Project Report

Characterization of Rail Track Ballast Fouling Using Ground Penetration Radar and Field Sampling

by

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Summary Sheet
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1. Title of the Project: **CHARACTERIZATION OF RAIL TRACK BALLAST FOULING USING GROUND PENETRATION RADAR AND FIELD SAMPLING**

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   This report presents an overview (requirements) of rail track aggregates, the ballast gradation adopted in railways in different countries and their comparison with Indian ballast gradation. Further in situ ballast sampling, testing and ballast fouling quantification are also presented for typical track ballast. Ten ballast samples were collected from in and around Bangalore, India and fouling values were estimated as per international procedures followed for determining the fouling indices. Results show that fouling values of station tracks increase with
time. Non coal/ore transport tracks and track on firm sub grade experience moderate fouling due to the breakdown of ballast and naturally occurring materials like dust, dirt, soil, etc. Fouling indices are specific to fouling materials and gradations. In this study it was found that the existing fouling indices are unable to reflect the representative fouling values for Indian railway ballast studied, hence alternate fouling indices are suggested for Indian railway ballast gradation.

A lack of substructure reengineering/characterization has resulted in maintenance cycles becoming more frequent and increasingly expensive. Early and accurate assessment of rail track substructure characterization will facilitate railway engineers to undertake cost-effective maintenance at suitable interval. At present, the current assessment is usually very time consuming, expensive and not accurate enough. In this study, non-destructive technique of ground penetrating radar (GPR) has been used to assess subsurface condition of track including ballast fouling of field track. GPR survey has been carried out on a newly laid track near Chennapatna railway station using 100 MHz, 500 MHz and 800 MHz antennas. This study shows that GPR antenna having central frequency of 800 MHz is giving good subsurface information and degree of ballast fouling. However it is difficult to get exact quantity of ballast fouling using GPR radargram. Hence the model track sections are constructed in the laboratory with known degree of fouling using fouling material of iron ore and broken ballast, then GPR survey has been carried out. GPR wave traces are used to estimate velocity of electromagnetic wave and further used to estimate dielectric constant of ballast model section. Degree of ballast fouling is correlated with dielectric constant of respective fouled ballast section. Finally this project bring out the deficiency of present ballast gradation, maintaining of ballast section, percentage of fouling and fouling index suitable for Indian railway and correlation between ballast fouling and GPR dielectric constant. These results will help to improve Indian railway track foundation and maintenance strategy, in particular South Western Railway tracks fouled by iron ore and coal. This study shows a new direction for ballast fouling in Indian railway, which is the main cause for misalignment of rails leads to derailing of trains.

6. Publications

Journals - 2
Conferences - 1
Chapter -1

Ballast Fouling and Fouling Indices

1.1 Introduction

The railway ballast breaks due to the repeated cyclic load of the trains and this breakage contaminates the track by filling the voids. The railway track also gets contaminated when Iron ore/coal spills on the railway track when they are being transported by train wagons. This process of breaking and/or contaminating the railway track is called as ballast fouling and this increases the track settlement contributing to track degradation. Therefore, it is imperative to investigate in detail the deformation behavior and degradation characteristics of ‘fresh’ ballast for typical loading and drainage conditions specific to railway tracks. Also, it is necessary to identify the factors that highly affect their variation. Better design of ballast foundation provides higher track performance and ensures reduced maintenance costs. Also, the degradation caused by traffic loading (in field conditions) requires proper measure based on the Indian specifications in order to effectively plan the ballast-cleaning cycles so the maintenance costs are kept under control. This chapter presents an overview of Indian Ballast gradation, comparison with international ballast gradation and fouling measurements of railway tracks of southwestern railway by conventional methods. Fouling indices are specific to fouling materials and gradations. In this study it was found that the existing fouling indices are unable to reflect the representative fouling values for Indian railway ballast studied, hence alternate fouling indices are suggested for Indian railway ballast gradation. Salient points are added here and more details can be found in the enclosed publications end of this chapter.

1.2 Field sampling of fouled ballast and quantification of fouling in the laboratory

To understand ballast fouling, initially the fouling properties were measured as suggested by various researchers. The in situ ballast samples were collected at the locations where technical feasibility and safety existed from the southwestern railway tracks. Fouled ballast samples were collected from Whitefield railway station (WHFR) and Yeshwanthpur railway station (YPR). A total of 15 samples were collected from each station with approximate quantity of about 15 kg. Among these 10 samples one track sample was collected from the relatively new track i.e. fresh.
The samples were collected from the site and graded according to the IS2720 (Part I)-1983. The sieve used are 63 mm, 53 mm, 37.5 mm, 26.5 mm, 19 mm, 13.2 mm, 9.5 mm, 4.75 mm, 2.36 mm, 1.18 mm, 0.6 mm, 0.3 mm, 0.212 mm, 0.150 mm and 0.075 mm. It was found
that all the samples were Poorly Graded Gravel (GP). Many researchers have developed different scales to measure the fouling of ballast. They are a) Percentage of fouling, b) Fouling index, c) Effective degree of fouling, d) Percentage void contamination, e) Relative ballast fouling ratio. More details these scales can be found in the enclosed publications. It was found that these fouling scales were developed by different researchers based on their country’s specification which cannot be used for Indian railway ballast or any other country’s railway ballast. So we have developed a new formula for Indian Railway ballast (equation 1) for which 20 mm is the least size of the ballast used. Even though proposed definition for fouling index and percentage fouling formula for Indian track is relatively comparable with Selig and Waters (1994) and Ionescu (2004) definition. But it is not enough to accurately define the fouling status of Indian track because the aggregates in the range of 4.75 mm to 20 mm will have good permeability and bearing capacity. More research is needed to precisely define the fouling scale and classification system for Indian rail ballast by accounting the bearing capacity, settlement and permeability.

\[ FI = F_{4.75} + F_{20} \]  

Eq (1)
Publication-I

Title: Rail Track Geotechnical Engineering and Ballast Fouling in India

Journal: *Indian Geotechnical Journal*

Volume: 42(2)

Pages: 87–99
Study of Ballast Fouling in Railway Track Formations

P. Anbazhagan · T. P. Bharatha · G. Amarajeevi

Abstract This article presents an overview (requirements) of rail track aggregates, the ballast gradation adopted in railways in different countries and their comparison with Indian ballast gradation, drainage of rail track and ballast fouling in India. Further in situ ballast sampling, testing and ballast fouling quantification are also presented for typical track ballast. Ten ballast samples were collected from in and around Bangalore, India and fouling values were estimated as per international procedures followed for determining the fouling indices. Results show that fouling values of station tracks increase with time. Non coal/ore transport tracks and track on firm sub grade experience moderate fouling due to the break down of ballast and naturally occurring materials like dust, dirt, soil, etc. Fouling indices are specific to fouling materials and gradations. In this study it was found that the existing fouling indices are unable to reflect the representative fouling values for Indian railway ballast studied, hence alternate fouling indices are suggested for Indian railway ballast gradation. The article also presents an overview of the recent advancements in the identification of subsurface rail track problems using geophysical methods and conventional track monitoring and cleaning. The Indian railway follows coarser ballast gradation and conventional procedure to identify the rail track subsurface problems. Many advanced methods need to be experimented in Indian rail tracks to modernize the railway track foundations for the fast transportation of goods and passengers.

Keywords Rail track · Ballast · Gradation · Fouling

Introduction

Railways are massive transport systems, which carry large quantity of goods as well as passengers when compared to any other modes of transport system. The Indian railways is one of the largest of its kind in the world. Derailing of trains is routine and a major disaster in railways and this happens due to the change in alignment of rails and many other reasons. The geotechnical component of rail track i.e. ballast bed plays an important role in maintaining the gauge between sleepers and there by alignment of the rails. Defects in ballast bed may lead to settlements and deformation of ballast section, which in turn lead to misalignment of rails. The rail track is 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 ballast) placed above the sub ballast and below the rails. The loads from the sleepers are distributed to the sub ballast and compacted earth through the main ballast section. A rail ballast bed acts as the main foundation above the capping layers and performs many roles for the proper functioning of the railway network. 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 shear strength of soil due to local liquefaction and clay pumping. A high lateral movement of ballast may occur due to the over limit of wheel load. 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 materials can be dust from surroundings, 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 [12]. Finding a means of reducing the maintenance costs and reducing the frequency of regular repair cycles have been a priority for most of the railway organizations. Although the research conducted on geotechnical engineering particularly on sand and clay, road base and rock fills has been extensive, limited research has been conducted on geotechnical issues related to the rail track, particularly in India. Many researchers have indicated that a major portion of the track maintenance budget is spent on tamping, ballast cleaning and renewal operations [12]. If a scientific approach is followed with modern technology, the maintenance cost and frequency of the maintenance can be reduced to the maximum possible extent. Many countries are using modern techniques like ground penetrating radar (GPR) to evaluate the quality of ballast in track [2]. This article presents an overview of ballast gradation in Indian railways, collection of fouled ballast samples from selected tracks, fouling measurement. It also highlights the comparison of Indian railway ballast gradation with international gradation standards, track drainage and the recent advancement in the assessments of fouling and subsurface in the railway tracks.

Railway Ballast

The primary geotechnical component of a rail track foundation is the ballast section. Ballast performance depends on four major geotechnical properties (index and engineering) of ballast materials [12]: characteristics of the constituting particles (size, shape, surface roughness, particle crushing strength and resistance to attrition, etc.), bulk properties of the granular assembly (particular size distribution, void ratio or density and degree of saturation), loading characteristics (current state of stress, previous stress history and applied stress path) and particle degradation (combined effects of grain properties, aggregate characteristics and loading).

Kolbuszewski and Frederick [25] indicated that the angle of shearing resistance increases with large particle size. But Marachi et al. [27] and Indraratna et al. [13] presented experimental data to show that the angle of internal friction decreases with an increase in the maximum particle size and hence the drastic reduction in the friction component of the shear strength which can cause significant reduction in the load carrying ability. The main functions of the ballast layer are to control the stress intensity projected onto the weaker sub grade, to decrease the frequency of track maintenance by minimizing the track settlement and sleeper movement and to promote rapid drainage via the large pore structure [16].

Particle shape plays an important role in shear strength. Angularity of particles increases the frictional interlock between grains and thereby increases the shear strength. The angle of internal friction is remarkably high for angular aggregates when compared to the sub-rounded aggregates when compared to the sub-rounded aggregates [13, 11, 26, 34]. Surface roughness or texture is the key factor that governs the angle of internal friction. Raymond [29] concluded that the particle shape and surface roughness are important and influence the track stability. Most ballast specifications stipulate crushed or fractured particles, which are defined as grains having a minimum of three crushed faces [12]. 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 other countries. But the overall major problems of track stability, settlement and drainage problems are the result of ballast breakdown. Breakdown is dependent on ballast properties, grading, load aspects, etc. When ballast breaks due to over load, repeated cyclic loading of train wheels, interaction with other particles and sleeper movement etc., the stress carrying capacity is reduced and hence the stress intensity projected onto the weaker sub grade is increased which results in the failure of the sub grade [15]. Volume of load carrying ballast is considerably reduced due to breakage and hence movement of sleeper takes place which causes discomforts to the passengers and the voids are filled due to the breakage and hence the drainage reduces which causes further more problems.

The settlement of ballast can be both elastic (such as the initial settlement due to the compaction of ballast) and plastic (due to breakage of ballast particles). As identified by Selig and Waters [31], settlement of ballast may not be a problem if it occurs uniformly along the length of the track. In fact, differential track settlement is more important than the total track settlement. The settlement behavior of ballast with different particle size distribution was investigated under cyclic loading by Indraratna et al. [14]. Indraratna et al. [14] highlighted that the moderately graded samples display least settlement, followed by the gap-graded specimens. Researchers are working around the world to optimize the railway ballast gradation in order to meet future requirements of heavy traffic and freight movements.
Universal Ballast Gradation

Ballast gradation is a primary factor affecting the stability, safety and drainage of tracks. A specified ballast gradation must provide the following two key objectives [12]: 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 and ballast must have high permeability to provide adequate drainage; this readily dissipates excess pore water pressures and increases the effective stress. This can be ensured by specifying uniformly graded ballast. These two objectives are different and require optimized particle distribution in addition to quality. The optimum ballast gradation needs a balance between uniform and broad gradations. Many countries have optimized ballast gradation through wide range of research studies. Indian railway ballast gradation is not much different from the East Indian rail company period ballast gradation. The presently followed Indian railway ballast gradations are specified in IRS-GE-1 [20]. The ballast gradation followed in American Railway Engineering and Maintenance of way Association [4] and Indian Railways is shown in Fig. 1 (U and L indicated in figures represent the upper and lower limit). It clearly shows that the least particle size used in American railways is 9.5 mm whereas it is 20 mm in the case of Indian railways. American railway gradations are relatively well graded when compared to Indian railway gradations. Figure 1 shows the ballast gradation followed by French railways and British railways [28] in comparison with Indian railways. French and Indian railways gradation curve is similar for more than 50 %. The gradations followed by British railways almost matches with the Indian Railways. Indian railway ballast gradation is perhaps comparable because Indian railway ballast gradations are older and are adapted from the East Indian Rail Company, without much modifications and research. French railway ballast gradation is coarser than Indian railway gradation and the minimum particle size of ballast used is 25 mm. Figure 1 also shows the upper and lower limit gradation followed in Australian (AU) railways [5] and Indian railways. About 70 % Indian railway lower limit gradation curves match with the upper limit of the AU railway gradation curve. About 70–40 % Indian railway gradation lower limit curves are in between the upper and lower limit gradation curves of the AU railway. Less than 40 % lower gradation and 20 % upper limit gradation curves of Indian railways match with the lower limit gradation curve of the AU railways. The upper limit of the Indian railway gradation curve closely matches with the lower limit gradation curve of the AU railways. The upper and lower limits of Indian railway gradations are very narrow and poorly graded. From Fig. 1, it is very clear that in Indian railways the upper and lower gradation curves are in a narrow band and have a larger particle size, which are poorly graded when compared to American and Australian railways. This means that Indian railway gradations fulfill the drainage criteria, but may not be 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 the settlement. This can create track instability and other consequences. They are the major cause of the derailing of trains, and discomfort to passengers. Indraratna and Salim [12] suggested modified gradations to Australian railways considering settlement and breakage of ballast without a compromise on the drainage requirement based on research carried out in the large scale cyclic triaxial equipment. Figure 1 shows the modified

Fig. 1 Ballast gradation
followed in India, American, French, British and Australia railways with [12] modified gradation for Australia. Note R–U and R–L is railway upper and lower ballast gradation.
graduation curve by Indraratna and Salim [12] and upper and lower limit gradations followed in India and Australian railways. Lower limit gradation curve of the Indian railway closely matches with 80% of the upper limit of the modified gradation of AU railways. Comparing Indian railway ballast gradation with international ballast gradation clearly shows that Indian Railway ballast is poorly graded. Poor gradation of ballast leads to excess of certain particles and deficiency of other. This leads to the movement of the ballast particles under loading and results a poorly packed section. Literature shows that more voids and movement of particles can cause breakage of particles. Hence Indian railway ballast is more likely to undergo breakage as compared to other ballast gradations.

Indian railway ballast standards do not address the requirements of bulk density and particle density for the rail ballast. The Australian standard [5] specifies that the bulk density of ballast material shall not be less than 1,200 kg/m$^3$ and that the particle density on a dry basis of ballast material shall not be less than 2,500 kg/m$^3$. In order to ensure the stability of the track and the quality of the ballast, bulk density and particle densities are very important and therefore similar parameters can be included in the Indian railway ballast standard of IRS-GE-1 [20]. The durability of ballast is usually assessed by the aggregate crushing value (ACV), wet attrition values, wet/dry strength variations and Los Angeles values in America, Australia and British railways. Indian railway ballast standard of IRS-GE-1 [20] specifies the requirements of aggregate abrasion value, water absorption and impact values. The impact value of ballast for Indian railways has to be determined in accordance with IS 2386 part IV, 1963 [22]. This test is similar to the ACV test followed by other countries. This test should be carried out for the maximum and minimum particle size of 12.5 mm and 10 mm respectively. IS 2386, part IV (1963) is basically for the testing of small aggregates used for concrete. Indian railways are using this test as a standard for railway ballast requirements. The samples are prepared to the required size as per IS 2386 by crushing the ballast and are used without any modifications in the test procedures and instruments. The literature shows that the size of the particles and the testing method influence the impact value and crushing values of the testing materials. Hence, using the standards IS 2386 part IV, 1963 [22] developed for concrete aggregates without any modification may not be appropriate for railway ballast. After selecting the appropriate ballast considering aggregate properties and suitable gradation, performance of the track ballast can reduce due to another major problem called ballast fouling. Summary of ballast fouling quantification, in situ ballast sampling and fouling estimations are presented in the following sections.

Drainage of Ballast Sections

One of the main factors that determine the safety and stability of a track structure is drainage. Drainage is typically defined as the interception, collection and subsequent disposal of water away from the rail track [10]. It plays a major role in track maintenance and stability which is evident by the saturated track condition that is created in the event of an inefficient drainage. Subsequently it results in plastic strain accumulation, decrease in stiffness, decrease in strength and increase in settlement due to the excess pore water pressure under train loading [31, 17]. This needs for a quick and efficient drainage system, most importantly the quick disposal of water from the formation top/slopes of the track.

One of the major requirements for efficient track maintenance is the presence of ballast that is fairly permeable to drain water and maintain dry condition. Various guidelines issued by Research Development and Standard Organization (RDSO) suggest the same [10]. Clean ballast can have free drainage. However, the free drainage path gets blocked in fouled ballast section starts holding the water because of the fines that have accumulated with the clean ballast. The amount of moisture and blocking also increases considerably if the degree of fouling is more in the rail track section. The ideal ballast is a poorly graded or uniformly graded aggregate with a particle size in the region of 20–50 mm giving high void ratio [24]. Due to fouling there is considerable change in the gradation of the track section leading to the reduction of the permeability of the track. The permeability of fouled ballast less than $10^{-4}$ m/s is considered unacceptable based on Selig and Waters [31] and Anbazhagan et al. [1].

Anbazhagan et al. [3, 1] used ballast fouled with clayey sand and coal to demonstrate the variation in shear strength and permeability with the percentage of fouling. As the fouling of the track bed increased, the shear wave velocity also increased and the overall ballast permeability decreased rapidly before approaching optimum fouling point (OFP). Following OFP the permeability decreased marginally. The shear wave velocity of fouled ballast decreased less than the clean ballast when permeability was approaching $10^{-4}$ m/s for ballast fouled with clayey sand and coal. This point is defined as Critical Fouling Point, beyond which track maintenance becomes necessary [3, 1]. Change in gradation due to the breakage and reduction of permeability are the functions of fouling materials, sub-surface condition and other factors. Hence it can be concluded that a good drainage condition should be maintained within the ballast to ensure acceptable track performance.

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. Possible factors for ballast fouling are breakdown of ballast due to mechanical forces, ballast degradation (fine particles that migrate downwards), coal/iron ore from the railcars, dust from surroundings—naturally occurring: dust, dirt, plant life decay etc., traction sand-slurried (pumped) formation soil (soft clays and silts liquefied under saturated conditions), brake shoe dust, diesel soot and rail road maintenance practices. Figure 2 shows typical fouling process and fouled ballast sections of the rail track. Fine ballast due to breakdown of ballast and fines from railcars migrates from top to bottom as shown in Fig. 2a. In this case subgrade will be hard and all fines will be accumulated in the base of ballast layer as shown by the arrow where less fines in the top are indicated in light color and more fines at the bottom indicated in dark color. If rail track has soft soil subgrade then the fouling takes place from top as well as from bottom as shown in Fig. 2b. In this case the rate of fouling and amount of fouling will be much more than the previous case and also this is the worst fouling condition. Figure 2b is also a typical section of highly fouled track due to mud pumping from the soft soil subgrade. Ballast fouling can cause reduction in resistance to the vertical (including uplift), lateral and longitudinal forces applied to the sleepers to retain the track in its required position, decrease in resiliency modulus/strength and energy absorption capacity, reduction in the voids there by leading to a considerable decrease in the movement of particles through the ballast, poor drainage of water falling onto the track, vegetation growth in the rail track, increase in noise level, inadequate electrical resistance between rails [3, 12]. Therefore it is mandatory to identify the degree of fouling and to remove the fine materials before resulting in a decrease in the performance of the rail track and other severe problems. Quantification of ballast fouling is a unique problem in geotechnical engineering because of two similar and/or dissimilar materials are evaluated and represented in single value. Detailed classification scheme is available for most of the geotechnical materials. But limited classification scheme is available for two dissimilar materials combination, which is a case for most of the ballast fouling. Ballast fouling results due to mixing of two distinct materials having large variation in particle size, particle shape and specific gravity. In order to evaluate ballast fouling there are several fouling scales presented by different researchers worldwide in compatible with their country’s track conditions. Summary of these scales are presented below:

Fouling conditions are measured using five methods which are fouling index, percentage of fouling, D-bar method, effective degree of fouling, percentage void contamination and relative ballast fouling ratio. The first four measures are commonly used, the fifth one is used by Queensland Railways and sixth one is recently developed [1, 18]. These methods are laboratory based and require field sampling and testing, which are normally carried out by digging trenches with even spacing.

Fouling Index

Selig and Waters [31] considered clay pumping and the infiltration of the foreign materials as the other major sources of fouling. Foreign material penetrating into the ballast from the surface can include objects delivered with the ballast, dropped from trains, or wind and water blown matter. They have proposed quantification of fouling in terms of fouling index (FI)

\[ FI = P_{0.075} + P_{4.75} \]  

where \( P_{0.075} \) and \( P_{4.75} \) are percent by weight of ballast sample passing 0.075 mm sieve and 4.75 mm.
North American railway systems use typical ballast sizes ranging from 4.75 to 51 mm. However, Australian railways [5, 33] uses ballast sizes varying from 13.2 to 63 mm. Thus fouling index defined in equation above needs to be modified to suit the Australian railways track condition. Hence, Ionescu [19] had proposed a new ballast fouling index as follows

\[ FI_p = P_{0.075} + P_{13.2} \]  

(2)

where \( P_{13.2} \) is percent by weight of ballast sample passing 13.2 mm sieve.

Ionescu [19] has also suggested use of more practical ballast fouling index given as below:

\[ FI_D = \frac{D_{90}}{D_{10}} \]  

(3)

where \( D_{90} \) and \( D_{10} \) grain diameter corresponding to 90 \% passing by weight and 10 \% passing by weight respectively.

Percentage of Fouling (% fouling)

Selig and Waters [31] also stated the percentage fouling to be obtained as the ratio of dry weight of material passing 9.5 mm sieve to the dry weight of total sample. Both the methods calculate the ballast fouling based on mass calculation in the sieve analysis.

The percentage of fouling and fouling index are based on mass calculations in the sieve analysis and thus do not consider the relative densities of fouling material and ballast. When fouling material and ballast have different unit weights, then the above indices does not represent the correct volume or quantity of fouling materials with respect to ballast. Hence Feldman and Nissen [9] proposed new test method i.e. percentage void contamination (PVC).

Percentage Void Contamination (PVC)

Feldman and Nissen [9] defined PVC as the ratio of volume of voids in ballast to the volume of contaminates present in the ballast (fouling materials). It is measured in percentage.

\[ PVC = \frac{V_2}{V_1} \times 100 \]  

(4)

where \( V_2 = \) volume of voids in the ballast and \( V_1 = \) volume of contaminants in the ballast.

Although the PVC method is a direct measure of percentage of voids occupied by fouling particles, the measurement of volume is time consuming. Furthermore, as the bulk volume of fouling particles is used, the gradation of fouling particles cannot be taken into account. For example, if the contaminates are all composed of coarse particles (4.75–9.5 mm) there should still be sufficient voids between the fouling particles, hence the Ballast drainage capacity would not be significantly reduced. In this regard PVC may overestimate the extent of fouling. Anbazhagan et al. [1] and Indraratna et al. [18] have suggested the use of the solid volume of fouling particles rather than the bulk volume in calculating the PVC. By using the solid volume, smaller value of PVC will be obtained if there is an insufficient quantity of fine particles within contaminates, and vice versa.

Relative Ballast Fouling Ratio (\( R_{b-f} \))

Relative ballast fouling developed by Anbazhagan et al. [1] and Indraratna et al. [18] is defined as the ratio of the dry weight of fouling particles (passing 9.5 mm sieve) to the dry weight of ballast (particle retaining on 9.5 mm sieve). It is calculated by using the formula given in Eq. 5.

\[ R_{b-f} = \frac{M_f \times \frac{G_{S-f}}{G_{S-b}}}{M_p} \times 100\% \]  

(5)

where \( M_f \) and \( G_{S-f} \) are the mass and the specific gravity of ballast fouling (fines), \( M_b \) and \( G_{S-b} \) are the mass and specific gravity of ballast. In this, only the mass and specific gravity of the ballast as well as fouled material need to be measured. Authors’ claim that \( R_{b-f} \) will greatly speed up the measurements compared to the PVC method and hence will be more attractive to the practicing track engineer. However limited experimental evidence has been given to strengthen their findings.

In Situ Sampling

Clean Ballast placed in the rail track is fouled because of several reasons as discussed above, but its quantification is not universal. Several consequences are frequently reported in Indian railway due to ballast fouling, but very limited attempt has been made to scientifically understand the same. The old track ballast is periodically cleaned in Indian rail tracks. But cleaning interval is constant for particular type of track and is not based on quantified fouling values. Indian Railway field engineers report reveals that old track are widely cleaned once in 10 years irrespective of the track condition and also there are few tracks not cleaned for more than 15 years. Limited attempt is made to decide the cleaning interval by considering the scientific research. Many advanced technologies are followed in other countries to identify the ballast fouling and prioritize the maintenance cycles. In order to understand ballast fouling in Indian tracks, in this study an attempt has been made to collect the field fouled ballast samples and the fouling content have been estimated by carrying out laboratory experiments. Necessary permission was obtained from railway authority to collect the samples. The in situ samples were collected at
the locations where technical feasibility and safety existed. Fouled ballast samples were collected from Whitefield railway station (WHFR) and Yeshwanthpur railway station (YPR) in Bangalore, Karnataka, India. Total 5 samples were collected from each station with approximate quantity of about 15 kg. Among these 10 samples, one sample was collected from the relatively new track i.e. fresh ballast.

The Whitefield samples from the actively running railway track route from Bangalore to Chennai and the sampled location was about 30 km from Bangalore city towards Kollure. These track routes are about 150 year old and are high traffic routes because of frequent passengers and goods railcars. The samples collected from Yeshwanthpur are from the tracks within the station operating limit. The trains are operated with limited speed in these station tracks. In order to capture the actual status of fouling in the field, high resolution photos are captured at each location and selected photos are presented in Fig. 3. Figure 3a, b shows the fouling status of Yashwanthpur tracks. It can be observed from Fig. 3a, b that YPR station tracks are fouled by brake shoe dust, diesel soot and dust from surroundings-naturally occurring: dust, and dirt, etc. The last cleaning or replacement period in years (approximate age of track) of each sample at YPR were gathered from the railway staff during sampling. Aggregate particles at YPR were having smoothed surface and no breakage of particle was found. Figure 3c, d, e show the fouling status of the tracks in the Whitefield station limit. Photos clearly show that these tracks are fouled by break down ballast and surroundings-naturally occurring: dust, dirt, soil, etc. It is observed that the ballast samples close to rail sleepers (Fig. 3c, d) fouled by many angular broken aggregates and samples from centre of the track fouled by soil and surroundings naturally occurring dust (Fig. 3e). Station (Yeshwanthpur) tracks lines were having less fouling materials when compared to the main line tracks (Whitefield). Standard procedures are available for collection of field samples for fouling estimation outside India. No such standardized procedure is available and/or followed in India. In this study field samples are collected manually, stored in empty cement bags and transported to geotechnical laboratory, Indian Institute of Science, Bangalore for further laboratory tests.

Laboratory Testing

All samples were air dried in the laboratory and the necessary tests like sieve analysis and specific gravity tests were carried out to estimate the fouling content. The samples were graded according to the IS 2386 (Part I) [21] and IS2720 (Part I) [23]. The sieves used were 63, 53, 37.5, 26.5, 19, 13.2, 9.5, 4.75, 2.36, 1.18, 0.6, 0.3, 0.212, 0.150 and 0.075 mm. Grain size distribution of each samples are estimated and presented in Figs. 4 and 5. Figure 4 shows the grain size distribution of fouled and fresh ballast collected from YPR station and these samples are collected from the centre of the track. Among YPR samples, YPRS1 is the fresh and clean ballast from recently constructed track. Particle size distribution shows that more than 70% particle distribution matches with the Indian railway ballast standard of IRS-GE-1 [20], but the lower portion of the particle size of the gradation is coarser than the standard upper and lower limit boundary. Approximate ages of collected fouled samples are gathered from the railway staff in the station. Sample YPRS2 is from 2 year old track, YPRS3 and YPRS4 are from the three and 5 year old tracks. Particle size distribution curve of these samples reveal that fines are increasing with increase in age of the track. Similar fouling materials were found in all the samples and fine contents are increasing with respect to time. Age of YPRS5 samples is not known but it can be inferred from the above results that this track is relatively new and age may be less than 1 year. Particle size distribution of Whitefield station samples are shown in Fig. 5. Samples are collected from same track line, this means that the age of sample is same and collection locations are different. Ballast samples of WHFS2–WHFS5 are collected close to the sleepers and WHFS1 is collected from centre of the track. Figure 5 shows that all samples are having fines (size less than 20 mm) of about 15 % of total material collected. Difference in fouling material particle size can also be observed in Fig. 5. Broken aggregates with less soil size particles are noticed in WHFS2-WHFS5 from the photos in Fig. 3c, d and more soil size particle and less broken aggregate are noticed in the photo in Fig. 3e for WHFS1. Among 15 % fine materials, more than 13 % of the materials are having size 4.75 to 20 mm in WHFS2-WHFS5 and these are broken aggregates due to heavy rail traffic load. More soil size particles are noticed in WHFS1 when compared to the other samples from the same track. Coefficient of uniformity (Cu) and coefficient of curvature (Cc) are estimated from the particle size distribution curves for each sample. The Cu values for all the samples were found to be less than 4 and the Cc values for all the samples were found to be in the range of 1–3 and hence all the samples used for the tests were poorly graded gravel (GP). Fouling content of each sample is estimated and are presented in next section.

Indian Railway Ballast Fouling

Several fouling scales are followed by different countries. Particular fouling scale should be used based on type of the fouling materials. Mass based fouling scales are suitable for fouling material having comparable specific gravity values with ballast. Volume based fouling scales are suitable for fouling material having different specific gravity values.
with ballast. Even though Anbazhagan et al. [1] and Indraratna et al. [18] discussed these differences, but more experimental investigations are needed to compare different fouling scales with various fouling materials. This study is limited to fouling content estimation considering mass based methods. Because percentage void contamination and relative ballast fouling ratio require standard apparatus and these apparatus are not readily available right now. Fouling indices and percentage of fouling has been estimated for all samples and are given in Table 1. The range of fouling values used to classify fouled ballast track are given in Table 2. Fouling index of all the ten samples are given in

[Fig. 3 Typical fouled sections of rail track where filed samples were collected. a, b Photo from Yashwanthpur railway station (YPR) and c–e photo from Whitefield railway station]
column 2 of Table 1 as per Eq. 1 given by Selig and Waters [31]. YPRS1 and 5 are classified as clean ballast and other samples are classified as moderately clean ballast except YPRS4 as per row 1 in Table 2. The YPRS4 sample having a fouling index value of 14.41, can be classified as moderately clean ballast as per fouling index but the same sample can be classified as a moderately fouled ballast as per percentage of fouling. Similarly YPRS4 sample can be classified as moderately clean as per percentage of fouling and moderately fouled as per Fouling index. This highlights need for comprehensive study of ballast fouling scales and classification scheme. This study clearly shows that Indian track ballast samples are fouled because of several reasons. Samples collected for this study are from the station and non coal/ore transport lines with firm sub grade. Fouling values may be more if samples are collected from coal/ore transport lines and/or soft soil sub grade lines. More studies may be carried out on these tracks to understand complete fouling status.

**Fouling Indices for Indian Railway Ballast**

Fouling indices and percentage of fouling were developed in North America and Australia based on the ballast gradation and fouling material used in their region. For the same Indian railway fouled ballast sample different fouling values are noticed in Table 1. Selig and Waters [31] and Ionescu [19] have developed fouling index and percentage of fouling considering the least particle size in the recommended ballast gradation. This might be the reason for getting different fouling values for the same sample. Moreover Indian railway ballast has the least particle size of 20 mm and which is much larger than North America’s and Australia’s least particle size. But, fouling index and the percentage of fouling are estimated and classified as per Selig and Waters [31] and Ionescu [19] for initial understanding and are not directly applicable to the Indian railway ballast because these scales giving different fouling values for the same sample. To propose fouling scale and classification for Indian railway ballast, a detailed study need to be carried out considering the bearing capacity and permeability on fouled ballast. This needs sophisticated laboratory setup and huge amount of materials and man power. As an initial attempt, alternate fouling index and percentage of fouling are defined for Indian railway ballast based on this study and considering the particle size similar to Selig and Waters [31] and Ionescu [19] approach. Indian
railway ballast fouling index may be calculated using the relation (6).

\[ FI_{IN} = P_{0.075} + P_{20} \tag{6} \]

where \( P_{0.075} \) and \( P_{20} \) are percent by weight of ballast sample passing 0.075 mm sieve and 20 mm sieve respectively.

Percentage of Fouling of Indian railway ballast may be estimated by taking the ratio of dry weight of material passing 20 mm sieve to the dry weight of total sample. As per Indian railway ballast gradation any ballast having size less than 20 mm may be treated as fines. Fouling index and percentage of fouling as per Indian railway ballast gradation has been estimated and given in column 4 and 7 of Table 1. These values represent full gradation curve and values that concur with the qualitative field observation and age of the track. Indian railway ballast fouling index (\( FI_{IN} \)) increases with the increase in the age of track. Based on \( FI_{IN} \) values it is assumed that YPRS5 sample is about less than a year (about 9 months) old track. Figure 6 shows Indian railway ballast fouling index versus ages of track based on five samples collected from Yeshwanthpur station tracks. Percentage of fouling versus age of track is also shown in Fig. 6. It can be observed that no trend has been observed between percentage of fouling and age. With limited samples and fouling materials it is difficult to propose fouling classification suitable to Indian track. Even though proposed definition for fouling index and percentage fouling formula for Indian track is relatively comparable with Selig and Waters [31] and Ionescu [19] definition. But it is not enough to accurately define the fouling status of Indian track because the aggregates in the range of 4.75 to 20 mm will have good permeability and bearing capacity. More research is needed to precisely define the fouling scale and classification system for Indian rail ballast by accounting the bearing capacity, settlement and permeability.

### Track Maintenance and Recent Advancement

The foundation of rail tracks deforms vertically and laterally under cyclic wheel loads causing a deviation from the design geometry. Even though the deviations are apparently small, they are irregular and are based on the geotechnical properties of the track foundation, which in turn further effects track alignment and stability. Worldwide rail track maintenance is a costly and routine exercise. A major portion of the maintenance budget is being spent on geotechnical problems [30, 32, 13]. Maintenance is mandatory because of ballast fouling and the weakening of track

### Table 1 Fouling values for Indian fouled ballast samples

<table>
<thead>
<tr>
<th>Samples</th>
<th>Fouling index (FI)</th>
<th>( F_{ID} )</th>
<th>Percentage fouling</th>
</tr>
</thead>
<tbody>
<tr>
<td>YPRS1</td>
<td>0</td>
<td></td>
<td>0</td>
</tr>
<tr>
<td>YPRS2</td>
<td>4.55</td>
<td>5.60</td>
<td>7.18</td>
</tr>
<tr>
<td>YPRS3</td>
<td>1.87</td>
<td>5.09</td>
<td>11.20</td>
</tr>
<tr>
<td>YPRS4</td>
<td>14.41</td>
<td>16.59</td>
<td>18.16</td>
</tr>
<tr>
<td>YPRS5</td>
<td>0.29</td>
<td>0.59</td>
<td>2.1</td>
</tr>
<tr>
<td>WHFS1</td>
<td>4.46</td>
<td>7.60</td>
<td>14.15</td>
</tr>
<tr>
<td>WHFS2</td>
<td>2.25</td>
<td>4.66</td>
<td>8.92</td>
</tr>
<tr>
<td>WHFS3</td>
<td>3.32</td>
<td>7.45</td>
<td>12.83</td>
</tr>
<tr>
<td>WHFS4</td>
<td>2.65</td>
<td>5.80</td>
<td>10.77</td>
</tr>
<tr>
<td>WHFS5</td>
<td>1.83</td>
<td>3.87</td>
<td>8.17</td>
</tr>
</tbody>
</table>

### Table 2 Fouling status of track ballast based on fouling values

<table>
<thead>
<tr>
<th>Fouling quantity with reference</th>
<th>Clean</th>
<th>Moderately clean</th>
<th>Moderately fouled</th>
<th>Fouled</th>
<th>Highly fouled</th>
</tr>
</thead>
<tbody>
<tr>
<td>FI [31]</td>
<td>&lt;1</td>
<td>1 to &lt;10</td>
<td>10 to &lt;20</td>
<td>20 to &lt;40</td>
<td>≥40</td>
</tr>
<tr>
<td>FI [19]</td>
<td>&lt;2</td>
<td>2 to &lt;10</td>
<td>10 to &lt;20</td>
<td>20 to &lt;40</td>
<td>≥45</td>
</tr>
<tr>
<td>( F_{ID} ) [19]</td>
<td>&lt;2.1 and ( P_{13.2} \leq 1.5 % )</td>
<td>2.1 to &lt;4</td>
<td>4 to &lt;9.5</td>
<td>9.5 to &lt;40</td>
<td>≥40, ( P_{13.2} \geq 40 % ), ( P_{0.075} &gt; 5 % )</td>
</tr>
<tr>
<td>Percentage of fouling [1]</td>
<td>&lt;2</td>
<td>2 to &lt;9.5</td>
<td>9.5 to &lt;17.5</td>
<td>17.5 to &lt;34</td>
<td>≥34</td>
</tr>
</tbody>
</table>
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Characterization of Clean and Fouled Rail Track
Ballast Subsurface Using Seismic Surface Survey Method: Model and Field Studies

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 present 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...
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 with 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.
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 microzoning 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...
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 ton/m³ 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 ton/m³. An average SWV of 135 m/s corresponds to the second layer of clean ballast having a bulk density 1.59 ton/m³. 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 ton/m³ [30]. Density of 1.6 ton/m³ 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 ton/m³. 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

![Image: 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.](image-url)
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
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

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

![Image](https://via.placeholder.com/150)

(a) Clean ballast

(b) Dirty ballast with fine particles filling voids

(c) Fouled ballast with aggregate to aggregate contact lost
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

![Fig. 8—Shear wave velocity of filed Ballast samples.](image)

![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.](image)
(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 and 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 ball fouling is derailing of trains; many derailings 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
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 graded 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 (2005) L and U 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
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 coarser 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 have 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


Chapter- 2

Identification of Ballast fouling using Ground Penetrating Radar Survey

2.1 Introduction

The traditional selective ground drilling method is usually used to measure ballast thickness and evaluate its condition which is very time consuming and requires lot of man power. In addition, it does not provide a continuous measurement. Ground penetrating radar (GPR), a non-destructive method, on the other hand, can provide a rapid, effective, and continuous prediction of track substructure conditions. This chapter presents GPR survey using multiple GPR antenna in field to identify best suitable GPR antenna to study Indian railway subsurface. GPR is an electromagnetic sounding technique that is employed to investigate shallow sub-surface which have contrasting electrical properties (Daniels, 2004; Gallaghera et al., 1999). The GPR operates by transmitting short electromagnetic waves into the subsurface and recording and displaying the reflected energy. The data obtained from GPR testing is the time domain waveform representing the electromagnetic energy transmitted from the antenna and reflected off subsurface boundaries back to the antenna (Sussmanna et al., 2003). An examination of the reflected radar waveforms enables an interpretation of the material and/or structure under investigation.

Most of the GPR testing was carried out on actual railway lines (Brough et al., 2003; Carpenter et al., 2004; Eriksen et al., 2004). There are a lot of uncertainties within the actual rail track and it is difficult to calibrate the GPR data with actual ground condition because of a limited number of trenches and time constraint. Variation of degree of fouling also varies from site to site. In previous investigations limited attempt has been made to known degree of fouling and type of fouling using GPR testing on large scale model track. Leng and Al-Qadi(2010) carried out GPR survey on controlled model study in the laboratory and measured accurately the dielectric constants of two common ballast types, granite and limestone, under various fouling and moisture conditions. In order to investigate the relationship between recorded GPR data and ballast fouling conditions, a number of experiments are conducted on the model track with best suitable GPR antenna frequency.
2.2 Ground Penetrating Radar and Railway Studies

Ground penetrating radar is a device which works on a principle similar to radar at Airport. It sends EM waves through the transmitter and receives it from the receiver after it is reflected back from subsurface and plots it as a radar gram of distance versus depth or two way travel time. The depth of penetration depends on various factors such as properties of soil, dielectric constant of material, water content, porosity, etc. GPR is used most widely these days for subsurface studies, geological studies, forensic investigations, utilities, etc (Collins and Doolittle, 1987, Doolittle 1987, Doolittle 1983; Shih and Doolittle1984; Collins et al., 1986, Doolittle et al., 1990). In recent days GPR is used in US and other countries to maintain railway track and for detecting anomalies in the track structure (leng and Al-Qadi, 2009, Philip M Reppert, et al, 2000). Most of the GPR testing was carried out on actual railway lines in abroad (Brough, 2003; Carpenter, 2004; Eriksen, 2004). Leng and Al-Qadi, (2010) carried out GPR survey on controlled model study in the laboratory and measured accurately the dielectric constants of two common ballast types, granite and limestone, under various fouling and moisture conditions. GPR signals can detect the wave reflections from the layers of substructure (Gallagher et al. 1999; Jack and Jackson 1999; Sussmann et al. 2003). Ballast fouling can be identified from the radargram by variations in the depth of interface (low frequency antennae) or its scattering pattern (high frequency antennae) (Al-Qadi Imad 2008). In previous investigations limited attempt has been made to known degree of fouling and type of fouling using multiple GPR antennas and testing configuration in field track. Hence in this study an attempt has been made to identify the Ballast fouling of South Western Railway track using different antenna frequency.

This study consists of two parts, first part focusing on selection of suitable GPR antenna and second part discuss model study and results. GPR survey has been carried out on a newly laid track near Chennapatna railway station using 100 MHz, 500 MHz and 800 MHz antennas. Figure 7a-c shows typical field survey photos. Recorded GPR wave form data are processed and used to get radargram.
Figure 7a: GPR survey on newly laid track near chennapatna railway station using 100 MHz antenna GPR antenna.

Figure 7b: GPR survey on filed track using 500 MHz antenna GPR antenna.
2.3 GPR Data and Processing

Data were acquired using 100MHz, 500 MHz and 800 MHz ground coupled antennas are processed. Wheel encoder was used to measure the traveling distance of the antennas over rail surface. Raw data were processed using data processing software. The aim of this processing is to enhance signal–noise ratio and highlight interfaces and radargram textures. The processing includes band pass filtering, DC removal, subtract mean trace and gain control. Only very fundamental filters were applied to the raw data to avoid introducing artificial textures into the radargram. A comparison between raw and processed data from the 800 MHz antenna traveling along the left side of the track in the longitudinal direction is presented in Fig. The depth in the radargram was calculated based on an estimated wave velocity of $1.1 \times 10^8$ m/s. From the raw data, five continuous hyperbolas at the respective interfaces can be observed below the time of about 5 ns but no useful information can be obtained close to the ballast surface because of noise. After the above mentioned filters have been applied, an obvious improvement of the signal/noise
ratio can be observed. The interface between ballast and capping layer is revealed at the time of about 5 ns. Differences between textures of radargram at different locations can be observed which can help us judge that the condition of the ballast is not uniform.

Fig. 8. Comparison between raw (top) and processed (bottom) GPR data from the 800 MHz antenna.

Figures 9(a), 9(b) and 10 show processed GPR radargram from the same track location using 100 MHz, 500MHz and 800MHz antenna. it can be noted from Figure maximum subsurface information is possible only from 800 MHz antenna. Hence 800 MHz antenna is considered as best suitable GPR antenna for the further study.
Figure 9(a): Railway Ballast Section obtained from 100 MHz antenna.

Figure 9(b): Railway Ballast Section obtained from 500 MHz antenna.
To find out the dielectric constant of ballast section typical GPR wave from trace is considered. By knowing the depth and time of arrival of electromagnetic wave, velocity of the wave can be calculated as per below equations.

\[ t = \frac{2d}{v} \]  

(2)

Where, \( t \) = two way travel time,
\( v \) = velocity of penetration,
\( d \) = depth of the ballast.

And by the relation of dielectric constant to the velocity of penetration dielectric constant was calculated at various conditions as shown below.

\[ \varepsilon = \left( \frac{ct}{2d} \right)^2 \]  

(3)

Where, \( \varepsilon \) = dielectric constant,
$c$ = velocity of light in vacuum, $3 \times 10^8$ m/sec

$t$ = two way travel time,

$v$ = velocity of penetration,

$d$ = depth of the ballast.

### 2.4 GPR Model Studies and Results

Experiments were carried out in lab to find out the dielectric constant of the pure ballast, coal fouled ballast, iron ore fouled ballast and screen ballast fouled ballast at different percentages from 5 to 30% at increments of 5%. The model was constructed using the ballast with bottom width of 1m and top width of 0.6 m and a depth of 0.3 m as shown in figure 11. After this the GPR was moved on the top surface of the ballast. For this purpose the 800 MHz shielded antenna was used because of good radargram for ballast section. The MALA control unit, MALA 800MHz shielded ground coupled antenna, monitor and ground vision software was used for recording the setup. After the data was recorded it was processed using radd explorer software and desired results were found out. For different percentages of fouling the fouling material was mixed thoroughly with the ballast and reconstructed at different percentages like 5 %, 10 %, 15 %, etc up to 30 % and same was tested using GPR.

![Figure 11: Fresh ballast model at IISc lab with 800 MHz antenna.](image)
2.4.1 Coal fouled ballast

In India coal is used as a major source of energy in power plants, most of coal are transported through railway track. Thus railways play a major role in transportation of coal material from mines and harbour to the power plants as a bulk. While transporting coal in open wagons/containers, coal particles falls on the ballast and the track gets fouled due to accumulation of material with time. It important to know the amount of coal mixed with ballast for the better track maintenance. The coal fouled track will be deteriorated and thus the track needs time to time maintenance. In this study, model section with different degree of coal fouling was constructed and GPR survey has been carried out. GPR data are processed and dielectric constant of each model was estimated using procedure discussed above. Selected GPR radargram of the coal fouled ballast model is shown in Figures 12 and 13.

![Radargram of Coal Fouled Ballast](image)

Figure 12: The figure shows the radargram of the model ballast done using 800MHz antenna. Radargram of coal fouled ballast for percentages of fouling 5% (left) and 10% (right) respectively.
Figure 13: The figure shows the radargram of the model ballast done using 800 MHz antenna. Radargram of coal fouled ballast for percentages of fouling 15% (left), 20% (middle) and 25% (right) respectively.
From processed data wave form are extracted and used to estimate dielectric constant. Figure 14 shows the typical plot of wave forms for 10% coal fouled ballast section. The velocity of the penetration for 10% fouling is 0.1234cm/ns for a known depth. The dielectric constant was found to be 5.90 for this section. Similar procedure was used to estimate dielectric and average value is taken. The dielectric constant was calculated for all percentages of fouling is used to generate correlation between dielectric constant and fouling percentage. Figure 15 shows electromagnetic wave (EMW) velocity of coal fouled ballast versus percentage of fouling. Increasing in Fouling values results reduction of voids and therefore reduction in the EMW velocity.

![Figure 14: Selected GPR wave form trace for the radargram of 10% coal fouled ballast.](image)
Figure 15: Electromagnetic wave (EMW) velocity versus percentage of fouling for coal fouled ballast.

Figure 16: Dielectric constant versus percentage of fouling for coal fouled ballast.
Figure 16 shows fouling percentage versus dielectric constant for coal fouled ballast. It can be noted from Figure that increasing of fouling results in increase of dielectric constant. In this study correlation generated can be used to get percentage of fouling in the coal fouled ballast track by estimating dielectric constant.

2.4.2. Iron ore fouled ballast

India is a mineral rich country. One of the most abundant resource is iron ore. Iron ore is a raw material which is used in steel industries to produce lot of steel items like cars, rails, axle wheel, spare parts etc. Also iron ore is exported in large quantities to other countries as well, thus making it necessary for transportation of iron ore to industries and harbours for the export. Here the railways play a vital role in this regard and transporting of iron leads to fouling of ballast due to spilling. Thus it is necessary to study the fouling of iron ore and model studies were made similar to coal fouling from 5 to 30% with 5% increase and 800MHz GPR antenna was used for the study. The typical radargrams of iron ore fouled ballast section are shown in Figures 17 and 18.

Figure 19 shows the selected GPR EMW form data corresponding to 20% fouling of iron ore. Dielectric constant of fouled sections are estimated using the depth of fouled ballast i.e 0.3 m and the EMW velocity i.e. 0.1108 cm/ns. Similar procedure was used to estimate dielectric and average value is taken. The dielectric constant was calculated for all percentages of fouling and is used to generate correlation between dielectric constant and fouling percentage. Figure 20 shows electromagnetic wave (EMW) velocity of iron ore fouled ballast versus percentage of fouling. Increasing in Fouling values results reduction of voids and thereby reduction in the EMW velocity. Figure 20 shows fouling percentage versus dielectric constant for iron ore fouled ballast. It can be noted from Figure 20 that increasing of fouling results in increase of dielectric constant, however trend of variation is different from coal fouled ballast. This correlation generated can be used to get percentage of fouling in the iron ore fouled ballast track by estimating dielectric constant.
Figure 17: Radargram of iron ore fouled ballast model section for percentages of fouling 5% (left), 10% (middle) and 15% (right) respectively using 800MHz antenna.
Figure 18: Radargram of iron ore fouled ballast model section for percentages of fouling 20% (left), 25% (middle) and 30% (right) respectively using 800MHz antenna.
Figure 19: Selected GPR wave form trace for the radargram of 20% iron ore fouled ballast.

2.4.3 Fouled by Screen ballast

The ballast section also fouled by different means apart from coal and iron ore transportation. Other means of fouling was discussed in "Rail Track Geotechnical Engineering and Ballast Fouling" of these breakage of ballast due to heavy cyclic loads due to train wheels and soil from surrounding play major role in this type of fouling major. In order to understand GPR application of these type of fouled track, study has been carried out using broken ballast fouling materials. This broken ballast is accumulated at bottom and mixed with fine particles to be called as screen ballast. Screen ballast samples are collected from railway after deep screening processes. Screen ballast fouled section are constructed and GPR survey has
been carried out. GPR radargram of screen ballast fouled section are shown in Figures 22 and 23.

Figure 20: Electromagnetic wave (EMW) velocity versus percentage of fouling for iron ore fouled ballast.

Figure 21: Dielectric constant versus percentage of fouling for iron ore fouled ballast.
Figure 22: Radargram of iron Screen ballast model section for percentages of fouling 5% (left), 10% (middle) and 15% (right) respectively using 800MHz antenna.
Figure 23: Radargram of screen fouled ballast model section for percentages of fouling 20% (left), 25% (middle) and 30% (right) respectively using 800MHz antenna.
Figure 24 shows the selected GPR EMW form data corresponding to 30% fouling of screen ballast. Dielectric constant of fouled section are estimated using the depth of fouled ballast section i.e 0.3 m and the EMW velocity i.e. 0.1182 cm/ns. Similar procedure was used to estimate dielectric constant and average value is taken. The dielectric constant was calculated for all percentages of fouling is used to generate correlation between dielectric constant and fouling percentage. Figure 25 shows electromagnetic wave (EMW) velocity of iron ore fouled ballast versus percentage of fouling. Increasing in Fouling values results reduction of voids and there by reduction in the EMW velocity. Figure 21 shows fouling percentage versus dielectric constant for iron ore fouled ballast. It can be noted from Figure 21 that increasing of fouling results in increase of dielectric constant, however trend of variation is different from coal and iron ore fouled ballast section. This correlation generated can be used to get percentage of fouling in the Screen ballast fouled track by estimating dielectric constant.

![GPR Trace Amplitude](image)

**Figure 24:** Selected GPR wave form trace for the radargram of 30% screen ballast fouled section.
Figure 25: Electromagnetic wave (EMW) velocity versus percentage of fouling for Screen fouled ballast.

Figure 26 Dielectric constant versus percentage of fouling for screen ballast fouled sections.
Chapter - 3

Summary and Conclusions

Studies across the world show that fouling of ballast create several problems in track foundation and thereby resulting misalignment of the rails leading to derailments of the trains. Very limited ballast related study has been carried out for Indian railway. Many researchers around the world have developed Scales to evaluate the fouling content of the ballast based on their country’s specification and hence they can’t be used in India. In this project first research study on Indian railway ballast was presented. The following conclusions are arrived from this study:

- Study shows that the ballast gradation followed by the Indian railways is poorly graded and more favorable for drainage.
- Fouling indices are specific to the ballast gradation and type of fouling materials. Fouling values are estimated considering existing fouling scale and further new fouling indices are suggested in this study based Indian railway ballast gradation. However more experimental research are needed to define the suitable fouling indices and fouling classification scheme for Indian track by considering different fouling materials.
- The proposed fouling indices can be used to quantify ballast fouling for Indian rail track.
- Strength and permeability of fouled ballast are different from that of fresh ballast, more research is needed to understand the mechanics and permeability character of Indian fouled ballast.
- The inspection of track foundations and the maintenance followed in Indian railways are conventional and the cleaning of ballast is once in 10 years irrespective of the amount and type of fouling. In this GPR has been used to investigate field track.
- GPR study on field rail track using 100 MHz, 500 MHz and 800 MHz antenna frequency shows that 800 MHz best suitable antenna to understand ballast section.
- In order to identify degree of ballast fouling in the field track, model study was carried in the project considering different fouling materials in India and best suitable GPR antenna.
- In this report correlation between dielectric constant and percentage of fouling for ballast fouled by coal, Iron Ore and screen ballast are presented. These correlations can be used to estimate degree of fouling in filed track by carrying out GPR survey and plan effective deep screening of fouled track section to reduce problem due to ballast fouling.
References


