Proceedings of 14th IOE Graduate Conference
Peer Reviewed
Year: 2023 Month: December Volume: 14
ISSN: 2350-8914 (Online), 2350-8906 (Print)

Ground Response Analysis for Train-Induced Vibration

Swati Acharya[a], Ram Chandra Tiwari[b]

[a,b] *Department of Civil Engineering, Pulchowk Campus*
[a] acharya70.swati@gmail.com , [b] rct2075ce_rctiwari@pcampus.edu.np

Abstract

Construction of railways as mass rapid transit system is essential to cater the traffic load of Kathmandu valley in near future. This poses the problems of vibration in nearby structures and irritation to human due to transmission of waves as a result of rail-soil interaction. The quantitative values of such impact helps an urban planner to develop city infrastructures proportionately. Due to limited railway infrastructure in Nepal, physical data of actual impact is unavailable to large extent. In such scenarios, numerical modeling and finite element method based analysis can be implemented to evaluate the possible impact. This paper evaluates the impact of vibration due to railway in different setup of embankment, ballast stiffness and speed of train. Ground modeling is based on the soil investigation data in Bhimsengola, Kathmandu whereas train modeling is based on Winkler foundation model concept. The simulation are carried out in industry standard Plaxis 3D software. It was observed that the resultant vibration is proportional to the train speed. Stiffness of the ballast has minimal impact whereas, height of embankment highly influences the ground vibration. Thus, it is recommended to increase the height of embankment as far as practicable.

Keywords
railway, vibration, embankment, ground response, winkler beam

1. Introduction

Nepal is undergoing rapid urban growth with the Kathmandu valley being no exception. The annual population growth rate of Kathmandu valley is around 3.3% [1]. With this, the traffic issues are on the rise with small road space available for roads despite higher vehicles, heavy traffic congestion, inadequate transport services, inefficient measures of traffic control [2]. Railways, as a form of mass rapid transit, has become a necessity at the core part of the valley in order to maintain a balance between preserving its historic value and offering an efficient transport system in densely populated area [3].

However, with development of railways, the vibration impact in the surrounding can be a subject of concern. The operation speed of the high speed train can be closer to Rayleigh wave velocity of soil, and are capable of inducing strong ground vibration [4]. The vibration impact of the railway can affect the settlement of tracks, stability of surrounding structures, buildings, buried structures and cause overall irritation to humans and other animals.As per ISO 2631-1:1997, the absolute threshold of perception of weighted vertical vibration in human is around 0.015 m/s^2 [5]. The vibration effect depends upon speed of train, soil type, sensitivity of the structure and vibration assessments are required to determine the effect of vibration on local communities [6] for further planning and design consideration for the structures.

The source of vibration in the railway is the interaction of train with the track structures like rail, sleepers, embankment, ballast, ground support that induces dynamic forces between rail and wheels. Factors like axle weight of train, speed of train, spacing of sleepers, stiffness of ballast, ground properties, rail defects among others have influence on the level and characteristics of train induced ground vibration [7]. This paper evaluates the impact of vibration due to railway in different setup of embankment, ballast stiffness and speed of train.

2. Literature Review

The energy which causes ground motion is transmitted through the earth by elastic displacement waves also known as seismic half waves assuming the earth can be simulated by homogeneous, isotropic, elastic half space [8]. The longitudinal and shear waves, collectively known as body waves are the wave that propagate in the soil. Since a stress free edge is defined to model ground surface as elastic half waves, the interaction between inclined body waves and the free surface of half –space, surface waves are introduced, the most prominent one being Rayleigh's wave.

The vibration generated from the train is random and the dynamic load acting on the track is complicated. [9] used the empirical relations to predict the "A weighted sound levels"(frequency range to cover 20 Hz to 20kHz)in buildings at various distances from the subway tunnels. [10] used a statistical method to predict ground borne vibrations in buildings and yield methods to predict in small distances.

Various numerical model were developed for the depiction of train load in geotechnical studies over the years. [11] modelled the high speed train tracks with rail, sleepers and rail pads supported by ballast, sub ballast, capping layer and supporting soil in 2 dimensions. He suggested that for speed below critical speed, quasi static load can be assumed instead of dynamic load established that the load distribution can be established using the solution of Winkler beam for the movement of load. According to [11], the distribution of the load under each axle will follow the analogous distribution as equation 1.

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

Where, $F(s)$ represents the distribution of the force due to each axle as a function of Force F_e correspondent to the axle; S is the moving referential; L is characteristic length; L can be adjusted to obtain certain amount of axle load at point s=0 (underneath the axle)

With identification of the problem that plain strain (2D) model can not accurately model the interaction between primary wave and reflected wave whereas the 3D modelling is too time consuming, a compromise between the two analysis, 2.5D model was proposed. The effect of moving load in the profile of the half space normal to the load moving direction is considered, which makes the problem some what between 2D and 3D [12]. [13, 14, 15] used 2.5D analysis to model the train simulations using various FEM softwares to simulate the waves travelling behavior of the moving load.

[16] modelled moving loads in 3 dimensions. He estimated the shear forces in the rail by statistics analysis using theory of “Beam on elastic foundation” (Winkler Foundation). The shear forces obtained by this analysis was used as dynamic multipliers (time history of loading) of each loading point in FEM software. The rail, sleepers and rail clips were modelled as beam, beam and node to node anchor elements respectively. He suggested that in low frequency domain, presentation of velocities rather than displacement is suggested to avoid the second integration leading to increase in errors.

The approach by [16] was adopted by [17] to model the response analysis of ballasted rail track in flood plain of the Ganges – Brahmaputra delta and studied the impact of sub ballast stiffness. The stiffness of sub ballast did not seem to influence vertical stress of other layers or displacement of ballast. Also, the prediction of maximum settlement was done using the model. [18] used the modelling technique by the same author, [19]. He also modelled the [11] and got a better result in predicting the measured accelerations in the checkpoints compared to results from 2D modelling by [11]. [20] used 3D numerical modelling to model the complex geometries associated with the track elements in detail for highly realistic simulation of force of transmission from vehicle to track. [21] modelled dynamic load of train as triangular time steps to analyse the response of the underground pipe due to train on embankment showed a good response with the measurement value.

[22] adopted the numerical method to find the dynamic multiplier of each of the dynamic load. He modelled the train on subway twin tunnels with track modelling similar to [19] extending the 2D model presented by [11] to 3D and concluded that the mathematical approach of [11] formulated in plain strain can be used to precisely simulate the moving load in 3D as well.

3. Materials and Model

The analysis is carried out in Finite Element Method analysis software Plaxis 3D Version 21. The soil considered in this analysis is from the Soil Investigation of proposed Kathmandu Valley Metro Railway done for Kathmandu Mass Rapid Transit Consortium (KMRTC) Project. The soil investigation was carried out by drilling three boreholes each to a depth of 50 m. The locations of boreholes were Ratna Park, Kathmandu (BH-01), Bhimsengola, Kathmandu (BH-02) and Lagankhel, Lalitpur (BH-3). The soil data from BH-02 is considered as base for this research. Since the soil at the location was mostly sandy, Wash Boring Method was carried out. since the impact of vibration for higher depth is not very significant, the soil was modelled till 38 m depth to decrease the model size for dynamic analysis. The Mohr- Coulomb model was used as material model for the soil. The soil properties were correlated from SPT value.

Table 1: Summary of soil parameters for silty layer

Depth, m	N_{60}	E, kN/m^2	γ_{sat}	γ_{unsat}	$\phi'_{adopted}$
0-4.5	22	8400	19.02	18.2	33
4.5-6	19	7500	18.99	17.9	32
6-33	23	8700	19.03	18.3	33
33-38.5	7	3900	18.87	16.7	29

3.1 Modelling of train structures

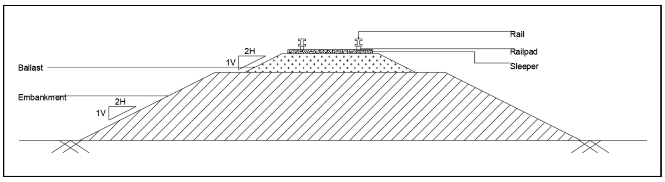

Figure 1: Cross Section of Railway Structures

The rail is modelled as beam section with the same properties as UIC60 beam [16]. The spacing between is rail for Indian railway is usually 1.676 m Broad Gauge. The spacing of 1.6 m between rails is adopted for modelling. The sleeper is modelled as beam section with the same properties as B70 sleepers [16]. The length of the sleepers is adopted as 2.4 m and the standard 0.6 m spacing is adopted for each sleeper. The rail pads are modelled as node to node anchor in Plaxis 3D with value of EA as $2 \times 10^6 kN$.

Table 2: Properties of Rail and Sleepers

Parameter	**Rail**	**Sleeper**
Cross section area (A), m^2	7.7×10^{-3}	5.13×10^{-2}
Unit weight (γ), kN/m^3	78	25
Young’s modulus (E), kN/m^2	200×10^6	36×10^6
Moment of inertia around the second axis (I_3), m^4	3.055×10^{-5}	0.0253
Moment of inertia around the third axis (I_2), m^4	5.13×10^{-6}	2.45×10^{-4}

The thickness of ballast is adopted as 35 cm with side slope of 2H:1V. The side slope of 2H:1V is adopted for embankment the height of embankment is varied from 1 m to 3 m to analyse the impact of height of embankment in vibration transmission. The linear elastic model is used for both ballast and embankment.

Table 3: Properties of ballasts and embankment [21]

Type	Ballast	Embankment
Material model	Linear Elastic	Linear Elastic
Drainage Type	Drained	Drained
Γ, sat	20 kN/m^3	19 kN/m^3
Γ, unsat	19 kN/m^3	18 kN/m^3
E'	200 - 300 MPa	200 MPa
ν'	0.3	0.3

3.2 Dynamic Loading

The Loading of one car of train is taken from [23] and is shown in figure 2.

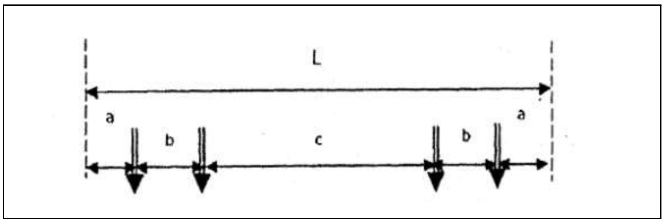

Figure 2: Axle arrangement of the car of train

Where, L = 22.100m (Length of a car); a = 2.250m (overhang); b = 2.500m (Wheel base in a bogie); c = 12.600m (Distance between Axle-2 and Axle-3 in the car)

The axle load of 25 tonne (250 kN) is assumed in the analysis. According to [11], the load due to an axle at sub critical speed is given in equation 1.

Where, $F(s)$ represents the distribution of the force due to each axle as a function of Force F_e correspondent to the axle; S is the moving referential; L is characteristic length. L can be adjusted to obtain certain amount of axle load at point s=0 (underneath the axle). He recommends that around 40 to 60% of the load is distributed to adjacent sleepers. Assuming 60% of the load is beared by point directly underneath the point load i.e at s=0, L=0.831 is obtained. For unitary load, the distribution of axle load as calculation in computational software is shown in figure 3.

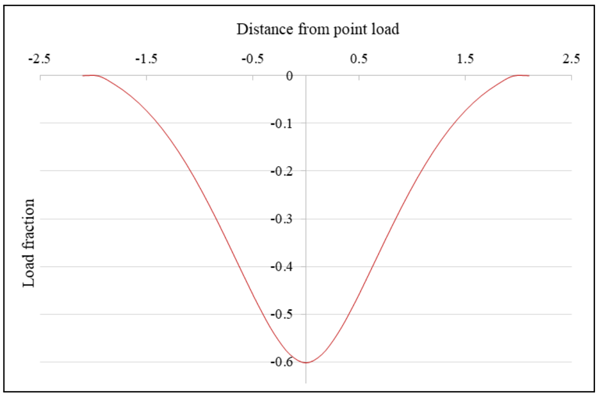

Figure 3: Distribution of load on rail due to unit wheel load

The effect of train loading can be obtained considering of overlapping of load distribution of the axle of time. Figure 4 is an example of the distribution of load at each point load at arbitrary time for speed 30 m/s due to superposition of 8 unit axles.

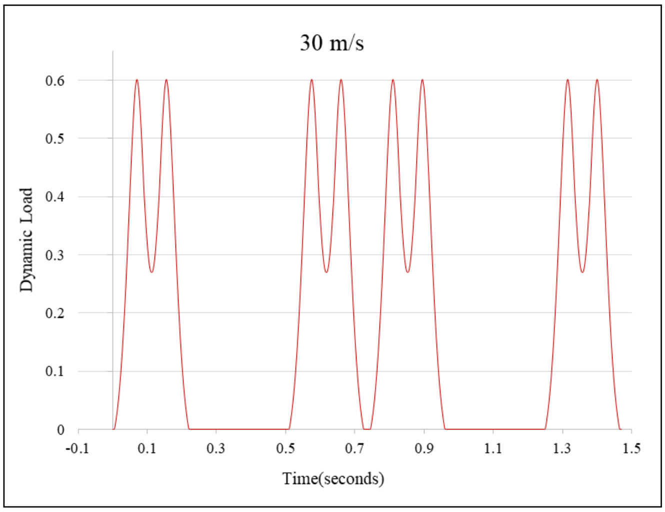

Figure 4: Time History of unit axle load at 30 m/s train speed

4. Numerical Modelling

4.1 Project Properties

The full type model is considered for the analysis. For dynamic analysis, larger area requires higher computational time and hence a section of 6 m is considered. The boundaries of the model considered are X_{min}= 0 m; X_{max}= 35 m; Y_{min}= 0 m and Y_{max}= 6 m.

4.2 Geometry and Boundary Conditions

The soil stratigraphy is defined by creating a borehole, adding and assigning respective materials and levels for different soil layers. The effect of ground water table is ignored for this research and hence the head is set at -38.5 m. The embankment and ballast with the side slope of 2H:1V is created. The sleepers are modelled as beam of length 2.4 m over ballast in case of railway over embankment. The spacing of the sleepers is taken as 0.6 m and hence 11 numbers of sleepers are modelled. The rail is modelled as two beams of 6 m length each with 1.6 m spacing. The sleepers and rails are connected by rail pads of thickness 0.10 m modelled as two node to node anchors in each sleeper. The negative interface is added to the rectangular surface around sleepers in order to model the interaction between said sleepers and soil materials.

4.3 Creating Dynamic Loads

The axle load is 250 kN, therefore each point load in the pair has a magnitude of 125 kN. The pair of point load is applied over each sleeper at rail and were arrayed at distance of 0.6 m along y axis. Hence, the model has 11 pairs of point loads. Each point load is defined as dynamic point load with Fz as -125 kN. To simulate a train passage, the pairs of point loads are activated and deactivated in turn. A load multiplier, which is essentially a time history, is written for each point load so that it may be programmed to act in a certain way over the dynamic time interval. Eleven different load multipliers is assigned to eleven pairs of dynamic load similar to figure 4. The multiplier for the every point load in the pair is an exact copy, since the two wheels of an axle move as single unit over time, and the multipliers for the next pair look the same but are slightly displaced time wise. As Plaxis reads each of these multipliers over the course of the dynamic time interval, the train passage is simulated.

4.4 Meshing

Once the geometry is created in full, including soil material, structural elements, loads and interfaces, the mesh for FEM analysis is generated. Generating mesh using a very fine mesh option provides better result accuracy in dynamic analysis. However, the computation time also increases greatly. Hence, fine mesh is generated.

4.5 Calculation

The construction process has not been a focus point in this project. Therefore, the calculation phase following the initial phase sports the full final model fully active. After that the dynamic analysis is done. The time period and Maximum number of steps of dynamic analysis depends upon the interval of input signal to ensure good match between input signal and calculation steps. The dynamic time is taken as the time between the first axle entering the model and last axle exiting the model along with spare time.

Table 4: Cases considered for Dynamic Analysis of Train on embankment

Height of Embankment	1 m, 2 m, 3 m
Stiffness of Ballast	200 Mpa, 250 MPa, 300 Mpa
Speed of Train	30 m/s, 40 m/s, 50 m/s, 60 m/s

4.6 Model Verification

The data of the vibration measurements made during the passage of Thalys train between Brussels and Paris and its numerical simulation in Plaxis 2D by [11] is taken as reference for model verification. The train load as mentioned in [11] is represented as time history at each point of sleeper at c/c distance of 0.6m. The soil properties and thickness is referred from the mentioned paper and [18] and the proportional modelling is done for missing dimensions.The time history of the dynamic loading due 26 axles of the Thalys train for each sleeper position is written in MS Excel. The dynamic time interval is taken as 1/300 s. The value of each dynamic vertical load is taken as -1 kN. The table 5 shows the comparison between the peak acceleration from measurement data, result from 2D analysis by [11] and 3D simulation method adopted in this thesis at different checkpoints. The result is seen in better agreement with the measurement acceleration of than the 2D modelling.

Table 5: Comparison of acceleration for different check points

Points	**Meas.**	**[11] (2D)**		**Research Model**	
	Accl. (m/s^2)	**Accl. (m/s^2)**	**Error**	**Accl. (m/s^2)**	**Error**
A4	45.67	4.84	89.40%	27.28	40.27%
A5	1.23	2.8	127.64%	1.407	14.39%
A7	0.32	1.61	403.13%	0.37	15.63%

5. Results and Discussion

The results that are obtained from parametric analysis for different cased listed in Table 4 are analysed. The effect of factors like stiffness of ballast, track speed, height of embankment on the ground borne vibration is studied. Also, the effect of speed of train on ground vibration due to subways is studied.

5.1 Ground Response due to Moving Train on Embankment

The change in vertical velocity and vertical acceleration for 1 m high embankment for speed of train of 60 m/s at rail and ballast top is shown in figure 5 and 6 respectively.

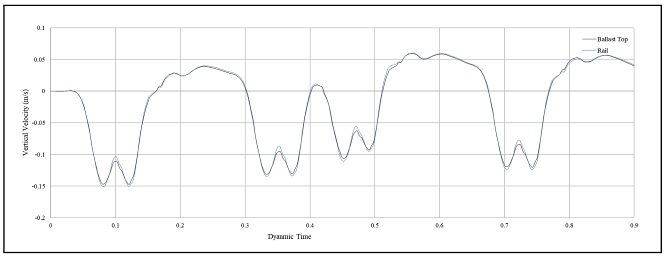

Figure 5: Vertical Velocity vs Dynamic Time

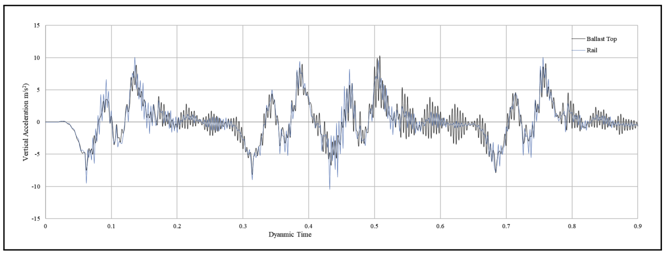

Figure 6: Acceleration vs Dynamic Time

The absolute displacement ($|u|$) contour pattern at section at x=5.9 m and y= 3 m is shown in figure 7.

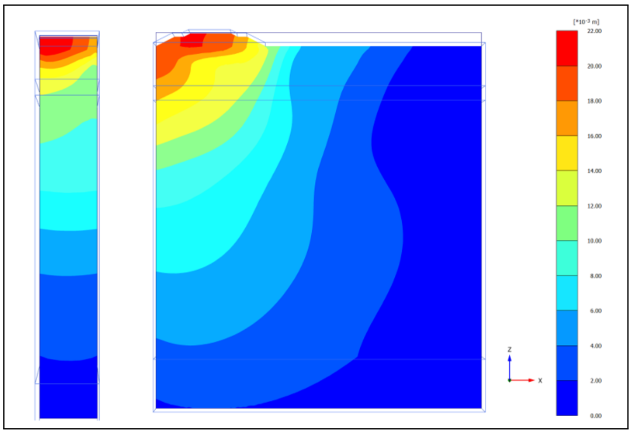

Figure 7: Variation of absolute displacement at dynamic time, t= 0.7 s

5.2 Effect of Speed of the train on Vibration

The influence of train speed in the vibration transmission has been studied for four different cases. The speed of the train is varied from 30 m/s to 60 m/s. The following are the deformation diagrams for trains of different speed at 1 m high embankment. Figure 8 and figure 9 shows the variation of peak velocity and peak acceleration at rail and edge of ballast at different speeds.

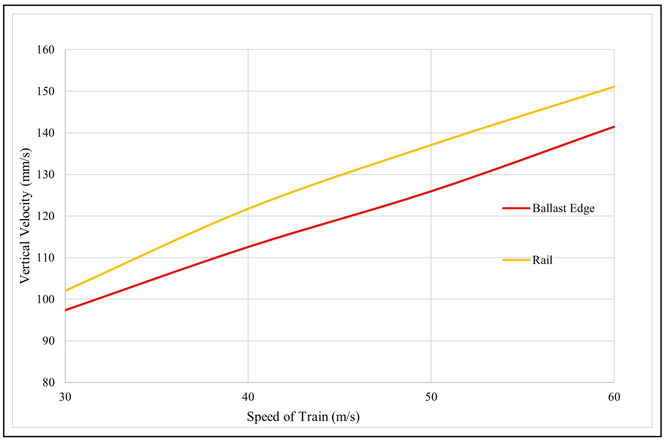

Figure 8: Vertical Velocity vs Speed

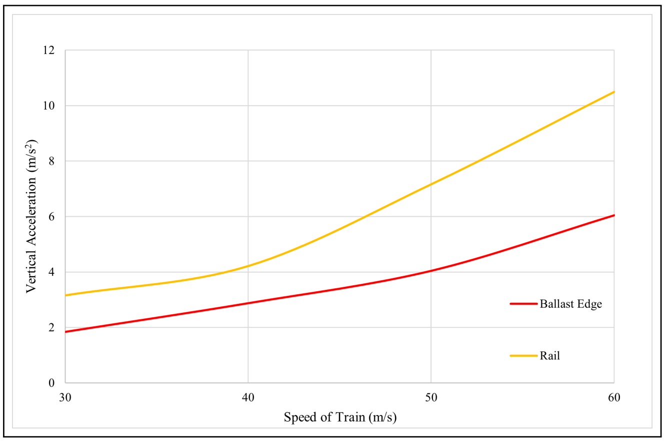

Figure 9: Vertical Acceleration vs Speed

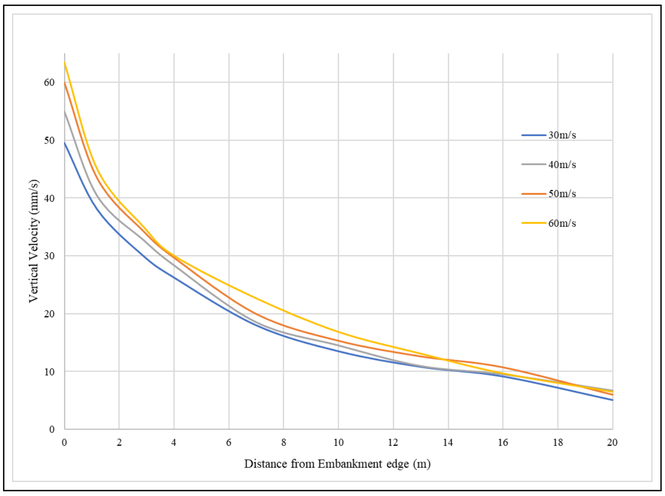

Figure 10: Vertical Velocity vs Distance from Embankment edge at different train speed

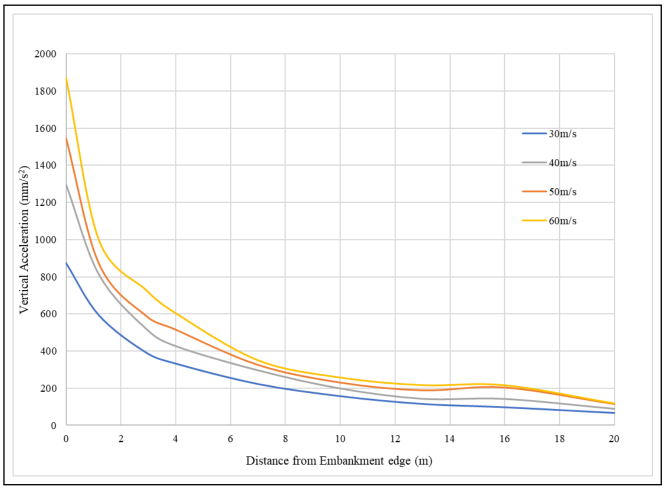

Figure 11: Vertical Acceleration vs Distance form Embankment Edge at different train speed

The major concern regarding the vibration is the impact on the surroundings. Figure 10 and figure 11 shows the variation of peak vertical velocity and acceleration at horizontal distance from embankment edge. The plots shows that there is significant increase in ground response with increase in speed of train for nearer distances from the edge i.e. nearer from the source of vibration.

5.3 Effect of Stiffness of Ballast on Ground Response

The effect of the stiffness of the ballast on the ground response was analysed. Figure 12 and figure 13 shows the variation of peak vertical velocity and acceleration at horizontal distance from embankment edge at different stiffness of ballast material for train speed of 60 m/s. There is about 2% decrease in the vertical acceleration resposne at ground level with the increase of ballast stiffness from 200 MPa to 300 MPa. Similar response of ground was seen at other train speeds.

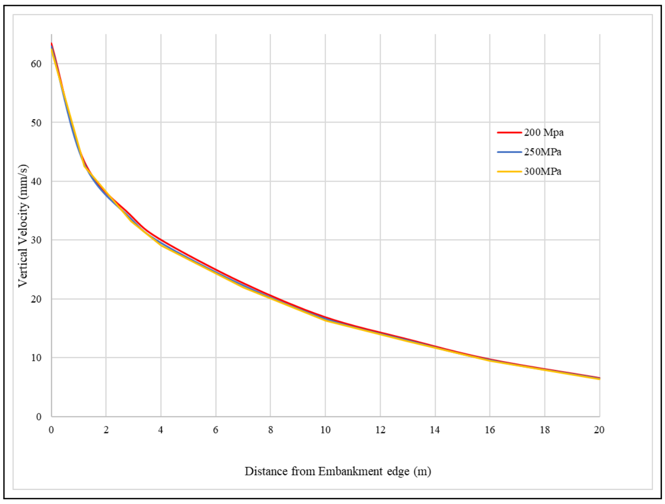

Figure 12: Vertical Velocity vs Distance from Embankment edge at different stiffness

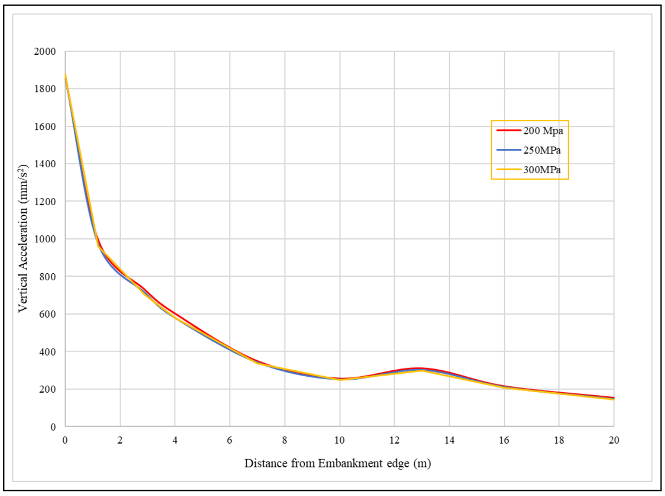

Figure 13: Vertical Acceleration vs Distance form Embankment Edge at different stiffness

5.4 Effect of Height of Embankment on Ground Response

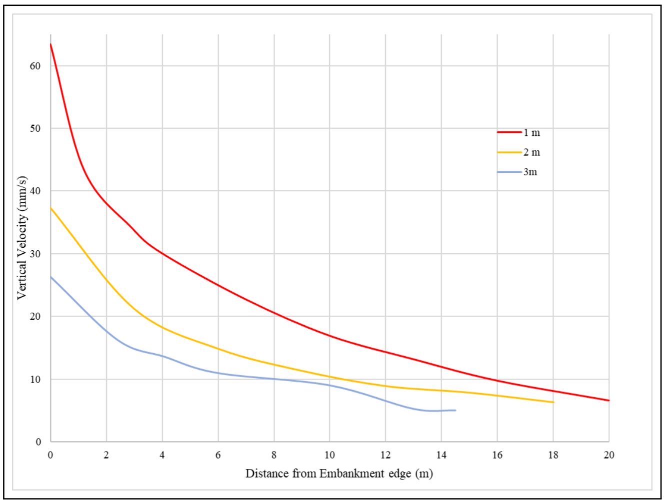

Figure 14: Vertical Velocity vs Distance from Embankment edge at different height of embankment

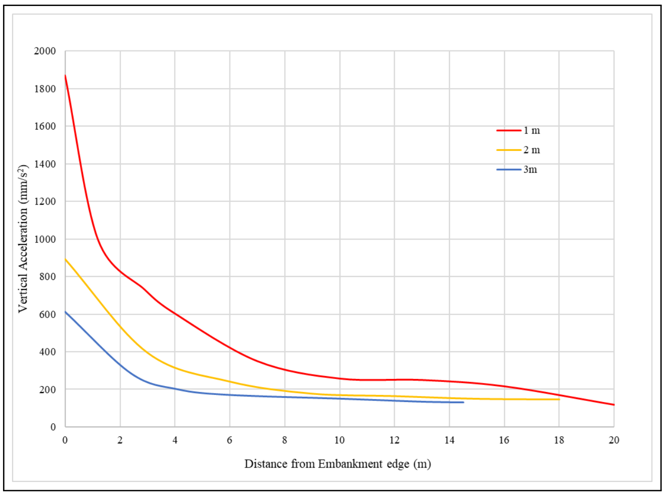

Figure 15: Vertical Acceleration vs Distance from Embankment Edge at different height of embankment

The influence of the height of embankment in vibration transmission is analysed. The response of vertical velocity of soil with distance from embankment edge is shown in figure 14. Similarly, the response of vertical acceleration with distance from embankment edge is shown in figure 15. The plots shows that the height of embankment has significant impact on the vibration. The increase in embankment height decreases the ground response to the receptor through higher distance to the source as well as longer, stiffer path. However, The increase in height of embankment will require larger land area for stability of the slope.

6. Conclusions

A numerical study was carried out to study the behaviour of ground response due to ballasted railway on embankment in cohesionless soil. Simulation of dynamic train load is done using Winkler beam approach. A three dimensional analysis is carried out to analyse the ground response, primarily vertical velocity and vertical acceleration of soil particle, due to variations of the speed of train, stiffness of ballast and height of the embankment. The speed of the train has high influence in the vibration of the rail which is the primary receptor of the vibration of train. The increase in train speed from 30 m/s to 60 m/s shows around 50% increase in vertical velocity and more than 230% increase in vertical acceleration of the rail element.

With increase in train speed, significant increase in the ground vibration can be seen at the distance nearer to the source while the influence decreases with increase in distance. Similar trend in ground response is seen in the vertical distance from the rail centre.

Significant change is not seen in the ground response due to increase in ballast stiffness. Around 2% decrease in peak vertical velocity of the soil particle at the edge of embankment is seen with increase in stiffness of ballast from 200 MPa to 300 MPa. However, stiffer ballast can increase the stability of the formation of railway.

The increase in embankment height can be useful in decrease of the vibration impact of the railway. The decrease in vertical velocity and vertical acceleration of soil particle at edge of embankment by about 58% and 67% respectively is seen with increase in height of embankment from 1 m to 3 m. The influence of the height of embankment is significant for the nearer distance from the source i.e. train.

The study recommends further studies focusing on influence of other factors and wider range of study area and soil conditions in order to study the dynamic behaviour and impact of the railways. Wide range of study can help in proper mitigation techniques and precautions for the development/ improvement of structures nearby.

References

[1] Macrotrends. Kathmandu, nepal metro area population 1950-2023. `https://www.macrotrends.net/cities/21928/kathmandu/population`, August 2023.

[2] Anil Marsani and Jeni Rajbamshi. Traffic problem in kathmandu and use of gis in urban traffic. *Journal on Geoinformatics Nepal*, May 2004.

[3] L. Dr. Binod Amatya. How to build the underground metro rail in kathmandu. In *Promoting cultural change in engineering*, pages 43–51. Society of Nepalese Engineers UK, 2020.

[4] Wei Xie, Guangyun Gao, Jian Song, and Yu Wang. Ground vibration analysis under combined seismic and high-speed train loads. *Underground Space*, 7(3):363–379, 2022.

[5] International Organization for Standardization. *Mechanical Vibration and Shock: Evaluation of Human Exposure to Whole-body Vibration.* International Organization for Standardization, 1985.

[6] D. P. Connolly, G. Kouroussis, A. Giannopoulos, O. Verlinden, P. K. Woodward, and M. C. Forde. Assessment of railway vibrations using an efficient scoping model. *Soil Dynamics and Earthquake Engineering*, 58:37–47, 2014.

[7] Lars Hall. Simulations and analyses of train-induced ground vibrations in finite element models. *Soil Dynamics and Earthquake Engineering*, 23(5):403–413, 2003.

[8] Richard D Woods. Screening of surface wave in soils. *Journal of the soil mechanics and foundations division*, 94(4):951–979, 1968.

[9] Leonard G Kurzweil. Ground-borne noise and vibration from underground rail systems. *Journal of Sound and Vibration*, 66(3):363–370, 1979.

[10] A Trochides. Ground-borne vibrations in buildings near subways. *Applied Acoustics*, 32(4):289–296, 1991.

[11] A Gomes Correia, J Cunha, João Marcelino, Laura Caldeira, J Varandas, Z Dimitrovová, A Antão, and MGD Silva. Dynamic analysis of rail track for high speed trains. 2d approach. *5th Intl Worksop on Application of Computational Mechanics on Geotechnical Engineering*, 4, 2007.

[12] Richard N Hwang and John Lysmer. Response of buried structures to traveling waves. *Journal of the Geotechnical Engineering Division*, 107(2):183–200, 1981.

[13] Yeong-Bin Yang and Hsiao-Hui Hung. A 2.5 d finite/infinite element approach for modelling visco-elastic bodies subjected to moving loads. *International Journal for Numerical Methods in Engineering*, 51(11):1317–1336, 2001.

[14] DJ Thompson, James Jiang, MGR Toward, MFM Hussein, E Ntotsios, Arne Dijckmans, Pieter Coulier, Geert Lombaert, and Geert Degrande. Reducing railway-induced ground-borne vibration by using open trenches and soft-filled barriers. *Soil Dynamics and Earthquake Engineering*, 88:45–59, 2016.

[15] Arne Dijckmans, Pieter Coulier, J Jiang, MGR Toward, DJ Thompson, Geert Degrande, and Geert Lombaert. Mitigation of railway induced ground vibration by heavy masses next to the track. *Soil Dynamics and Earthquake Engineering*, 75:158–170, 2015.

[16] M. Shahraki, M. R. S. Sagaghiani, K. J. Witt, and T. Meier. 3d modelling of train induced moving loads on an embankment, 2014.

[17] Iram Lamiya Hoque, Shamontee Aziz, Joya Rani Mallick, Md Arifuzzaman Nayeem, Tamanna-E Maisha, FM Hossain, AFMS Amin, et al. Response analysis of a ballasted rail track constructed on soft soil by 3d modeling. *Advances in Civil Engineering*, 2023, 2023.

[18] M Shahraki, MR Salehi Sadaghiani, KJ Witt, and T Meier. Model quality investigations of induced moving loads of high-speed trains. In *Proceedings of the 8th European Conference on Numerical Methods in Geotechnical Engineering, NUMGE*, volume 2, pages 1169–1173, 2014.

[19] M Shahraki, MRS Sadaghiani, KJ Witt, and T Meier. 3d modelling of train induced moving loads on an embankment. *Plaxis Bulletin*, 36(2014):10–15, 2014.

[20] David Connolly, Antonios Giannopoulos, and MC Forde. Numerical modelling of ground borne vibrations from high speed rail lines on embankments. *Soil Dynamics and Earthquake Engineering*, 46:13–19, 2013.

[21] O Aagah and S Aryannejad. Dynamic analysis of soil-steel composite railway bridges. *Master of Science, KTH Royal Institute of Technology*, 2014.

[22] DV Singh and Y Seth. 3d modelling of ground surface vibration induced by underground train movement. *Procedia Engineering*, 173:1580–1586, 2017.

[23] Delhi Metro Rail Corporation Limited. Outline design specifications for phase-iv. Technical report, Delhi Metro Rail Corporation Limited, 2021.