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A study on the deformation characteristics of subgrade in the simulation of rail-track substructure system considering high train speeds

Keywords: Subgrade, rail-track substructure, numerical modelling.

ABSTRACT

With the huge demand for high speed railways across the world, major emphasis is laid on safety and a reduction in the journey time. There is much talk about high speed trains plying at over 200 km/h in certain sectors of India. The first of such sectors being talked about is the Mumbai-Ahmedabad corridor, which would drastically slash the journey time by around 5 hours. This leads to huge quasi-static and dynamic loads on the track, which further accelerates the process of the formation of fines, ballast degradation (through abrasion, attrition and grain fracturing) and a potential accumulation of excess pore water pressure and high vertical deformations in the subgrade. Furthermore, this pumping action generated leads to an infiltration of fines into the subgrade. Under poor conditions of drainage and workmanship, severe cases of fouling occur where the sleepers are surrounded by mud that retains a pool of water around them. To prevent such formation of mud holes in the soil, the implementation of proper drainage is essential to prevent stagnation of water at the ends of the sleeper. This also contributes to the stability of the track substructure by ensuring separation of the fine subgrade soil underneath with the coarse ballast above.

Certain advances have been made in the field of mud hole management. In their manual, A.R.T.C. Ltd. (2001, 2013) pointed out the stagnation of water due to the lack of drainage being the major contributor to mud hole formation. Various methodologies for the modelling of the ballast and subgrade layer have been suggested. Kruse and Popp (2003) suggested the use of the Molecular Dynamics method to model the granular material, where every single stone of the ballast is taken into account along with calculation of the contact forces from the overlap areas of particle geometries. Modelling of resilient rubber pads with future applications to a reduction in the ballast settlements have been performed by Knothe *et al.* (2003). Baessler and Ruecker (2003) showed the influence of the lower load during cyclic loading, especially for understanding track settlement during the existence of a gap between the sleeper and ballast surface. Wegener and Herle (2010) used an axisymmetric finite element (FE) model with a constant modulus and no material damping. A clear difference between the behavior of the soil close to the loading area and in a zone situated at a larger distance from the location of the load. The energy dissipation was much more significant in the form of radiation damping at larger.

Relatively lesser studies have been done to analyze the subgrade performance in the event of dynamic loading. Shan *et al.* (2013) modelled the rail-track-subgrade system using the FE software ANSYS. A comparison was made between two scenarios: a bridge and a subgrade which was normally used for high velocity passenger lines (250 km/h). Ricci *et al.* (2005) studied the dynamic behavior of the system under the action of a moving load. They demonstrated through their model that the velocity of the moving loads and the underlying stiffness have significant effects on the vertical accelerations and displacements in the ballast layer. The advantage of their model is that it can be extended to general multi-layers as well. Speed effects of the train were studied by Duley *et al.* (2015), who investigated an existing model to calculate velocity dependent displacements up to and beyond the critical velocity.

In this study, quasi-static and dynamic loads from train-traffic are applied to the entire track system, including the superstructure, substructure and subsoil. The objective of the current work is an analysis of the subgrade under the influence of high speed trains. A simplified numerical simulation of one axle of an Inter-City Express (ICE) traversing along the rail with various speeds has been investigated. Multiple axles have not been considered to eliminate complexities arising from dynamic interactions between the axles. In the model, water table has not been considered to eliminate any complexities arising from pore water pressure variation. Comparisons are made between the vertical velocity profiles for all the different speed cases. Later on, the work will be extended to the case of mud holes, with suggestions as to a better and improved mud hole management scheme.

The model considered in this study is adopted from Moormann *et al.* (2016) and is shown in Fig. 1. A small section of 8 m was considered in the analysis to save computation time owing to the dynamic nature of the problem. The rail and sleepers were modelled using beam elements, and are connected to each other by node-to-node anchors (Shahraki *et al.*, 2014). Water table has not been considered to eliminate any pore water pressure effects. There are four distinct layers: the embankment overlying the peat and the two sand layers below. The side slope of 2:1 (H:V) was considered for both the ballast and the backfill soil.

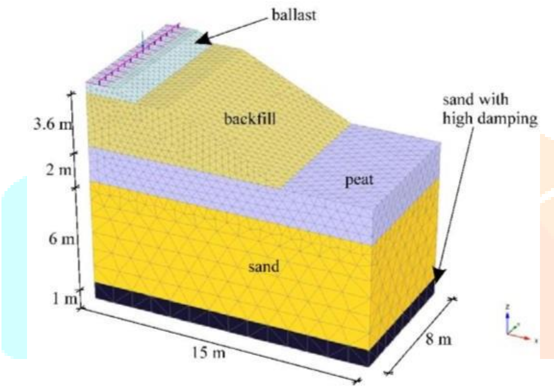

Fig. 1. Geometry of the model used for analysis adopted from Moormann *et al.* (2016)

Furthermore, the ballast and subgrade (backfill) layers have a height of 0.6 m and 3 m respectively. The standard B70 sleeper, 2.5 m wide, 0.214 m deep has been considered. The distance between the rails has been kept at 1.5 m. The bottom sand has a depth of 1 m and is provided with high damping in the frequency range of 1 Hz to 100 Hz so as to avoid wave reflection at the boundaries and eliminate any creep deformation. Owing to symmetry, half-track geometry as well as half axle of the ICE has been modelled. The magnified loading approach has been shown in Fig. 2.

Linear elastic model has been adopted for all the soil layers although the hardening soil model is better suited for dynamic calculations. This has been done to avoid complexities in the calculation and minimize computation time. The material properties for the various layers have been obtained from Vogel *et al.* (2013) and are listed in Table 1. The material properties for the beam elements (rail and sleepers), listed in Table 2, are obtained from Shahraki *et al.* (2014).

Standard default fixities which fixes the bottom in all directions and the vertical sides in the horizontal directions, are applied.

Absorbent viscous boundaries are applied to prevent wave reflection at the boundaries. The normal and tangential relaxation coefficients were kept at 1 and 0.25 for the best results (Brinkgreve and Vermeer, 2013).

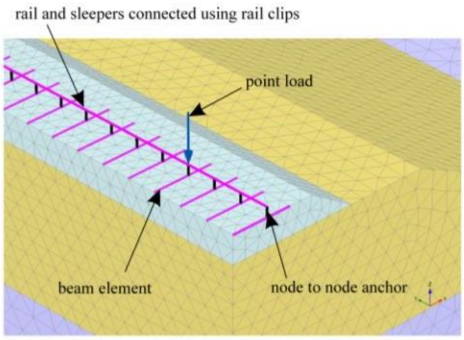

Fig. 2. Magnified view of the rail and sleepers connected through node-to-node anchors (Moormann *et al.* 2016)

Table 1. Material properties of the soil layers used in the numerical analysis (Moormann *et al.* 2016)

Parameter	Ballast	Subgrade	Peat	Sand
γ_{unsat} (kN/m^3)	18	19	11	20
γ_{sat} (kN/m^3)	20	21	11.3	20
υ	0.3	0.35	0.49	0.48
E (kN/m^2)	1,95,000	2,09,300	18,770	1,49,500
G (kN/m^2)	75,000	77,500	6,300	50,500
Rayleigh α	6	4	2	2
Rayleigh β	0.00075	0.0005	0.00025	0.00025

Table 2. Input properties for the beam elements (rail and sleepers) obtained from Moormann *et al.* (2016)

Parameter	Rail (beam)	Sleeper (beam)
Cross section area (m^2)	$7.7 \cdot 10^{-3}$	$5.13 \cdot 10^{-2}$
Depth (m)	-	0.214
Unit weight γ (kN/m^3)	78	25
Elastic modulus (E) (kN/m^2)	$200 \cdot 10^6$	$36 \cdot 10^6$
Moment of inertia around the second axis (I_3) (m^4)	$30.55 \cdot 10^{-4}$	$2.53 \cdot 10^{-2}$
Moment of inertia around the third axis (I_2) (m^4)	$5.13 \cdot 10^{-6}$	$2.45 \cdot 10^{-4}$

Considering one axle of an ICE with an axle load of 110 kN, the load considered is 55 kN. The loads are applied to the rail in the form of dynamic multipliers as shown in Table 3 (for a train with a speed of 90 km/h). It is assigned in such a way so that when the point load is fully acting, there is no other load in the entire system; but with the passage of time, the initial load starts to decrease in magnitude while the second load for the next point starts to increase till it reaches the peak half axle load value. In this way, simulation of a moving train has been achieved.

Comparisons have been made for the deformation characteristics in the subgrade at a train travel distance of 4.2 m due to the effect of high speed trains. Total 4 cases of train speeds ranging from 90 km/h to 250km/h are considered for the analysis. Owing to symmetry, vertical velocities are plotted for the top surface of the subgrade as shown in Fig. 3 shows half of the cross section of the subgrade layer only. It is evident that a high vertical velocity exists under the point of application of the load, i.e. directly underneath the rail, which explains the depression in the curve at a distance between 0.3 and 1.2 m. This values are considerably significant and increases with an increase in the speed, thus implying increased dynamic influence on the system.

Table 3. Load multipliers for a moving train (90 km/h)

Load multiplier	Distance (m)	Time when it acts (s)
Load multiplier 1	0.6	0.024
Load multiplier 2	1.2	0.048
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Load multiplier 13	7.8	0.312
Load multiplier 14	8	0.320

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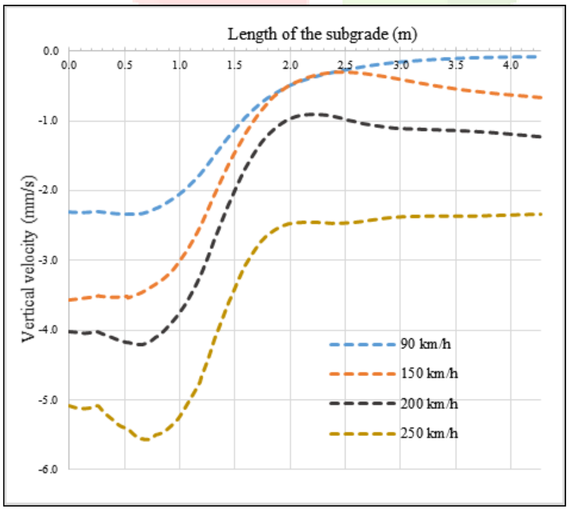

Fig. 3. Vertical velocity profile at the top surface of the subgrade layer for a train travelling with different speeds

For trains with relatively lower speeds, the dynamic effects arising due to speed does not spread along the length of the embankment, which is evident from the very less vertical velocities at the surface away from the point of loading. However, an increase in speed causes high vertical velocities across the subgrade in general. This implies the significance of subgrade to resist vertical deformations is essential before designing tracks for high speed trains.

Fig. 4 shows the vertical velocity profile along the top surface of the subgrade across the entire travel distance of 8 m with the load acting directly at 4.2 m from the start (left to right). High vertical velocities are encountered underneath the loads. High elastic rebound of the subgrade soil is noted, especially for trains with increasing speeds, at distances before 4.2 m as the load has moved on to the next point. It can be seen that the influence of the higher speed impacts the subgrade to a greater extent than the lower ones, with particularly high velocities noticed at succeeding points.

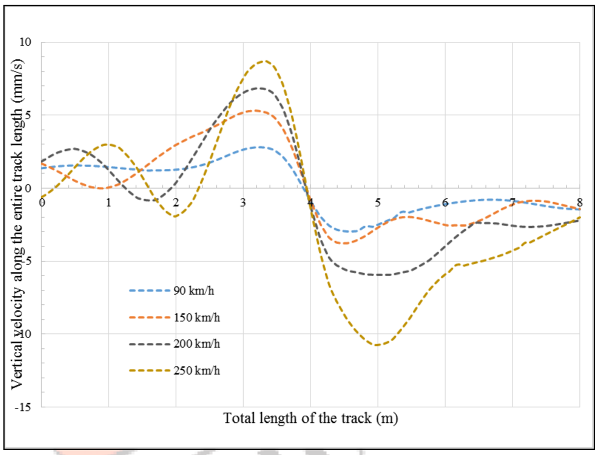

Fig. 4. Vertical velocity profile along the entire track length with the load at a distance of 4.2 m from the left

Fig. 5 shows the vertical velocity profile along the subgrade for the four above cases. It is very evident that comparatively higher velocities are encountered across the depth of the subgrade for trains with higher speeds. There is not much of a difference between the trains with speed lesser than 150 km/h; however, higher speeds exceeding 200 km/h show a consistent velocity even at the bottom of the subgrade. Higher speeds exhibit vertical velocities of a greater magnitude, which shows higher dynamic interaction between the train and the underneath soil.

The ballast, being in direct contact with the track does take up high stresses from the moving trains, however, unless the underlying subgrade is of adequate strength, there are high chances of a formation failure. The problem gets compounded in case of subgrade soil coupled with high ground water table. This leads to the formation of mud holes in the ballast as well as subgrade, leading to inadequate drainage. High pore pressures are induced which leads to a loss in track alignment as well as heaving of the soil layers. This study highlights the importance of a compacted subgrade on resisting high deformations thus ensuring a longer service life. In future, the problem will be extended to the critical case of mud hole fouling with an aim to avoid interim of long term repaircosts.

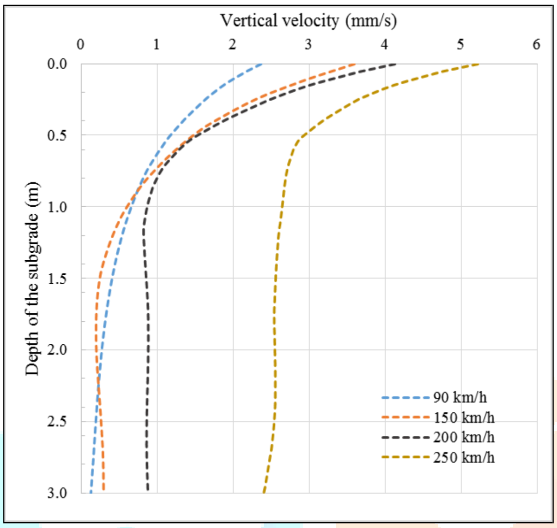

Fig. 5. Vertical velocity profile for the different cases along the depth of the subgrade layer

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