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Identification of type and degree of railway ballast fouling using ground coupled GPR antennas

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ABSTRACT

GPR is widely used for ballast fouling identification, however, there are no robust guidelines to find the degree and type of fouling quantitatively. In this study, GPR studies were carried out on model and actual railway tracks using three ground coupled antennas and considering three fouling materials. Three ground coupled antennas viz., 100 MHz, 500 MHz and 800 MHz antennas were used for the initial survey and it was found that the 800 MHz ground coupled antenna is an optimum one to get quality results. Three major fouling materials viz., screened/broken ballast, coal and iron ore were used to construct prototype model sections, which were 1/2 of the actual Indian broad-gauge railway track. A separate model section has been created for each degree and type of fouling and GPR surveys were carried out. GPR study shows that increasing the fouling content results in a decrease in the Electromagnetic Wave (EMW) velocity and an increase in the dielectric constant. EMW velocity of ballast fouled with screened ballast was found to be more than coal fouled ballast and iron ore fouled ballast at any degree of fouling and EMW velocity of iron ore fouled ballast was found to be less than coal and screen ballast fouled ballast. Dielectric constant of iron ore fouled ballast was found to be higher than coal and screen ballast fouled ballast for all degrees of fouling. Average slope of the trend line of screen ballast fouled section is low (25.6°), coal fouled ballast is medium (27.8°) and iron ore fouled ballast is high (47.6°).

1. Introduction

In a demographically large country like India, railways play a major role in the movement of passengers and freight from one place to another. Railroad system effectively connects all major ports and refineries to the major cities of India, which plays a pivotal role in the transportation of goods. Ballast railroad plays an important role keeping the rail in position, supporting the heavy cyclic load from train wheels and transforming/dissipating train load with less track deformation. It also provides free drainage of water from the railway track formation and prevents the growth of vegetation that might interfere with the rail movement. Ballast is usually made of crushed stone from materials like granite, dolomite or quartzite; sometimes it may consist of undesirable material though. The mechanical and physical properties desirable for a good ballast are they must be strong, stable, drainable, workable, easily available locally and most of all cheap to purchase (William, 1982). When the railways were first introduced, engineers did not know the importance of the railway ballast formation and locally available soft materials like limestone, ashes, chalk and cinders from locomotives were used as ballast. Soon with time, they came to know that good quality ballast rock is important for good foundation stability and good drainage for the railway tracks (Solomon, 2001; Bonnet, 2005). Size smaller or larger than 9.5 mm to 65 mm is not desirable as smaller sizes can reduce the drainage properties and larger size may dissipate the track loads in a nonuniform manner. Railway ballast layer is the most important component of the railway track foundation. It is subjected to both traffic loads and exposure to environmental changes. Due to this the ballast bed deforms and degrades, hence adversely affecting the performance of the railway track. Ballast gets fouled due to train load, spillage of goods and weak subsurface soil (William, 1982).

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 decreases the performance for which it has been designed and results in the deformation of the track section. The decrease in track performance is controlled by the type of fouling and also the amount of fouling (Selig and Waters, 1994). At moderate degrees of fouling, softer fouling material such as fine soil can create an adverse slippery effect (mud pumping) when compared to harder fouling materials such as iron ore and broken blast. Degraded ballast in non-screened track has large amount of fine particles accumulated within the voids (i.e., fouling) thus impeding drainage. When fouling becomes extreme, then excess pore water pressure is generated under fast moving trains (i.e., high cyclic loading), thereby reducing the track resiliency and stability in undrained conditions (Indraratna et al., 2010). For this reason, it

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is important to detect the ballast fouling in time to maintain the track properly and optimize the life cycle cost of the track foundation system. A traditional way of pit excavation at regular intervals is used to monitor the ballast thickness and fouling in the ballast system, but it is a time consuming and non-continuous method. Non-destructive testing methods like ground penetrating radar (GPR), infra-red imaging, seismic survey and electrical resistivity are popular among others, for fouling identification in the field (Anbazhagan et al., 2010). However, none of the testing method has been quantified to assess the degree and type of fouling. To address these issues, this paper presents GPR study on a clean and fouled prototype model section. The study has been carried out considering three fouling materials (screened ballast, coal and iron ore). Prototype model track sections are constructed using fresh ballast and different degrees of fouled ballast. GPR studies have been carried out using 800 MHz antenna and dielectric constant has been estimated by adjusting the velocity for a known thickness. The fouling materials of coal, iron ore and screen ballast are examined and dielectric constant for each fouling material is estimated. Finally the correlation between dielectric constant versus degree of fouling has been developed and discussed in this paper. Li Jun et al. (2010) presented a study on different fouling materials using a similar GPR antenna. It can be noted that Li Jun et al. (2010) constructed only limited (i.e. 3 and less) fouled sections. Most of the previous studies are concentrated on identifying the degree of fouling and very limited attention was paid to study the type of fouling. In this study, three fouling materials and more than 5 fouled sections for each fouling material are studied. The study shows that the degree of fouling can be identified considering a dielectric constant and type of fouling can be identified considering the slope of the line connecting few dielectric constants.

2. GPR for railway track study

GPR wave character/radargram image quality depends mainly upon the dielectric properties of the materials. Also, it depends on density, moisture content, and porosity. Thus, from the GPR data if we know the velocity of penetration, depth of material and two way travel time, the dielectric constant of the material can be determined (Leng and Al-Qadi, 2010). Dielectric constant of the material can be estimated using the relation given below:

$$\varepsilon = (ct/2d)^2 \tag{1}$$

where, ε = dielectric constant, c = velocity of light in vacuum (3×10^8 m/s), t = two way travel time and d = depth of ballast model.

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 radargram and it is difficult to calibrate the GPR data with actual ground condition because of a limited number of trenches and time constraint. A wide range of GPR antennas is being used in the railway track field study; most of them being high central frequency antennas (>1000 MHz). Recently Anbazhagan et al. (2011a) used 500 MHz, 800 MHz, 1.6 GHz and 2.3 GHz ground coupled antennas in a small scale model study and found that the 800 MHz gives good results when compared to other antennas for Australian railway ballast. In order to find out the best suitable GPR antenna in the real track, three ground coupled GPR antennas have been used in the field study. MALA shielded ground coupled antennas having a central frequency of 100 MHz, 500 MHz and 800 MHz with an X3M control unit and an XV11 monitor has been used for the study.

3. Selection of GPR antennas

In order to precisely see the GPR wave form and non availability of air-coupled antennas, in this study it was decided to use a ground coupled antennas. In order to identify the effective GPR antenna frequency, three ground coupled GPR antennas having a central frequency 100 MHz, 500 MHz and 800 MHz were used. GPR survey has been carried out on a relatively fouling free track (newly laid track). Antenna mounting trolley has been designed and constructed in such a way that it can be used on both railway track and on the road. The GPR antenna is placed on an acrylic base which completely transmits the electromagnetic waves and does not reflect them back. The height of this acrylic base can be adjusted from 0 to 0.2 m depending upon the requirement. The wheels of the trolley are insulated in a manner similar to that of the standard railway trolley. Fig. 1 shows typical field GPR survey photos with dedicated wheel insulated trolley. Recorded GPR waveform data are processed and used to get radargram. The aim of this processing is to enhance signal–noise ratio and highlight interfaces and radargram textures. Comparison of different radargrams obtained by simple processing steps of respective antennas are presented in Fig. 2. Fig. 2(a), (b) and (c) shows processed GPR radargram from the same track location using 100 MHz, 500 MHz and 800 MHz antenna and these radargrams includes a fundamental processing which includes a band pass filtering, DC removal, subtract mean trace and gain control. The interface of different layers in these radargrams can be interpreted by the texture of the radargram and amplitude of the waveform. Roberts et al. (2006) suggested an alternate approach based on scattering amplitude envelope to effective identification of ballast layers for 2 GHz air coupled antennas.

Scattering amplitude envelope approach suggested by Roberts et al. (2006) has been applied to our data, which involved the following filters to be applied to the raw GPR data viz., a) time zero correction, b) background removal, c) gain restoration, d) Hilbert transformation, e) horizontal moving average, f) vertical low pass filter and g) colour transform. The resulting scans of data from Hilbert transformation or reflection strength filter of processing are referred to as the scattering amplitude envelopes. Resulting processed radargrams are given in Fig. 3(a) and (b) for 500 MHz and 800 MHz antenna respectively. Fig. 3(a) and (b) corresponds to simple step processing radargram given in Fig. 2(b) and (c). Data obtained from 100 MHz is not yielding good layer variation processed radargram by scattering amplitude envelope approach when compared to 500 MHz and 800 MHz processed radargram. It can be seen from both the figures that interpretation of the interface of ballast and soil layer is almost similar. It can be noted here that radargram texture variation can be clearly seen in Fig. 2(b) and (c) when compared to Fig. 3(a) and (b). This may be due to that automated scattering amplitude envelope approach was developed for high frequency air coupled antenna data, in this study low to medium frequency (100 MHz to 800 MHz) ground coupled antennas were used. More studies may be required to comment about the applicability of the scattering amplitude envelope approach to low to medium frequency ground coupled antenna data. Subsurface layers are delineated

Fig. 1. Typical GPR survey at real track using 800 MHz antenna using specially designed wheel insulated trolley.

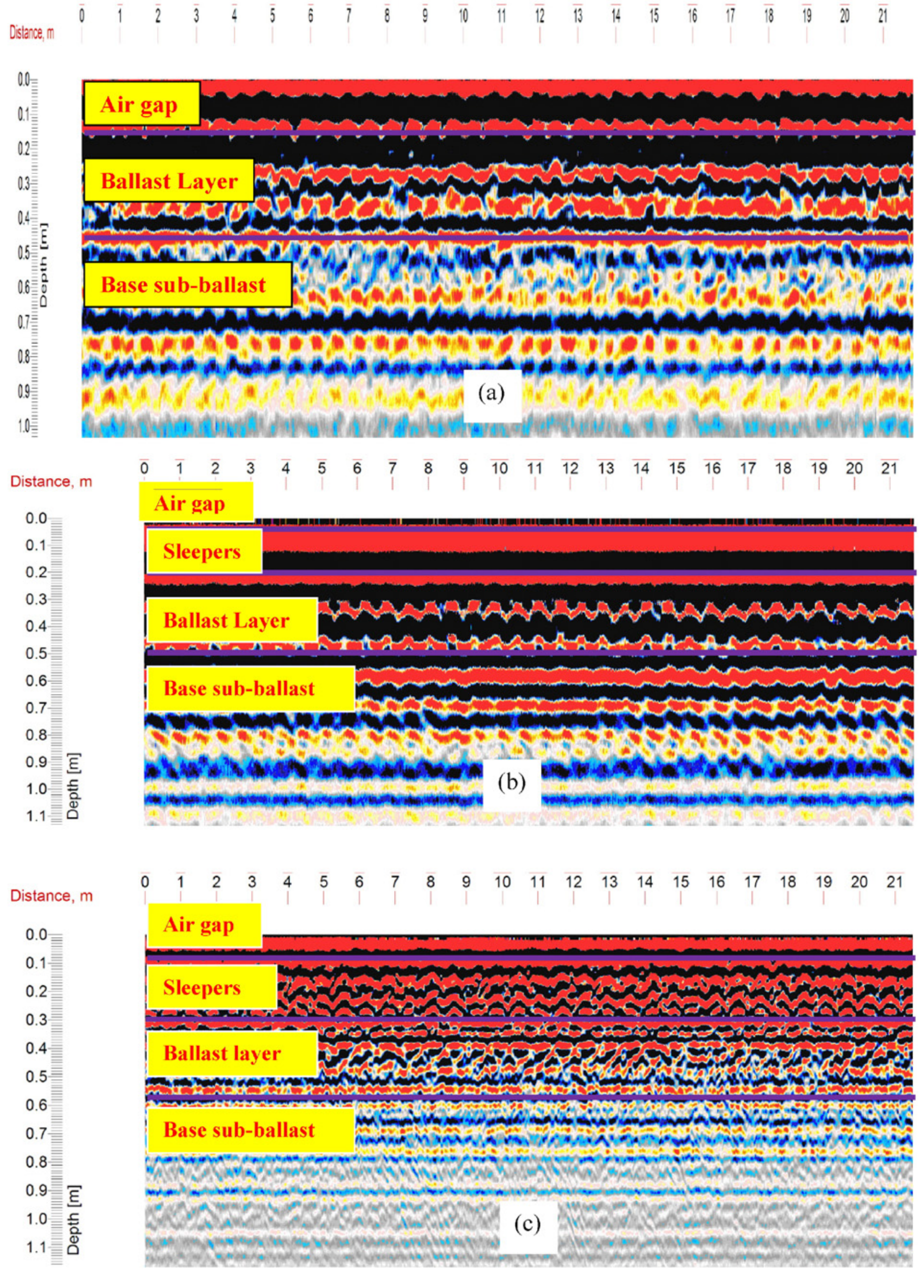

Fig. 2. Radargram of real railway track using (a) 100 MHz GPR antenna, (b) 500 MHz GPR antenna and (c) 800 MHz GPR antenna.

by considering radargram texture and GPR wave amplitudes by simple processing and also by scattering amplitude envelope approach. It can be noted from the both analysis radargrams that the maximum subsurface information is possible only from 800 MHz antenna radargram. Hence, 800 MHz antenna is considered as the best suitable GPR antenna for further study.

4. Materials and properties

For the construction of model sections, fresh ballast from local ballast supplier were collected. These samples are similar to the widely used ballast in Indian railway and are also as per IRS-GE-1 (2004) specification. Indian railway ballast is generally of crushed stone derived from granite rock, which is predominant in India. The specific gravity of the ballast was found to be 2.847 according to AASHTO T85 and the Coefficient of Uniformity (Cu) and Coefficient of Curvature (Cc) values were found to be 2.27 and 1.24 respectively. The presently followed Indian railway ballast gradations are specified in IRS-GE-1 (2004). As per IRS-GE-1 (2004) Ballast should follow that maximum retained on 65 mm sq·mesh sieve is 5%, retained on 40 mm sq·mesh sieve is 40%–60% and retained on 20 mm ssq·mesh sieve is not less than 98% for machine crushed and not less than 95% for hand broken. Upper and lower gradation curves of Indian ballast are given in Fig. 4. The upper and lower limits of Indian railway gradations are very narrow (Anbazhagan et al., 2012). Indian ballast can be classified as poorly graded gravel as per Unified Soil Classification System (USCS). The Indian ballast size is larger than the international ballast size and more favorable for drainage and breakage (Anbazhagan et al., 2012). The fresh ballast is fouled due to several reasons; information on Indian ballast fouling and more discussions about Indian ballast fouling can be found in Anbazhagan et al. (2011b). In this study, three widely reported fouling materials in India are considered. The most important fouling material is broken ballast mixed with other materials like dust and soil, which is also called as screen ballast. The screened ballast was collected

Fig. 3. Processed radargram of real railway track by applying the scattering amplitude envelope approach. (a) 500 MHz GPR antenna and (b) 800 MHz GPR antenna.

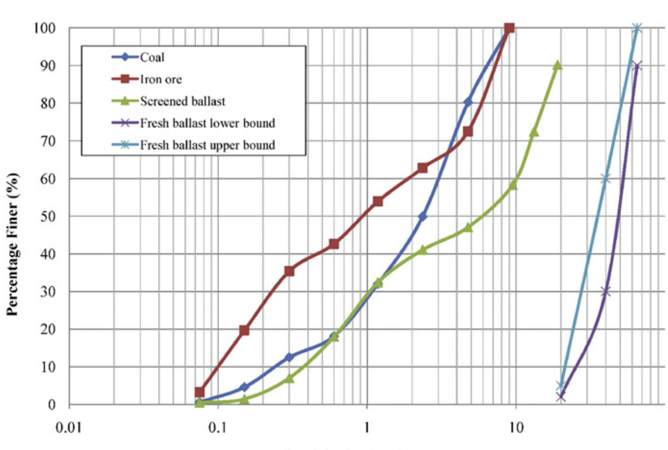

Fig. 4. Particle size distribution of fresh ballast and fouling materials of coal, iron ore and screen ballast.

from the dump yard, close to the recently screened track. The screened/broken ballast contained different particle size materials i.e. fine (<4.75 mm which constituted about 30.26% of the total sample), medium (4.75–19 mm which constituted about 52.32% of the total sample) and coarse (>19 mm which constituted about 17.41% of the total sample) group. The specific gravities of these groups are 2.24, 2.42, and 2.63 respectively as per IS: 2720 (Part 3/Set 1, 1980 and AASHTO T 85. Particle gradation of screen ballast is shown in Fig. 4. Next predominant fouling material is coal, which is spilled from the coal transporting rail car. Coal sample was collected from the coal transporting railcar. The specific gravity of coal was found to be 1.13 and gradation is shown in Fig. 4. Iron ore is transported in railcar from mines to harbor and steel plant. Iron ore was collected from the Bellary railway station. The specific gravity of iron ore is 4.21 as per IS: 11896 (1986). The gradation curves of all the three selected fouling materials are shown in Fig. 4. It can be noted from Fig. 4 that the fouling material is having a maximum of 10 mm size particle and which is 1/2 times the minimum particle size in fresh ballast. Required quantities of these fouling materials were mixed with fresh ballast to construct the fouled section.

5. Model section

Many GPR studies have been carried out on the real track, whereas a limited study has been carried out in controlled field/model ballast section. Zhen and Al-Qadi (2010)carried out a GPR study on different ballast layers in the wooden box. Anbazhagan et al. (2011a) used the similar model sections concept in a bigger scale. Each section consisted of subgrade layers of clayey sand, a capping layer of road base material and a ballast layer with a width of 0.5 to 1.5 m. Both study sections are rectangular and sections are confined within the box. In order to create a prototype of railway track in this study, the section was constructed on a 1/2 scale of the real track section. Typical cross section dimension of prototype section is shown in Fig. 5. In order to determine the dielectric constant of clean ballast, typical 1/2 rail ballast section with different thicknesses has been constructed using clean ballast. Fig. 6 shows the typical model section of clean ballast with different thicknesses/heights along with GPR survey using 800 MHz antenna. As discussed earlier, prototype model of fresh ballast was constructed similar to the cross section given in Fig. 5, up to a length of about 10 m. The first section is constructed with ballast thickness of 390 mm up to a length of about 1.5 m (section A–A) and then about 0.5 m length with a ballast thickness of 300 mm. Section B–B is constructed up to 3.5 m with a ballast thickness of about 450 mm. After this section, ballast thickness is kept at 300 mm up to 6.0 m and which is called as section C–C. + Ballast section after 6 m is constructed on a gently sloped ground and called as section D–D. This section is constructed to know which GPR antenna shows ballast depth accurately and also to find out the dielectric constant of clean ballast in a field scale model with different thicknesses. GPR survey results in a clean ballast model are discussed in the next section. Fouled model sections were constructed with three fouling materials with uniform thickness of 300 mm. Percentage of Fouling and Fouling Index by Selig and Waters (1994) are most widely used ballast fouling assessments methods and these depends on ballast gradation and any change in fouling material results in misinterpretation of fouling assessment. To overcome this misinterpretation Feldman and Nissen (2002) proposed volume based fouling scale of Percentage Void Contamination (PVC). In PVC volume of fouling material is calculated by compaction and which does not always represent the actual volume of fouling accurately (Tennakoon et al., 2012). Tennakoon et al. (2012) modified PVC and proposed Void Contaminant Index (VCI). In our study new fouling index proposed by Anbazhagan et al. (2012) for Indian Railway ballast has been used to estimate required fouling materials for different degrees of fouling i.e. 5, 10, 15, 20, 25 and 30%.

Model section was constructed by adopting two methods. Method-1: The lower degree of fouling model sections was constructed by constructing clean ballast section layers first and sprinkling required fouling material and regular tapping. Method-2: Higher degree of fouling model sections were constructed by using blended materials. Required amount of fouling material is blended with fresh ballast and constructed by layer system with necessary compaction by tapping. Care has been taken in the process of tamping such that there is no damage to the fresh ballast.

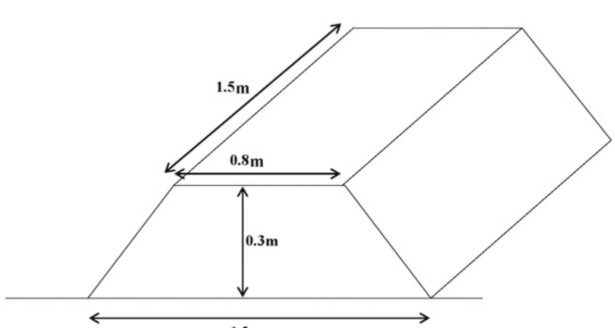

Fig. 5. Typical prototype model section constructed for the study.

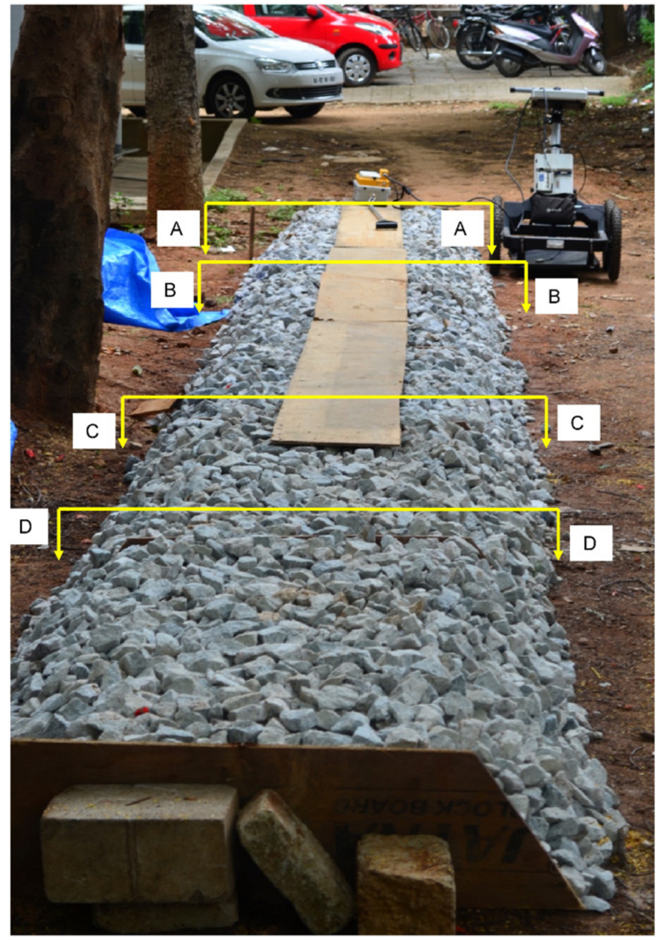

Fig. 6. Prototype fresh ballast model section with different thicknesses of ballast and the GPR survey using 800 MHz.

GPR survey was carried out on each model section using 800 MHz ground coupled antenna. Results from each model study and dielectric constant are discussed in the next section.

6. GPR survey results and validation

Here 800 MHz ground coupled GPR antenna has been used for all the model studies. Thin plywood has been placed over the model section for smooth movement of the antenna (see Fig. 6). GPR wave forms are recorded up to a length of 10.0 ns. and sampling at every 2 cm with electromagnetic wave velocity of 10 cm/ns. The raw data were processed using data processing software RADEXPLORER. The processing includes a band pass filtering, DC removal, subtract mean trace and gain control. After the aforementioned filters have been applied, an obvious improvement of the signal/noise ratio was observed. Differences between the textures of radargram at different locations were observed and used to evaluate the condition of the ballast fouling. Fig. 7 shows the processed radargram for fresh ballast model section given in Fig. 6. As depth of each section is known, the GPR electromagnetic wave velocity is adjusted to get accurate depth information by trial and error. Adjusted velocity values give different time periods trace wave amplitudes. GPR waveform trace amplitudes are used to distinguish the interface of ballast and ground surface. Adjusted velocity for matching of thickness of model section are used to further identify the time difference between trace amplitudes for each trace. This travel time and thickness are coupled in Eq. (1) and dielectric values are estimated. Table 1 shows the actual section thickness, time after adjusting velocity and dielectric constant. It is noticed that the dielectric constant of fresh ballast is about 5.17, which is comparable with the average dielectric constant of

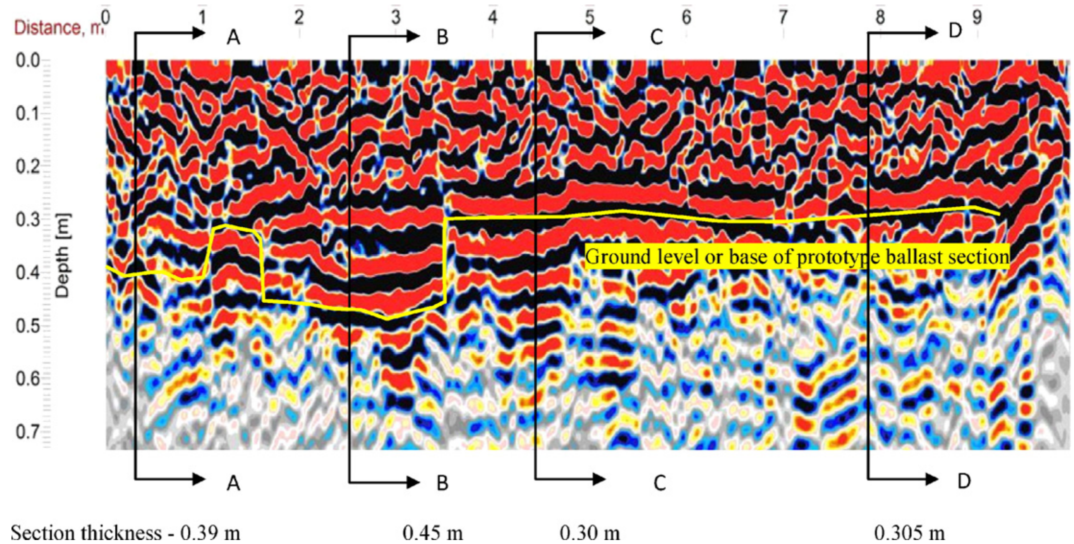

Fig. 7. GPR radargram from fresh ballast prototype model section using 800 MHz antenna.

granite stone given by Philip et al. (2000) and slightly more than what Leng and Al-Qadi (2010) got. The dielectric constant values in the paper of Leng and Al-Qadi (2010) are different, which may be due to differences in the gradation and composition of the ballast.

Fouled ballast section was prepared for the percentage of fouling as 0%, 5%, 10%, 15%, 20% and 22.5% for coal, 0 to 30% with 5% increment for iron ore and screen ballast. Model sections were constructed as described in the previous section. GPR survey was carried out on fouled ballast model sections with different degree of fouling (mixture of fresh ballast and fouling materials) and wave form data are processed as discussed earlier. Adjusted velocity gives accurate time travel of the waves for a model depth and which is further used to estimate dielectric constant of each fouled section. Fig. 8 shows the typical radargram for 5% and 20% fouled sections for three fouling materials. The difference in radargram texture for slightly fouled (5%) section (left side, i.e. panels a, c and d) and highly fouled (20%) section (right side i.e. panels b, d and f) can be clearly noticed. Processed radargram of each model section is converted to ASCII format and which gives time and amplitude of each trace in the radargram. These data are used to estimate EMW velocity and dielectric constant for each model. Variations of the EMW velocity for a given depth of 300 mm with the respective degree of fouling for different materials are shown in Fig. 9. In Fig. 9, it can be observed that irrespective of the fouling material type, increase in the percentage of fouling leads to decrease in EMW velocity. This can be predicted using a linear model for the coal and screen ballast fouling sections. Fig. 10 shows the relationship between percentage fouling and the dielectric constant for ballast fouled with coal, screened ballast, and iron ore respectively. A significant increase in relative dielectric constant can be observed in Fig. 10 when the degree of fouling is increased. For fouling with the same percentage, the dielectric constant for ballast fouled with iron ore was more than coal and screen fouled ballast because the dielectric permittivity (dielectric constant) for iron ore is larger than the soil and rock material. Slope of the trend line for each fouling material has been estimated and given in Fig. 10. It can be noted that screen fouled ballast has a low slope (25.8°), coal fouled ballast has moderate (37.8°) and iron ore fouled ballast has high (47.6°) slopes. These average slopes can help to find out the type of fouling. These results indicate that the degree of fouling and type of fouling can be estimated by measuring and calculating the dielectric constant of fouled ballast. Single dielectric measurement may be used to find out the degree of fouling. More than two values of dielectric measurement can be used to get the slope and correlated with average slope values given in this study to know the type of fouling. So few accurate estimates of dielectric constant can also help to find out the degree and type of fouling materials using results presented here.

Table 1
Dielectric constant of fresh ballast section from prototype model with different thicknesses.

Section	Measured thickness (m)	Time (s)	Dielectric constant (ε)
A–A	0.392	5.94E−09	5.166343
B–B	0.42	6.36E−09	5.166222
D–D	0.300	4.54E−09	5.161984
C–C	0.305	4.62E−09	5.172346

The model study shows that the dielectric constant of clean ballast filled with air is constant irrespective of the thickness of the section. When air is replaced with other fine fouling materials, EMW velocity decreases due to increase in the volumetric percentage of mixture components i.e. reduction in the porosity. Reduction in porosity i.e. the increase in fouling percentage results in a decrease in EMW velocity. Hence fouled ballast dielectric constant values are slightly larger than the clean ballast (Li Jun et al., 2010). Dielectric constant of ballast fouled by screened ballast as fouling material is comparable with Li Jun et al. (2010). However, dielectric constant of clean ballast and coal fouled ballast values is slightly larger, which may be because of different mineral composition of rock and coal and also gradation differences between Indian and Australian ballast. In order to check the model study values with the field values, in-situ GPR survey has been carried out on real rail track where the thickness of ballast is measured by pit excavation. GPR survey has been carried out on newly laid track (track having a thickness of about 300 mm and zero degree fouling). Similarly GPR survey was also carried out on a track which was deep screened about 3 years ago and predominantly fouled by screen ballast. The average depth of the ballast layer is 300 mm excluding the 200 mm capping layer in both the tracks. Recorded EMW data are processed and EMW velocities are adjusted to show the accurate measured depth; dielectric constants are determined using adjusted time and measured depth in the field track. Fig. 11 shows a variation of dielectric constant with a percentage of fouling for screen ballast fouling and field measured dielectric constant values for similar fouling. It can noticed in Fig. 11 that the model track dielectric constant values are matching with field track

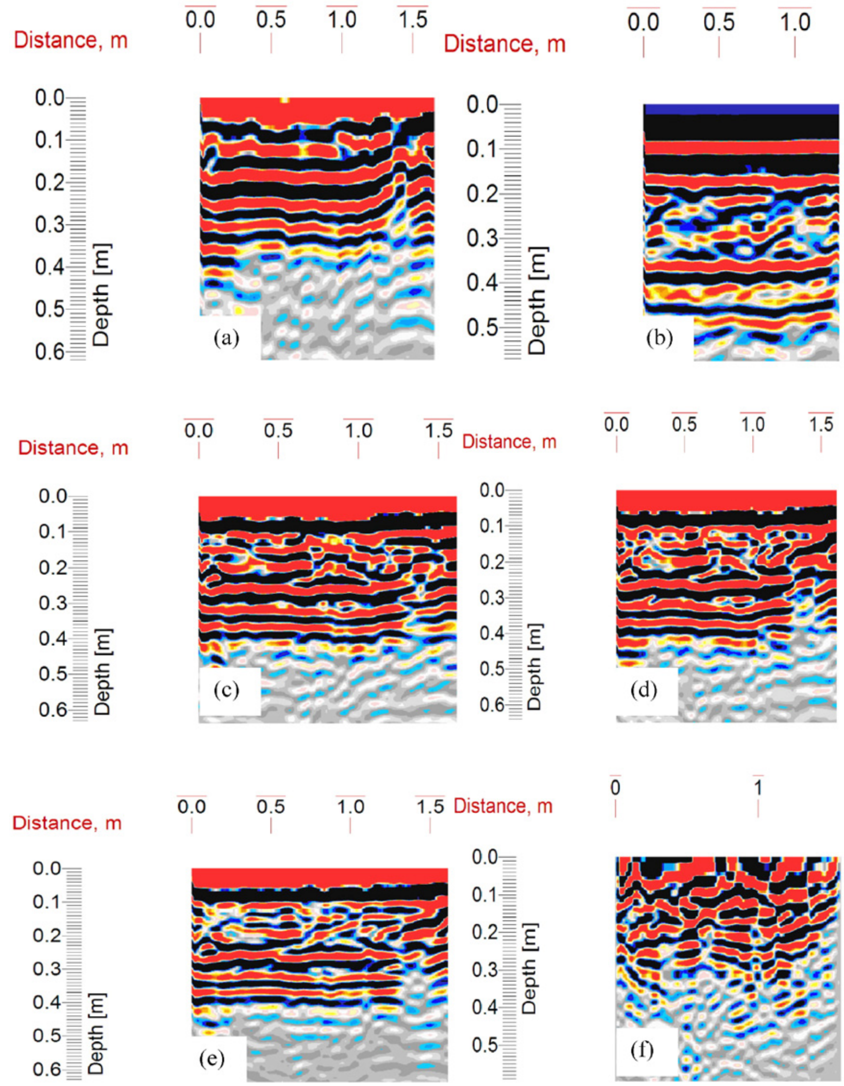

Fig. 8. Radargrams of the fouled ballast section using 800 MHz antenna. Panels a, c, and e correspond to 5% fouled by coal, iron ore and screen ballast respectively. Panels b, d, and f correspond to 20% fouled by coal, iron ore and screen ballast respectively.

values. Li Jun et al. (2010) has given dielectric constant for 20% screen ballast fouled ballast, which very well matches with the model study carried out in this study. Dielectric constant of the field track can be compared with model track results presented in this study to determine the amount of fouling and also type of fouling.

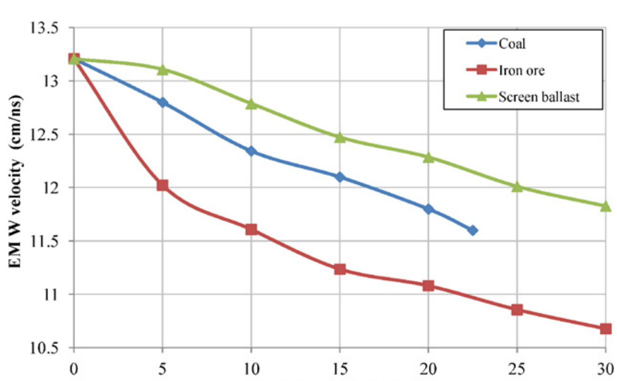

Fig. 9. Electromagnetic wave (EMW) velocities for a given depth of 300 mm for clean and fouled ballast by three fouling materials.

7. Conclusions

Studies across the world show that fouling of ballast creates several problems in track foundation and thereby results in misalignment of rails thus leading to derailments of the trains. Very limited ballast

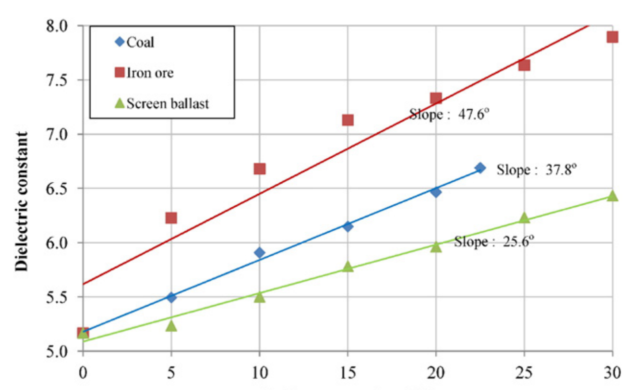

Fig. 10. Variation of dielectric constant with percentage of fouling for three fouling materials.

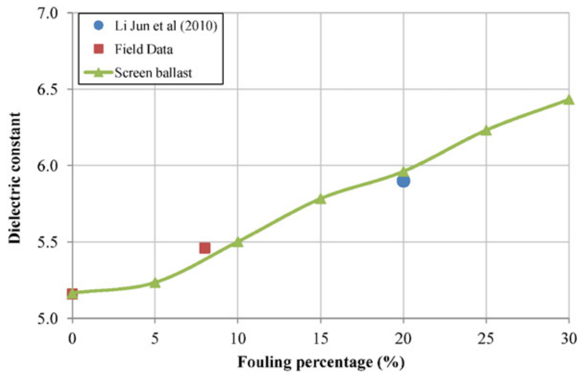

Fig. 11. Variation of dielectric constant with a percentage of fouling for ballast fouled with screen ballast. Field samples and model with screen ballast are from India and Li Jun et al. (2010) from Wollongong Australian ballast.

related study was carried out in India. This paper presents a GPR study on clean and fouled ballast and the following conclusions were arrived. GPR study on field rail track using 100 MHz, 500 MHz and 800 MHz antenna frequency shows that 800 MHz is the best suitable antenna to understand the ballast section. Radargram obtained from 800 MHz is having a clear texture and are useful to estimate dielectric constant. Prototype model section of 1/2 of real track was constructed using clean and fouled ballast with 300 mm thickness. Electromagnetic wave velocity and dielectric constant of each model section were estimated. Ballast filled with air voids has higher EMW velocity and lower dielectric constant when compared to ballast filled with fines i.e. fouling materials. Increasing fines/degree of fouling results in a decrease in EMW velocity and the increase in the dielectric constant. EMW velocity of ballast fouled with screened ballast is more than coal fouled ballast and iron ore fouled ballast for any degree of fouling. EMW velocity of iron ore fouled ballast is less than coal and screen ballast fouled ballast. Dielectric constant of iron ore fouled ballast is higher than coal and screen ballast fouled ballast for all degrees of fouling. The dielectric constant obtained in this study is comparable to the previous study and matches well with the filed track values. Model study results may be used to find out the degree and type of ballast fouling in the field track by measuring EMW velocity and estimating dielectric constants.

- 100 MHz, 500 MHz and 800 MHz antennas were used and found that the 800 MHz is suitable.
- Electromagnetic Wave (EMW) velocity is decreasing and dielectric constant increases for increasing of fouling content.
- Dielectric constant of iron ore fouled ballast is higher than coal and screen ballast fouled ballast.
- Slope of fitted line of fouled ballast by screen ballast is low (25.6°), coal is medium (27.8°) and iron ore is high (47.6°).

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