Available online at www.sciencedirect.com

ScienceDirect

Procedia Engineering 173 (2017) 1580 – 1586

Procedia Engineering

www.elsevier.com/locate/procedia

11th International Symposium on Plasticity and Impact Mechanics, Implast 2016

3D Modelling of Ground Surface Vibration Induced by Underground Train Movement

D.V. Singh[a,]*, and Y. Seth[b]

[a] *B.Tech Student, Department. of Civil Engineering, Indian Institute of Technology (IIT) Delhi, Hauz Khas, New Delhi – 110 016, India*
[b] *B.Tech Student, Department. of Civil Engineering, Indian Institute of Technology (IIT) Delhi, Hauz Khas, New Delhi – 110 016, India*

Abstract

Correia et al. [1], developed an expression to model the force distribution due to axle loads, with respect to the moving referential. The above force distribution was used for Finite Element Analysis using PLAXIS 3D. A code is developed in MATLAB to generate a matrix of dynamic multipliers for each static point load applied along the railway track with each time step. The amount of load applied is equal to the axle load of the train resulting from the solution of the Winkler Beam for the movement of a load. The results can be used for gauging the effect of changing various geological and physical parameters on the distribution of force due to axle load. Once calibrated to geotechnical and physical data corresponding to sites above actual underground train tracks, the model can be used to predict the effect of vibrations on existing infrastructure.

Peer-review under responsibility of the organizing committee of Implast 2016

Keywords: Axial Load; Finite Element Analysis; Peak Particle Velocity; Plaxis 3D; Vibration; Underground Train

1. Introduction

Over the past few decades, rapidly increasing population has been demanding more sophisticated and efficient means of transit, thus calling for a paradigm shift in the way public transport system is commonly perceived. This has led to an increased focus on underground transit systems. Underground trains are exceedingly becoming the first choice of public transport for most countries all over the world.

Underground traffic networks, however, have their own set of complexities associated with them. Construction of high-speed and high traffic-intensity modern railway track networks demand extensive research, testing and complex analysis to be done in order to incorporate the dynamic behavior of soil [2]. Proper modelling of the entire railway track system, taking into account embankment, soil, sub-soil, trainload, and railway track, is essential during the designing phase of underground construction.

Peer-review under responsibility of the organizing committee of Implast 2016
doi:10.1016/j.proeng.2016.12.253

Rail track design is one of the most complex soil-structure interaction problems to analyze. The various elements in design process comprise [3]: (1) multi-axle loading varying in magnitude and frequency; (2) deformable rails attached to deformable sleepers with flexible fixings and sleeper spacing which can be varied; (3) properties and thickness of ballast, sub-ballast, and prepared subgrade (if adopted); (4) properties of underlying soil subgrade layers.

This paper is aimed at giving an account of numerical modelling of soil behavior in PLAXIS 3D by simulating the train movement on a soil strata of given soil characteristics.

The effect of a moving load on a soil stratum is much different and much less investigated as opposed to a static load. A moving load causes repeated loading and unloading of any section of soil and thus may lead to significantly higher displacements in soil. The net cumulative inelastic deformation occurred in soil is dependent on a number of parameters, namely, soil and sub soil characteristics, track irregularities, vibrations induced by moving trains, load applied, frequency of loading-unloading cycle, embankment characteristics, etc. Although small amount of settling of railway tracks may be acceptable, very often a differential settlement in both tracks is observed, primarily due to non-uniformity of soil strata and external factors (like the load applied, etc.). This differential settlement is primarily responsible for degradation of railway tracks [4].

Fast moving trains require careful analysis to estimate differential settlement in order to prevent them from derailing during their run. Another consideration to be made here is the dynamic response of soils to fast moving trains. After a certain critical speed (function of the soil strata), a dynamic amplification factor needs to be considered (to be multiplied with load) for estimating displacements [5].

For the purposes of this paper, we have considered trains operating below critical velocity thus avoiding the need to use a dynamic amplification factor.

Nomenclature

L	Characteristic length
L_T	Maximum distance between extremity axles
$F(s)$	Load distribution as a function of the spatial variable s
F_e	Force corresponding to the axle (axle load)
F_{net}	Net axial force
s	Coordinate with respect to the moving load
t	Time
v_o	Train speed
v_z	Vertical Velocity
x	position of train in global coordinate

2. Model Formulation

The results presented in this report are based on 3D modelling using Plaxis 3D software, coupled with an extension of the 2D mathematical model presented by Correia et al. [1] on dynamic analysis of rail track for high speed trains.

2.1. Mathematical Model

Plane strain conditions are assumed for the calculations. Since a point load in plane stress conditions translated to a distributed load in a three dimensional model, the following simplifications and assumptions to limit its validity to the distances reported in Gutowski et al. [6]:

First, the validity of the linear load is assumed to be limited to a distance of $d = L_T/\pi$. This essentially means that the results obtained by Correia et al. [1] using a 2D approach were considered to be valid up to a distance d.

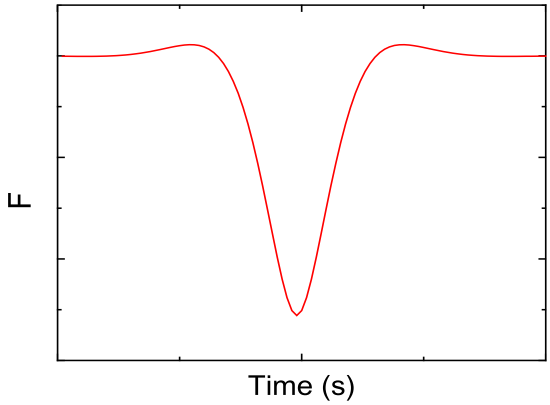

Fig. 1. Load distribution due to a single axle (from [1])

Additionally, the response of the railway track to the application of point loads is also factored. By virtue of the stiffness of the railroad, the applied point load is felt as a distributed load by the track. Correia et al. [1] argue that the exact shape of the curve of distributed load (at velocities less than critical velocity) would be a function of the speed of moving load, but it assumes this general shape for all velocities less than critical velocity. It tends to be thinner and less spread out for higher velocities, whereas in case of lower velocities the peak load is realized gradually. In case of velocities greater than critical speed, the peak load is realized after the axle has passed over that point, thus creating an unsymmetrical distribution of load with time.

Thirdly, a mathematical function is needed to model how the axle load is distributed over time, given the sub-critical velocity of the train. Correia et al. [1] used a simple approach by considering the solution for the Winkler beam. The distribution of load over time is calculated using Eq. (1)

$$F(s)=\left(\frac{F_e}{2L}\right).\left(e^{-\left|\frac{s}{L}\right|}\right).\left(\cos\left|\frac{s}{L}\right|+\sin\left|\frac{s}{L}\right|\right) \tag{1}$$

A possible approach to define the load distribution can be considered, admitting a distribution adjusted to the sleeper spacing as is considered in the Japanese regulations. In accordance with this document, a changeable part between 40 and 60% of the load is distributed to the adjacent sleepers [1]. The value of moving referential is calculated using Eq. (2)

$$s=\left(\frac{1}{L}\right).\left(x-v_o t\right) \tag{2}$$

Thus, for s=0 one has 60% of the axle load, L=0.831 will be obtained. The load distribution corresponding to each axle is presented in Fig. 1 for a unitary load.
The net effect of all axles is incorporated using principle of superposition:

$$F_{net}=\sum F_i \tag{3}$$

Also, it is important to note that the modelling must be started sometime before the train arrives at the first section of calculation, since its effect starts before it reaches that section. Accordingly, the computation must end sometime after the last axle has passed the last section of calculation. This spare time is calculated by dividing the distance up to which the effect of an axle load is considered with the velocity of the train [1]. This distance is called as ‘spare distance’.

Each axle load here is considered to be same. The difference in peak value occurs due to placement of axle loads relative to each other; if axles are close by, then higher peaks are obtained by superposition of several loads.

3. Plaxis 3D Model

3.1. Geometry of 3D-model

A 40 m x 40 m x 25 m soil strata was considered for modelling. Standard fixities and absorbent boundaries were applied to reduce wave reflection at the boundaries. A typical railway track with rails, rail clips (rail fastening system), and sleepers resting on ballast and subsoil with different soil layers was modelled in Plaxis.

Circular twin tunnels of 2.85 m radius were created at a depth of 20 m below the ground, using the Plaxis 3D 'Create Tunnel' command. Concrete lining of 0.25 m, with 'Linear Elastic' material model, was provided.

The rail is modelled as a beam element of length 50 m with rectangular cross-section, with its properties resembling standard UIC 60 rail. The rail clips are modelled as node to node anchor elements. Each sleeper is connected to the rail with two rail clips. The standard B70 sleeper is modelled as beam element with required moment of inertia and area. 67 sleepers with a 60 cm center-to-center distance are provided. Fig. 2 shows the model in Plaxis 3D. The needed parameters for modelling of beam element are listed in Table 1.

Table 1. Properties adapted in Plaxis 3D for rail and sleeper

Parameter	Unit	Rail	Sleeper
Cross Section Area (A)	[m^2]	$7.7x10^{-3}$	$5.13x10^{-2}$
Unit Weight	[kN/m^3]	78	25
Young's Modulus	[kN/m^3]	$200x10^6$	$36x10^6$
Moment of inertia around the second axis (I_3)	[m^4]	$3.055x10^{-5}$	0.0253
Moment of inertia around the third axis (I_2)	[m^4]	$5.13x10^{-6}$	$2.45x10^{-4}$

3.2. Material Properties

To define node to node anchor in Plaxis, the maximum forces that the element can carry in compression as well as in tension are required, along with the axial stiffness parameter [7]. The properties of rail clips are listed in Table 2.

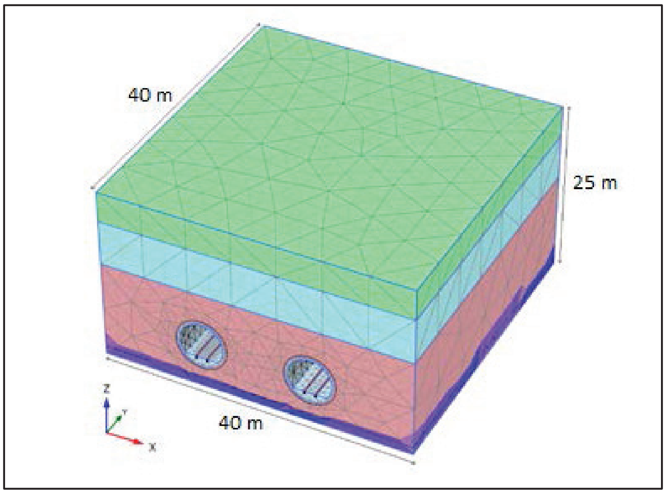

Fig. 2. Details of the model.

A standard saturated and unsaturated density, Poisson’s ratio, and shear modulus is used for modelling of soil behaviour with the linear elastic constitutive model. To model the soil behaviour with HS-small model, oedometric parameters, tangent parameters, unloading and reloading shear modulus, reference shear modulus, and shear strain along with some other basic and advanced parameters were calculated from secant modulus [8]. Material properties of different soil layers are given in Table 3, Table 4, and Table 5.

Table 2. Properties of rail clips

Parameter	Unit	Rail
Maximum tension force $\lvert F_{max,ten} \rvert$	[kN]	312
Maximum compression force $\lvert F_{max,com} \rvert$	[kN]	1716
Axial stiffness (EA)	[kN]	$2x10^6$

Table 3. Material properties of the clay layer

Model	γ_{sat} [kN/m^3]	γ_{unsat}[kN/m^3]	υ’ [-]	Φ’[º]	C’[kN/m^2]	Ψ [º]	E’[kN/m^2]
Mohr-Coulomb	18	16	0.35	25	5	0	$10x10^3$

Table 4. Material properties of the sandy clay layer

Model	γ_{sat} [kN/m^3]	γ_{unsat}[kN/m^3]	υ’ [-]	E’ [kN/m^2]
Linear Elastic	20	20	0.3	$50x10^3$

Table 5. Material properties of the sand layer

Model	γ_{sat} [kN/m3]	γ_{unsat} [kN/m3]	E_{oed}^{ref} [kN/m^2]	E_{50}^{ref} [kN/m2]	E_{ur}^{ref} [kN/m2]	m [-]	Φ’ [º]	Ψ [º]
Hardening-soil	20	17	$35x10^3$	$35x10^3$	$105x10^3$	0.5	33	3

3.3. Calculation Phases and Results

The calculation consists of three phases. The first phase is common for generating the initial stresses with active groundwater table. A plastic drained calculation type is chosen in phase two. In this phase, all elements of the railway track (sleepers, rails and rail clips) should be active. The dynamic option should be selected in phase three to consider stress waves and vibrations in the soil. In this phase, all dynamic point loads on the rail are active [2].

Simulation is performed using a combination of Linear Elastic (LE), Mohr-Coulomb (MC), and Hardening-Soil (HS) Model. The top most sand layer is modelled using HS Model, the middle sandy clay layer using LE Model and the bottom most clay layer using MC Model. Velocity is varied over a certain range while simulating.

In dynamics, velocities, instead of displacements are used to prevent double integration and increased errors in low frequency domain [1]. The velocity amplitude decreases by propagation of wave to the deeper soil layers. Material and geometric damping are the main reasons for the decreasing velocity amplitude in deep layers [2]. In this model, only geometric damping is considered.

3.4. Dynamic Multiplier Matrix

The Dynamic Multiplier Matrix is generated by running a simulation using C++ code. Fig. 3 shows the graph obtained for dynamic multipliers along the length of the track.

The graph obtained completely resembles the load variation graph obtained by Correia et al. [1], thus validating the C++ simulation.

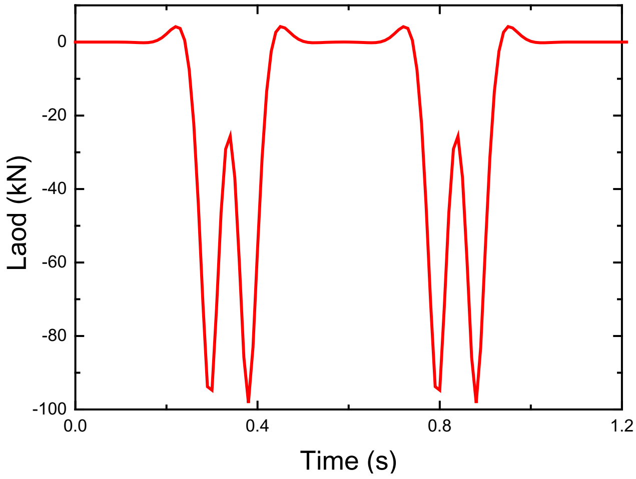

Fig. 3. Loading for the train moving at v=90 km/h.

3.5. Results

The results obtained can be used for qualitative assessment of variation of vertical velocity and PGV, for validating the mathematical simplifications and subsequent assumptions, and for calibrating the given soil profile to soil strata at the site where prediction of these factors is required.

Once calibrated, the proposed PLAXIS model can be used to predict the settlement, PGV, and other important parameters of consideration by simulating site conditions.

4. Conclusions

The mathematical approach of the 2D model presented by Correia et al. is extended to 3D, in order to generate the dynamic multiplier matrix. This matrix is imported to PLAXIS to precisely simulate the moving load conditions produced by underground moving trains. Various parameters can be obtained directly from PLAXIS results. This paper concludes that modelling can be effectively simulated in 3D FEM.

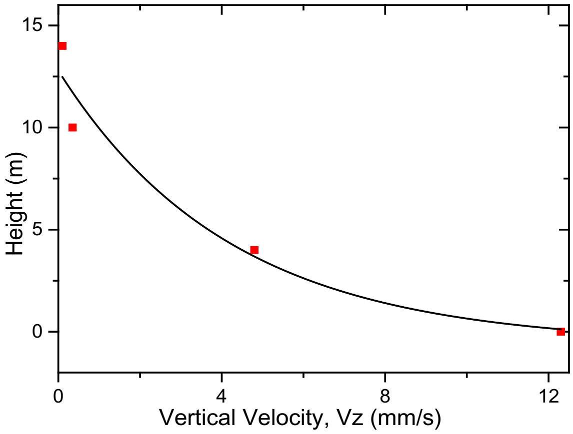

Fig. 4. Height variation of Vz from the top of the tunnel.

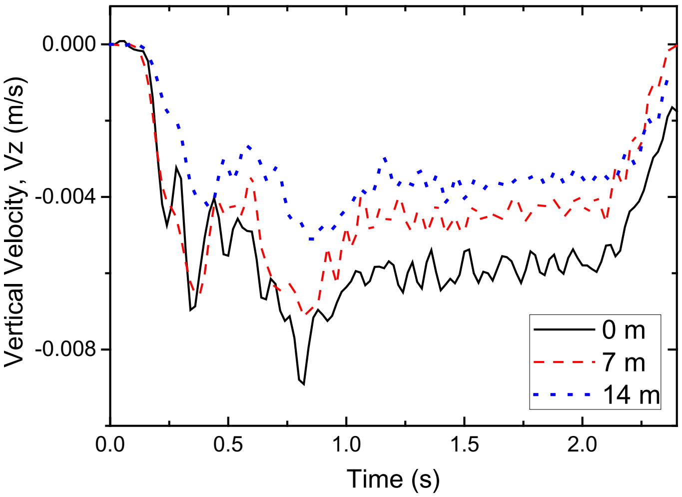

Fig. 5. Distance variation of Vz at the top of the tunnel on Ground Level (GL)

Fig. 4 shows the variation of vertical velocity with height above the tunnel whereas Fig. 5 shows the distance variation of vertical velocity from the tunnel at the ground level. These plots can be used to analyze the effects of ground surface vibrations induced by underground train movements on structural entities and predict the likely structural damage caused by underground train operations.

Acknowledgment

Authors are immensely grateful to Professor G.V. Ramana of Civil Engineering Department, IIT Delhi, for his valued insights and suggestions during the course of this research, and his feedback on this paper.

References

[1] A. G. Correia, J. Cunha, J. Marcelino, L. Caldeira, J. Varandas, Z. Dimitrovová, A. Antão, and M. G. d. Silva, “Dynamic analysis of rail track for high speed trains. 2D approach,” in 5th Intl Worksop on Application of Computational Mechanics on Geotechnical Engineering, Portugal 2007, p. 14.
[2] M. Shahraki, M.R.S. Sadaghiani, K.J. Witt, T. Meier, 3D Modelling of Train Induced Moving Loads on an Embankment, Plaxis Bulletin Issue 36, Autumn 2014.
[3] J.A. Lord, Railway foundations: Discussion paper, Proc. 12th ECSMGE, Geotechnical Engineering for Transportation Infrastructure (Barends et al., eds.), Balkema, Rotterdam, 1999.
[4] T. Dahlberg, Railway track settlements - a literature review, Linköping, Sweden, 2004.
[5] C. Madshus and A. M. Kaynia, High-Speed Railway Lines on Soft Ground: Dynamic Behaviour at Critical Train Speed, Journal of Sound and Vibration, vol. 231, pp. 689-701, 2000.
[6] T.G. Gutowski, C.L. Dym, Propagation of ground vibration: A review, Journal of Sound and Vibration 49(2), (1976) 179-193
[7] Plaxis bv, PLAXIS 3D 2011-Material-Models vol. 3. Netherlands: PLAXIS, 2011.
[8] Plaxis bv, PLAXIS 3D 2011-Reference vol. 2. Netherlands: PLAXIS, 2011.