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Study on the behavior of track formation under varying axle loads at design speed through scaled-down model testing

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ABSTRACT: Understanding the dynamic behavior of railway tracks is crucial for ensuring operational safety and optimizing the design of infrastructure. This investigation presents comprehensive experimental studies conducted on a 1:3 scaled model of a railroad track to evaluate its dynamic characteristics under varying loading conditions. The scaling methodology adhered to the conservation of acceleration law. The multi-layered track formation comprises a subsoil, a subgrade of silty sand type, a blanket layer, and ballast, with layer thicknesses designed according to standard guidelines. Three railway loading combinations were investigated: 17T-240 km/h, 25T-120 km/h, and 32.5T-120 km/h, executed for one million cycles. The track formation setup was fitted with several sensors to capture the dynamic response. Experimental results demonstrate that both the stresses and accumulated settlement at each interface achieved an equilibrium state after 10,000 loading cycles. The blanket stress at the formation interface is 2.6-3.3 times less than the maximum permissible value of 300 kPa. The maximum vertical effective stress got reduced by 76-87% as it dispersed from the bottom of the ballast layer to the bottom of the subgrade for the loading combinations under consideration due to the presence of a blanket layer. Also, it was observed that the maximum formation settlement increased by 1.45 mm with the increase in the axle load from 25T to 32.5T operating at 120 km/h. The stress and settlement analysis from this study provides design guidelines for the safe operation of the railway track.

1 INTRODUCTION

Ballasted railway infrastructure plays a pivotal role in transportation networks, bearing heavy and increasing traffic loads that pose engineering and operational challenges. To meet the increasing traffic loads, several problems are encountered in a railway track, which comprise ballast fouling, mud pumping, subgrade swelling and shrinkage, ballast penetration, track settlement, and speed restrictions. Among the various methods for mitigating problems, the placement of a granular blanket/sub-ballast layer between the ballast and subgrade has been adopted by several countries. The blanket layer is a mechanically produced material by crushing the stones and mixing naturally available materials using suitable equipment such as a crusher or pug mills. The main functions of the blanket layer are the reduction of the subgrade stresses to the tolerable limit, separation, and drainage.

According to the guidelines, it was found that the thickness of the blanket layer adopted in the design of track formation is dependent on the type of subgrade soil and the axle load of the traffic. In several guidelines, the blanket/sub-ballast thickness is provided for traffic up to 25T. The International Union of Railways (UIC 719R, 1994) established a curve between axle load range between 200 kN and 250 kN, and the thickness of blanket layer contributed by axle load parameter '*d*' which had been exercised in Indian Railways guidelines (RDSO, 2007) (after extrapolating up to 32.5T ≈ 325 kN axle load (Figure 1). However, validation through laboratory testing of the blanket thickness adopted in the Indian subcontinent is missing. To address this gap, detailed experimental investigations are required to ascertain the blanket layer thickness for mixed traffic conditions, which in turn will enhance the behavior of the track formation.

A field test with proper instrumentation is one of the most reliable and efficient techniques to observe the dynamic interaction of the track-ballast-subgrade system (Feng et al., 2021). However, field test instrumentation is costly, and long-term effects cannot be ensured over a fully running track (Luo et al., 2023; Bian et al., 2016; Al Shaer et al., 2008). To overcome the drawback of field testing, the mechanical performance of the track-ballast-subgrade due to heavy axle load and high-speed transit system can be investigated using laboratory model testing (Zhao et al., 2024). The design guideline for the track formation suggests incorporating the blanket layer. However, there is a lack of reason behind adopting the blanket layer thickness in the Asian guidelines directly from the UIC standards. Also, the blanket layer thickness is adopted empirically and without any basis of experimental validation. An experimental study is hereby essential to determine the effect of blanket layer thickness. In the present study, a scaled-down model testing was performed to analyze the influence of blanket layer thickness on the performance of the railway track in terms of interfacial stresses and track settlement. To support this scaled-down model testing, element testing of each material constituting the track formation is conducted. A proper instrumentation scheme has been adopted to simulate practical train loading, and the track response was recorded in the form of stress and deflection, which is measured through sensors. Through this experimental investigation, this study made efforts to form the basis of proper design guidelines.

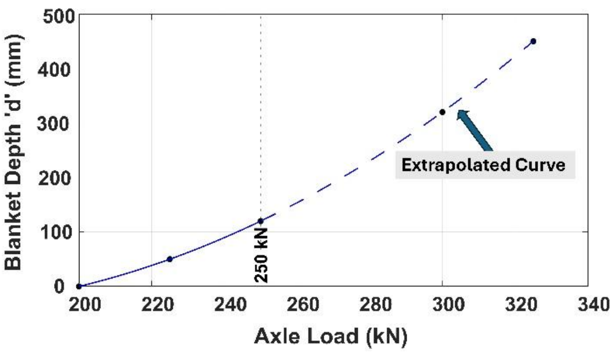

Figure 1. Depth of blanket layer contributed by axle load parameter 'd' value (Referred by RDSO, 2007).

2 ELEMENT TESTING ON TRACK MATERIALS

2.1 Ballast, Blanket, and Subgrade Materials

A conventional ballasted railway track formation consists of a subsoil layer, a subgrade layer, a blanket layer, and a ballast layer.

The ballast and blanket materials were procured from a site adjacent to the Old Iron Bridge, Shastri Park, New Delhi. For the scaled-down model testing, particles were mapped to a one-third scale parallel to the specification and parameters recommended by Indian Railways. At the range of confining stresses pertinent to track loading, monotonic drained triaxial tests on scaled and full-size ballast revealed no differences in strength and stiffness between the two types of ballast (Sowmiya, 2013). Therefore, using a scaled ballast was appropriate from a mechanical standpoint. The results of Sevi (2008) and Le Pen et al. (2014) are in line with this.

The element testing on the various track materials, such as ballast, blanket, and subgrade materials, was conducted to ensure safety, compliance, and quality assurance as per the Indian codal provisions. The grain size distribution curve of the soil is shown in Figure 2.

The element testing on the various track materials, such as ballast, blanket, and subgrade materials, was conducted to ensure safety. The various tests conducted on the ballast material were the abrasion test, the impact test, the water absorption test, the flakiness index test, and the elongation index test, while the test conducted on the blanket material was the abrasion test. The subgrade soil was subjected to tests like the sieve analysis, Modified Proctor Test, California Bearing Ratio (CBR) Test, and the Triaxial Test-Unconsolidated Undrained (UU).

The properties of ballast, blanket, and subgrade materials as determined are shown in Table 1. The fine content of the subgrade soil is found to be 9.7%. Consequently, the soil can be graded as SQ3 & QS3 according to the Indian guidelines (RDSO, 2020) and International Guidelines (UIC 719R, 1994, 2008, IRS 70719, 2020, respectively), and the soil is classified as well-graded silty sand (SW-SM).

Table 1. Results of Element Tests on Track Materials

Material	Test performed	Value
Ballast	Abrasion Test	28%
	Impact Test	19%
	Water Absorption Test	0.6%
	Flakiness Index Test	28.33%
	Elongation Index Test	27.04%
Blanket	Abrasion Test	36.14%
	Sieve Analysis	% of Fines = 2.9%
Subgrade	Modified Proctor Test	OMC = 11.48%
		MDD = 1849 kg/m^3
	CBR	14.37%
	Cohesion	6.8 kPa
	Angle of Internal Friction	33°

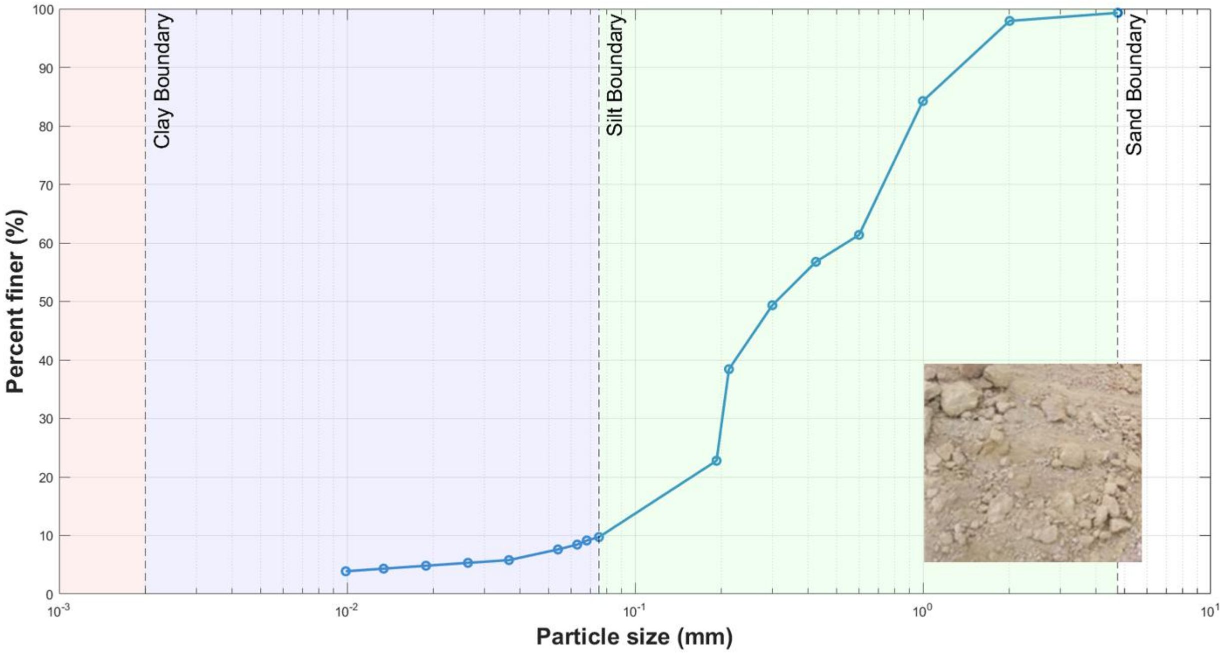

Figure 2. Grain Size Distribution of the Subgrade Soil.

3 MODELING CONSIDERATIONS

3.1 Overview

Tests were conducted on a railway track prepared at a reduced scale of 1:3 to the prototype. Typical prototype track structures were represented by the models used in this study. Any linear dimension of the model divided by the equivalent dimension of the real prototype track is known as the similitude ratio. This study uses a full-panel model track with a scale ratio of 3. The model test setup is shown in Figure 3.

Since the dynamic behaviour of the railway track is of interest, a similitude law abiding by the conservation of acceleration was adopted, like the study conducted by Al Shaer et al. (2008).

Figure 3. Railway Test Track Setup.

3.2 Applied Force: Cyclic Load

The passages of train loads were simulated by applying signals through two actuators placed over the track with a shift in time mimicking the passage of a bogie. The applied loading signal was an M-shaped waveform in which the peak resembled the bogie load at reduced scale (Figure 4). The applied loading waveform by the bogie on the sleepers at reduced scale was obtained through an analytical solution, as shown in Al Shaer et al. (2008). The expression of the force is given by the following equation.

$$F_{1/n^{(t,Q,v)}} = \frac{Q\times Y}{n^3}\left[X^{\left(\frac{vt-a}{d}\right)^2} + X^{\left(\frac{vt-a-L}{d}\right)^2}\right]$$

Where Q = axle load (kN), n = scale factor (n = 3 in this study), v = velocity, X and Y are constants depending on the elasticity modulus of soil, a and L are constants depending on the sleeper-to-sleeper distance and axle spacing.

The waveform was obtained by substituting the values for different axle load-vehicle model combinations, such as a freight train for 25 T and 32.5T, a passenger train for 17 T, respectively.

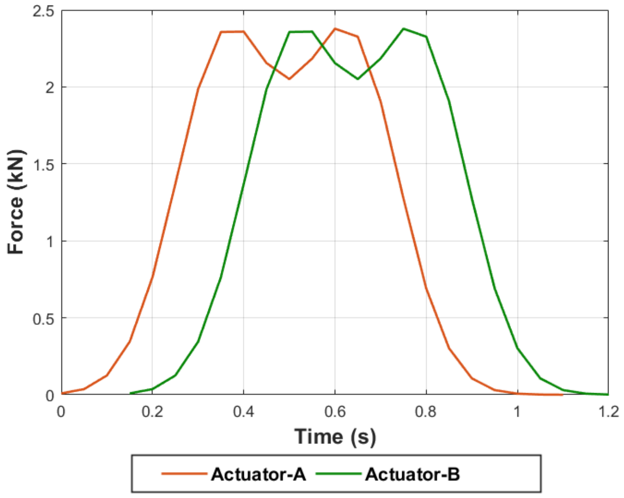

Figure 4. Loading Waveform at reduced scale.

3.3 Sensors

The various sensors that were used in the model test are pressure sensors for measuring the interfacial vertical stresses and linear variable differential transformers (LVDTs) for measuring the track settlement. The pressure sensors were placed at each layer interface, and the LVDT was installed over the blanket layer. The diameter of the pressure sensors used was 52 mm, and they are flush diaphragm strain-gauge-based pressure transducers. The pressure sensors were calibrated using a precise triaxial loading frame. The voltage-to-pressure relationship was established by applying known vertical stress increments across the full operating range of the sensors with the aid of a calibrated load cell, ensuring a high linear correlation between the applied load and the voltage output. The sensors used are shown in Figure 5. The sensors were connected to a data acquisition system, which mainly consisted of the data acquisition box, which in turn was connected to the laptop. The data captured by the sensors were recorded as shown in Figure 6, in the laptop, which was subjected to further processing and analysis.

Figure 5. Sensors used in the model test: (a) LVDT, (b) Pressure Sensor.

4 RESULTS AND DISCUSSION

The thickness of the blanket layer is selected based on the range specified by Indian guidelines for different loading combinations. Three thickness values of 20 cm, 40 cm, and 60 cm are adopted to study the variation in the interfacial stresses and settlements of the track formation for different loading combinations.

Based on the combination of blanket layer depth, each scaled-down model was set up in the laboratory, and the results in the form of vertical stress and vertical displacement were investigated over 1 million loading cycles. The vertical stresses were obtained at each track layer interface, such as subsoil-subgrade, subgrade-blanket, and blanket-ballast interface, respectively.

The results indicated a resilient response to cyclic loading, i.e., an initial settlement increasing with repeated loading, but the subsequent residual displacements diminished significantly after numerous cycles and finally attained a steady state. The interfacial stresses also increased in the initial loading stages at each interface and finally achieved a steady state after 10,000 loading cycles. The variation of the maximum vertical stress in each formation layer for the three design loading combinations and at various blanket layer thicknesses is shown in Figure 7. The blanket stress at the formation interface is 2.6-3.3 times less than the maximum permissible value of 300 kPa. The track settlement under multiple loading conditions and blanket thicknesses is represented in Figure 8.

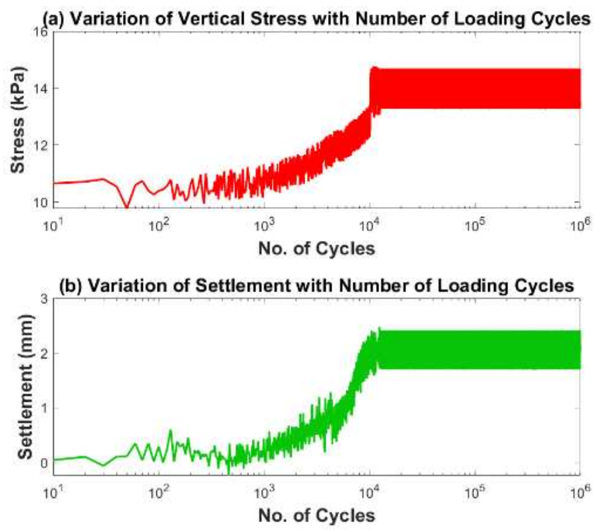

Figure 6. Plot showing Variation of (a) Stress and (b) Settlement with No. of Loading Cycles as recorded by the sensors.

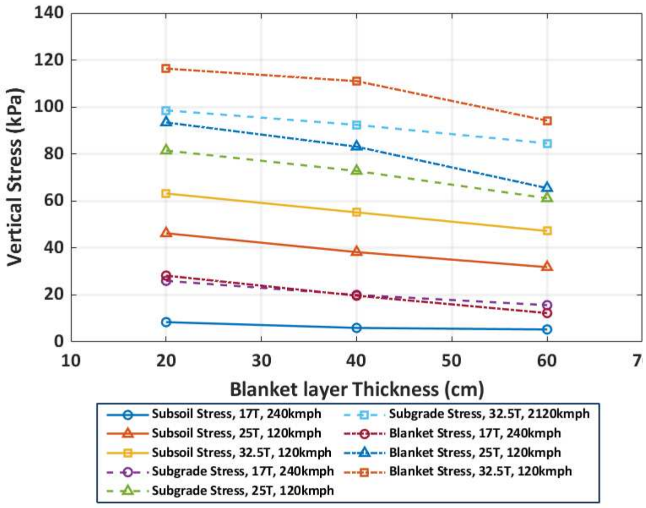

Figure 7. Variation of Interfacial Stresses with Blanket Layer Thickness.

4.1 Variation of Interfacial Stresses for Loading Case 25T, 120 kmph

From the results, it is evident that the stresses at the various track formation layers reduced with an increase in the thickness of the blanket layer in all three cases of loading combinations. For the loading combination 25T-120 kmph, the subsoil stress showed a reduction of 23% and 22% when the blanket thickness was increased from 20 cm to 40 cm and 40 cm to 60 cm, respectively. The percentage decrease in the subgrade stress was recorded to be 11% when the blanket thickness was increased from 20 cm to 40 cm. When further increased to 60 cm, the stress experienced by the subgrade was reduced by 16%. The ballast-blanket interfacial stress also exhibited a decreasing pattern with an increase in the blanket thickness. The blanket stress was reduced by 6% and 8% when its thickness was changed from 20 cm to 40 cm and 40 cm to 60 cm, respectively.

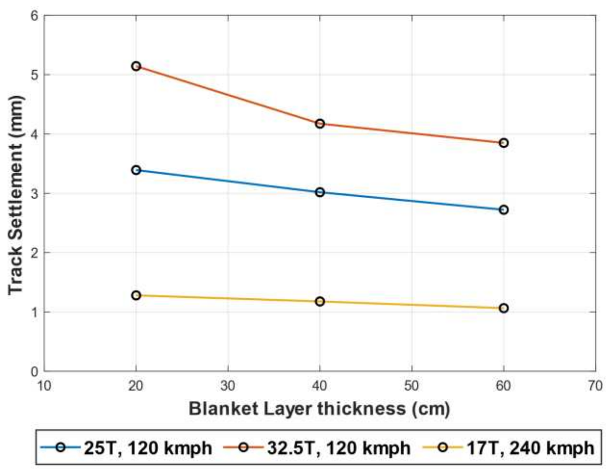

Figure 8. Variation of Track Settlement with Blanket Layer Thickness.

4.2 Variation of Interfacial Stresses for Loading Case 32.5T, 120 kmph

For the loading combination 32.5T-120 kmph, the maximum stresses at the subgrade-subsoil, blanket-subgrade, and ballast-blanket interfaces decreased by 30%, 11% and 5% respectively, with the increase of blanket thickness from 20 cm to 40 cm. The corresponding values for the increase in the blanket thickness from 40 cm to 60 cm are 38%, 21% and 15% respectively. The percentage decrease in the interfacial stresses is shown in Figure 9.

4.3 Variation of Interfacial Stresses for Loading Case 17T, 240 kmph

For the loading combination 17T-240 kmph, 29%, 17% and 13% reduction in the maximum stress at the subgrade-subsoil, blanket-subgrade, and ballast-blanket interfaces were recorded when the blanket layer thickness was increased from 20 cm to 40 cm. The corresponding stress reduction values were 11%, 17% and 14% respectively, when the blanket thickness was increased from 40 cm to 60 cm, as depicted in Figure 9.

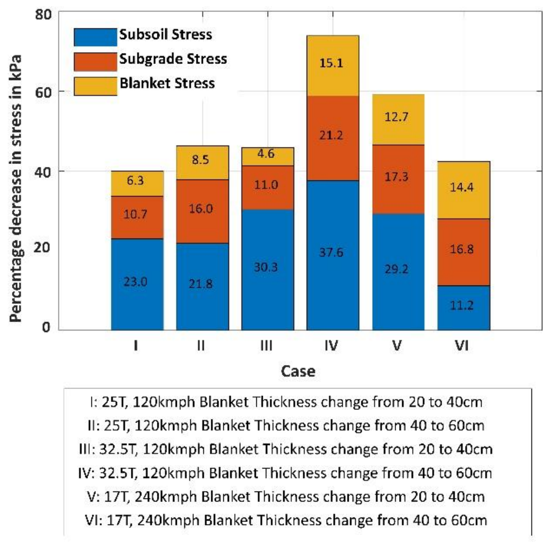

Figure 9. Percentage Decrease in Interfacial Stresses.

4.4 Variation of Track Settlement for Various Loading Combinations

Figure 8 suggests that the track settlement reduced from 3.4 mm to 3 mm, i.e., by 11% when the blanket layer thickness was increased from 20 cm to 40 cm in the case of loading combination 25T-120 kmph. For the same increase in the blanket layer thickness, the track settlement reduced by 19% in the case of loading combination 32.5 T-120 kmph, and by 8% in the case of loading combination 17T-240 kmph. The reduction in track settlement, as shown in Figure 10, was 10%, 8%, and 10%, respectively, for the same loading conditions when the blanket thickness was increased from 40 cm to 60 cm. The maximum formation settlement increased by 1.45 mm with the increase in the axle load from 25T to 32.5T.

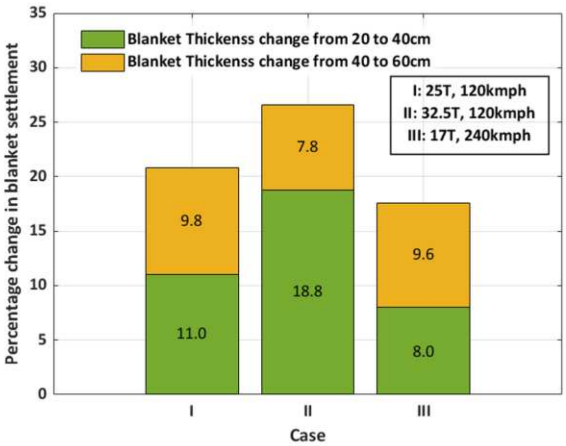

Figure 10. Percentage Decrease in Track Settlement.

The allowable formation settlement is 2 mm for loading conditions 25T, 120 kmph, and 17T, 240 kmph, and 3 mm for the loading condition 32.5T, 120 kmph, according to the guidelines of Indian Railways. To satisfy the allowable formation settlement criteria, the optimum blanket layer thicknesses are 40 cm for 25T, 120 kmph, and 20 cm for 17T, 120 kmph. The optimum blanket layer thickness for the loading condition 32.5T, 120 kmph, should be greater than 60 cm.

5 CONCLUSIONS

Scaled-down model tests were performed in the study to determine the optimum blanket layer thickness of the railway track formation for three design loading conditions scaled up to the equivalent field scale. From the results obtained, the major conclusions derived from the present study are:

a) The blanket layer is effective in reducing the stress on the subgrade and the subsoil. The vertical effective stress gets reduced by 76%, 81% and 87% when it is dispersed from the ballast-blanket interface to the subgrade-subsoil interface in case of the loading combinations 25T-120 kmph, 32.5T-120 kmph, and 17T-240 kmph, respectively.

b) The settlement of the track formation has reduced significantly when incorporated with the blanket layer. The track formation settlement gets reduced by 20%, 25% and 17% when the blanket layer thickness is increased from 70 mm to 200 mm in case of the loading combinations 25T-120 kmph, 32.5T-120 kmph, and 17T-240 kmph, respectively. The maximum formation settlement increased by 1.45 mm with the increase in the axle load from 25T to 32.5T operating at 120 km/h.

c) The ideal blanket layer thicknesses are 40 cm for 25T, 120 kmph, 20 cm for 17T, 120 kmph, and more than 60 cm for 32.5T, 120 kmph, to meet the permitted formation settlement parameters.

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