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Characterization of Clean and Fouled Rail Track Ballast Subsurface Using Seismic Surface Survey Method: Model and Field Studies

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ABSTRACT: The efficiency of track foundation material gradually decreases due to insufficient lateral confinement, ballast fouling, and loss of shear strength of the subsurface soil under cyclic loading. This paper presents characterization of rail track subsurface to identify ballast fouling and subsurface layers shear wave velocity using seismic survey. Seismic surface wave method of multi-channel analysis of surface wave (MASW) has been carried out in the model track and field track for finding out shear wave velocity of the clean and fouled ballast and track subsurface. The shear wave velocity (SWV) of fouled ballast increases with increase in fouling percentage, and reaches a maximum value and then decreases. This character is similar to typical compaction curve of soil, which is used to define optimum and critical fouling percentage (OFP and CFP). Critical fouling percentage of 15 % is noticed for Coal fouled ballast and 25 % is noticed for clayey sand fouled ballast. Coal fouled ballast reaches the OFP and CFP before clayey sand fouled ballast. Fouling of ballast reduces voids in ballast and there by decreases the drainage. Combined plot of permeability and SWV with percentage of fouling shows that after critical fouling point drainage condition of fouled ballast goes below acceptable limit. Shear wave velocities are measured in the selected location in the Wollongong field track by carrying out similar seismic survey. *In-situ* samples were collected and degrees of fouling were measured. Field SWV values are more than that of the model track SWV values for the same degree of fouling, which might be due to sleeper's confinement. This article also highlights the ballast gradation widely followed in different countries and presents the comparison of Indian ballast gradation with international gradation standards. Indian ballast contains a coarser particle size when compared to other countries. The upper limit of Indian gradation curve matches with lower limit of ballast gradation curves of America and Australia. The ballast gradation followed by Indian railways is poorly graded and more favorable for the drainage conditions. Indian ballast engineering needs extensive research to improve presents track conditions.

KEYWORDS: Railway track, ballast, gradation, fouling, shear wave velocity

Introduction

Railways are massive transport system, which carry goods as well as passengers. Derailing of trains causes major accidents in many countries particularly in India. Mechanical aspects such as broken rails, faults in the train and its wheels, geotechnical aspects like misaligned rails due to track foundation problems and functional aspects of excessive speed can cause derailing. Most of the time geotechnical aspects play a vital role when compared to mechanical and functional aspects. The geotechnical components of rail tracks are a layered foundation consisting of ballast followed by compacted sub ballast or a capping layer placed above the formation soil. Ballast is a coarse granular medium (usually hard rock) placed above the sub ballast and below the rails. The load from the sleepers is distributed to the sub ballast and compacted earth through the main ballast section. A rail ballast bed acts as the main foundation for the above capping layers and performs many roles for the proper functioning of the railway networks. Rail ballast is a uniformly graded coarse aggregate produced from crushing locally available rocks such as granite, basalt, limestone, slag or gravel.

The efficiency of track foundation material gradually decreases due to insufficient lateral confinement, ballast fouling, and loss of the shear strength of soil due to local phenomena of liquefaction and clay pumping. A high lateral movement of ballast may occur due to the over limit of wheel load and ballast fouling. Ballast contamination or the filling of voids due to ballast breakdown and infiltration of other materials from the ballast surface or infiltration from the base of the ballast layer is called ballast fouling. The fouling of ballast can be from the surrounding dust, slurried (pumped) formation soil (soft clays and silts liquefied under saturated conditions) and coal from freight trains as well as ballast degradation (fine particles then migrating downwards). High maintenance costs in the railways are mainly due to the above geotechnical problems. Finding proper means of reducing the maintenance costs and the frequency of regular repair cycles has been a priority for most railway organizations. Extensive researches have been conducted in geotechnical engineering particularly on sand, clay, road base and rock fills (for dams). But limited research has been conducted on geotechnical issues related to the rail track worldwide particularly in India.

This paper presents the characterization of rail ballast and subsurface using seismic surface survey to identify problems related to ballast fouling and to measure strength of capping and sub grade layers. A model rail track was built with nine sub-sections, each having different fouling characteristics. MASW survey was performed on the top of each section of ballast. Shear wave velocity has been measured and used to characterize ballast bed and the layers below. Detailed discussion on model study for ballast fouling can be found in Anbazhagan et al. [1]. Shear wave velocities were measured three times in each section and average values were calculated. Measured shear wave velocity of clean and fouled ballast

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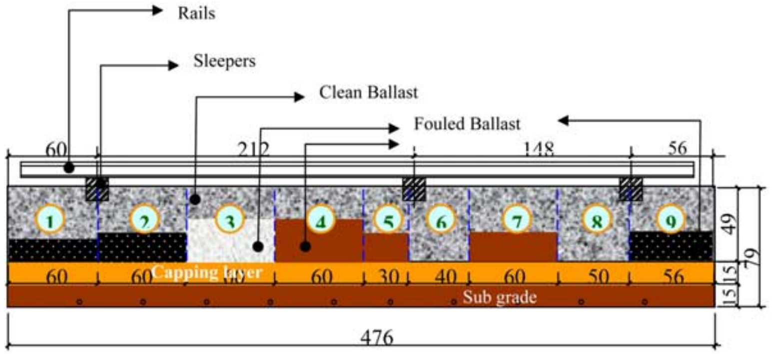


FIG. 1—*Sectional details of the model track constructed for the study (all dimensions are in cm).*

versus percentage of fouling form a curve similar to the typical compaction curve of soil, which is used to define optimum and critical fouling percentage. Coal fouled ballast reaches optimum and critical fouling point before sandy clay fouled ballast. An increase in degree of fouling decreases the drainage conditions of the track. Combination of permeability and SWV versus percentage fouling shows that permeability fouled samples after critical fouling point goes below acceptable limit of drainage condition. Defined optimum and critical fouling points are comparable with field performance of rail tracks in Bellambi (NSW) and Rockhampton (Queensland) in Australia. Model track SWV results are also compared with SWV from field experimental studies at Wollongong, NSW rail tracks. Field SWV values are more than model track SWV values for similar ballast fouling condition, which might be due to sleeper confinement in the field track. Railway ballast gradation of American Railway, French Railway, British Railway, and Australia Railway are summarized by highlighting its role and importance in the track performance. Indian ballast gradation is compared with internationally accepted ballast gradation. Further, present status of Indian railway track ballast fouling and gradations are discussed by collecting *in-situ* samples from different locations. Fouled ballast samples of different age groups were compared. Indian rail ballast is poorly graded when compared other countries ballast gradations. Limited research has been carried out in India to improve ballast gradation and to study ballast fouling.

Track Maintenance and Ballast Fouling

The foundation of rail tracks deforms vertically and laterally under repeated wheel loads (cyclic loading) causing a deviation from the design geometry. Even though the deviations are apparently small, but they are irregular and depends on the geotechnical properties of the track foundation, which in turn further worsens the track alignment and stability. Worldwide, rail track maintenance is an expensive and routine exercise. A major portion of the maintenance budget is being spent on geotechnical problems [2–4]. Maintenance is mandatory because of ballast fouling and the weakening of track subsurface layers (sub ballast and sub grade). Fouling is a term that indicates the contamination of ballast by the presence of fines. The major fouling reported worldwide is attributed to the breakdown of ballast (fine ballast), outside contamination by coal dust from trains carrying coal, and soil intrusions from the base. Fouled ballast can cause many major problems including reduction in vertical resistance, reduction in the void space thereby leading to a considerable decrease in the movement of particles through the ballast, poor drainage of water falling on the track and vegetation growth over the rail track. It is therefore mandatory to identify the degree of fouling and to remove the fine materials before critical problems occur, so as to increase the performance of the rail track. The scales that are widely used to determine fouling quantities are the Fouling Index, Percentage of Fouling, the D-Bar method, and Percentage Void Contamination [1]. The percentage of fouling (% fouling) is the ratio of the dry weight of material passing through a 9.5 mm sieve to the dry weight of the total sample [5]. The first three measures are commonly used; the fourth one is used by Queensland Railways. These methods are laboratory based and require field sampling and testing, which are normally carried out by digging out trenches with even spacing. These processes require a lot of resources (i.e., time, money and man power). The non-destructive testing of ground penetration radar, infrared imaging, seismic surveys and electrical resistivity are the other popular methods for identifying fouling in the field [1]. Various studies have been carried out using non-destructive testing of Ground Penetration Radar (GPR) to map the sub-surface of ballast sections. GPR is a modern geophysical approach, which can provide information about the formation of the track-bed interface [6]. 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 the information on fouling depth but it cannot clearly define the degree or type of fouling. Reference 1 measured shear wave velocity and density in the model track sections and estimated shear modulus of clean and fouled ballast. Authors have highlighted that MASW gives shear stiffness of ballast bed and are more effective than any other methods but it may require more time to carry out test in the field.

Model Rail Track

A section of full-scale railway track has been built in the Civil Engineering Laboratory, University of Wollongong for this study. The model track has all of the components of a Railway track system, including sub grade, capping layer, and ballast (clean/fouled). No loading tests were carried out on the model track and hence a box was constructed with two layers of plywood boards. The internal dimensions of the box were 4.76 m (length), 3.48 m (width), and 0.79 m (height). A sub grade layer of sandy clay, a capping layer of road base material and a ballast layer, forms the track. The thickness of these layers were 15 cm for the sub grade, 15 cm for the capping layer and 49 cm for the ballast. Figure 1 shows the cross section across the model track up to top of the rail. The sub grade and capping layers were being compacted and combined using a

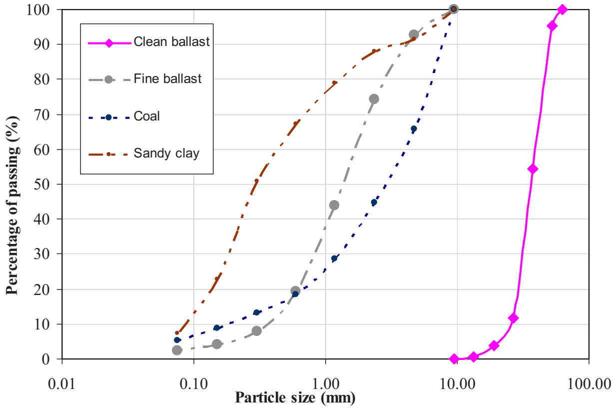


FIG. 2—*The particle size distribution of the materials used to construct model track.*

handheld vibrating compactor. In this study MASW was carried out before placing the sleeper and rails i.e., the total section height equal to 57 cm. The clean and fouled ballast were placed layer-by-layer having a thickness of 4–6 cm and compacted using handheld vibrating plate. During compaction, plywood boards were inserted between 2 sections as partitions to secure a distinct vertical interface between adjacent sections. A layer of Geotextile was placed between adjacent sections to prevent fouling materials flowing from one section to another. Two long timber bars with notches were used to fix the partitions. The materials used in the construction were clean ballast (CB), fine ballast/ pulverized rock (FB), coal (C), and clayey sand (SC). Figure 2 shows particle size distribution of materials used to construct model track. Table 1 shows sectional details with fouling charter and density. A handheld vibrating plate was used for compacting equal layers of ballast of clean sections (6 and 8). The dense clean ballast in Sec. 8 was built by using more layers than in Sec. 6. The fouled sub-sections were prepared by following two different methods. In Sections 1 to 5, a layer of fouling material was placed on top of a layer of clean ballast before the compaction. During the preparation, a layer of clean ballast was first placed in the section, and then the corresponding fouling material of quantity calculated according to a certain percentage of fouling value was spread uniformly on the ballast surface. After that, the ballast together with the fouling material was compacted using a hand-held compactor. For Secs. 7 and 9, by considering the volume of fouling materials, the ballast and fouling materials were mixed together using a concrete mixer and then compacted in the sections layer by layer as above. Detailed discussion on construction of model track and materials used can be found in Anbazhagan et al. [1].

Seismic Surface Wave Survey

A number of seismic methods have been proposed for near-surface characterization and measurement of shear wave velocity using great variety of testing configurations, processing techniques and inversion algorithms. The most widely used techniques are Spectral Analysis of Surface Waves (SASW) and Multichannel Analysis of Surface Waves (MASW). The SASW method was being used for subsurface investigation for several decades [7–11]. MASW is the new improved technique by incorporating a multichannel analysis of surface waves using active sources [12–14]. The MASW has been found to be a more efficient method for unraveling the shallow subsurface properties [12,15,16]. MASW is extensively applied to earthquake geotechnical engineering for the seismic microzonation and site response studies [17–20]. In particular, the MASW is used in geotechnical engineering for the measurement of shear wave velocity and dynamic properties [21–23], identification of subsurface material boundaries and spatial variations of shear wave velocity [24].

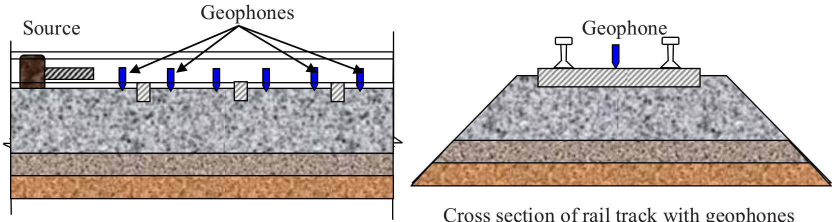
MASW systems consisting of 24 channel SmartSeis seismograph with 12 geophones of 10 Hz capacities were used. The seismic waves were created by impulsive source of 1 kg sledgehammer with 70 mm × 70 mm aluminum plate with a number of shots. 12 geophones were arranged parallel to the y-axis along Secs. 1–9 and survey was carried out. Figure 3(*a*) and 3(*b*) shows typical arrangement of geophones in the model track and field track with typical photograph image. Source to receiver distance and spacing of geophones were investigated, and a good signal was obtained for a geophone spacing (ΔX) of 0.25 m and source to first receiver spacing (X) of 0.5 m in the model track. These spacing were adjusted in the field based on sleeper locations and a good signal was obtained for ΔX of 0.6 m and X of 1.2 m. This configuration was used to survey all the sections and was similar to hard material (pavement) mapping field configuration [22]. Each section had been surveyed three times and the seismic signals were recorded at a sample interval of 0.125 ms and record length of 256 ms [1].

Shear Wave Velocity Of Ballast

Shear wave velocity (SWV) of the subsurface material is an important dynamic property which is mainly used in vibration analysis. SWV is also a recognized parameter to indicate the behavior of

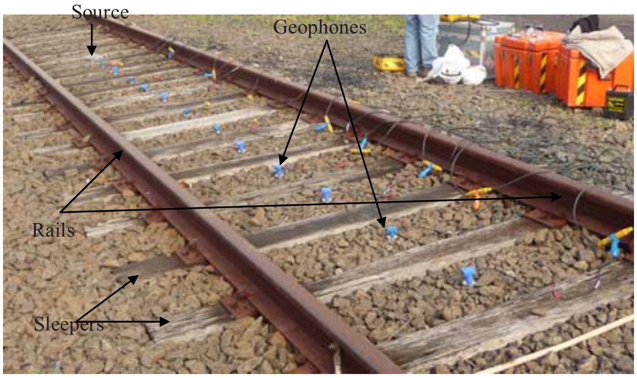
TABLE 1—*Sectional detail with degree of fouling and densities of model track.*

Section	Description	Fouling Percentage	Density (ton/m^3)	Average Shear Wave Velocity (m/s)
1	Ballast+Coal	4.94	1.675	141.24
2	Ballast+Coal	11.51	1.807	148.78
3	Ballast+Fine Ballast	20	2.017	142.75
4	Ballast+Clayey sand	19.35	2.096	142.0
5	Ballast+Clayey sand	8.76	1.753	137.69
6	Clean Ballast-I	0	1.587	125.0
7	Ballast+Clayey sand	32.43	1.899	125.29
8	Clean Ballast-II	0	1.636	155.00
9	Ballast+Coal	20.64	1.770	100.53



Geophones arrangements in Field and model track
(a)

Cross section of rail track with geophones
(b)



(c)

FIG. 3—*Typical arrangement of geophones over a ballast (a) model track; (b) section of typical rail track with geophones; and (c) testing in the field track.*

subsurface materials during earthquake. Dynamic moduli of ballast and subsurface are widely used to understand and model the subsurface behavior of track structure and below layers due to train loading. Properties of ballast considering the small-strain tests were appropriate to model the track and below layers as the repeated load induced by the train cause small strain in most of the cases. Even though SWV is an important parameter in many geotechnical applications, but its usage in railway engineering practice (ballast or subsurface layers) is very limited. It may be due to direct associated problems of carrying out SWV tests in the track beds, particularly on the field track. Seldom attempts have been made by the researchers to measure the shear wave velocity of ballast in the laboratories. Bei [25] carried out free-free Resonant Column Test [26] in a clean ballast sample of density 1.75 $\mathrm{ton/m^3}$ considering two vacuum levels of 37 kPa and 64 kPa. Author reported that the shear wave velocity of clean ballast is 156.4 m/s and 169.4 m/s for above vacuum levels. Ahlf [27], Narayanan et al. [28], and Suiker et al. [29] have also reported shear modulus of fresh ballast.

Measurement of shear wave velocity using non-destructive field testing is very popular in road and pavement engineering. But very limited literature is available for the field based shear wave velocity measurement in the rail track. In this study, an attempt has been made to measure the shear wave velocity of ballast bed and subsurface by constructing large-scale model track in the laboratory and in the field rail tracks. Sequences of experimental seismic data were recorded using geophones in the model and the field track, which were used to get dispersion curves of the rail track sections. The dispersion curve 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 were used to get a dispersion curve with a high signal to noise ratio of the each sections of ballast. The dispersion curves were constructed by considering frequencies of 25 to 100 Hz and had a signal to noise ratio of 60 and above. Typical dispersion curve of model track is shown in Fig. 4. An inversion analysis must be carried out by an iterative inversion process that requires the dispersion data to profile the shear wave velocity of the subsurface medium. Typical shear wave velocity profile obtained for Sec. 8 is shown in Fig. 5 and the interpretation will be presented in the next section. Figure 5 also gives sectional details of model track with SWV. The top layer has an average SWV of about 148 m/s, which corresponds to clean ballast having a bulk density of 1.66 $\mathrm{ton/m^3}$. An average SWV of 135 m/s corresponds to the second layer of clean ballast having a bulk density 1.59 $\mathrm{ton/m^3}$. The average SWV of 115 m/s and 103 m/s corresponds to the capping layer and sub-grade layer below the ballast layer. Below the sub-grade the SWV values increase because of the concrete floor under the model track. Shear wave velocity obtained for clean ballast is well comparable with Bei [25] results.

Results of Model Track

The shear wave velocity of model track Secs. 1–9 was determined by averaging three sets of results, which has a standard deviation of less than 9. The average shear wave velocity of clean ballast and fouled ballast are given in Table 1 column 4. Shear wave velocity of Sec. 6 is slightly less than Sec. 8, which may be due to the difference in the densities (see Table 1). Here it should be noted that the typical density of Australian rail tracks ballast is 1.587 $\mathrm{ton/m^2}$ [30]. Density of 1.6 $\mathrm{ton/m^3}$ and shear wave velocity of 135 m/s can be taken as a reference value for clean ballast. The average SWV of clayey sand fouled ballast and coal-fouled ballast sections are given in Table 1. Ballast fouled by fine ballast, i.e., Sec. 3 (broken pieces) has SWV of 142.75 m/s for a density 2.017 $\mathrm{ton/m^3}$. From the above results it can be observed that the SWV of fouled ballast is more than that of the clean ballast for lower percentage of fouling and less than clean ballast for higher percentage of fouling. The slightly higher shear wave velocity in coal fouled ballast in

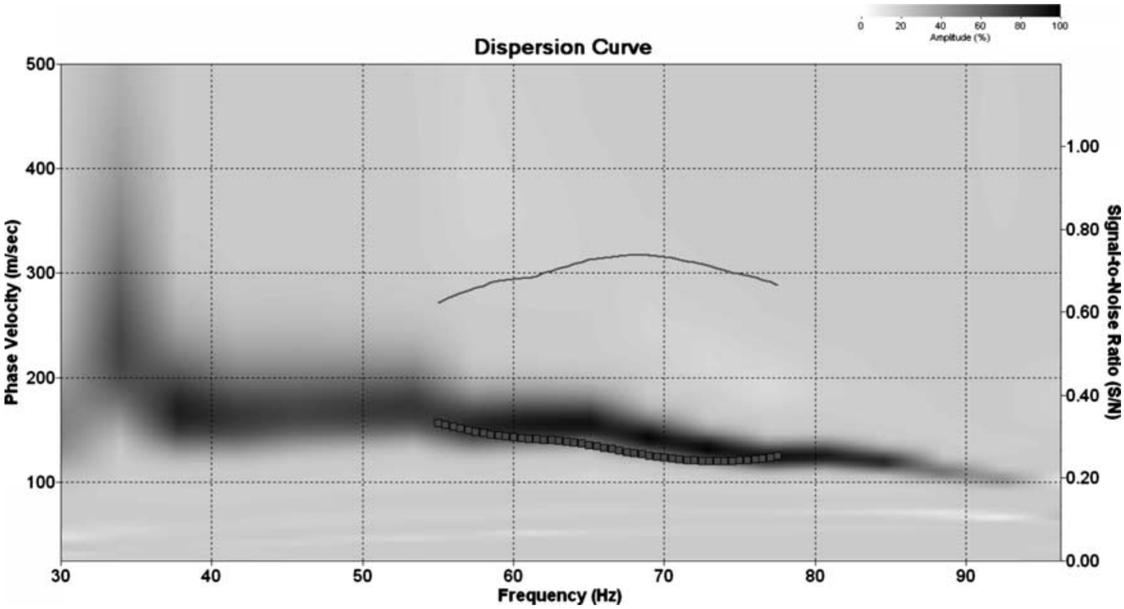


FIG. 4—*Typical dispersion curve obtained from the model track.*

lower percentage of the fouling may be attributed by the particle size of the coal (see Fig. 2). The particles of coal may break down in the concrete mixer, which could lower the shear wave velocity of fouled ballast more than the ballast fouled by clayey sand. However, a higher degree of fouling with coal leads to a lower shear wave velocity.

In total, a single clean ballast and three-fouled ballast SWV (four points) were available for each type of fouling materials. These points were connected using second order polynomial having R^2 value of 0.9 for the further discussion and interpretation. Figure 6 shows the variation of SWV with respect to the percentage of fouling. From Fig. 6 it can be observed that the SWV of the fouled ballast initially increased from clean ballast SWV and reached the maximum value, and then started decreasing. This can be explained better using Fig. 7(*a*)–7(*c*). Figure 7(*a*) shows a typical fresh clean ballast where there is no fouling and breakdown of ballast. This has a good load carrying capacity and drainage criteria according to design requirements. As time passes, ballast gets fouled by different means. When the degree of fouling is less i.e., enough to fill the voids in clean ballast, the ballast section becomes denser and compacted (see Fig. 7(*b*)), which increases the strength and reduces the drainage condition when compared to clean ballast (Fig. 7(*a*)). Filling of voids attributes to the increase of SWV in the lower degree fouling. When all the voids in clean ballast are filled, fouled ballast attains maximum strength and there will be considerable reduction in the permeability. Degree of Fouling keeps on

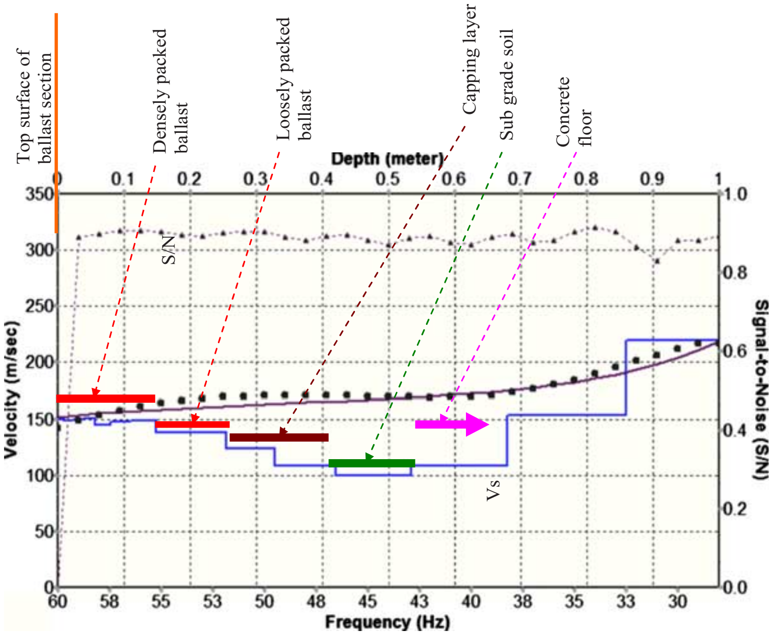


FIG. 5—*A typical shear wave velocity of Sec. 8 with sectional profile.*

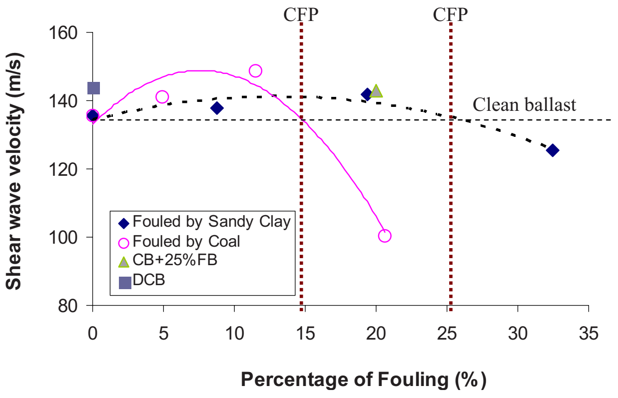


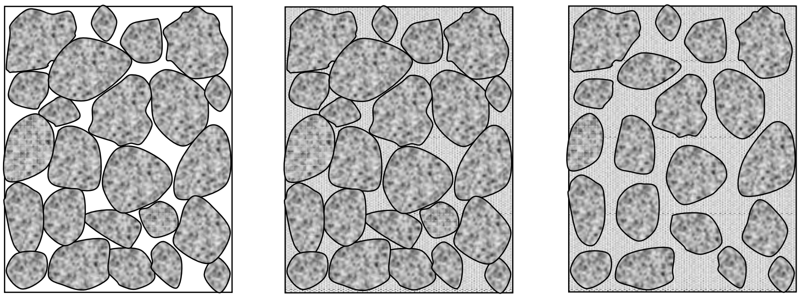
FIG. 6—*Shear wave velocity of ballast with respect to percentage of fouling (CB-clean ballast, FB-Fine ballast and DCB-Dense clean ballast).*

increasing beyond filling of voids due to trains and wagon movement. Filled fouling materials try to separate the ballast particles from being in contact with each others (loose contact of particles); typical illustration is shown in Fig. 7(*c*). At this stage, the strength and drainage conditions become considerably less than that of clean ballast(Fig. 7(*a*)) and all voids filled condition(Fig. 7(*b*)). If the fouling material fills all the ballast voids and the ballast is also in good contact with each other, the corresponding degree of fouling can show a maximum strength/SWV. These phenomena can also be observed in Fig. 6. The point corresponding to highest shear wave velocity because of ballast fouling, this can be called as the optimum fouling point (OFP). OFP of coal-fouled ballast is 8 % and clayey sand is 15 %. Beyond this peak point, the shear wave velocity decreases. Even though the SWV of fouled ballast decreases after the OFP, it is greater than the SWV of clean ballast which means that the track may be sufficiently resilient during this period. The shear wave velocity of fouled ballast reduces below shear wave velocity of clean ballast, which may not be acceptable in terms of strength and bearing capacity of the track. The degree of fouling corresponding to this point can be defined as critical fouling point (CFP) and beyond this point finer materials will be dominating. This study shows that Coal fouled ballast has CFP of 15 % and clayey sand fouled ballast has CFP of 25 %. It is noted that coal fouled ballast reaches the OFP and CFP before clayey sand fouled ballast. This may be attributed by the specific gravity difference between clayey sand fouled ballast and coal-fouled ballast. Different ballast Fouling scales and the influence of specific gravity of fouling materials were presented by Anbazhagan et al. [1] and Indraratna et al. [31].

Testing In The Field Track

MASW survey has been carried out in the field track in Wollongong Railway Station after necessary training and safety approval from New South Wales (NSW), Australia Rail Corporation. Three rail tracks have been indentified for the study, out of which one track is still used for parking the engine (called as up sliding track) and other two tracks are discarded for running and parking of trains. Survey carried out in the up sliding track has been presented in this section. Survey has been carried out in the two locations in the up sliding track. Instrument used for field track is similar to the model track but the spacing of geophones and source distances are adjusted according to sleeper spacing in the field rail track. Different source distance has been examined for constant geophone spacing of 0.6 m (equal to sleeper spacing in the rail track). The source distances of 0.6 m and 1.2 m have found to give good results with high resolution at top surface. Figure 3(*c*) shows geophone arrangements in the field track. Seismic signals are recorded and used for dispersion analysis to extract shear wave velocity as discussed previously. Typical shear wave velocity profiles obtained from both the locations in the up sliding track are shown in Fig. 8. Average shear wave velocity of 150 m/s for location 2 and 173 m/s for location 2 up to depth of 0.07 m was obtained. Shear wave velocity of subsurface is more than 180 m/s for both the locations indicating good sub ballast and sub-grade. Here it can be noted that both field ballast shear wave velocities are much more than model track shear wave velocities. In order to find out the degree of fouling in the up sliding field track, ballast samples were collected and tests were carried out in the laboratory.

Ballast section has been identified upto a depth of 55 cm in the location 1, below which the capping layer was found. Similarly ballast section has been identified upto a depth of 50 cm in the location 2, below which the hard layer was found which may be a weathered rock. Figure 9 shows particle size distribution of the field ballast samples with particle size distribution of clean ballast used in model track. Field ballast 1 had greater fines than field sample 2. Fouling measurement shows that field Ballast samples 1 and 2 have an average percentage of fouling of 2.25 and 11.50 %. This clearly shows that both ballast samples are well before optimum fouling points. Field ballast sample from location 2 has more fines (more



(a) Clean ballast

(b) Dirty ballast with fine particles filling voids

(c) Fouled ballast with aggregate to aggregate contact lost

FIG. 7—*[(a)–(c)] Ballast with different degree of fouling.*

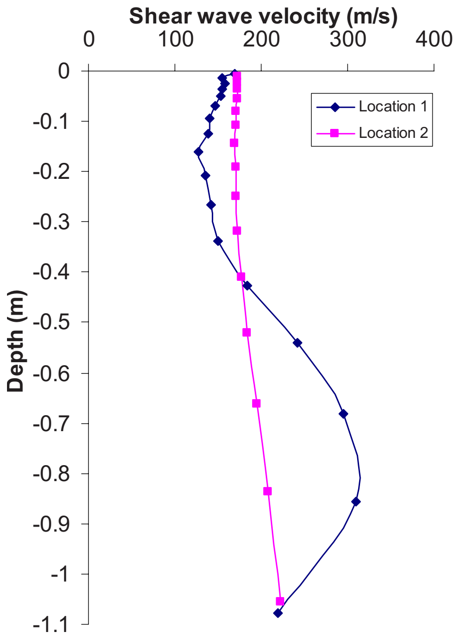
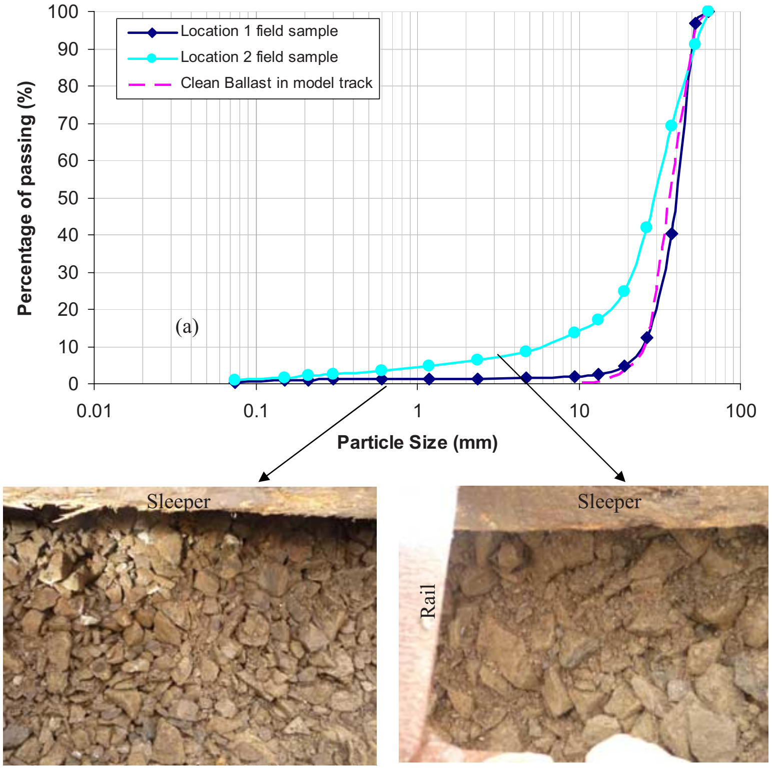


FIG. 8—*Shear wave velocity of filed Ballast samples.*

voids are filled so denser) than location 1 sample; this can be also evidenced by larger shear wave velocity of location 2 sample when compared with location 1 sample. Here it can also be noted that the particle size distribution curve of the field sample from location 1 is close to model track clean ballast gradation and, SWV of field sample 1 is slightly higher than model track dense clean ballast SWV of 144m/s (see Fig. 6, Y axis DCB). It should be noted that the density of field samples were not measured. But the SWV of the samples from locations 1 and 2 are higher than the model track SWV values, which may be attributed by type of fouling materials, density and ballast confinement by sleepers. It should be remembered that model track study was carried out before placing sleepers i.e., there was no confinement due to sleepers. Closer view of field fouled ballast samples for location 1 and 2 are shown in Fig. 9(*a*) and 9(*b*), respectively. This model track results may be used to assess the performance of fouled ballast track if ballast fouling is known. A detailed research is needed in the field track to confirm the trend of SWV variation in model track and variation of shear wave velocity for different degree of fouling.

Permeability and Shear Wave Velocity

The shear wave velocity gives an idea about the boundary for the optimum and critical degree of fouling. The SWV is indicative of only the strength of ballast foundation. In order to sustain good track performance, it is essential to maintain proper drainage conditions in the ballasted track apart from strength. The combined results of strength and permeability/Hydraulic conductivity are not available in the literature for the fouled ballast samples. Many studies have reported that the increase in the degree of fouling leads to the decrease in permeability in the field track and there by reducing the track resilience modulus, leading to growth of vegetation and reduction in performance. Permeability of fouled ballast of 10^{-4} m/s and less is unacceptable [5]. Degree of fouling was related to permeability of track ballast [5]. In this study the degree of



(b) (c)

FIG. 9—*[(a)–(c)] Field samples and model track sample; (a) particle size distribution of field samples with model track clean ballast; [(b) and (c)] photo of field samples from the location 1 and 2.*

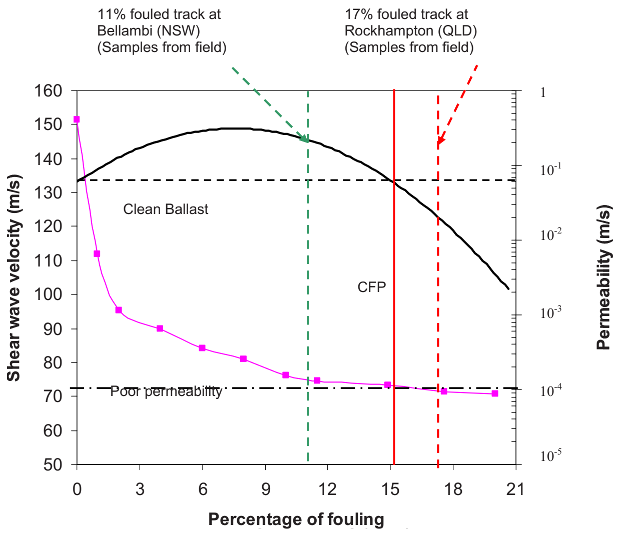


FIG. 10—*Combined plot of shear wave velocity and permeability with percentage of fouling; Field fouled ballast samples percentage of fouling with performance from the Australian rail industry.*

fouling is related to SWV of fouled ballast. Anbazhagan et al. [1] has complied permeability of clayey sand fouled ballast and coal-fouled ballast from experimental studies at University of Wollongong, Australia. Series of tests were carried out in University of Wollongong laboratory using large scale testing facility to measure the permeability of fouled ballast. The permeability can be related to shear wave velocity with common percentage of fouling in X axis [1]. The authors highlighted that the permeability is more than 10^{-4} m/s upto critical fouling point and beyond which permeability is less than 10^{-4} m/s, which is not acceptable. These combinations are also compared with the field performance record and fouled ballast samples. The coal fouled ballast samples from Bellambi (NSW) and Rockhampton (Queensland) in Australia were collected with rail industry performance note. 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 showed that the ballast bed could be categorised as 'moderately clean' based on the percentage of fouling but the sample from Rockhampton was categorised as fouled. Shear wave velocity of model track with CFP, permeability of coal fouled ballast and percentage of fouling of known track condition are shown in Fig. 10. The percentage of fouling at Bellambi was close to the optimum fouling point where the permeability is acceptable. The percentage of fouling of the Rockhampton samples falls after critical fouling point is reached and the SWV is less than the clean ballast; permeability is also unacceptable. These may be the reasons due to which Rock Hampton track performance is unacceptable and required immediate cleaning of ballast.

Derailing and Ballast Gradation

The primary geotechnical component of rail track foundation is the ballast section. Ballast section performance depends on four main geotechnical (index and engineering) properties of ballast materials [32]:

1. Character of constituent particles (size, shape, surface roughness, particle crushing strength and resistance to attrition, etc)
2. Bulk properties of the granular assembly (particular size distribution, void ratio or density and degree of saturation)
3. Loading characteristics (current state of stress, previous stress history and applied stress path) and
4. Particle degradation (combined effects of grain properties, aggregate characteristics and loading).

Many researchers outside India have studied the effects of the characteristics of constituent particles on the mechanical behavior of ballast and other coarse aggregates. Kolbuszewski and Fresrick [33] indicated that the angle of shearing resistance increases with large particle size. But Marachi et al. [34] and Indraratna et al. [4] presented experimental data to show that the angle of internal friction decreases with an increase in the maximum particle size. Particle shape plays an important role in shear strength. Angularity of particles increases the frictional interlocking between grains and thereby increases the shear strength. The angle of internal friction is remarkably high for angular aggregates when compared to that for sub-rounded aggregates [4,35–37]. Surface roughness or texture is the key factor that governs the angle of internal friction. Raymond et al. [2] concluded that particle shape and surface roughness are important and influence the track stability. Most of the ballast specifications stipulate crushed or fractured particles, which are defined as grains having a minimum of three crushed faces [32]. In a way similar to index properties, engineering properties also play a major role in track stability. It is interesting to note that the ballast behavior given by different researchers is indigenous and contradicting and may not be directly applicable to the ballast of the other countries. Selection of proper ballast (type and gradation) will help to optimize the track resilience modulus, which also reduces the breaking of the edges and there by to some extent fouling due to breakdown. Major problem due to ballast fouling is derailing of trains; many derails are being reported frequently in India.

Very limited literature or studies are available related to ballast fouling and its related research in India. In order to understand the problem in Indian rail tracks an attempt has been made to study the dimensional requirements of particle size distribution (grading) and particle shape by collecting different aged track ballast samples from the field. Poor gradation leads to the misalignment of sleepers and rails, reduces the bearing capacity of the track and increases the settlement. This can create track instability and other consequences. They are the major cause for the derailing of trains and discomfort to passengers. A specified ballast gradation must provide the following two key objectives:

- Ballast must have high shear strength to provide increased stability and minimum track deformation. This can be achieved by specifying broadly graded (well graded) ballast.
- Ballast must have high permeability to provide adequate drainage conditions; this readily dissipates excess pore water pressure and increases the effective stress. Specifying uniformly graded ballast can ensure this.

These two objectives are different and require optimized particle distribution without any compromise on quality. The optimum ballast gradation needs a balance between uniform and broad gradations. Developed countries have optimized ballast gradation through extensive research, but, in India, ballast gradations are uniform. Indian ballast gradations given in IRG-GE-1 [38] have been compared with the accepted international railway ballast gradations.

Figure 11 show the ballast gradation followed in American Railway Engineering and Maintenance of way Association [39] and Indian Railways (U and L indicated in figures represent the upper and

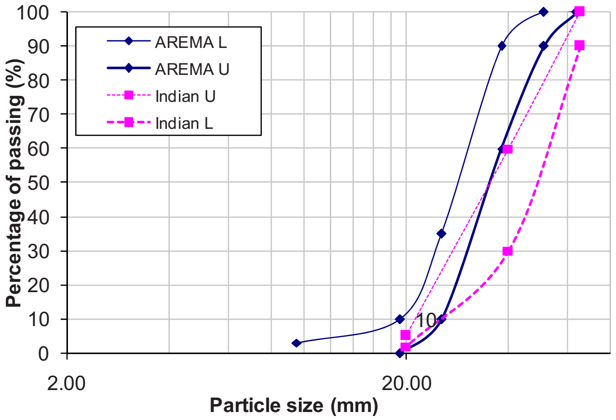


FIG. 11—*Ballast gradation followed in Indian with American Railway Gradation.*

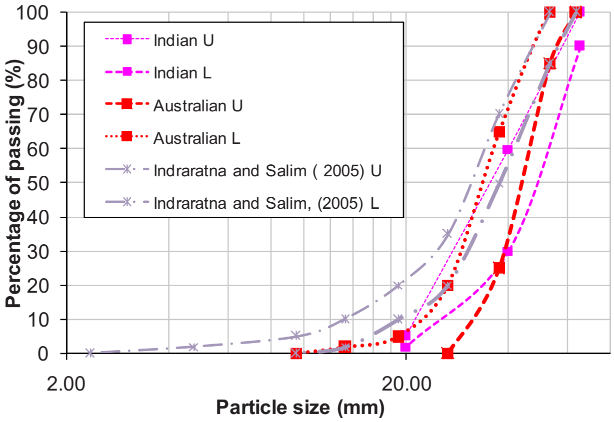


FIG. 13—*Ballast gradation followed in Australia and India with modified gradation suggested by Ref 26 based on Australian ballast study.*

lower limit). It clearly shows that the lowest particle size used in American railways is 9.5 mm whereas it is 20 mm in Indian railways. American railway gradations are relatively well gradated when compared to Indian railway gradations.

Figure 12 shows the ballast gradation followed by French railways and British railways [40] in comparison with Indian railways. About 50% gradations are similar for French and Indian railways. The gradations followed by British railways almost matches with Indian Railways. Indian ballast gradation is perhaps comparable because Indian railway ballast gradations are older and is adapted from the East Indian Rail Co., without much modification and research. French railway ballast gradation is coarser than Indian railway gradation and the minimum particle size of ballast used is 25 mm.

Figure 13 shows the upper and lower limit gradation followed in Australian (AU) railways [41] and Indian railways. From Fig. 13 it can be seen that, lower limit of 70 % passing gradation curves of the Indian railway ballast matches with the upper limit of the AU railway gradation curve. Lower limit of 70% to 40% passing gradation curves of Indian railway are in between the upper and lower limit gradation curves of the AU railway. Less than 40% passing lower gradation curves and 20% upper limit gradation curves of Indian railways match with lower limit gradation curve of the AU railways. The upper limit of Indian railway gradation curve closely matches with the lower limit of AU railway gradation curve. The upper and lower limits of Indian railway gradations are very narrow and poorly graded. From Figs. 11–13, it is very clear that in Indian railways the upper and lower gradation curves are narrow band and have larger particle sizes, which are poorly graded when compared to American and Australian railways. This means that the Indian railway gradations fulfill the drainage criteria, but not more favorable for stability and settlement criteria. Poor gradation leads to the misalignment of sleepers and rails, reduces the bearing capacity of the track and increases settlement with short time. This can create track instability and other consequences. They are the major cause for the derailing of trains, and discomfort to the passengers. Indraratna and Salim [32] suggested modified gradations to Australian railways based on a cyclic triaxial test considering settlement and breakage of ballast without a compromise on the drainage requirement. Figure 13 shows a modified gradation curve by Indraratna and Salim [32] and upper and lower limit gradations followed in Indian and Australian railways. Upper and lower limits gradation curves of the Indian railway closely match with the upper limit of the modified gradation of AU railways. Indian railway gradations may be modified by research considering the breakage of ballast, settlement, stability and drainage condition of the track foundation.

Further ballast samples were collected from the field tracks at selected locations in India and were analyzed in the laboratory for gradation and fouling. Ballast samples collected were 2–3 years, 6–7 years and 7–8 years old track. Figure 14 shows gradation of

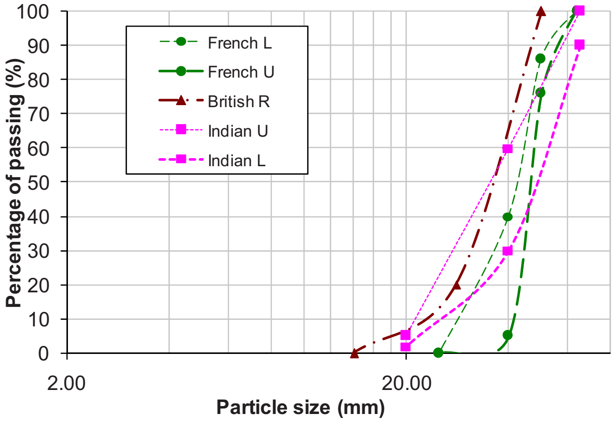


FIG. 12—*Ballast gradation followed by French, British, and Indian railway.*

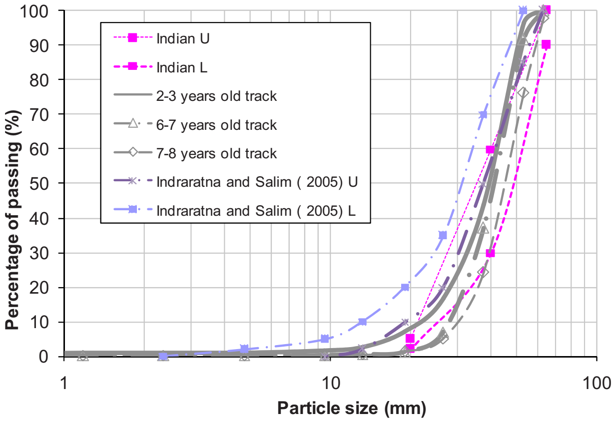


FIG. 14—*Ballast gradation of Indian field samples for different age, Indian railway gradation and modified gradation suggested by Ref 26.*

ballast samples collected from Indian rail track with Indian ballast gradations given in IRS-GE-1 [38] and modified gradation given by Indraratna and Salim [32]. The study shows that as age of track increases the fines content in the track also increases, because of ballast fouling and particle breaking. Figure 14 also shows that after several years Indian ballast gradation is courser than a modified gradation suggested by Indraratna and Salim [32], which means that resilience of Indian (course gradation) ballast is lower than that given by Indraratna and Salim [32]. The new (clean) and old (fouled) ballast gradation followed in Indian railway is poorly graded and more favorable for drainage criteria and may not be favorable for the other important factors like track stability, settlement and breakage of ballast.

Conclusions

Model track has been constructed with different fouling materials and degree of fouling. MASW survey had been carried out on the model track and shear wave velocity has been measured. Shear wave velocity of clean ballast is found to increase due to the addition of fines (fouling) and reach peak and then decrease below that of clean ballast. Two degree of fouling points has been defined, degree of fouling corresponding to peak SWV which is defined as the optimum fouling point and degree of fouling at which SWV of the fouled ballast equals the SWV of clean ballast which is defined as the critical fouling point. Variation of SWV with degree of fouling is similar to the typical compaction curve of soil. SWV of fouled ballast after reaching optimum fouling point decreases irrespective of fouling materials. Rate of decrease is more for coal fouled ballast compared to clayey sand fouled ballast. Coal fouled ballast has CFP of 15 % and clayey sand fouled ballast has CFP of 25 %. Combined plot of permeability and SWV with percentage of fouling shows that after the critical fouling point, the permeability of fouled ballast goes below the acceptable permeability limit. This is also confirmed by field fouled ballast samples with performance record. Fouling percentage of running track at Bellambi (NSW) is within in CFP and Fouling percentage of completely fouled track at Rockhampton (Queensland) after CFP defined in this study. MASW survey has been carried out in Australian field track and samples were collected to measure the degree of fouling. The SWV of the field samples are much more than that of model track sample for similar degree of fouling, which may be attributed to the sleeper confinement in the field track. More field studies may be needed to confirm the model track SWV values and pattern. Shear wave velocity obtained from MASW can be used to identify the track conditions.

Indian ballast gradation and fouling were evaluated to assess Indian railway track condition. Ballast gradation analysis shows that Indian ballast has larger particle size, which is poorly graded when compared to American and Australian railways. Indian railway ballast gradations are comparable with British and French railways gradation. Ballast gradation followed in India differs much from the modified gradation followed in Australia. Degree of fouling in Indian ballast increases with increase in the age of the track. The ballast gradation followed by Indian railways is poorly graded and favorable for drainage. Fouling measurements and identification in India is in infant stage with limited research.

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References

[1] Anbazhagan, P., Indraratna, B., Rujikiatkamjorn, C., and Su, L., "Using a Seismic Survey to Measure the Shear Modulus of Clean and Fouled Ballast," *Geomechanics and Geoengineering: An International Journal*, Vol. 5, No. 2, 2010, pp. 117–126.

[2] Raymond, G. P., Gaskin, P. N., and Svec, O., "Selection and Performance of Railroad Ballast," *Proc. of a Symposium Princeton University*, A. D. Kerr, Ed., Railroad Track Mechanics and Technology, 1975, pp. 369–385.

[3] Shenton, M. J., "Deformation of Railway Ballast Under Repeated Loading Condition," *Proc. of a Symposium Princeton University*, A. D. Kerr, Ed., Railroad Track Mechanics and Technology, 1975, pp. 387–404.

[4] Indraratna, B., Ionescu, D., and Christie, H. D., "Shear Behaviour of Railway Ballast Based on Large-Scale Triaxial Tests," *J. Geotech. Geoenviron. Eng.*, Vol. 124, No. 5, 1998, pp. 439–449.

[5] Selig, E. T., and Waters, J. M., *Track Geotechnology and Substructure management, London*, American Society of Civil Engineers, Publications Sales Dept., Thomas Telford, New York, 1994.

[6] Gallagher, G. P., Leipera, Q., Williamsona, R., Clarkb, M. R., and Fordeb, M. C., "The Application of Time Domain Ground Penetrating Radar to Evaluate Railway Track Ballast," *NDT Int.*, Vol. 32, 1999, pp. 463–468.

[7] Nazarian, S., Stokoe, K. H. II, and Hudson, W. R., "Use of Spectral Analysis of Surface Waves Method for Determination of Moduli and Thicknesses of Pavement Systems," *Transp. Res. Rec.*, Vol. 930, 1983, pp. 38–45.

[8] Al-Hunaidi, M. O., "Difficulties with phase spectrum unwrapping in spectral analysis of surface waves nondestructive testing of pavements," *Can. Geotech. J.*, Vol. 29, 1992, pp. 506–511.

[9] Stokoe, K. H. II, Wright, G. W., James, A. B., and Jose, M. R., 1994, "Characterization of Geotechnical Sites by SASW Method," *Geophysical Characterization of Sites: ISSMFE Technical Committee #10*, R. D. Woods, Ed., Oxford Publishers, New Delhi.

[10] Tokimatsu, K., "Geotechnical Site Characterization Using Surface Waves," *Proc. 1st Int. Conf. on Earth. Geotechn. Eng.*, IS-Tokyo, p-36, 1995.

[11] Ganji, V., Gukunski, N., and Maher, A., "Detection of Underground Obstacles by SASW Method—Numerical Aspects," *J. Geotech. Geoenviron. Eng.*, Vol. 123, No. 3, 1997, pp. 212–219.

[12] Park, C. B., Miller, R. D., and Xia, J., "Multi-Channel Analysis of Surface Waves," *Geophysics*, Vol. 64, No. 3, 1999, pp. 800–808.

[13] Xia, J., Miller, R. D., and Park, C. B., "Estimation of Near-Surface Shear-Wave Velocity by Inversion of Rayleigh Wave," *Geophysics*, Vol. 64, No. 3, 1999, pp. 691–700.

[14] Xu, Y., Xia, J., and Miller, R. D., "Quantitative Estimation of Minimum Offset for Multichannel Surface-Wave Survey with Actively Exciting Source," *J. Appl. Geophys.*, Vol. 59, No. 2, 2006, pp. 117–125.

[15] Zhang, S. X., Chan, L. S., and Xia, J., "The Selection of Field Acquisition Parameters for Dispersion Images from Multichannel Surface Wave Data," *Pure Appl. Geophys.*, Vol. 161, 2004, pp. 185–201.

[16] Anbazhagan, P., and Sitharam, T. G., "Mapping of Average Shear Wave Velocity for Bangalore Region: A Case Study," *J. Environ. Eng. Geophys.*, Vol. 13, No. 2, 2008, pp. 69–84.

[17] Anbazhagan, P. and Sitharam, T. G., "Seismic Microzonation of Bangalore," *J. Earth Syst. Sci.*, Vol. 117, No. S2, 2008, pp. 833–852.

[18] Anbazhagan, P., Thingbaijam, K. K. S., Nath, S. K., Narendara Kumar, J. N., and Sitharam, T. G., "Multi-Criteria Seismic Hazard Evaluation for Bangalore City," *India J. Asian Earth Sci.*, Vol. 38, 2010b, pp. 186–198

[19] Anbazhagan, P., and Sitharam, T. G., "Site Characterization and Site Response Studies Using Shear Wave Velocity," *J. Seismol. Earthquake Eng.*, Vol. 10, No. 2, 2008, pp. 53–67.

[20] Anbazhagan, P., Sitharam, T. G., and Vipin, K. S., "Site Classification and Estimation of Surface Level Seismic Hazard Using Geophysical Data and Probabilistic Approach," *J. Appl. Geophys.*, Vol. 68, No. 2, 2009, pp. 219–230.

[21] Sitharam, T. G. and Anbazhagan, P., 2008, "Seismic Microzonation: Principles, Practices and Experiments," EJGE Special Volume Bouquet 08, http://www.ejge.com/Bouquet08/Preface.htm, P-61 (Last accessed March 25, 2009).

[22] Anbazhagan, P. and Sitharam, T. G. 2008, "Application of Multichannel Analysis of Surface Wave survey in Geotechnical Engineering Problems," *Proceeding of 6th Asian Young Geotechnical Engineers Conference*, pp. 291–300.

[23] Anbazhagan, P. and Sitharam, T. G., "Relationship between Low Strain Shear Modulus and Standard Penetration Test 'N' Values," *Geotech. Test. J.*, Vol. 33, No. 2, 2010, pp. 150–164.

[24] Anbazhagan, P. and Sitharam, T. G., "Spatial Variability of the Weathered and Engineering Bed rock using Multichannel Analysis of Surface Wave Survey," *Pure Appl. Geophys.*, Vol. 166, 2009, pp. 409–428.

[25] Bei, S. 2005, "Effects of Railroad Track Structural Components and Subgrade on Damping and Dissipation of Train Induced Vibration," Doctoral thesis, The Graduate School, University of Kentucky, Lexington, KY, China.

[26] Kaminski, M. E. and Thummaluru, M. S. R., "A New Free-Free Resonant Column Device for Measurement of Gmax and Dmin at Higher Confining Stresses," *Geotech. Test. J.*, Vol. 28, No. 2, 2005, pp. 180–187.

[27] Ahlf, R. E., "M/W costs: how they are affected by car weight and the track structure," *Railway Track Struct*, Vol. 71, No. 3, 1975, pp. 34–37.

[28] Narayanan, R. M., Jakuba, J. W., Lib, D., and Eliasa, S. E. G., "Railroad Track Modulus Estimation Using Ground Penetrating Radar Measurements," *NDT Int.*, Vol. 37, 2004, pp. 141–151.

[29] Suiker, A. S. J., Selig, E. T., and Frenkel, R., "Static and Cyclic Triaxial Testing of Ballast and Subballast," *J. Geotech. Geoenviron. Eng.*, Vol. 131, No. 6, 2005, pp. 771–782.

[30] Budiono, D. S., McSweeney, T., Dhanasekar, M., and Gurung, N., 2004, "The Effect of Coal Dust Fouling on the Cyclic Behaviour of Rail Track Ballast," *Cyclic Behavior of Soil and Liquefaction Phenomena*, Triantafyllidis, Ed., Taylor & Francis Group, London, pp. 627–632.

[31] Indraratna, B., Su, L., and Rujikiatkamjorn, C., "A New Parameter for Classification and Evaluation of Railway Ballast Fouling," Technical note, Canadian Geotechnical Journal, (in press), IRS-GE Vol. 1, 2010, pp. 2004 (Specification for Track Ballast, published by Research Designs and Standards Organisation) (RDSO) (Ministry of Railways.).

[32] Indraratna, B. and Salim, W., *Mechanics of Ballasted Rail Tracks a Geotechnical Perspective*, Taylor & Francis, Great-Britain, 2005.

[33] Kolbuszewski, J. and Frederick, M. R., "The Significance of Particle Shape and Size on the Mechanical Behavior of Granular Materials," *Proc. European Conference on the Soil Mechanics and Foundation Engineering*, 1963, pp. 253–263.

[34] Marachi, N. D., Chan, C. K., and Seed, H. D., "Evaluation of Properties of Rock Fill Materials," *J. Soil Mech. Found. Div.*, Vol. 98, 1972, pp. 95–114.

[35] Holz, W. G. and Gibbs, H. J., "Triaxial Shear Tests on Pervious Gravelly Soils, *J. Soil Mech. and Found. Div.*," Vol. 82, 1956, pp. 867.1–867.22.

[36] Leps, T. M., "Review of Shearing Strength of Rock Fill," *J. Soil Mech. and Found. Div.*, Vol. 96, 1970, pp. 1159–1170.

[37] Vallerga, B. A., Seed, H. B., Monismith, C. L., and Copper, R. S., *Effect of Shape, Size and Surface Roughness of Aggregate Particles on the Strength of Granular Materials, ASTM STP*, Vol. 212, 1957, pp. 63–76.

[38] IRS-GE-1, 2004, *Specification for Track Ballast*, Research Designs and Standards Organisation (RDSO), Ministry of Railways.

[39] AREMA 2003, Manual for Railway Engineering. American Railway Engineering and Maintenance-of-way, Association, Vol.1 (track-Roadway and Ballast, USA AS 2758.7, 1996, Aggregates and rock for engineering purposes, part 7: Railway ballast standards Australia, NSW, Australia.

[40] Profillidis, V. A., *Railway Engineering*, Avebury Technical, Ash Gate Publishing Ltd, U.K., 1995.

[41] AS 2758.7, 1996, "Aggregates and Rock for Engineering Purposes," *Railway Ballast Standards Australia*, Part 7, NSW, Australia.