



Effect of High-Speed Train Vibrations on Ballast Fouling and Soil Formation Layer using ‘SASW’

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Abstract

The research study explores impact of high-speed rail on railway ballast performance, addressing issues like fouling, cyclic rail loads, and geotechnical factors. (Dingqing Li, James Hyslip, Ted, 2019) Spectral Analysis of Surface Waves (SASW) technology is a nondestructive technology employed to ascertain appropriate ballast health by measuring shear wave velocity (SWV). The research examines SWV variations in differently aged tracks before, during, and after high-speed train travel. The study recorded shear wave velocities before, during & after passage of the train at two locations, depicting the semi-elastic nature of the ballast bed. Shear wave velocities increase with fouling amount, with the optimum fouling point (OFP) and critical fouling point (CFP) being 13%, 13.75%, 15.5%, and 19%, respectively based on the samples collected. The strength tests, which included abrasion and impact strengths, were also performed at the two sites shown. Additionally, in-situ sample collection and analysis of the ballast gradation were carried out, revealing poor gradation of the ballast. Strength tests and ballast gradation analysis were conducted, revealing poor gradation of the ballast.

Keywords: Ballast, Gradation, Fouling, Shear wave velocity, Spectral Analysis of Surface waves (M. R. Mitchell; R. E. Link; P. Anbazhangan, 2011)

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1. Introduction

Railways play a crucial role in India's Transportation network, facilitating movement of both passengers and freight. Indian Railways, despite being the 4th largest railway network (68,103 km) and having 169-year-old rich heritage, however, experiences numerous train accidents caused by derailing. Derailments can be attributed to various factors including mechanical issues damaged rails or train components, geotechnical factors such as misalignment of railway tracks, and operational factors like high speed. The vast geographical coverage of the Indian rail networks introduces additional complexities, as it traverses diverse soil types, including alluvial soils in river basins, black cotton soils in the Deccan plateau, and red and laterite soils in southern India. These soil variations pose unique challenges to the railway infrastructure. Additionally, the existing railway formations, constructed with conventional techniques, were initially designed to accommodate lighter axle loads and slower train speeds. Over time, increased axle weights, higher speeds, and elevated traffic levels have placed additional stress on these formations. Despite the need for rehabilitation and formation enhancement to cope with the evolving demands, such measures are often expensive, time consuming, and disruptive to regular railway operations. Consequently, several stretches of the railway network continue to operate at restricted speeds in India.

Geotechnical components of rail lines include a capping layer, of compacted sub-ballast; below the rails is a coarse granular material known as ballast. It is often created from artificially crushed natural rock, categorized into three major groups: Igneous, Sedimentary, and Metamorphic [1]. The rail ballast bed serves several critical functions [2] to ensure the efficient operation of railway networks. Some of these key purposes include providing structural support, facilitating drainage, and distributing loads. Additionally, the ballast bed helps maintain track alignment, stability, and resilience to dynamic forces generated by moving trains.

- The sleepers' resistance to displacements in the vertical, horizontal, and lateral planes, which provides train a stable platform.
- Compressive pressures on the subgrade are decreased by transferring train forces to it.
- Maintaining the track's lateral and vertical geometry.
- Modification of the stiffness and elasticity of the track's overall structure.
- Drainage permeability, as well as noise and vibration absorption.
- Limiting the spread of plants around railway rails.

As previously established, ballast used in rail is a coarsely graded aggregate that is created by locally crushed accessible rocks such as granite, basalt etc. The efficiency foundation material, progressively reduces because of inadequate lateral support, ballast fouling, and loss of soil shear strength caused by liquefaction and clay pumping. The ballast may shift laterally as a result of overloading and ballast fouling. Ballast-degradation as well as surrounding dust, slurried soil, and coal from freight trains can all contribute to the fouling of ballast. These geological challenges contribute to increase in maintenance costs in the railways.

There has been concern over how to reduce normal repair cycles and maintenance expenditures in an efficient manner. But geotechnical issues with rail lines have not received much attention globally, particularly in India.

The exploration of engineering surface wave investigation using vibratory source, single receiver & oscilloscope was initially studied (Van Der Poel, 1951)[3]. Heisey et al.[4] made further advancements in this area. The (SASW) method was developed in 1982 utilizing an impact source and two receivers. It was based on the Fast Fourier Transform analysis of the phase spectra of surface waves produced by an impulsive source, such as a sledgehammer[5-9].

Shear modulus (low strain) was measured using the SWV method to evaluate the ballast characteristics (P. Anbazhagan, Buddhima Indraratna et al., 2010) [23]. The final result shows that the shear modulus reaches to a high value and then subsequently reduces as the percentage of fouling increases. The maximum SWV is equivalent to the OFP, which is the degree of fouling. It was determined that the CFP was the point at which drainage situation become unfavorable and the SWV dropped to a level below that of clean ballast.

Subsequent to this, a study conducted by (P. Anbazhagan, Buddhima Indraratna, and G. Amarajeevi, 2011) [27] focused on characterizing the subsurface of rail tracks using seismic surveys, providing a comparison between model and field tracks. Indian gradation standards came to the conclusion that Indian ballast samples were more appropriate for drainage since they were poorly graded. Research on several geophone arrays, such as CSR (Common Source Receiver), CMP, and others, to be utilized for seismic surveys to quantify SWV was done. (Common Mid-Point) and CRMP (Common Receivers Midpoint) found that the CRMP arrangement, which is employed in this investigation because it minimizes dispersion in the recorded data, performs better (Soheil Nazarian et al). The free-end resonant column (Bei, 2005) [30] test has been used in studies to quantify SWV in the lab (Bei, 2005) [30]. The results show that the SWV of clean ballast are 156.4 m/s for vacuum levels above and 169.4 m/s for those below.

A characterization of ballast degradation was carried out (Yu Qian et al., 2014) [31]. According to the study's evaluation, the fouling index [32] is an valuable parameter for assessment of fouling of the ballast. Tests for abrasion values were also shown, and a correlation between the degree of fouling and the ballast's abrasion value was noted. In a research (Indraratna et al., Anbazhagan, and G. Amarajeevi, 2011) [27], the gradation of Indian ballast was compared with that of various countries. The study concluded that while Indian ballast was more uniform and better suited for drainage circumstances, it was less favorable for strength and settling criteria. Inadequate gradation results in misaligned rails and sleepers, lessen the bearing capacity value of the railway track, and has an immediate effect on settlement. This might have additional impacts, such as track instability. Track characteristics are significantly influenced by particle shape, roughness, and angle of shearing resistance. Track stability is largely influenced by particle shape and surface roughness. The study shows that surface texture—rather than ballast shape or angularity—has greater impact on track stability (Raymond et al.) [33]. According to Kolbuszewski et al. [34], when particle size increases, consequently increases the angle of shearing resistance.

Addition to conventional methods, various contemporary methods, such Ground Penetration Radar (GPR), have been employed in several studies, to determine the subsurface of ballast sections. These geophysical techniques, like as GPR, gives information regarding the formation of the track-bed interactions [37]. On the basis of the shortcomings of the previous studies, this study aims to find SWV profiles for different train categories, measure SWV before, during, and after train passage, and assess ballast health by evaluating the change in shear velocity trend with depth resulting from train travel. The study also includes various train types such Vande Bharat Express, Shatabdi

Express, different Superfast and Express trains, as well as Freight trains like oil and coal freight trains.

2. Field Investigations

2.1 Field Location.

Two distinct ballast tracks, one from 2014 and the other from 2019, were identified along the stretch between Vadodara Junction (Location A: 22.33452409478455, 73.16969013961224) and D-Cabin (Location B: 22.3420532, 73.1612217). SASW tests were carried out at both locations for the trains operating on these track stretches.



Figure 1: Location A & B, SASW Field setup for Local trigger mode, Geophone arrangement

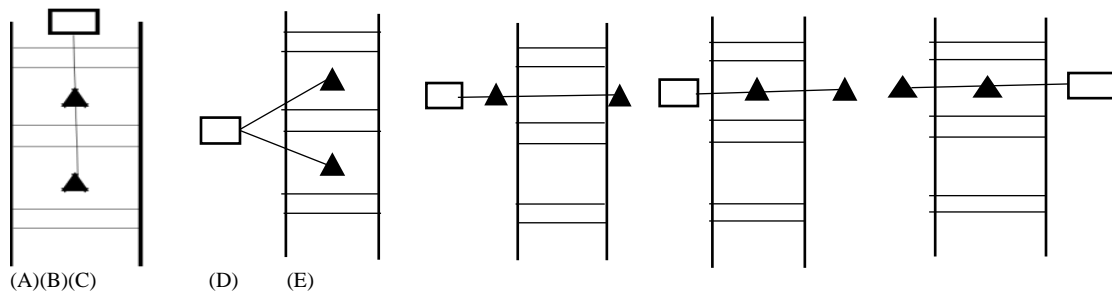


Figure 2: Geophone arrangements

Five distinct geophone arrangements were utilized in this study. The configuration depicted in Figure (2a) was employed with the remote trigger mode in the SASW setup, using a sledgehammer as the source. Figure (2b) was utilized when trains moved on the tracks, with geophones assembled on the track and triggered locally as the trains passed over them. Figure (2c) was employed to evaluate the SWV along the sleepers, with geophones arranged parallel to the sleepers on the track, using the remote trigger mode. Arrangements in Figures (2d) and (2e) were also utilized for comparative results. Ballast

samples were collected from stretches between the geophones for strength and gradation analysis, based on IRS GE-1[38]. Furthermore, tests with the remote trigger mode were conducted on both Location A and B, employing the CRMP arrangement along and parallel to the tracks, and results were compared with a stretch of track featuring recently replaced ballast.

3. SASW Test Schedule

Surface waves exhibit a rapid decrease in amplitude with depth as they move along a half space's surface. Rayleigh waves, predominantly caused by a vertical impact, constitute the major portion of surface waves. These waves propagate from the impact in a cylindrical wave front, closely following the medium's surface, with a speed approximately 90% that of shear waves. Measurement of these waves is carried out using the SASW setup, which includes two geophones (4.5 Hz), a 14 lbs. (Chih-Ping lin, Tzong-sheng Chang, 2004) sledge-hammer as the impact source (utilizing remote trigger), a control unit box, and a data ac acquisition system in the field.

Table 1. List of trains selected for SASW test in context to speed

<i>Sr.No</i>	<i>Train Name</i>	<i>Category</i>	<i>Avg. Speed (km/hr)</i>	<i>Max. Permissible Speed (km/hr)</i>
1	Vande Bharat Express	High Speed	88	130
2	Shatabdi Express	High Speed	75	130
3	Tejas Express	Semi High Speed	77	130
4	Rajdhani Express	Semi High Speed	69	130
5	Oil & Coal Freight Trains	Moderate Speed	57	80
6	Superfast Express	Moderate Speed	40	110

SASW tests are carried out using two modes: (a) Local trigger mode and (b) Remote trigger mode. In the local trigger mode, external vibrations, such as those generated by train movement in our study, serve as the vibration source to measure the SWV. Geophones are positioned on the tracks before the arrival of trains. Conversely, the remote mode employs a sledgehammer as the impact source on a strike plate, with geophones set up between the sleepers on the track, as illustrated in Fig 2. The SASW tests (refer table 1) in the local mode were conducted for various trains, and SWV with corresponding depths were recorded with trigger inputs before, during, and after the passage of the trains. The Fig. 3 corresponds to SAW test arrangements under progress for both Vande Bharat express and Tejas express trains. Tests were conducted under full supervision of railway officials and all safety precautions were taken well in advance.



Figure. 3 SASW Test arrangement on Vande Bharat and Tejas Exp on progress

4. Theoretical Background

It provides a brief of the key concepts and theories that are relevant to the investigation of ballast fouling and the characterization of railway formation layers using the (SASW) for high-speed railways in Gujarat. The section begins by understanding ballast, defining the concept of ballast fouling and its causes. This is followed by study on ballast gradation & ballast strength parameters. It then delves into the importance of characterizing the railway formation layer, which is the layer that supports the track structure, in order to assess its structural integrity and ensure the safe and efficient operation of trains.

4.1 Track Components

The track's constituent parts can be broadly classified into two general categories: which includes the rails, fastening system and sleepers as the superstructure and the substructure which comprises the ballast, sub ballast and subgrade as shown in figure below.

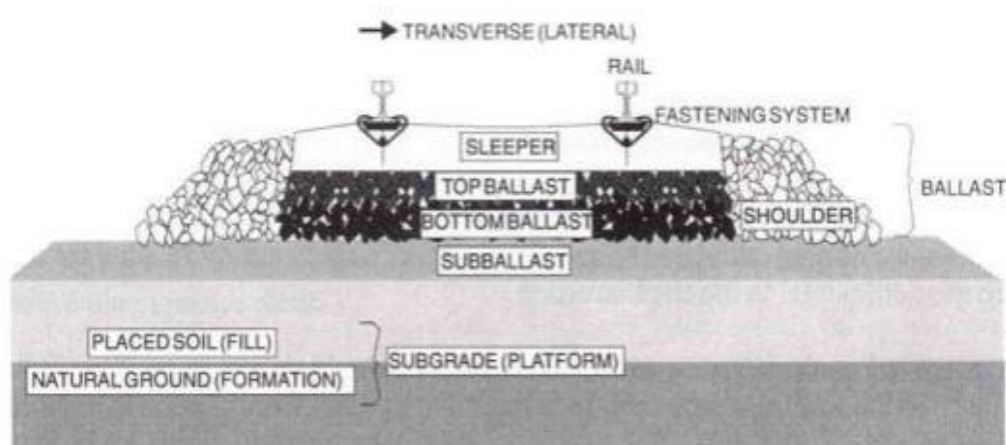


Figure. 4 Ballasted track (Typical section)

4.2 Ballast Specifications

The uppermost component of the substructure is called ballast, and is composed of crushed granular material that is placed in the cribs, and in the shoulders beyond the sleeper ends and all the way at the bottom of ballast layer. These include angular, crushed, hard stones. Thus, well graded sand-gravel mixtures that meet the filter requirements for both subgrade and ballast are the sub ballast materials. The Indian ballast is selected on the basis of specifications given in RDSO IRS GE-1 (June 2016), ‘‘Specifications for Track Ballast’’. According to these specifications, the ballast should be hard, durable, and angular and have relatively large voids. It should be dust and dirt free and should not be prone to cementation. The ballast materials should comply with the specifications of the Indian Standard Institution (ISI). The maximum size of the ballast, should not exceed 65mm and it should not be less than 20mm.

4.3 Ballast Fouling Measurement Parameters

Fouling Index: (Indraratna, Buddhima, Sanjay Nimbalkar, and Cholachat Rujikiatkamjorn, 2012) have defined it as the summation of percentage (by weight) passing the 4.75 mm & 0.075 mm IS-sieves.

$$FI = P_{4.75} + P_{0.075}$$

Percentage of Fouling: It is defined as the ratio of the dry weight of the fouling material (material passing through 9.5 mm sieve) to the dry weight of the total sample.

Table 2: Fouling Index and their category (Selig & Waters, 1994) (Qing Zhang, 2010)

Sr. No.	Category	Category
1.	Clean	$FI < 1$
2.	Moderately Clean	$1 < FI < 10$
3.	Moderately Fouled	$10 < FI < 20$
4.	Fouled	$20 < FI < 40$
5.	Highly Fouled	> 40

4.4 Ballast Strength & Gradation

(Selig, 1993) studied the effect of the degree of fouling on permeability and found that the hydraulic conductivity of ballast reduces considerably with increasing degree of fouling. The table 3 provided by (Selig et al., 1993) shows the hydraulic conductivity values at various degrees of fouling, ranging from clean to highly fouled, based on the fouling index (FI) measurement. In fact, according to Selig et al. (1993), when clean ballast becomes highly fouled, its hydraulic conductivity can reduce by a factor of 10^4 .

Table 3: Hydraulic conductivity values for ballast (Selig, 1993)

Sr. No.	Fouling Category	Fouling Index (%)	Hydraulic Conductivity (mm/s)
1	Clean	<1	25-50
2	Moderately Clean	1-9	2.5-25
3	Moderately Fouled	10-19	1.5-2.5
4	Fouled	20-39	0.005-1.5
5	Highly Fouled	>39	< 0.005

Ballast is a critical component of railway tracks, as it supports the rails and the distribution of the load from passing trains to the underlying subgrade. The performance of the ballast is influenced by various factors, including its strength and gradation. Gradation refers to the distribution of particle sizes in the ballast, and it affects the of the particles arrangement and the ability of the ballast to provide good drainage.

According to Indian railway institute of civil engineering, Pune,

Ballast should satisfy the following size and gradation:

- a) Retained on 65mm Sq. mesh sieve - 5% Maximum
- b) Retained on 40mm Sq. mesh sieve- 40%-60%
- c) Retained on 20mm Sq. mesh sieve- Not less than 98% for machine crushed ballast and Not less than 95% for hand broken ballast

5. Results, Analysis & Discussion

SWV profiles have been assessed by carrying out SASW survey for different categories of trains running in India. Both local & remote trigger modes of the test were conducted using distinct geophone arrangements. The SWV profiles before, during & after travel of the trains have been determined for the different categories of the trains. SASW Hammer tests at both selected locations A & B had been conducted to observe the Shear wave velocity profile and by comparing them with the profiles of different train categories.

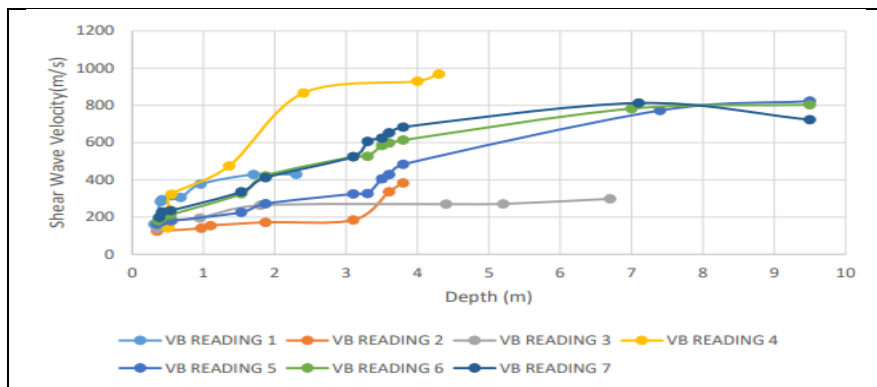


Figure. 4 SMV vs. Depth profile for Vande Bharat Express

Referring Fig. 3, 4 & 5, it was observed that the maximum depth of exploration achieved was 9.5m and average depth was 5.9m. The average SWV for Vande Bharat was 184.86

m/sec which was highest among the passenger trains due to the higher average running speed which results in a more compact packing of the ballast & the payload of 264 T as the train moves over the track and thus higher SWV values.

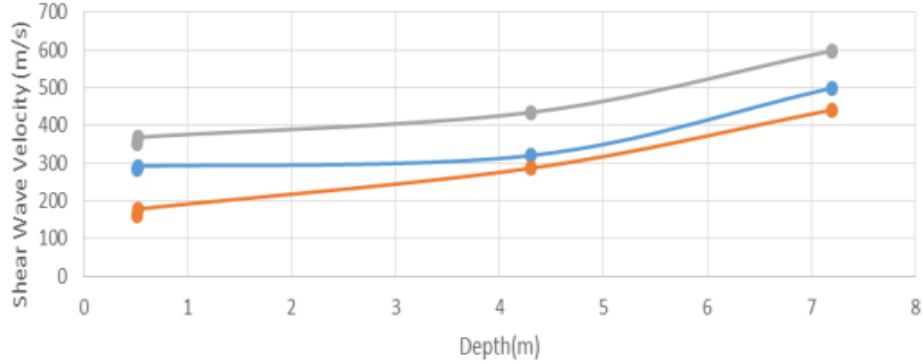


Figure. 5 SWV profile before, after & during travel of Vande Bharat Express

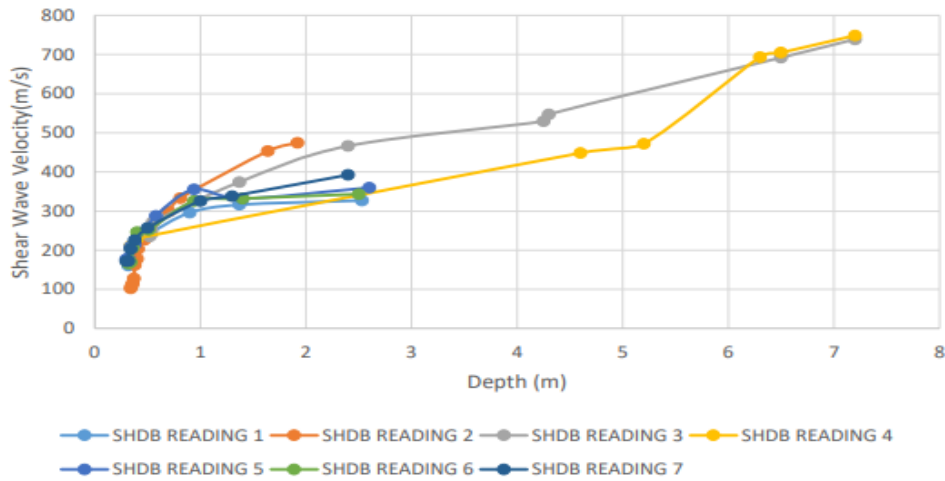


Figure. 6 SMV vs. Depth profile for Shatabdi Express

Referring Fig. 6, it is observed that the maximum depth of exploration achieved was 7.2m and average depth was 3.9m. The average SWV of the ballast layer was found to be 179.24 m/sec for all the observations for the Shatabdi Express.

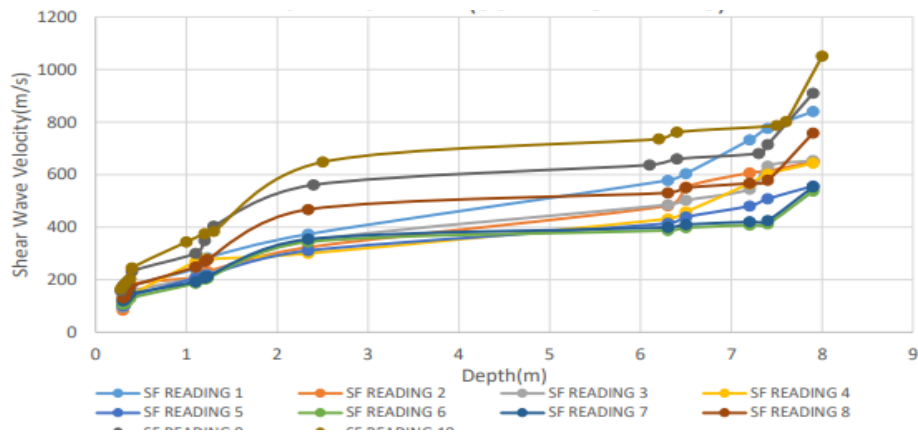


Figure. 7 SMV vs. Depth profile for Superfast Express

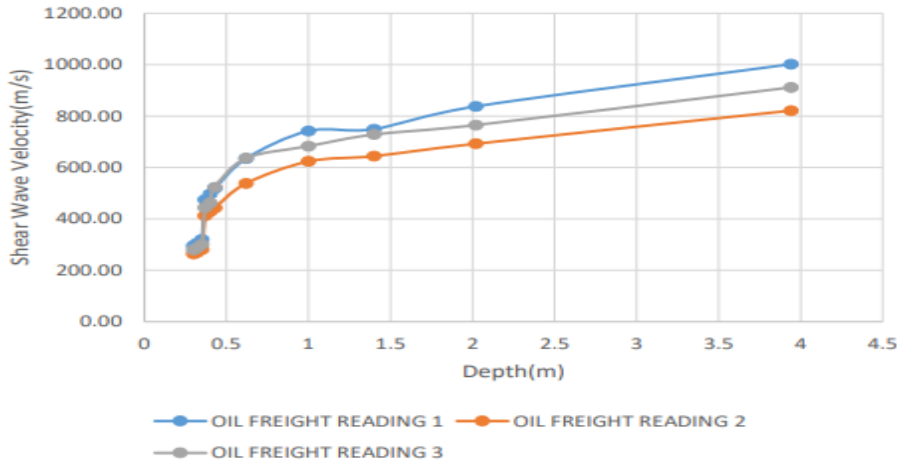


Figure. 8 SMV vs. Depth profile for Oil freight trains

Referring Fig. 7, for superfast trains, the maximum depth of exploration achieved was 9.0m and average SMV being 154.25 m/s. Similarly referring Fig. 8, for oil freight trains, the maximum depth of exploration achieved was 4.0m and average SMV being 375.73 m/s. The average payload for oil freight trains is 3800 tonnes.

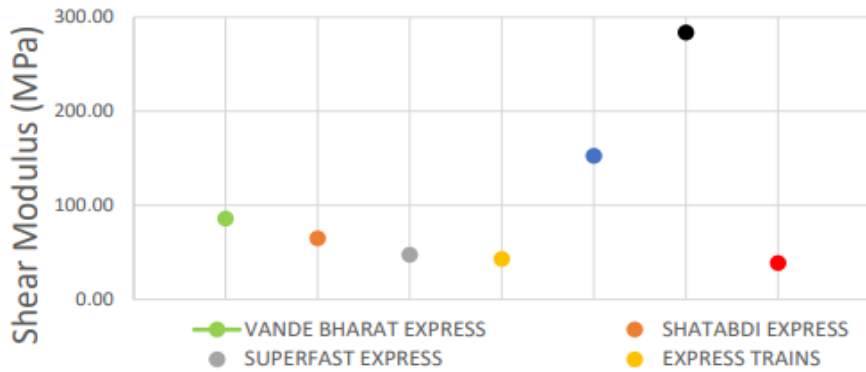


Figure. 9 Shear modulus values for both Location A & Location B

Referring Fig. 9, the 85.59 Mpa was the shear modulus observed for Vande Bharat Express, followed by 64.77 Mpa for Shatabdi Express, 47.26 Mpa for Superfast trains & 43 Mpa for Express trains. The highest shear modulus was found to be 283.71 Mpa for Oil freight trains, followed by 152.36 Mpa for the coal freight trains. In Indian railways, the ballast gradation is defined by specific size requirements. The gradation begins with a minimum size of 20 mm, indicating that a significant portion (98% by weight) of the ballast should be bigger than 20 mm. Additionally; a minimum size of 40 mm is specified, with a range of 40-60% by weight of the ballast needing to be greater than 40 mm. Moreover, the ballast should have only 5% by weight greater than the size of 65 mm. The Indian ballast was found to have a similar gradation with the British gradation. This similarity can be attributed to the influence of British railway engineering practices on Indian railway infrastructure development. For the Impact value test, it was observed that the impact values obtained for Location B were higher compared to Location A. The results for Location B were found to be unsatisfactory as per the specified strength values,

i.e., 20% in IRS GE-1. This can be attributed to the higher percentage of fouling observed at Location B, i.e., 14.17% for Location B, which is higher than Location, A (12.61%). However, both the abrasion values for the locations were satisfactory in accordance with the strength specified in IRS GE-1, i.e., 20%. As per IRS GE-1, the maximum water absorption values permitted are 1% for machinecrushed ballast. The values were found to be 0.24% & 0.15% for Location B and Location A, suggesting better condition of ballast for Location A based on all the strength tests conducted.

The Subgrade modulus values for the ballast of the two locations was determined based on the field densities measured & the measured shear wave velocities of the two locations. The formula by Tezcan et al. which was based on the work of Bowles (1982):

$$k = 4 * \gamma * SWV$$

Where, γ = Density SWV= Shear Wave velocity

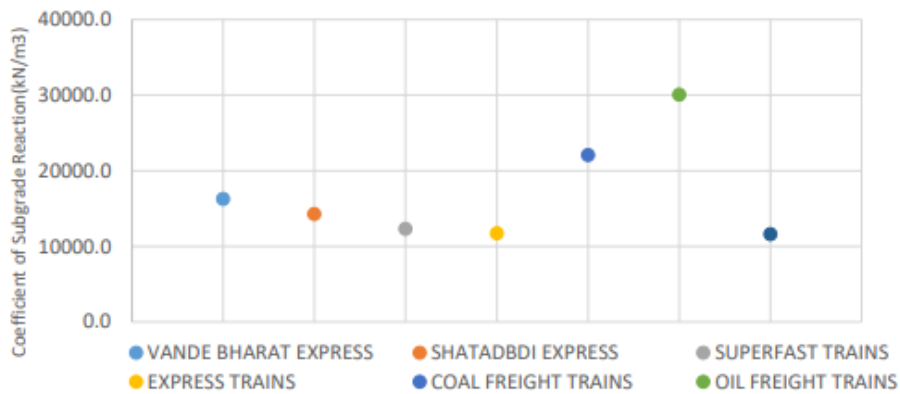


Figure. 10 Comparison of modulus of subgrade reaction for various trains

Referring Fig.10, it is noted that among the passenger trains, Vande Bharat trains were found to be having highest subgrade modulus values for the passenger trains. i.e. 17444.24 kN/m³, followed by Shatabdi Express, 14983.17 kN/m³, and 12897.48, 12225.01 kN/m³ were found for Superfast & Express trains. The highest subgrade modulus values were seen for Oil Freight trains and Coal Freight trains as 32127.64 kN/m³ and 23378.52 kN/m³ respectively (Buddhima Indraratna, 2019).

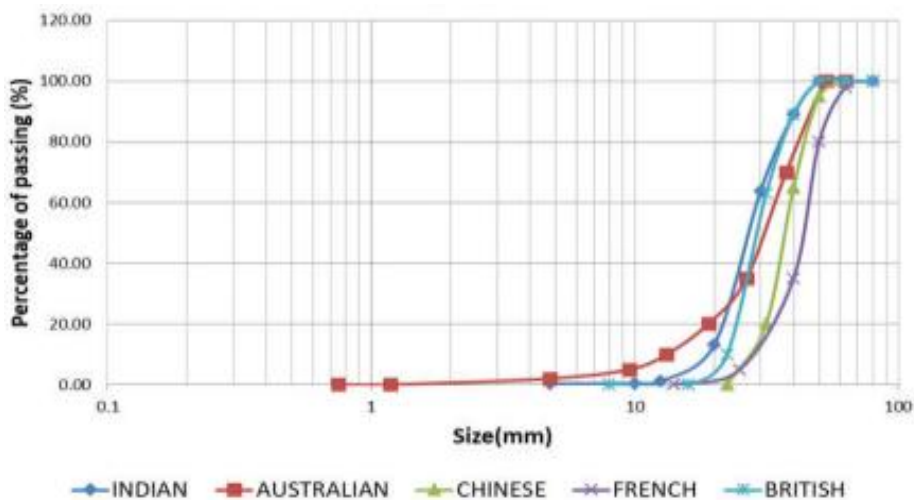


Figure. 11 Comparison of Ballast gradation with British, Chinese, French & Australian standards

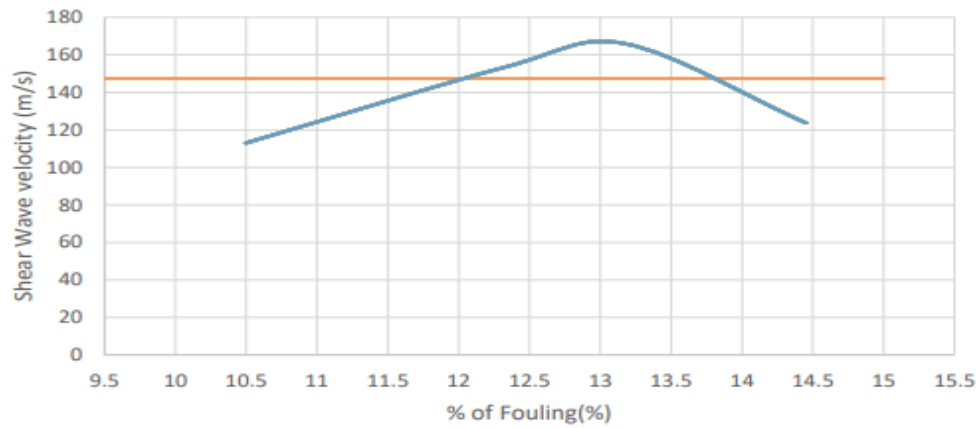


Figure. 12: Location A

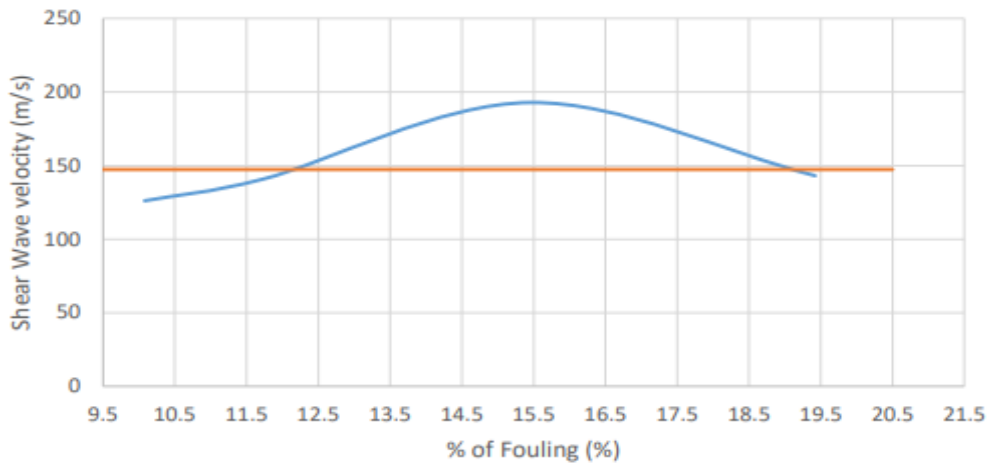


Figure. 13: Location B

Referring Fig. 11, Samples were taken to investigate in situ gradation, fouling, impact, and abrasion strengths at both Locations A and B. The serviceability of the track is influenced by various rock types. For instance, a study [39] delved into how rock strength affects the deterioration and settlement of ballast. Ballast samples were collected between the geophones after conducting SASW remote trigger tests. The C_u and C_c values for Location A were found to be 1.63 & 1.03 respectively. Additionally for Location B, C_u & C_c were recorded as 1.7

3 & 0.83. The impact, abrasion strength tests & water absorption tests were also conducted for both locations A & B with three sets of samples collected at varied distances along the track and the obtained values of the same can be referred in table below.

Table 4. Physical Properties (Ballast of both locations)

<i>Sr. No.</i>	<i>Location</i>	<i>Field Density (kN/m³)</i>	<i>Impact Value (%)</i>	<i>Abrasion Value (%)</i>	<i>Water Absorption Value (%)</i>
1	A	14.6	19.22	14.4	0.15
2	B	15.0	27.22	15.2	0.24

The degree of fouling was assessed with percentage of fouling. The fouling index [32] is another parameter which assesses fouling with percentage of weight passing the no. 4 IS sieve plus % of weight passing the no. 200 IS sieve. The results for fouling based on sample collection & gradation analysis are tabulated in table given below.

Table 5. Results of fouling for ballast at both sites

<i>Sr.No.</i>	<i>Location</i>	<i>% Fouling</i>	<i>Fouling Index</i>
1	A	12.61	1.5
2	B	14.17	2.3

The measurement of SWV velocity of recently replaced ballasted track was conducted and found to be 147.42 m/s. This value, when compared with above plot of SWV vs. % fouling can be used to assess OFP which is the percentage of fouling at which SWV peaks and the CFP, it is the percentage of fouling where SWV of fouled ballast becomes equivalent to the SWV of original ballast as (%) of fouling increases.

4. Conclusions

SWV profiles have been evaluated through SASW surveys for various train categories in India. Both local and remote trigger modes were employed with distinct geophone arrangements. The study considered different train categories based on their operational speeds. SWV profiles were determined before, during, and after train passage, revealing consistently higher values post-travel across all cases. This information sheds light on the condition of the ballast under various train categories. The inclusion of gradation and strength tests has facilitated the assessment of track ballast health.

- The SASW (remote trigger) conducted at Location A & B showed SWV of ballast layer was found to be 139.01 m/s for Location A & 150.77 m/s for Location B. The reason for the above results is the slightly denser condition of the ballast for Location B than Location A which is also suggested by the fouling assessment of the two locations.
- SASW Field testing for Vande Bharat Express: During travel of Vande Bharat Express, where the SWV was seen to reach up to 326.1 m/s for the ballast layer. The change in trend of SWV vs. depth caused by travel of Vande Bharat depicts the shear wave velocities with depth for top layers for both the trains ranging around 100-250 m/s before the arrival of the trains. The SWV with depth right after departure of the train shows the elasticity provided to the track by ballast as the SWV values of this case range around 150-400 m/s but with increased values for the same depth than the SWV measured before arrival of the trains.
- SASW Field testing for Freight trains: The SWV of the ballast layer for the coal train was recorded as 275.49 m/s whereas it was recorded as 375.73 m/s (1.36 times coal freight) for oil freight train indicating its much larger loading on the track.
- Geophone Arrangements: The arrangement (b) (longitudinal arrangement) was shown to provide higher depth of exploration The other arrangements (c),(d) & (e) have less depth of exploration but more SWV values for the same depth due to the confinement by the rail track/sleeper & the denser packing in the lateral direction.

- Shear Modulus: It is obtained from SASW hammer tests was determined as 38.65 MPa for Location A and 45.47 MPa for Location B. The most significant increase in G was observed with 283.71 MPa for Oil freight trains and 85.59 MPa for Vande Bharat Express among passenger trains. The shear modulus serves as crucial information regarding the ballast's capacity to endure shear stresses, providing insights into the structural strength and stability of the railway track.
- Ballast Fouling: The two fouling parameters considered in this study, % of fouling, showed values of 11.99 % for Location A for the % fouling & 12.42 % for Location B. The fouling index, was found to be 1.5 % for Location A & 2.3 % for Location B. For both the parameters, the fouling values observed were found to be satisfactory, i.e. results lied in the "moderately clean" category for % fouling & "clean" category as per fouling index parameter. The OFP & CFP was found to be 13 % & 13.75 % for Location A & 15.5 % & 19 % for Location B. The fouling was thus found to be lesser for location A than location B.
- Modulus of Subgrade Values: The modulus of subgrade values, were found based on the field densities obtained and the shear wave velocities of the two locations as well as the SWV values due to the travel of different categories of the trains The Location B was having value to be 9046.2 kN/m³ which was more than the value for Location A. i.e. 8118.18kN/m³. Among the trains, the oil freight trains were found to be having the highest subgrade modulus values, 32127.64 kN/m³, followed by the coal freight trains. For the passenger trains, Vande Bharat Express was found to be having highest subgrade modulus values i.e. 17444.24 kN/m³, followed by the Shatabdi Express, Superfast & Express trains.

The above field evaluation study using SASW setup reveals complete characterization of rail subgrade profile considering both lateral and longitudinal variations for high speed and low speed trains. Especially high speed train demands sustainable infrastructure and especially in India, where ballast layer is playing vital role in providing elastic cushioning and stress transformation, SASW test gives good insight to engineers, design consultants and execution firms.

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Author Contribution Statement

Manish V Shah: Concept, conceived and designed the analysis, field testing, permission, preparation, paper drafting

Simranjeet Singh: Contributed in doing experimental work, calculations and preparation of plots.

Priti J Mehta: Inputs in overall results and findings, manuscript verification

Conflict Of Interest

The authors declare no conflict of interest.

Data Availability Statement

The data that supports the findings of this study are available in the supplementary material of this article.