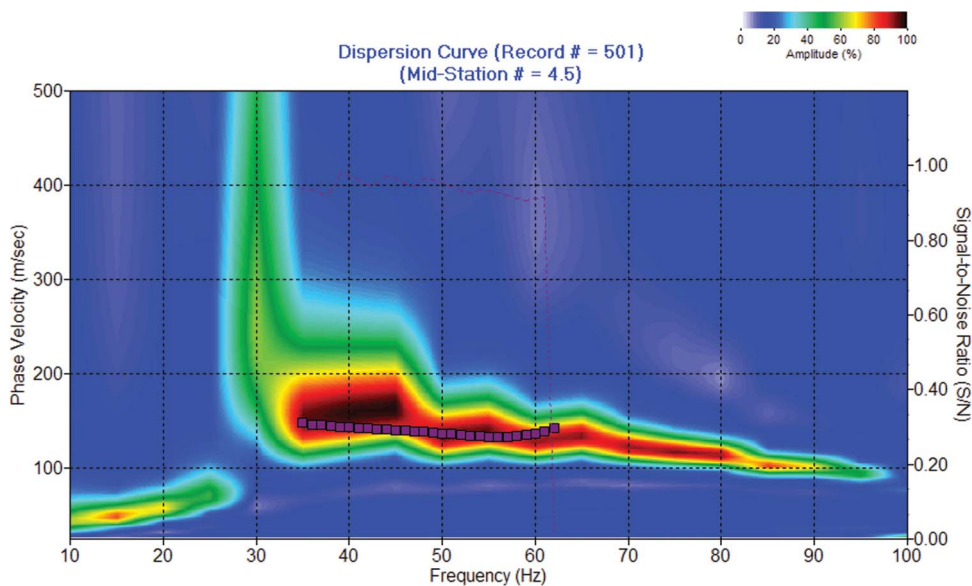


Figure 7. Typical dispersion curve of ballast bed.

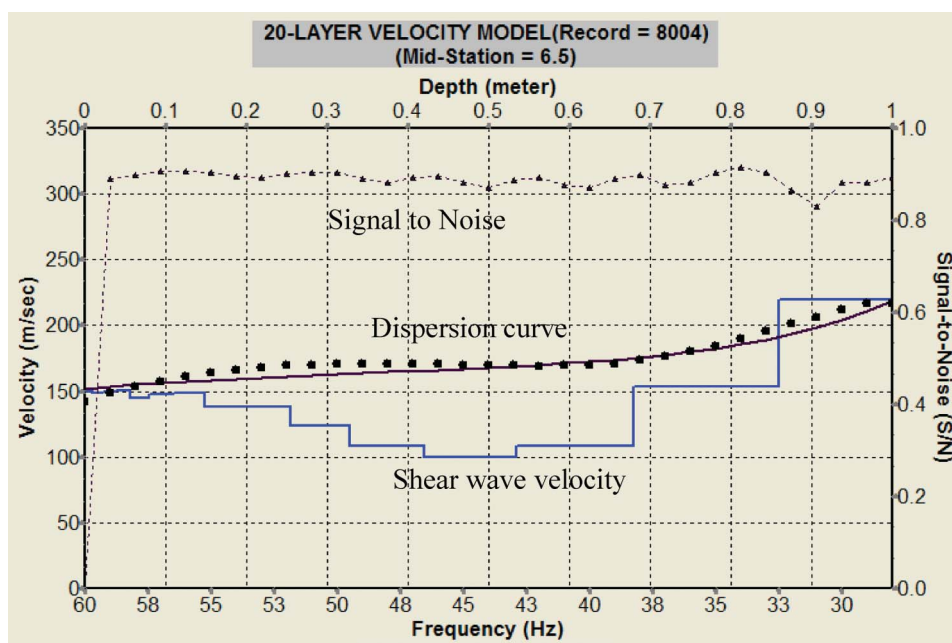


Figure 8. Typical velocity of ballast section corresponding to Figure 2.

velocity, measured using the resonant column test by Bei (2005). Figure 8 shows a typical shear wave velocity for cross-section H (refer Figure 2). The top layer has an average shear wave velocity (V_s) of about 148 m/s which corresponds to clean ballast having a bulk density of 1.66 ton/m^3 . An average V_s of 135 m/s corresponds to the second layer of clean ballast having a bulk density of 1.59 ton/m^3 . The average V_s of 115 and 103 m/s corresponds to the capping layer and sub-grade layer below the ballast layer. Below the sub-grade the V_s values increase because of the concrete floor under the model track.

In general the average shear wave velocity of clean ballast is above 125 m/s and fouled ballast is above 80 m/s.

Figures 9a and 9b show that initially increasing in the degree of fouling increases the velocity of the shear wave, which is similar to increasing the density due to initial fouling. The shear wave velocity of clean ballast increases when a certain amount of fouling materials is added, after which the velocity of fouled ballast is lower than the clean ballast. With a lower amount of fouling the shear wave velocity of ballast fouled with coal is slightly more than when fouled with clayey sand. However,

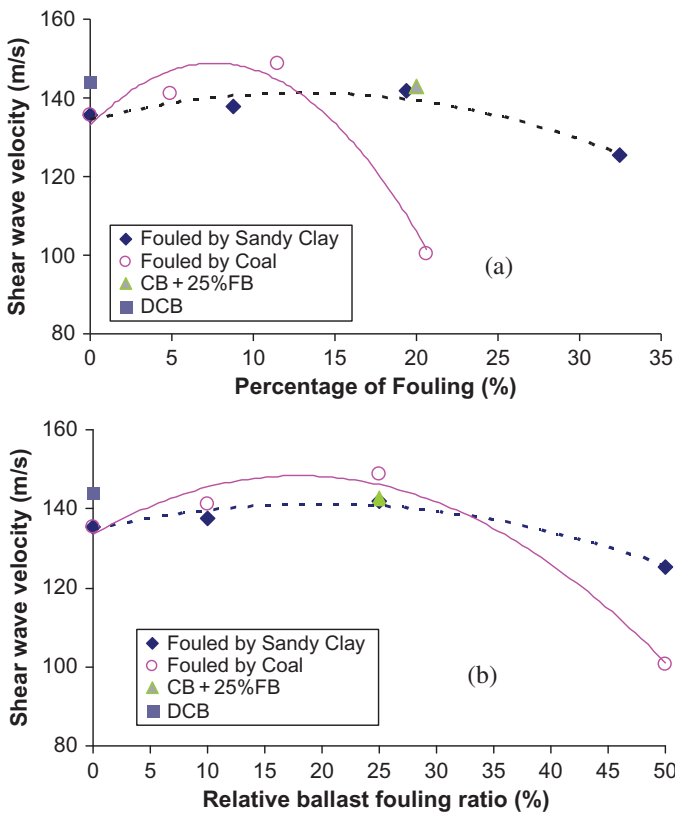


Figure 9. Shear wave velocity of ballast with respect to degree of fouling (a) shear wave velocity versus % of fouling and (b) shear wave velocity versus relative ballast fouling ratio.

a higher degree of fouling with coal leads to a lower shear wave velocity. Why the shear wave velocity is higher when the amount of coal fouling the ballast is less may be attributed to the size of the particles and specific gravity of the coal. The particles of coal may break down in the concrete mixer which could lower the shear wave velocity of fouled ballast more than ballast fouled by clayey sand. The shear wave velocity in section C with ballast fouled by crushed rock was similar to the ballast in Section D fouled with clayey sand.

Because this paper concentrated on ballast properties, only the shear wave velocities of the ballast layer are presented and discussed. The low strain shear moduli of each section were estimated using $G_o = \rho V_s^2$ whilst considering the average shear wave velocity and density of each section. The fouling characteristics and low strain shear modulus of clean and fouled ballast are shown in Figures 10a and 10b.

The shear moduli of clean ballast are above 29–34 MPa for the range of density from 1.58 to 1.64 ton/m³. These values are comparable to the shear modulus of fresh ballast given by Ahlf (1975), Narayanan et al. (2004) and Suiker et al. (2005). When compared to Sections F and H the increase in density of clean ballast increases the shear modulus, as expected. If clean ballast is mixed with 25% pulverized rock, the density and compaction of the track bed increases considerably, which results in higher values of G_{max} to about 41 MPa. The shear moduli of ballast fouled by clayey sand vary from 29 to 43 MPa. The shear

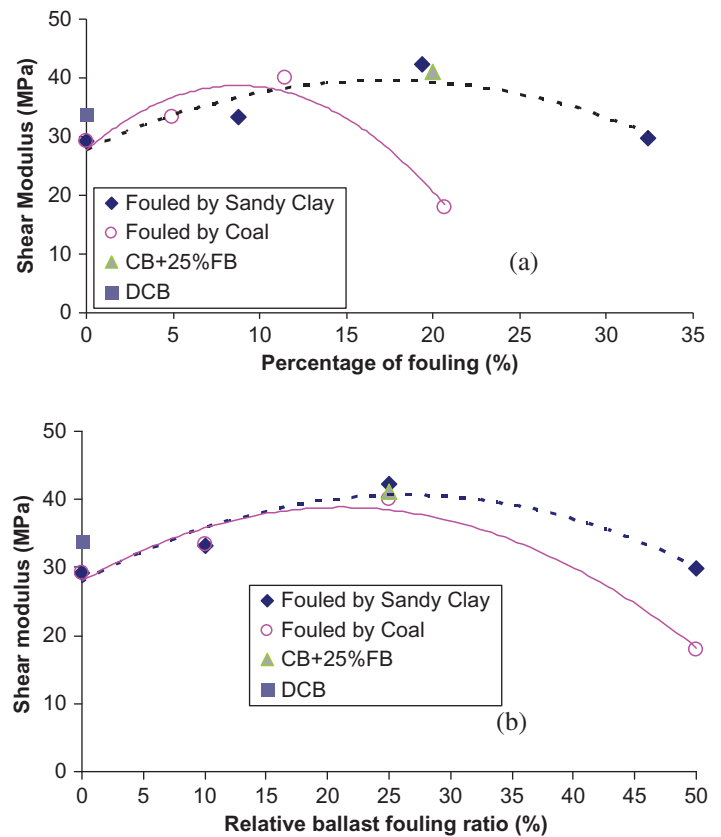


Figure 10. Shear modulus of ballast with respect to degree of fouling (a) shear modulus versus % of fouling and (b) shear modulus versus relative ballast fouling ratio.

moduli of ballast fouled by coal varies from 17 to 40 MPa. This is where the lowest shear modulus for Section I and highest value for Section B was observed. Similar patterns can be found between the sections of ballast fouled by coal and clayey sand due to variations in the specific gravity of fouling materials, as discussed earlier. The percentage of fouling has been used to further discuss the effects of the degree of fouling on shear properties and permeability. Figure 11 shows the measurement between the percentage of fouling and the R_{bf} .

Results and discussion

The shear moduli of all the Sections were normalised by the shear modulus of clean ballast with a density of 1.587 ton/m³, which is similar to the density of typical Australian rail tracks (Budiono et al. 2004), i.e. G_{max}/G_{clean} . Figures 12a and 12b show the G_{max}/G_{clean} ratio versus the percentage of fouling and R_{bf} for ballast fouled by coal and clayey sand, respectively. Figure 12a shows the different trends for ballast fouled by coal and clayey sand. This difference is attributed to the fact that the specific gravity of the fouling material was not considered. Figure 12b shows the revised patterns between the two types of fouling materials because R_{bf} considers the specific gravity of the fouling materials. It can be seen that the rate of increase

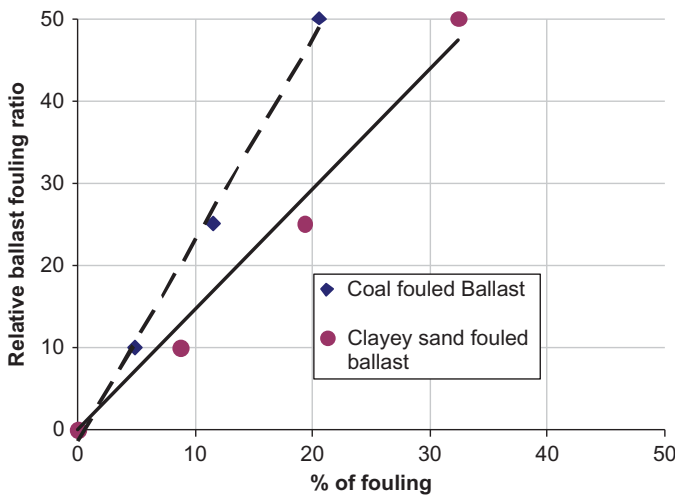


Figure 11. Relation between percentage of fouling to Relative ballast fouling ratio.

and decrease of G_{max}/G_{clean} of ballast fouled by coal is higher than when fouled by clayey sand. For the same percentage of fouling and R_{bf} , ballast fouled by coal has a higher G_{max}/G_{clean} on the left side of the peak while ballast fouled by clayey sand has a higher G_{max}/G_{clean} on the right side.

The shear wave velocity and modulus of fouled ballast increases initially to reach maximum values and then begins

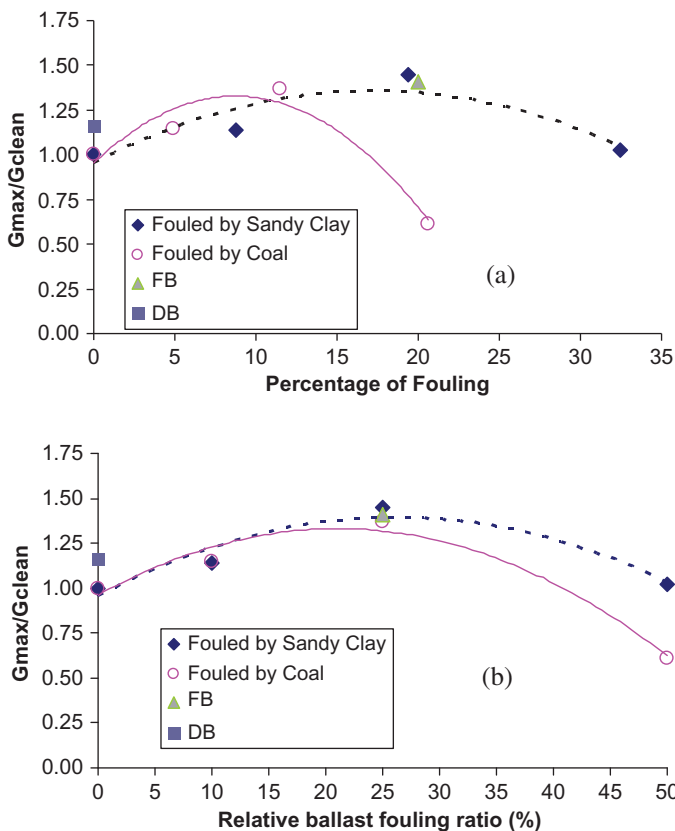


Figure 12. Normalized shear modulus for the fouled ballast, (a) shear modulus versus % of fouling and (b) shear modulus versus relative ballast fouling ratio.

to decrease. Track maintenance should be carried out based on the degree of fouling but at present there is no clearly defined criterion from which to begin maintenance. This study has shown that after a particular degree of fouling the shear properties of fouled ballast decrease with an increase in the degree of fouling. The OFP corresponds to the highest shear stiffness of fouled ballast, beyond which the shear stiffness decreases considerably. A certain amount of fouling material can be an advantage to the track by optimising the G_{max} of the ballast. To identify the OFP of ballast fouled with clayey sand the shear wave velocity and modulus with the percentage of fouling are shown in Figure 13. The OFP for ballast fouled with clayey sand ranges from 13 to 17% when both the shear wave velocity and shear modulus are considered. Figure 14 shows the variation in shear wave velocity and shear modulus, with the percentage of fouling, where the OFP for ballast fouled with coal is between 7 and 9%.

Figures 13 and 14 clearly show that the OFP based on shear modulus is slightly more than that based on the shear wave velocity. In the field the ballast density may not vary much so the shear wave velocity can be considered an ideal parameter for identifying the OFP. Even though the shear stiffness of fouled ballast decreases after the OFP it is still greater than the shear stiffness of clean ballast, which means that the track is resilient enough until it reaches a CFP. Beyond this point the stiffness and drainage conditions of fouled ballast may not be acceptable and track maintenance is required, as discussed later. The critical point is a percentage where the shear wave velocity of fouled ballast becomes less than clean ballast and the track shows unacceptable drainage. The permeability of fouled ballast less than 10^{-4} m/s is considered unacceptable based on Selig and Waters (1994). The results of the permeability test for ballast fouled with clayey sand are compiled from Wallace (2003), and unpublished work for ballast fouled with coal. To identify the CFP the combined plots of shear wave velocity and permeability have been plotted with respect to the percentage of fouling. Figures 15 and 16 show the variation in shear wave velocity and permeability with the percentage of fouling for ballast fouled

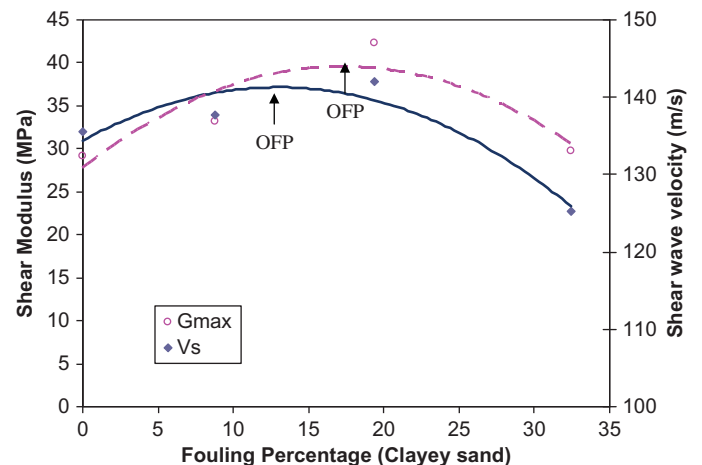


Figure 13. Optimum fouling of clayey sand fouled ballast.

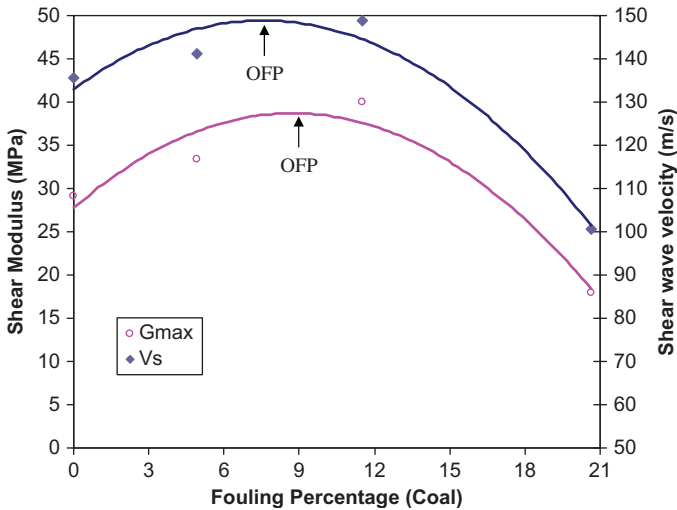


Figure 14. Optimum fouling of coal fouled ballast bed with best fit.

with clayey sand and coal, respectively. As the fouling of the track bed increases the shear wave velocity overall ballast permeability decreases rapidly before approaching OFP. After OFP the permeability decreases marginally. With both figures the shear wave velocity of fouled ballast decreases less than clean ballast (horizontal line) when the permeability approaching 10^{-4} m/s (vertical line). This point can be defined as the CFP where track maintenance becomes necessary. From these results the critical percentages of fouling for ballast fouled with clayey sand and coal are approximately 26 and 16%, respectively. These results of CFP from the model track can be reduced by considering other factors of fouling in the field track.

Practical implications

The OFP and CFP introduced from the model track in this study were compared to the performance of a real track. Two samples of

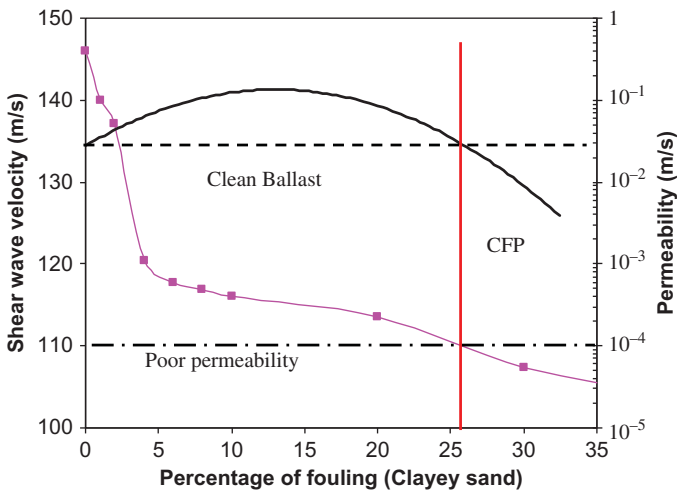


Figure 15. Shear wave velocity and permeability of clayey sand fouled ballast.

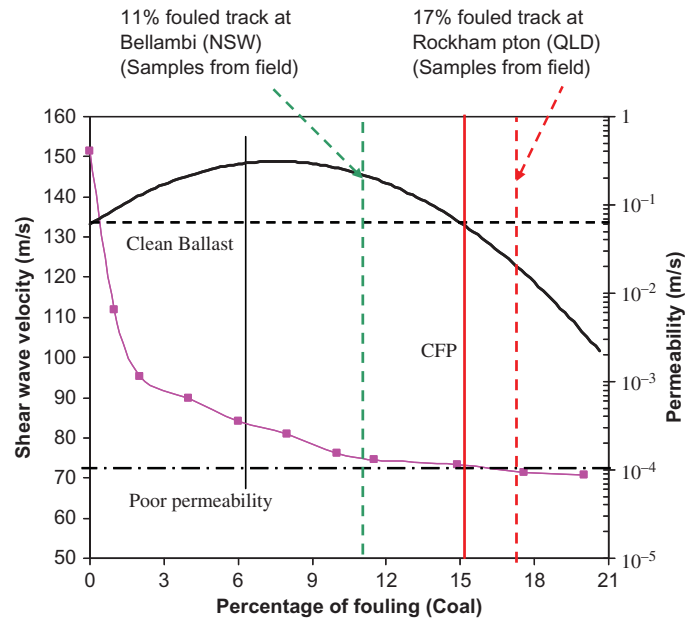


Figure 16. Shear wave velocity and permeability of coal fouled ballast

fouled ballast were collected from two different places in Australia i.e. Bellambi (NSW) and Rockhampton (Queensland), and the percentage of fouling was determined. Both samples were fouled mainly by coal dust. The particle size distribution and percentage of fouling are shown in Figure 17. According to the rail industry the condition of the track at Bellambi was normal but relatively poor at Rockhampton and was recommended for maintenance. The sample from Bellambi shows that the ballast bed could be categorised as ‘moderately clean’ based on the percentage of fouling but the sample from Rockhampton categorised the bed as fouled. The percentage of fouling for these field samples were plotted in Figure 16. The shear modulus at Bellambi was close to the OFP where the degree of fouling is acceptable while the samples from Rockhampton were after the CFP (Figure 16), which suggests that their performance is unacceptable in terms of shear stiffness and drainage.

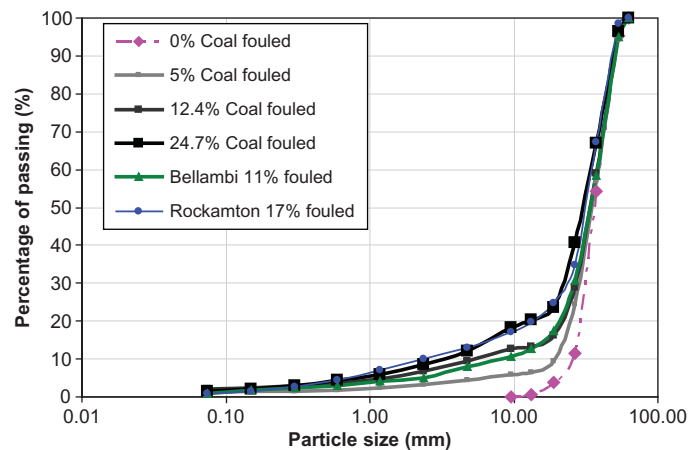


Figure 17. Gradation of field track samples at Bellambi and Rockamton with coal fouled ballast and clean ballast

Conclusions

A typical model track of clean and fouled ballast beds was designed and built at the University of Wollongong. A one dimensional MASW survey was carried out and average shear wave velocities were measured. The shear stiffness of fouled ballast immediately increases to a maximum value and then decreases. The point corresponding to the peak shear strength is called an OFP. A ballast bed fouled with coal reaches its OFP ahead of ballast fouled with clayey sand. Ballast fouled with coal has relatively higher shear strength before OFP but ballast fouled with clay has relatively higher shear strength afterwards.

The shear stiffness and drainage criteria of fouled ballast were combined to defined the CFP, the point at which the shear stiffness of fouled ballast is less than clean ballast and drainage is unacceptable. The critical fouling percentage for ballast fouled with clayey sand is 26 and 16% for ballast fouled with coal. The results from these model tracks were compared to a field track fouled by coal. The percentage of fouling of normal track at Bellambi (NSW) was close to the OFP, whereas the relatively poor track at Rockhampton (Queensland) was close to the CFP.

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