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Modeling of vibrations induced by Mecca-Medinah high-speed train and earthquake mitigation analysis

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ABSTRACT

In recent years, a new high-speed rail (HSR) network, known as the Al-Haramain HSR, has been developed to connect the two holiest Muslim cities in Saudi Arabia, Mecca and Medina. The operation of the HSR generates ground-borne vibrations that may affect the surrounding neighborhoods. This study investigates ground vibration measurements collected at a farm located adjacent to the Al-Haramain HSR track. The soil stratigraphy was investigated using the Multichannel Analysis of Surface Waves (MASW) method to determine the shear-wave velocity profile. In the MASW procedure, a series of 12 geophones, spaced at 3 m intervals, were used to measure and record the seismic surface waves generated by a seismic source. Sledgehammer (5.0 kg) was used to generate surface (Rayleigh) waves. In addition, a three-dimensional finite element model was developed using PLAXIS 3D software to further elucidate the vibration characteristics and propose a vibration mitigation solution. The model involves a coupled track/soil system with moving axial loads, which simulates a vertical moving load with the same speed as the HSR. The comparison of the numerical and experimental results demonstrates that the numerical model can correctly predict the ground vibration produced by the high-speed train. To explore vibration mitigation schemes, the validated numerical model was used to examine the effectiveness of Tire Derived Aggregate (TDA) barrier as well as geogrid mesh in reducing the lateral rail vibration arising from potential earthquakes. The numerical results showed that TDA barrier can effectively reduce the lateral rail vibration.

Keywords: High-speed train, Vibration, Geofoam, Geophones, Modeling, TDA

1. Introduction

Al-Haramain High-Speed Rail train connects two holy cities in Saudi Arabia, Makkah and Madinah, with an electrified passenger railway line, approximately 450 km in length, with a commercial operating speed of 320km/h (Figure 1). The train provides safe and fast transportation between the holy cities utilizing a state-of-the-art proven technology. Al-Haramain High-Speed Rail is projected within the parameters of a European high-speed line. The high-speed rail (HSR) industry has seen continuous development with innovative technologies. However, the high-speed train is still considered a major source of ground vibration noise in the communities located near the HSR lines [2]. Over the past decade, several studies have investigated the train-induced ground vibrations and proposed different mitigation techniques [3].

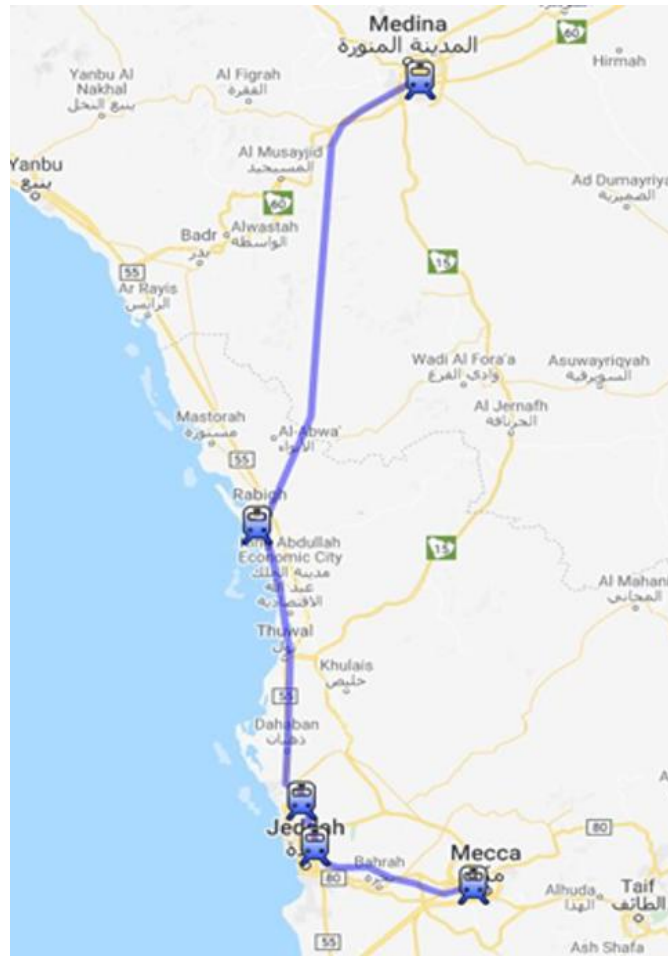


Fig 1: Al-Haramain High-Speed Rail Rout

2. Literature Review

Modern technological advancements have allowed trains to reach high speeds (over 300 km/hr), which has raised concerns about excessive displacements and track vibrations [4]. Ground vibration is an oscillatory motion, which can be expressed in terms of displacement, velocity, or acceleration [5]. The dynamic load induced due to the movement of a high-speed train on a rail generates vibrations that are transmitted from sleepers to ballast and sub-ballast, and ultimately to the ground [6, 7]. Some research was conducted to study the dynamic properties and behavior of railway tracks [8, 9], while other studies investigated the ballast deformation under cyclic loading [10, 11]. Field instrumentation has been used to study and track substructure behavior [12]. For instance, Sayeed and Shahin [13, 14] have developed an innovative method to design the foundation of ballasted railways to support HSR and heavy axle loads. Recent studies investigated HSR induced vibration using different approaches including field experiments, finite element analyses and modeling and centrifuge experiments. For instance, continuous sinusoidal vertical vibration (20, 40, 60, 80, 95, and 100 Hz) was generated using a mass vibrator operated by a portable power generator [15]. A continuous service system was used to record readings from geophones (0.5 m from each other).

The effect of HSR on different earthwork profiles, including at-grade, embankment, cutting and overpass, has been investigated [16]. The results showed that vertical vibrations are not always the most dominant and that horizontal vibrations should be considered. It is also found that the lowest vibration was recorded on embankment earthwork, while the highest was reported on the cutting. Also, centrifuge tests have been conducted to study and mitigate the vibration induced by HSR [17]. The results showed that the surface waves guide the propagation pattern of ground vibration, and a double geofoam barrier is more efficient in mitigating vibration than a single geofoam barrier. The behavior of ground vibrations induced by trains with rail roughness was investigated. The results showed that at high speed, the vibrations are not different in the case of smooth or rough rails [18].

In a previous study, a three-dimensional finite element model was used to simulate multi-layered ground and radiation damping using viscous boundary conditions [19]. The results clearly showed an increase in track deflection with train speed. The material damping model allows a realistic prediction of the track vibration and train body dynamics at high speeds [19]. Feng et al. (2017) [20] developed a three-dimensional track-ground model to study vibrations induced by high-speed trains. The train loads are simplified as a series of moving point loads. The Fourier transform is applied to solve the governing equations. The results indicated that the existence of groundwater significantly influences the surface displacement of the ground, while the influence on velocity and acceleration is weaker at critical speeds [20]. Also, the loading speed greatly influences pore-water distribution, while the influence of drainage conditions is relatively small.

Geofoam materials can be used for thermal insulation, lightweight fill in earthworks, compressible inclusions to reduce earth pressures, vibration and noise damping and drainage [21] [5]. Ground vibrations due to human activity can be reduced by employing geofoam barriers within the soil [21]. Previous experimental results showed that both open air and GeoFoam barriers can effectively reduce the transmitted waves [22]. The beneficial effects of a protective geofoam barrier could be enhanced by increasing barrier thickness only up to a certain limit, beyond which further increase in thickness did not result in additional reductions [22]. Murillo et al. [23] conducted centrifuge tests to simulate the traffic vibration and to test the efficiency of EPS barriers in ground-borne vibrations. They also conducted a numerical study to investigate the EPS barriers effectiveness based on the dimensionless geometry of the barrier and its location from the source of disturbance. The results showed that the barrier effectiveness is mainly dependent on the barrier depth and its location from the vibratory source. Furthermore, the barrier width had a minor influence in the case of deeper barriers and higher frequencies. However, the barrier width had a remarkable influence on the screening effectiveness of low-frequency vibration for shallow barriers.

Alzawi and ElNaggar [24] conducted a full-scale field study to simulate the vibration induced by a machine on a foundation and to test the efficiency of various barriers with various geometries in mitigating ground-borne vibrations. They also developed a numerical model using ABAQUS to investigate the effectiveness of the barriers based on the achieved reduction in soil particle velocities through a parametric study by changing the exciting frequency and the location of the wave barriers. The results showed that the barrier effectiveness is mainly dependent on the normalized barrier depth and its proximity to the vibratory source. Furthermore, the results of the FE model were in good agreement with the experimental observations.

The vibration propagation due to high-speed trains close to vibration-sensitive structures poses a risk to their structural health, especially when the ground vibrations arriving at the structure are amplified through the height of the structure at resonant frequencies [25]. The effect of the presence of alluvium deposit on top of the basaltic rock layers on the HSR-induced vibration and wave barrier effectiveness has not been investigated in the available literature. Therefore, this paper investigates the ground-borne vibration due to the Al Haramian high-speed rail and evaluates the feasibility of using a vibration barrier to mitigate the induced Earthquake lateral vibrations.

3. Research Methodology

The study involved a field campaign of ground vibration measurements collected at a farm located at the side of the Al-Haramian high-speed trains, and the results were used to validate a three-dimensional finite element model developed using PLAXIS 3D. A multichannel analysis of surface waves (MASW) survey was conducted in the vibration monitoring area. The collected data were analyzed to establish dispersion curves of the generated surface waves, and to establish the shear wave velocity profile of the soil layering. The field campaign of ground vibration monitoring was conducted for several train passages employing an advanced vibration monitoring system comprising three-dimensional field vibration sensors. A numerical model was then developed using the commercial finite element software PLAXIS 3D, which was calibrated and validated utilizing the field measurements. Finally, the numerical model was used to investigate the wave barriers' protective effectiveness.

4. Site Investigation and Material Properties

The tests were carried out at a farm area 8 km south of Al-Madinah city, adjacent to the HSR line. A borehole investigation was carried out near the railway using a standard penetration test (SPT). The results indicated that the top 1.5 meters below the ground surface consisted of light brown silty clay sand with gravel. Basalt rock was encountered between 1.5 and 3 meters. From 3 to 4.5 meters, the soil was composed of a mixture of light brown materials, including silty sand with gravel, cobbles, basaltic tuff, and basalt rock boulders. This stratigraphy suggests a gradual transition from finer, clayey soils near the surface to coarser materials and rock at greater depths, reflecting varying depositional environments or past geological events. The ballast for the Haramain High-Speed Railway was constructed in accordance with standard EN13450 Aggregates for railway ballast [26]. The soil stratigraphy was investigated using the Multichannel Analysis of Surface Waves (MASW) method to determine the shear-wave velocity profile. In the MASW procedure, a series of 12 geophones, spaced at 3 m intervals, were used to measure and record the seismic surface waves generated by a seismic source. Sledgehammer (5.0 kg) was used to generate surface (Rayleigh) waves. The subgrade measurements were taken near the HSR track embankment, while the sub-ballast measurements were taken on the HSR embankment. A series of field measurements of the train-induced vibration was carried out using triaxial 1 Hz seismometers very sensitive to three-dimensional field vibrations.

Table 1 shows the material properties of the railway track and the surrounding native soil.

Table 1: The track and soil material properties.

FEM part Description	Young's Modulus (GPa)	Poisson's ratio	Density (kg/m ³)	Layer Thickness (m)
Rail	210	0.25	7900	
Sleepers	30	0.4	2400	
Ballast	0.1	0.35	1800	0.3
Subballast	0.3	0.35	1900	10
Subgrade	0.127	0.35	1900	14

The ballast for the Haramain High Speed Railway was constructed in accordance with standard EN13450 Aggregates for railway ballast [37]. The embankment soil was classified as AASHTO A-1-b.

5. Numerical Model Geometry and meshing

A numerical model was established using the commercial finite element software PLAXIS 3D [27, 28]. Figure 1 shows AutoCAD drawings of the HSR rail embankment, sleepers and track system. The geometry of half the track system was imported into Plaxis 3D; then, a 3D model was generated by extruding the 2D drawing outline, as shown in Figures 2a and 2b. The numerical model comprised ten-node tetrahedron elements to simulate the sleepers and soil volumes, and three-node beam elements to simulate the rails. As shown in Figure 2a, the HSR embankment dimensions in the PLAXIS 3D model simulate the real constructed embankment. Also, Figure 2 a shows that the depth of the embankment is 7.5 m underlain by a 6 m subgrade soil layer simulating the silt-clay layer and part of the basaltic rock stratum. The depths of these layers were obtained from the boring log data. The model dimension in the Y-axis direction was 70 meters to allow for the estimation of the attenuation behavior of the model surface wave. The model dimension in the X axis was 100 meters to capture the effect of the passage of seven train vehicles and to reduce the calculation time. The target element dimension was 3 meters minimum, calculated by substituting the overall 3D model dimensions and a coarseness factor of 0.5 into the following equation:

$$l_e = r_e \times 0.05 \times \sqrt{(x_{max} - x_{min})^2 + (y_{max} - y_{min})^2 + (z_{max} - z_{min})^2} \quad [1]$$

The surface Rayleigh wavelength was 29 m, estimated from the measured shear wave velocity of the subgrade soil of 501 m/s, using field geophysical exploration, with a model frequency of 20 Hz. The ratio of the element size to the wavelength is 0.13. This ratio is equal to the recommended ratio of 1/8 in finite element simulations. The movement of the train was modelled with a moving load of 88-92 kN with a speed of 50 m/s, matching the speed of the train when it passes in front of the research site. During the dynamic analysis, general viscous boundary conditions were imposed around the soil volume to absorb the surface waves and body waves with the default relaxation coefficient C1=1 and C2 = 0.25 [27]. The fastening system, which connects sleepers with the rails, was modelled with a small vertical beam with dimensions equal to those of the elastomer plate of the fastening system. The vertical track stiffness of the fastening system was 80 kN/mm as per the manufacturer's specifications.

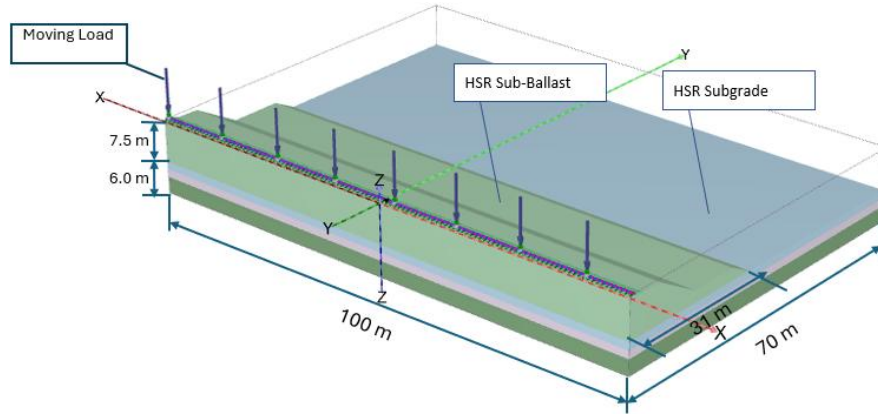


Fig 2a: The Geometry of the numerical model

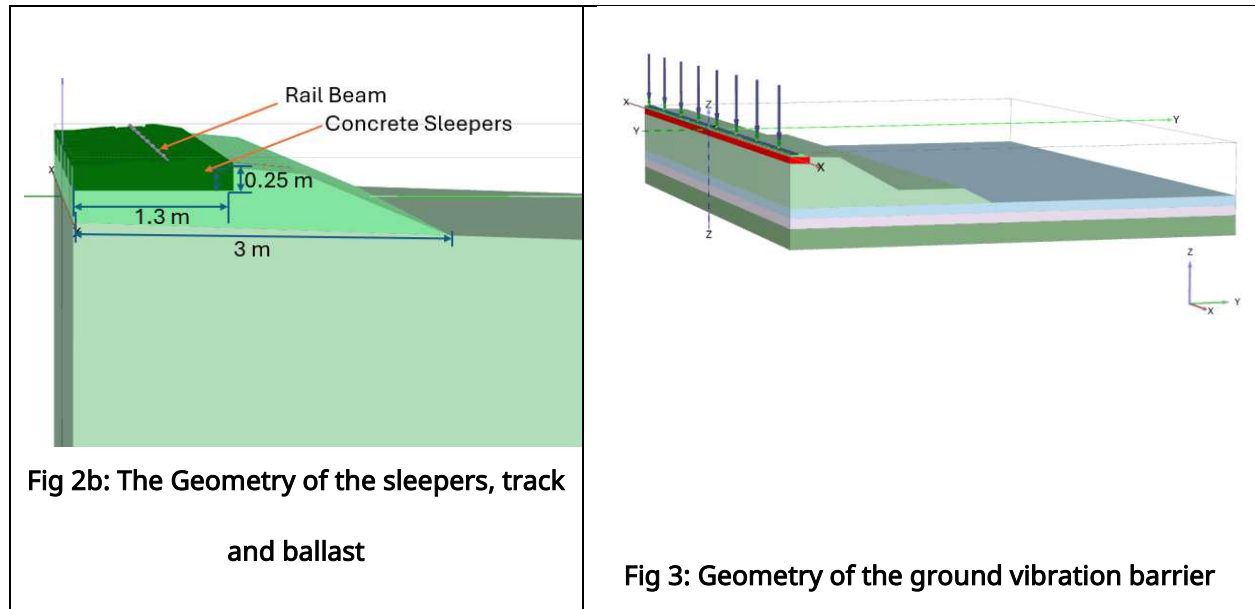


Fig 2b: The Geometry of the sleepers, track
and ballast

Fig 3: Geometry of the ground vibration barrier

6. Barrier model dimensions:

A model barrier was created to guide future vibration measurement when constructing the barrier in the field. A model barrier was embedded at one location. To investigate its effect on attenuating the lateral earthquake vibration on HSR rail, the barrier models simulate a strip or pad 100 m long, 3 m wide and 1 m deep. Figure 3 shows the geometry of the barrier. The barrier material parameters were chosen to simulate a TDA barrier.

7. Adding the Earthquake signal procedure:

The present research investigates the effect of a scaled earthquake signal on the HSR track system. The earthquake signal was recorded from an earthquake that hit Al-Ais town in the Al-Madinah region in the year 2009. The acceleration time history of that earthquake was scaled to a stronger earthquake that occurred in Sanaa (southern Arabian Shield) in December 12, 1982 with ($M_s = 6.1$) [29]. The response spectra of Sanaa earthquake were used as the target spectrum to scale the earthquake signal of the Al-

Madinah region with 5% damping using SiesmoMatch. A sine wave with a maximum velocity and a predominant frequency matching the scaled signal was generated. This sine wave was used to cause the lateral vibration in the Y direction by adding it to the displacement surface at the base of the Plaxis 3D model, as shown in Figure 4.

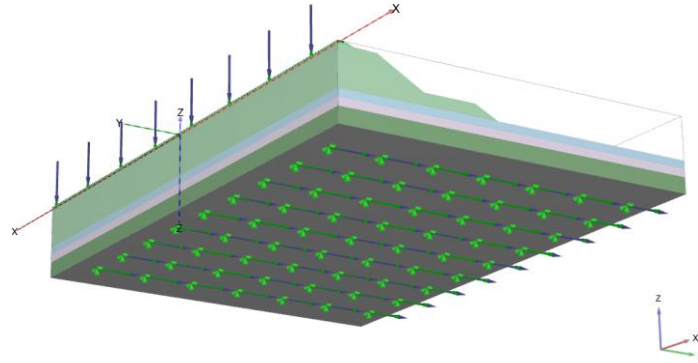


Fig 4: The ground displacement surface attached to the base of model soil layers.

8. Constitutive modeling of the ballast, sub-ballast and subgrade layers

The constitutive behavior of the ballast and TDA was modeled as linear elastic. The sub-ballast and subgrade soils' constitutive behavior were modeled using the PLAXIS (HSSMALL) model. This model accounts for the stiffness degradation for different types of soils when subjected to primary deviatoric loading. Simultaneous irreversible plastic strains develop in soils during deviatoric loading, causing the yield surface to change in size. In contrast to the elastic perfectly-plastic soil models, the yield surface of the HS model expands due to plastic straining and varies in the principal stress space. Also, the HS model captures the variation of the plastic axial strain with the deviatoric stress by using the theory of plasticity rather than the theory of elasticity and introducing a yield cap [28]. The HSSMALL model parameters in this research were calculated following the methodology adopted by Taha et al. (2015) [30]. The TDA material parameters were taken from the research work by Tandon et al. (2023) [31]. Table 2 shows the material model parameters.

The numerical calculations were executed in four phases: 1. the geostatic equilibrium, 2. construction of rails 3. the application of moving loads and earthquake signal without barriers, 4. the application of the earthquake signal with moving loads with barriers.

Damping calculation procedure:

Soil damping ratio is one of the important parameters needed for precise modelling of the dynamic behavior of soil embankment. Ju and Ni (2007) [32] studied the least-squares method to evaluate the Rayleigh damping parameters for the finite element analysis of wave propagation in soils. Using both field experiments and finite element analysis, they found that the least square method is accurate and valid. In this research, the absorption coefficient a was determined using experimental measurements at two different vibration frequencies. The vibration signals were generated using a motor seated on the subgrade. The amplitudes of the induced ground vibration were recorded at 0.5 m and 4.5 m from the motor. After recording two amplitudes 0.04 mm/s and 0.01 mm/s at two frequencies 44 Hz and 20 Hz, the absorption coefficient a was calculated for using the equation:

223 $[k][\alpha] = [F]$

224 Table 1: Material model parameters

	Rail	Elastomer Plate	Sleepers	Ballast	Sub-Ballast	Subgrade	TDA
Constitutive model	Linear Elastic	Linear Elastic	Concrete	Linear Elastic	HS small	HS small	Linear Elastic
γ_{unsat} (kN/m ³)	50.6	8E-3	24	17.6	19.5	20	6
E' (MPa)	210	7.55	25	100	-	-	16.25
ν'	0.25	0.48	0.15	0.35	0.28	0.28	0.3
G (MPa)	-	-	-	37	-	-	-
E_{50}^{ref} (MPa)	-	-	-	-	370	255	-
E_{oed}^{ref} (MPa)	-	-	-	-	296	204	-
E_{ur}^{ref} (MPa)	-	-	-	-	1109	764	-
$\gamma_{0.7}$	-	-	-	-	0.058E-3	0.026E-3	-
G_o^{ref} (MPa)	-	-	-	-	4330	2984	-
Velocities	-	-	-	-	-	-	-
V_s (m/s)	-	-	-	144	750	500	101
V_p (m/s)	-	-	-	300	7400	1000	189
Damping	-	-	-	-	-	-	-
Rayleigh α	-	-	-	124	19.9	19.9	0
Rayleigh β	-	-	-	2.5E-05	4.41	4.41	0

225 Accordingly, two damping ratios (D1 and D2) were calculated at the obtained absorption coefficients from
 226 the obtained absorption coefficients using the equation:

227
$$D = \sqrt{\frac{1}{1 + \left(\frac{\omega}{v\alpha}\right)^2}}$$

228 Finally, the β coefficient was calculated at the damping at two different circular frequencies (ω_1 and ω_2)
 229 using the relation:

230
$$\beta = 2(D_2\omega_2 - D_1\omega_1)/[\pi(\omega_2^2 - \omega_1^2)]$$

231 The damping ratio of the ballast was obtained from Brinji (2016) [33], who studied the mechanical behavior
 232 of a railway's ballast using both field experiments and laboratory testing.

233 9. Barrier model dimensions:

234 A model barrier was created to guide future vibration measurement when constructing the barrier in the
 235 field. A model barrier was embedded at one location. To investigate its effect on attenuating the lateral
 236 earthquake vibration on HSR rail, the barrier models simulate a strip or pad of 100 m long, 3 m wide and 1
 237 m deep. Figure 2 shows the geometry of the barrier. The barrier material parameters were chosen to simulate
 238 a TDA barrier. In addition to the TDA layer, a model geogrid layer was added at the bottom of the ballast

and surrounded with a layer with enhanced shear strength that model the effect of gravel-geogrid interlock. The geogrid layer was surrounded with positive and negative interface layers on top and bottom.

10. Results and Discussion

In this study, the influence of the high-speed train on the level of the ground was examined using numerical modeling. A coupled finite element model of the track, sleepers and subsoil is employed, adopting a formulation in the moving frame of reference following the high-speed train. Figure 5 compares the wave propagation pattern of the transmitted vibrations measured from the field and calculated from the numerical model. Figure 6 compares the Fourier amplitude and frequency content of the field transmitted vibrations and the calculated frequency content from the numerical model. The general trend of the observed behavior is similar in both cases with respect to frequency content. However, the calculated amplitude falls on the conservative side, and it is less than the measured amplitude by around 40%. In general, the model results follow the trend of experimental results, but with slightly higher values at some points and lower values at others [15]. This may be attributed to considering the horizontal homogeneous soil layers in the model, which may not be the case in the field. Previous studies reported a discrepancy between field test and finite element model results, and that the calculated amplitude falls within the conservative side.

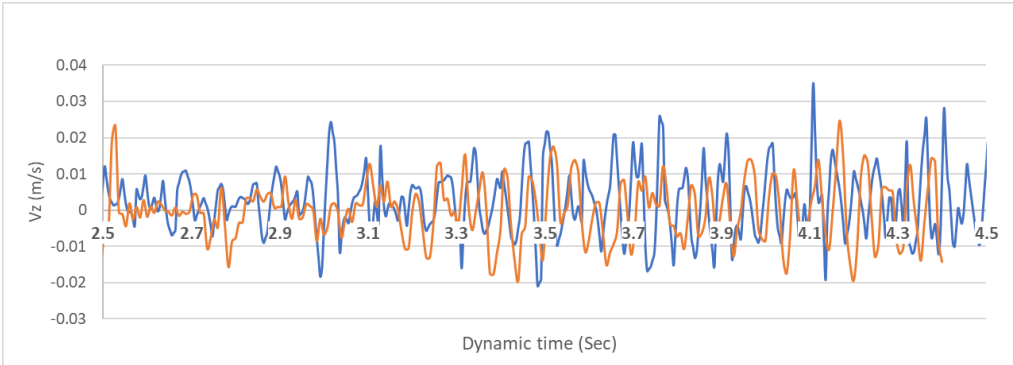


Fig 5: Calculated vs. Measured time history comparison

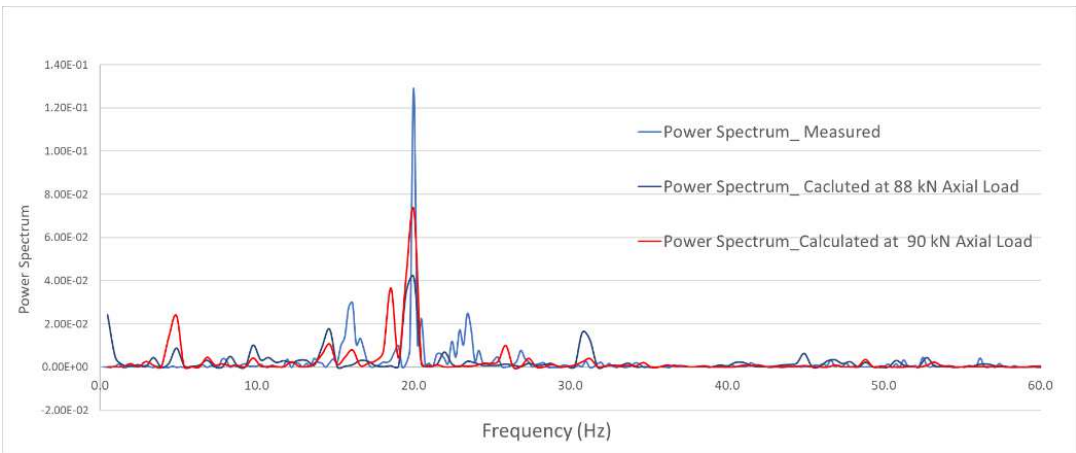


Fig 6: Frequency content comparison: Field vs. model

The calculated attenuation results of the surface wave along a line extending up to 60 meters from the HSR track demonstrate that the numerical model captures the attenuation behaviour of the surface wave as the wave travels farther away from the vibration source. Similar results were obtained by [24], where the recorded vibrations indicated increasing attenuation of the generated surface waves at locations farther from the source of vibration.

Figure 7 compares the model results for the time history of the proposed TDA barrier to isolate vibrations and the same model without isolation. It can be noticed that the FE model captured the amplification effect of the soil layering. Also, the FE model revealed that the TDA pad attenuated the vibration of the rail beam significantly compared to that without activating the TDA pad. In addition, the FE model results suggest that the rail beam vibrates with higher amplitudes and frequency compared to the surface soil layer and sub ballast. This can be owed to the fact that the rail beam is supported by the elastomer plate which adds to it fixability.

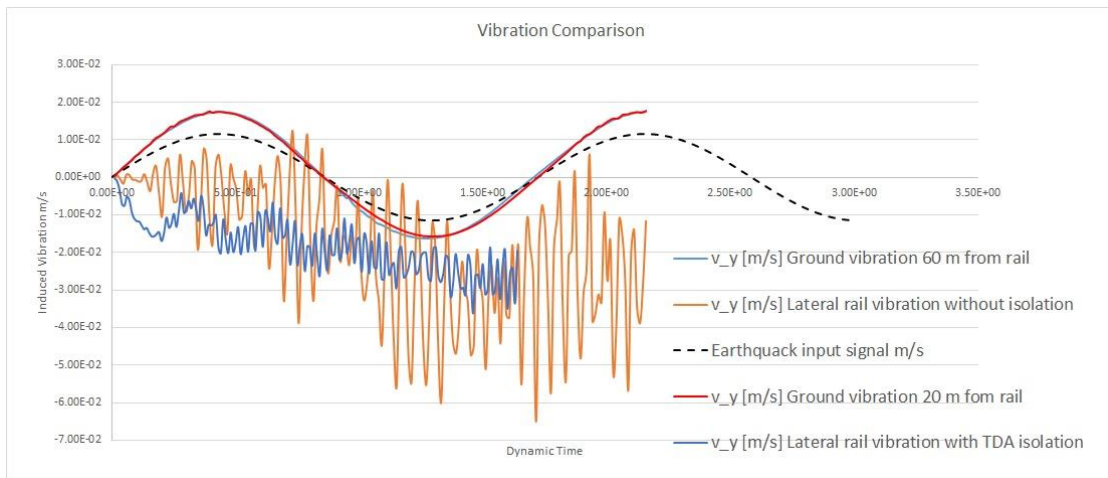


Fig 7: Comparison of the barrier effectiveness considering different barrier materials

Figure 8 compares the model results for the effect of TDA and the geogrid layer on the lateral dynamic performance of the sleepers. The figure shows that applying a TDA layer at the bottom of the ballast attenuates the lateral vibration of sleepers. The figure also shows that applying a geogrid layer at the bottom of the ballast further attenuates the lateral vibration. It can be seen that the effect of the geogrid alone is almost equal to the effect of adding the geogrid plus the TDA in the ballast.

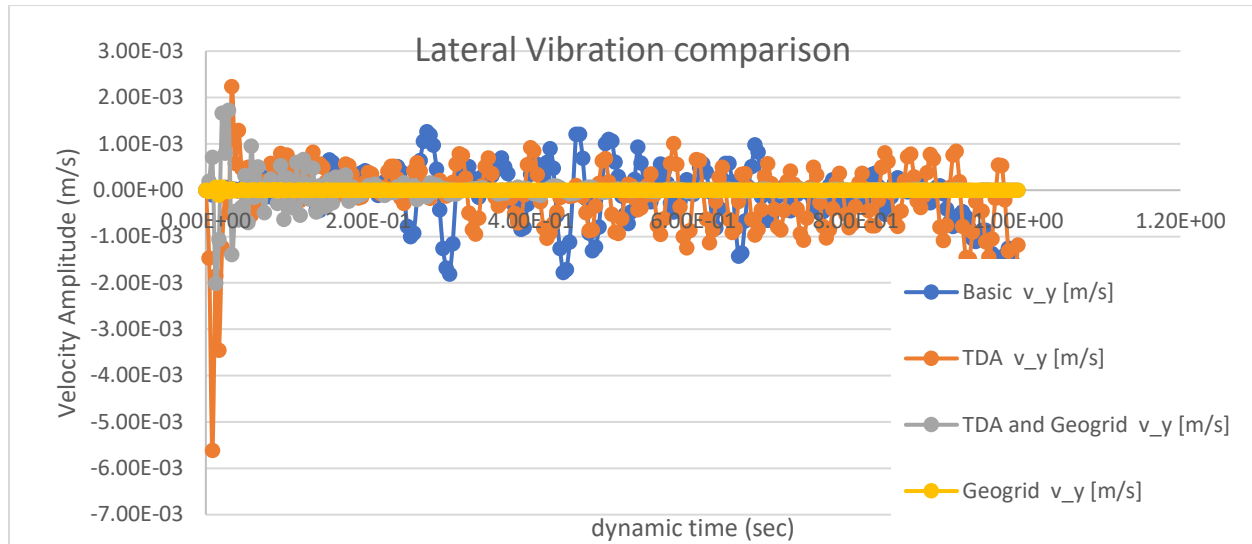


Fig 8: Lateral Vibration Comparison

10 . Conclusion

Field measurements were conducted to investigate the effect of vibration induced by a high-speed train (Al Haramain train) near Al Madinah Al Munawara, Saudi Arabia. Finite element analysis was used to develop a numerical model to simulate the train vibration. The calibrated model was used to further investigate the effect of adding TDA isolation under the HSR track system. A strong earthquake motion was induced at the base of the FE model. The main findings can be summarized in the following points.

1. It was observed that the FE model was successful in capturing the attenuation behavior in the induced vibration signal and the frequency of the measured vibration, but with a lower amplitude. This observation was recorded in previous modelling work [31].
2. The numerical model shows that the FE model was successful in capturing the earthwork amplification effect due to the soil layering.
3. It can be noticed from the FE model that the proposed TDA barrier was effective in isolating the vibrations induced by the earthquake-scaled signal.
4. The FE model shows that adding a geogrid layer at the bottom of the ballast can be used as an alternative for the TDA layer for attenuating the lateral vibration of the sleepers.

11. Acknowledgements

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12. Data availability statement

We (the authors) confirm that our manuscript has no associated data.

13. Statements and Declarations

The authors declare that they have no competing financial or non-financial interests related to the work reported in this manuscript. The authors have no affiliations with or involvement in any organization or entity that could have influenced the content of this article. Furthermore, the authors have no financial or proprietary interests in any material discussed in this manuscript.

References

1. A, H.W. Model Tests on Screening of Surface Waves. *Soil Mech. Found. Eng.* 10th Int. Conf. 1981 Vol3 1981, 215–222.
2. Al-Malki, M.A., Al-Amri, A.M. (2013). Seismic zones regionalization and hazard assessment of SW Arabian Shield and Southern Red Sea Region. In: Al Hosani, K., Roure, F., Ellison, R., Lokier, S. (eds) *Lithosphere Dynamics and Sedimentary Basins: The Arabian Plate and Analogues*. *Frontiers in Earth Sciences*. Springer, Berlin, Heidelberg.
3. Alzawi, A.; Naggar, M.H.E. Full Scale Experimental Study on Vibration Scattering Using Open and In-Filled (GeoFoam) Wave Barriers. *Soil Dyn. Earthq. Eng.* **2011**, 3, 306–317, doi:10.1016/j.soildyn.2010.08.010.
4. Baziar, M.H.; Kazemi, M.; Shahnazari, H. Mitigation of Ground Vibrations Induced by High Speed Railways Using Double Geofoam Barriers: Centrifuge Modeling. *Geotext. Geomembr.* **2019**, 47, 712–728, doi:10.1016/j.geotexmem.2019.103482.
5. Boler, H.; Mishra, D.; Hou, W.; Tutumluer, E. Understanding Track Substructure Behavior: Field Instrumentation Data Analysis and Development of Numerical Models. *Transp. Geotech.* 2018, 17, 109–121, doi:10.1016/j.trgeo.2018.10.001.
6. Brinji, Osama Saud M. 2017 "Investigating the Mechanical Behaviour of Railway Ballast." PhD diss., Monash University.
7. Brinkgreve RBJ; Kumarswamy S; Swolfs WM, et al. PLAXIS. Netherlands, 2014.
8. Brinkgreve RBJ and Vermeer PA. PLAXIS Finite Element Code for Soil and Rock Analysis-Version 7. Rotterdam: Balkema, 1997.41.
9. Carl, E.H.; P.E., J.; David, T.; Carl E. Hanson, P.E., Jason C. Ross, P.E., and David A. Towers, P.E. High-Speed Ground Transportation Noise and Vibration Impact Assessment 2012.
10. Chew, J.H.; Leong, E.C. Field and Numerical Modelling of Sand-Rubber Mixtures Vibration Barrier. *Soil Dyn. Earthq. Eng.* **2019**, 125, 105740, doi:10.1016/j.soildyn.2019.105740.
11. Connolly, D.P.; Kouroussis, G.; Woodward, P.K.; Alves Costa, P.; Verlinden, O.; Forde, M.C. Field Testing and Analysis of High Speed Rail Vibrations. *Soil Dyn. Earthq. Eng.* **2014**, 67, 102–118, doi:10.1016/j.soildyn.2014.08.013.
12. De, A.; Morgante, A.N.; Zimmie, T.F. Numerical and Physical Modeling of Geofoam Barriers as Protection against Effects of Surface Blast on Underground Tunnels. *Geotext. Geomembr.* **2016**, 44, 1–12, doi:10.1016/j.geotexmem.2015.06.008.
13. El Kacimi, A.; Woodward, P.K.; Laghrouche, O.; Medero, G. Time Domain 3D Finite Element Modelling of Train-Induced Vibration at High Speed. *Spec. Issue UK Assoc. Comput. Mech. Eng.* **2013**, 118, 66–73, doi:10.1016/j.compstruc.2012.07.011.
14. Feng, S.-J.; Li, Y.-C.; Chen, Z.-L.; Chen, H.X. Response of Railway Track Coupled with a Stratified Ground Consisting of Saturated Interlayer to High-Speed Moving Train Load. *Soil Dyn. Earthq. Eng.* **2017**, 102, 25–40, doi:10.1016/j.soildyn.2017.08.018.
15. Ferrara, R.; Leonardi, G.; Jourdan, F. A Contact-Area Model for Rail-Pads Connections in 2-D Simulations: Sensitivity Analysis of Train-Induced Vibrations. *Veh. Syst. Dyn.* **2013**, 51, 1342–1362, doi:10.1080/00423114.2013.801996.
16. Gao, Y.; Huang, H.; Ho, C.L.; Hyslip, J.P. High Speed Railway Track Dynamic Behavior near Critical Speed. *Soil Dyn. Earthq. Eng.* **2017**, 101, 285–294, doi:10.1016/j.soildyn.2017.08.001.
17. Giovanni, L.; Buonsanti, M. Reduction of Train-Induced Vibrations by Using Barriers. *Res. J. Appl. Sci. Eng. T.* **2014**, 17, 3623–3632, doi:org/10.19026/rjaset.7.715.

18. Ju, S.H.; Liao, J.R.; Ye, Y.L. Behavior of Ground Vibrations Induced by Trains Moving on Embankments with Rail Roughness. *Soil Dyn. Earthq. Eng.* **2010**, *30*, 1237–1249, doi:10.1016/j.soildyn.2010.05.006.
19. Ju, S.-H.; Ni, S.-H. Determining Rayleigh Damping Parameters of Soils for Finite Element Analysis. *Int. J. Numer. Anal. Methods Geomech.* **2007**, *31*, 1239–1255.
20. Kece, E.; Reikalas, V.; DeBold, R.; Ho, C.L.; Robertson, I.; Forde, M.C. Evaluating Ground Vibrations Induced by High-Speed Trains. *Transp. Geotech.* **2019**, *20*, 100236, doi:10.1016/j.trgeo.2019.03.004.
21. Mahdavisefat E; Salehzadeh H; and Heshmati AA. Full-scale experimental study on screening effectiveness of SRM-filled trench barriers. *Geotechnique*. **2018**, *68*: 1–14.
22. Mahmoud, A.; Siegmund, J. Introducing High-Speed Rail System in Middle East (Kingdom of Saudi Arabia): A Comparison of Past, Current And Future Networks. *Glob. J. Eng. Sci. Res. Manag.* **2017**, *4*, 59–70, doi:10.5281/zenodo.832614.
23. Murillo, C.; Thorel, L.; Caicedo, B. Ground Vibration Isolation with Geofoam Barriers: Centrifuge Modeling. *Geotext. Geomembr.* **2009**, *27*, 423–434, doi:10.1016/j.geotextmem.2009.03.006.
24. Ngo, N.T.; Indraratna, B.; Rujikiatkamjorn, C. Simulation Ballasted Track Behavior: Numerical Treatment and Field Application. *Int. J. Geomech.* **2017**, *17*, 04016130, doi:10.1061/(ASCE)GM.1943-5622.0000831.
25. Sayeed, Md.A.; Shahin, M.A. Design of Ballasted Railway Track Foundations Using Numerical Modelling. Part I: Development. *Can. Geotech. J.* **2018**, *55*, 353–368, doi:10.1139/cgj-2016-0633.
26. Sayeed, Md.A.; Shahin, M.A. Design of Ballasted Railway Track Foundations Using Numerical Modelling. Part II: Applications. *Can. Geotech. J.* **2018**, *55*, 369–396, doi:10.1139/cgj-2016-0634.
27. Taha, A., El Naggat M., Turan A. (2015). Numerical modeling of the dynamic lateral behavior of geosynthetic-reinforced pile foundation system. *Soil Dynamics and Earthquake Engineering*, *77*: 254–266.
28. Tandon K; Kumar D; Ayothiraman R; Manna B and Ramana G. Numerical evaluation of tire chips–filled trench barriers for effective vibration isolation. *Journal of Low Frequency Noise, Vibration and Active Control*. **2023**, *42*(1): 325–344.
29. Woods, R.D. Screening of Surface Wave in Soils. *J. Soil Mech. Found. Div.* **1968**, *94*, 951–979. doi:10.1130/0016-7606(1985)96<817:PMAOTA>2.0.CO;2.
30. Zhai, W.; Wei, K.; Song, X.; Shao, M. Experimental Investigation into Ground Vibrations Induced by Very High Speed Trains on a Non-Ballasted Track. *Soil Dyn. Earthq. Eng.* **2015**, *72*, 24–36, doi:10.1016/j.soildyn.2015.02.002.
31. Zhang, X.; Zhao, C.; Zhai, W. Importance of Load Frequency in Applying Cyclic Loads to Investigate Ballast Deformation under High-Speed Train Loads. *Soil Dyn. Earthq. Eng.* **2019**, *120*, 28–38, doi:10.1016/j.soildyn.2019.01.023.
32. Zhang, Z.; Zhang, X.; Qiu, H.; Daddow, M. Dynamic Characteristics of Track-Ballast-Silty Clay with Irregular Vibration Levels Generated by High-Speed Train Based on DEM. *Constr. Build. Mater.* **2016**, *125*, 564–573, doi:10.1016/j.conbuildmat.2016.08.079.