Mitigation of Train-induced Vibration Using EPS Geofoam Filled Trench

DR. MAINAK MAJUMDER

Engineering Research Manager, Larsen & Toubro Construction Limited, Transportation Business, Mumbai, Maharashtra, India

Abstract— ***Owing to the havoc infrastructural development the noise in the form of ground vibrations have been inevitable in the urban areas. EPS geofoam has been found to be one of the vast applications of geosynthetics family to mitigate ground vibrations due to high-speed machines/highways, traffics and trains. In the present study an attempt has been made to understand the efficacy of the expanded polystyrene (EPS) Geofoam as an in-filled trench material in reducing train-induced ground vibrations. Base Isolation, tuned mass damper, tuned liquid column damper or magneto-rheological dampers are some of the widely used solutions to minimize the vibrations in structures, but in case of reducing the ground borne shocks; open-trench, in-filled trenches are the most common methods. Thus, to understand the behaviour of the EPS Geofoam in-filled trench a finite element model has been developed using ABAQUS software considering all the parameters like geometric parameters of trench, train speed, EPS density, shear wave velocity mismatch between soil and EPS using commercially available ABAQUS FEM software. The screening efficiency of EPS filled trench has been found to be in the range of 42-65%.***

Indexed Terms—***Ground borne vibrations, EPS Geofoam, vibration screening, FEM, open trench, in-filled trenches.***

I. INTRODUCTION

Recent urbanization and industrialization forces transportation infrastructures like high-speed railway lines to be build up through closely spaced urban areas and residential buildings. Especially developing countries like India which comprises of a network of 60,700 km railway route, largest among the Asia out of which approximately 60,000 km is of broad gauge (1676 mm gauge). Train vibrations can effectively result in damages and detrimental effects in the surrounding buildings and nearby sensitive structures. Utilization of high-speed train can cause more adverse effects, especially many stretches which are proposed to be constructed on the different challenging soils like high swelling black-cotton soils, rocky soils, soft clays etc. There are several types of mitigation techniques like base isolation, tune-mass damper, providing lightweight material at the base of the foundation etc. are available to protect the buildings from the danger of vibrations induced by moving train which vary with the location, structure, soil-profiling etc. Out of all possible available techniques open and in-filled trenches are found to be cheap and easy to implement in near-by or far away from the ground vibration sources.

II. LITERATURE REVIEW

1. Open trenches are most effective owing to the fact that no elastic waves can pass through a void medium. The oldest approach on the vibration screening using open trench has been carried out by Woods et al. [1–3]. Although few of their experiments have been unsuccessful due to lack of knowledge on the vibration screening mechanism in presence of trench or hollow medium. The screening efficiency of the open trenches have been evaluated considering 75% value and the minimum depth of the trench has been found out as the $0.6L_R$ for active system and 1.33 L_R for passive screening system.
2. Later numerous works [4–7] have been reported either by using Finite element method (FEM), Finite Difference Method (FDM) or Boundary Element Method (BEM). However, there are some serious practical limitations for constructing open trenches because of their stability problems and infiltration of surface run-off into the void spaces.

Therefore, to overcome this drawback, a few theoretical and experimental studies are carried out with different types of in-filled materials such as soft and stiff in-filled trenches [8–12], rows of piles [13] and wave impeding blocks (WIB) [14] next to railway track. Although most of the times, barriers have been provided in a rectangular form with very high aspect ratio (Width/depth <<1), several other forms like alternate barrier, multiple trenches, staggered trenches have been investigated as vibration screening techniques. Ideally, it is easier to install stiffer materials than the surrounding soil as they can tolerate the lateral pressure as well as surface surcharge loads.

3. Celebi *et al* [15–17]investigated experimentally the vibration isolation performance of the building foundations nearby moving trains by employing open and in-filled trench barriers. The frequency of the vibration source plays crucial role for both the active and passive cases. According to their research Geofoam barrier is more effective in stiff soils as compared to soft soil.

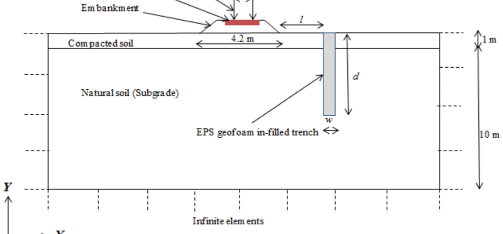
Zoccali et al. [18,19] have presented a 3D FEM model to mitigate the vibration induced by the transits of the train using three different in-filled trenches, which are materials soil-bentonite, rubber chips and concrete. The distance among the source, trench and receiver and the frequency content of the train loading have been considered as important parameters in their study.

4. Overall, the position and shape of the EPS Geofoam in-filled trenches along with the different other geometric parameters are crucial in obtaining effective vibration screening. Expanded polystyrene Geofoam (EPS) has gained the recognition in the geotechnical engineering due to its desirable mechanical properties such as light-weight, volume contraction under deviatoric compressive loading, availability, ease of use and low manufacturing costs. The EPS geofoam as infilled material for vibration screening system has been used by many researchers earlier [20–26] for different ground vibration sources. However, the research of EPS geofoam as the vibration screening material under the high-speed train is not much in available literature. The present research aims to find out the utility of the EPS geofoam as the effective vibration screening material under high-speed train.

III. NUMERICAL MODEL DEVELOPMENT

In this section, the efficiency of the EPS Geofoam in-filled trench has been verified for the train loading which is basically series of point loads acting over an embankment. For this purpose, a two-dimensional finite element model has been developed. where the railway track and the trench span extend longitudinally. A moving train with speed *V* (km/h) travels on a continuous railway track resting on an embankment soil system. The compacted subgrade soil subjected to wave propagation is assumed to be homogenous, isotropic and linearly elastic. The effect of change in the subgrade density due to various loading has not been taken in to account in the present study. The influence domain is divided in to three parts; the superstructure (the railway track consisting of sleepers and ballast), the sub-structure (compacted soil and natural soil (near field)), and the soil deposit (far field). The primary objective is to determine the active vibration screening efficiency of Geofoam filled trench in terms of the amplitude reduction ratio (*ARR)* where *ARR* can be determined by measuring the average value of the velocity reduction factor (*VRF*) over a specific distance ($3\lambda_R$) along the ground surface. This distance has been fixed, based on the variation in the vertical velocity amplitude after this specified distance the variation of vertical velocity is almost negligible (around 3.5%). Hence, *VRF* and *ARR* can be defined as follows: *VRF* = (Absolute maxima of velocity with trench)/ (Absolute maxima of velocity without trench) & $ARR = \frac{1}{c} \times \int_0^c VRF(y/x).dy/dx$.

In FE model the contribution of the P, S and R waves can't be distinguished since the vibration used to come in mixed form of all types of waves.



Schematic diagram of influence domain and geometric parameters of trench

In the present study, a plane strain FE model is developed in *ABAQUS* [27] to investigate the screening efficiency of the EPS Geofoam in-filled trench. Soil is modelled as elastic, isotropic, homogenous media. The whole influence domain has been discretised using quadratic four noded elements (*CPE4R*); the far field of the domain has been discretised using infinite elements (*CINPE4*). The contacts of sleeper with ballast and ballast with soil have been assumed as hard contacts, where finite sliding between surfaces has been ensured without any indentation. Based on the average vertical displacement at the side boundary a sensitivity analysis has been carried out to determine the optimum half-domain size along the horizontal direction. The average element size (0.42 m) is chosen based on the criteria of wave propagation as proposed by Kramer [28]. However, to capture the wave propagation more accurately, finer mesh is considered near the source and the trench, where the average element size is considered as 0.32 m and 0.16 m respectively. A mesh sensitivity analysis has been carried out for individual layers to know the optimum value of the mesh size.

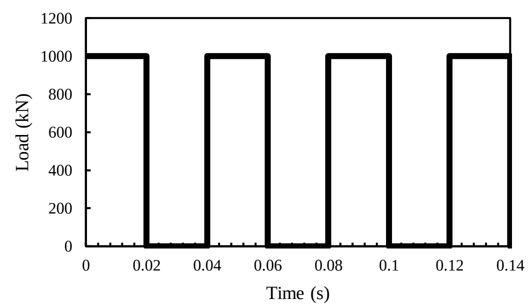
The time increment for the analysis is determined based on the fastest propagation velocity of the wave and the element size [29]. The total dynamic excitation time is considered as 10 sec. The energy dissipating mechanism for the soil is simulated with Rayleigh damping. The mass and stiffness coefficients for the Rayleigh damping are determined as α =1.2 and β = 0.0004, which provide the damping ratio (ξ) of 5%.The first and second mode of natural frequencies have been calculated based on the frequency analysis with no trench condition. In the present analysis, the Rayleigh wavelength (λ_R) is found to be 2.04 m with train speed of 60 km/h. Different other train speed values have been considered later for parametric study.

IV. MATERIAL PROPERTIES

The properties of the soil are considered according to the geotechnical investigation reported by Zakeri *et al.* [30]. As reported in their study [30], the soil deposit includes the top 1 m depth of compacted soil overlain a homogenous soil deposit of 10 m. As per [31] the available density of EPS Geofoam varies from 11.2 kg/m^3 (EPS 12) to 45.7 kg/m^3 (EPS 46).

Properties	EPS12	EPS15	EPS19	EPS29
Density (ρ in kg/m^3)	11.2	14.4	18.4	28.8
Elastic modulus (E in MPa)	3.3	5.5	8.9	16.5
Poisson's ratio (ν)	0.1	0.1	0.1	0.1

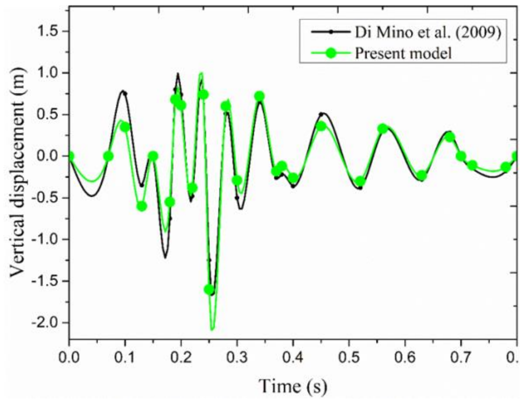
In this study, the train load has been modelled as series of pulse type moving step loads. Although in real practice, the train loading is three-dimensional in nature the effect of longitudinal direction has been ignored in the present study. The pattern of the load is corresponding to the passage of freight train moving at a speed of 60 km/h with bogie axle distance of 9 m [32]. Two concentrated loads act over the rails at a spacing of 2.4 m. The history of each load consists of four consecutive pulses; each pulse has time duration of 0.02 sec and amplitude of 1000 kN.



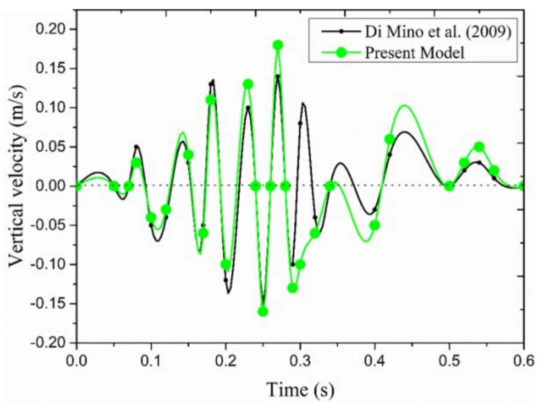
Time history of train loading

V. MODELVALIDATION

The developed FEM model along with the specifying loading conditions has been validated with the existing available literature. As the pattern of train loading considered for the present analysis is similar to [32], the present FE model has been validated with the displacement and the velocity response reported by them at a certain point (1m from the toe of the embankment) in sandy soil deposit for the 'no trench' condition. the variation of vertical displacement and velocity along the *y* axis, with time is compared with that results reported by Di Mino *et al.* [32]. It can be seen that the average variation of the vertical displacement and the velocity response between the study of [32] and the present analysis is found to be 6.5% and 5.4% respectively. This ensures the correctness of the present model.



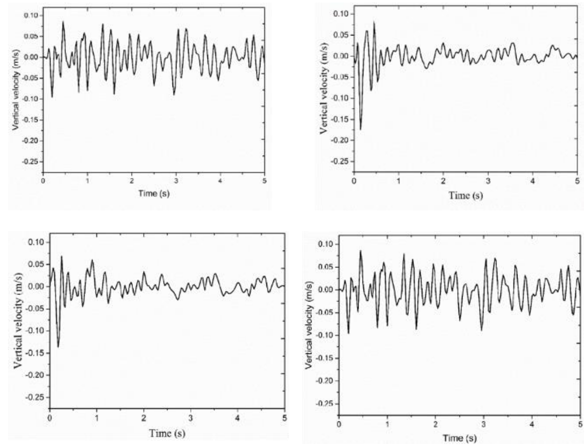
Validation of displacement variation (in vertical direction)



Validation of velocity variation (in vertical direction)

VI. FREE FIELD RESPONSE

The free field dynamic response (Vertical velocity time history) has been shown along the ground surface at various distances from the toe of the embankment (0.5 m, 1 m, 1.5 m 10.5 m) for the train moving at a speed of 60 km/h. The value of absolute maximum vertical velocity at different pick-up locations is found to be in the range of 0.0678 to 0.1036 m/s, which is expected to cause some serviceability issues. In similar way, the horizontal component of velocity has been calculated for all the locations. Among total 560 scenarios, 46 are related to free field ground vibration and rest of them to ground vibration with trenches.



Free field response for train-induced vibration at 0.5 m, 1.0 m, 1.5 m, and 10.5 m from the toe of the embankment.

VII. PARAMETRIC STUDY

To evaluate the screening efficiency of EPS Geofoam in-filled trench, various parameters related to geometry of the trench, train loading and soil properties are considered. The parameters of this study have been tabulated. Different results have been produced by varying the range of parameters as shown in Table below. In the present study, a total of 12 different soil types are defined arbitrarily.

Parameters	Symbols	Units	Minima	Maxima
Train Speed	*V*	km/h	50	200
Width of Trench	*w*	m	0.5	2.5
Depth of trench	*d*	m	0	6.5
Location of Trench	*l*	m	0	2
Soil Shear Wave velocity	V_S	m/s	50	250

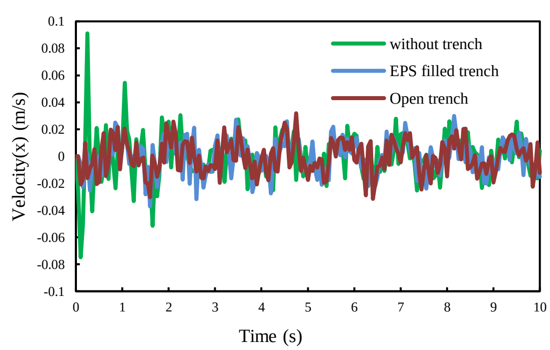
Range of different parameters

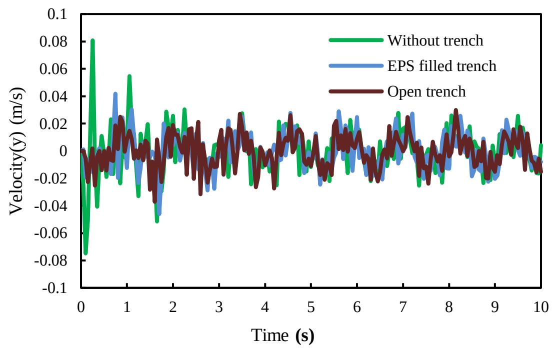
The performance of EPS Geofoam in-filled trench is controlled by the several factors. To investigate the screening efficiency in terms of *ARR (x, y)* as defined earlier have been calculated; the maximum and minimum values of vertical velocities (*x*, *y* direction) obtained in the significant points are tabulated. To develop more rational model all the parameters like trench dimensions (depth, width and location), train speed, soil properties are represented in dimensionless form. The geometric parameters are normalised by the

Design Parameters	Symbols	Units	EPS filled trench	Open Trench
Normalised Depth	*D*	unitless	1.2	0.7
Normalised width	*W*	unitless	0.5	0.25
Normalised Location	*L*	unitless	0.75	0.5
EPS Geofoam Density	-	kg/m^3	11.2-28.8	-
Soil Damping Ratio	ξ	%	4-6	4-6
Bed rock Layer depth	*T*	m	10-17.5	10-17.5
Train Speed range	*V*	m/s	50-200	50-200
Average Vibration screening efficiency	*ARR*	-	0.35-0.58	0.22-0.35

Rayleigh wavelength (λ_R) of the soil. For the considered parameters a detailed parametric study has been conducted to prepare a rational design. Thus an open trench and EPS Geofoam in-filled, are shown in the time history of velocity in x and y directions. From Figures it can be seen that the EPS Geofoam filled trench can significantly reduce the train vibration. The parameters used for this purpose are d = 1.5 m, w = 0.5 m, l = 1 m and EPS12 has been considered for all the analyses unless otherwise specified. The minimum and maximum velocity and displacements in both the directions have been shown in Table below. In the present study, soil with shear wave velocity (Vs) is varied between 50 m/s to 250 m/s and their different max & min velocities and displacements are tabulated in below Table. Maximum peak vertical velocities are in the range of 0.32-0.41 m/s, which is significant to produce ground vibrations. By calculating *ARR* the screening efficiency of the both the trenches have been compared.

	Velocity (*x*) (m/s)		Velocity (*y*) (m/s)		Displacement (*x*) (m)		Displacement (*y*) (m)	
V_s (m/s)	Min	Max	Min	Max	Min	Max	Min	Max
50	0.01	0.54	0.03	0.62	0.00068	0.0078	0.00076	0.0086
75	0.04	0.58	0.08	0.68	0.00072	0.0086	0.00079	0.0095
100	0.06	0.63	0.16	0.71	0.00079	0.0092	0.00086	0.0103
125	0.09	0.70	0.25	0.76	0.00085	0.0098	0.00098	0.0115
200	0.16	0.79	0.28	0.82	0.00089	0.0108	0.00106	0.0119
250	0.21	0.81	0.32	0.89	0.00095	0.0116	0.00117	0.0128





Time history of the velocity in x and y direction for the pick-up point located 4.25 m from the toe of the embankment

The depth of the trench is found to be the most crucial geometric parameter. By keeping all the geometric parameters constant, the depth of the trench has been varied from D = 0.4 to D = 3.2. It is well established from [1] study that minimum D for the open trench is nearly 0.6, in the present study for the EPS filled trench it is found to be 1.2. The *ARR* value has been decreased significantly as shown in below Figure, the range comes in between 0.40 to 0.56 for both the directions.

Trench width has been appeared to be less important parameter as compared to other geometric parameters. However, in case of in-filled EPS Geofoam trench, width has an important role in vibration screening efficiency. For the EPS filled trench width has been varied from 0.25 to 1.25 to find out the optimum width from its effectiveness as well as from economic point of view. The optimum width factor W has been found as 0.5 for EPS filled trench whereas for the *OT* the W has been fixed as 0.25 for all the cases. The variation of *ARR* with the W has been shown in Figure below, where the ranges come in between 0.44 to 0.56 for the different values of W from 0.5 to 2.5.

To determine the optimum location factor of the trench the initial value has been chosen as the L = 0.5, which is very close to the railway embankment. The optimum value obtained as L = 0.75 for EPS filled trench and 0.5 for *OT* respectively. The variation of the *ARR* with different L has been shown in Figure; the range of *ARR* has been obtained in between 0.43 to 0.54 for both the directions.

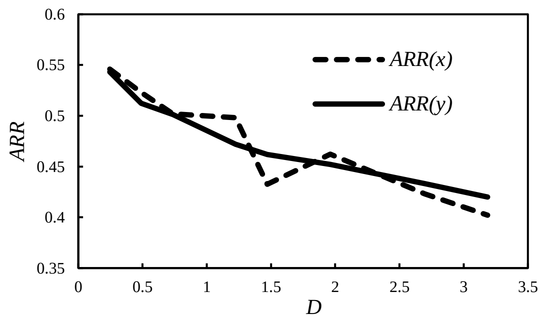
The depth of the bed rock layer from ground surface (T) has an important role to play in the screening efficiency of the in-filled trench. Bed rock layer to trench depth (T/d) ratio has been varied in the rage of 4-7 to find out the ARR for the both the directions as shown in Figure. It has been found that *ARR* value increases from 0.47 to 0.62 with the increase in T/d from 4 to 7. Since, the distance between trench and bed rock increases more stress waves will be reflected back to the ground surface which will ultimately be converted to Rayleigh waves through mode conversion.

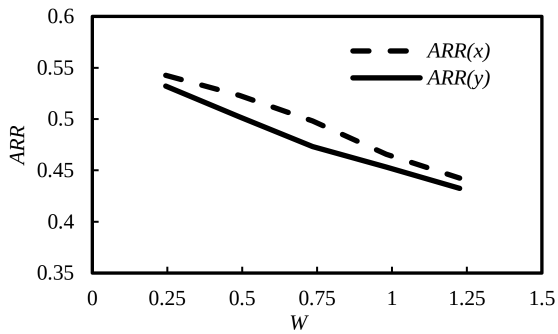
To show the importance of the mismatch of the shear wave velocity between soil and in-filled materials a parametric study has been conducted with different V_b/V_s values. The range of V_b/V_s has been chosen in between 0.25 to 2.5 as shown in Figure. The impedance mismatch between the soil and in-filled material is the crucial in the screening effectiveness.

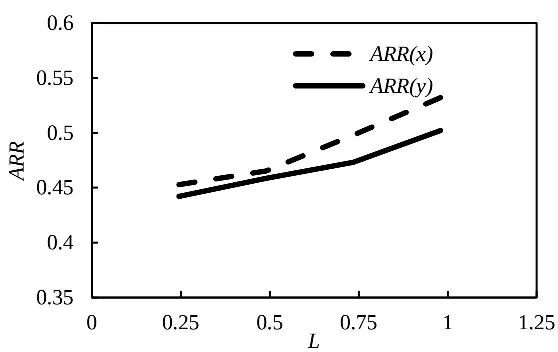
EPS Geofoam density plays a crucial role in screening effectiveness, as of now the EPS density has been considered as 11.2 kg/m^3 (EPS12). For the purpose of parametric study EPS Geofoam density has been varied from 11.2 kg/m^3 to 28.8 kg/m^3 as shown in Table. The increase in EPS Geofoam density decreases the screening effectiveness; however, the choice of density is dependent on the availability and soil properties. In the Figure, the variation of *ARR* has been shown with the different values of EPS Geofoam density.

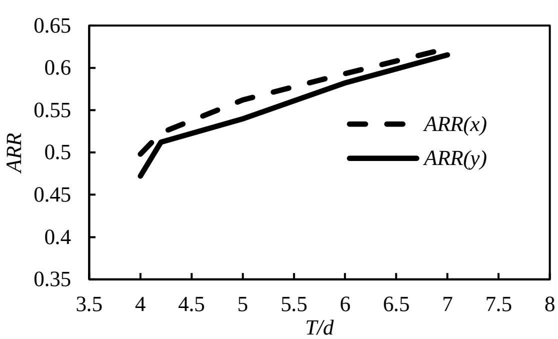
In the present study, the train different range of train speed has been considered for the parametric study. For this purpose Mach number (M_2) which is defined as the ratio of the train speed (V) and shear wave velocity of the soil (V_s). M_2 equals to 1.0 correspond to the critical speed, whereas $M_2 < 1.0$ and > 1.0 are sub-critical and super-critical speeds respectively. In the Figure below the variation of the *ARR* with different critical speed region has been shown to know the screening effectiveness. It can be seen that EPS filled trench is more effective in reducing the vibration of train moving with super critical speed which is well-established fact for the in-filled trench in reducing ground vibrations. To show the utility of trench in the sub-critical and super-critical region the vertical velocity responses are plotted in the frequency domain in Figures below It is clear from the Figures that reduction in the vertical velocity is higher in supercritical region with the EPS filled trench.

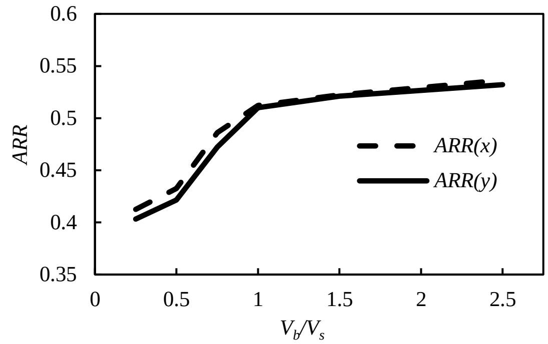
From the above parametric study, the quantification of the screening effectiveness can be visualised with influences of different parameters.

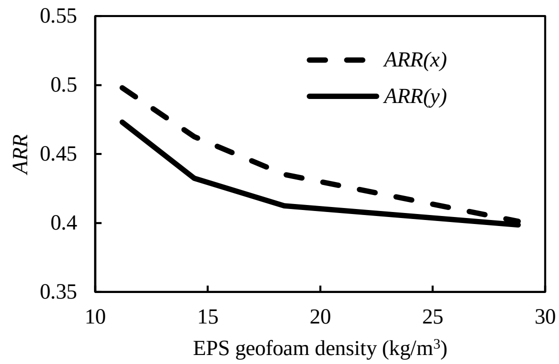


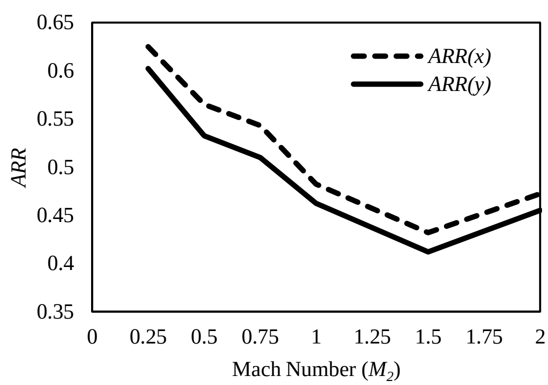




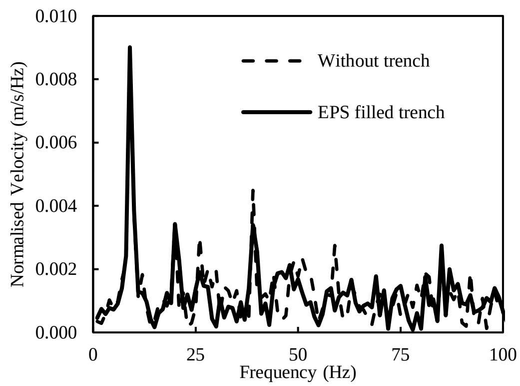


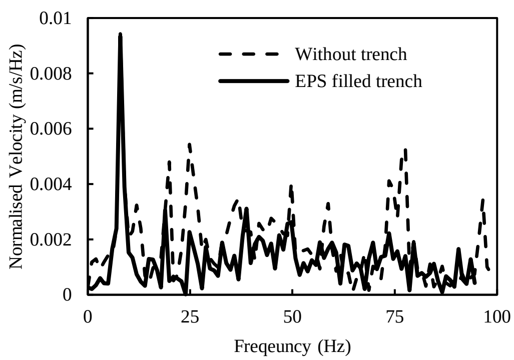






Variation of ARR with different normalised parameters depth, width, location, the Vb/Vs, different EPS Geofoam density, different Mach number, and ratio of the bed rock depth to depth of the trench.





The frequency distribution of the velocity in sub-critical speed region, super-critical speed region.

CONCLUSION

The performance of EPS Geofoam filled trench has been evaluated using finite element model under train induced vibrations. A 2D FEM model has been developed to investigate the influence of different parameters. The conclusions of the present study can be drawn as follow:

- The analyses have been carried out for both the open and EPS filled trenches to find out the design recommendations. The screening effectiveness in terms of the amplitude reduction ratio has been shown for the different trench parameters.
- The range of screening efficiency obtained by using EPS filled trenches are in the range of 43-65% whereas with open trench it is in the range of 76-86%.
- The depth of the trench, shear wave velocity and Poisson's ratio of the EPS Geofoam are found to be crucial in vibration screening.
- The location of the trench has an important role to play in construction of trenches. Three different range of train speed critical, super-critical and sub-critical have been considered in the present study.

  The results show the EPS filled trench is very much effective in high-speed train vibrations.

ACKNOWLEDGMENT

The author acknowledges his mentor Prof. Priyanka Ghosh, Indian Institute of Technology Kanpur for his encouragements.

REFERENCES

[1] R.D. Woods, Screening of elastic surface waves by trenches, (1967).

[2] N.E.B.R.S. R.D. Woods, Holography, a new tool for soil dynamics, Proc. ASCE. 100 (1974) 1231–1247.

[3] F.E. Richart, J.R. Hall, R.D. Woods, Vibrations of soils and foundations, (1970).

[4] T. May, B.B.-E.E.& Structural, undefined 1982, The effectiveness of trenches in reducing seismic motion, Wiley Online Library. (n.d.). https://onlinelibrary.wiley.com/doi/abs/10.1002/eqe.4290100203 (accessed August 21, 2020).

[5] T.W. May, B.A. Bolt, The effectiveness of trenches in reducing seismic motion, Earthquake Engineering & Structural Dynamics. 10 (1982) 195–210. https://doi.org/10.1002/eqe.4290100203.

[6] K. Emad, G.D. Manolis, Shallow trenches and propagation of surface waves, Journal of Engineering Mechanics. 111 (1985) 279–282. https://doi.org/10.1061/(ASCE)0733-9399(1985)111:2(279).

[7] K.L. Leung, I.G. Vardoulakis, D.E. Beskos, Vibration Isolation of Structures from Surface Waves in Homogeneous and Nonhomogeneous Soils, in: Developments in Geotechnical Engineering, 1987: pp. 155–169. https://doi.org/10.1016/B978-0-444-98957-4.50016-8.

[8] B.D.I.V. D Beskos, Vibration isolation using open or filled trenches, Comput Mech. 1 (1986) 43–63. https://doi.org/10.1007/bf00298637.

[9] B. Dasgupta, Vibration isolation of structures on homogeneous soil, (1986).

[10] D.B.I.V. B Dasgupta, Vibration isolation using open or filled trenches part 2: 3-D homogeneous soil, Comput Mech. 6 (1990) 129–142. https://doi.org/10.1007/bf00350518.

[11] T.A.-H. S Ahmad, Simplified design for vibration screening by open and in-filled trenches, J Geotech Eng. 117 (1991) 67–88. https://doi.org/10.1061/(asce)0733-9410(1991)117:1(67).
[12] S.A. TM Al-Hussaini, Design of wave barriers for reduction of horizontal ground vibration, J Geotech Eng. 117 (1991) 616–636. https://doi.org/10.1061/(asce)0733-9410(1991)117:4(616).
[13] F.S.-S. J Avilés, Piles as barriers for elastic waves, J Geotech Eng. 109 (1983) 1133–1146. https://doi.org/10.1061/(asce)0733-9410(1983)109:9(1133).
[14] H. Takemiya, A. Fujiwara, Wave propagation/impediment in a stratum and wave impeding block (WIB) measured for SSI response reduction, Soil Dynamics and Earthquake Engineering. (1994). https://doi.org/10.1016/0267-7261(94)90041-8.
[15] E. Celebi, F. Goktepe, O. Kirtel, Vibration isolation measures for reductions of structural responses due to passage of high-speed trains, in: Proceedings of the 8th International Conference on Structural Dynamics, EURODYN 2011, 2011.
[16] S.F.G.B.İ.Ç.İ.V.O.K. E Çelebi, Field experiments on wave propagation and vibration isolation by using wave barriers, Soil Dyn Earthq Eng. 29 (2009) 824–833. https://doi.org/10.1016/j.soildyn.2008.08.007.
[17] E. Çelebi, S. Firat, G. Beyhan, I. Çankaya, I. Vural, O. Kirtel, Field experiments on wave propagation and vibration isolation by using wave barriers, Soil Dynamics and Earthquake Engineering. (2009). https://doi.org/10.1016/j.soildyn.2008.08.007.
[18] P. Zoccali, G. Cantisani, G. Loprencipe, Ground-vibrations induced by trains: Filled trenches mitigation capacity and length influence, Construction and Building Materials. (2015). https://doi.org/10.1016/j.conbuildmat.2014.09.083.
[19] G.C.G.L. P Zoccali, Ground-vibrations induced by trains: filled trenches mitigation capacity and length influence, Constr Build Mater. 74 (2015) 1–8. https://doi.org/10.1016/j.conbuildmat.2014.09.083.
[20] M. Majumder, P. Ghosh, Finite element analysis of vibration screening techniques using EPS geofoam, in: Computer Methods and Recent Advances in Geomechanics - Proceedings of the 14th Int. Conference of International Association for Computer Methods and Recent Advances in Geomechanics, IACMAG 2014, 2015. https://doi.org/10.1201/b17435-112.
[21] P.G. M Majumder, Active screening for axi-symmetric machine loading using EPS geofoam, Jpn Geotech Soc Spec Publ. 2 (2016) 2238–2243.
[22] S.E. D Liyanapathirana, Application of EPS geofoam in attenuating ground vibrations during vibratory pile driving, Geotext Geomembr. 44 (2016) 59–69. https://doi.org/10.1016/j.geotexmem.2015.06.007.
[23] D.S. Liyanapathirana, S.D. Ekanayake, Application of EPS geofoam in attenuating ground vibrations during vibratory pile driving, Geotextiles and Geomembranes. (2016). https://doi.org/10.1016/j.geotexmem.2015.06.007.
[24] M.R. Khan, S.M. Dasaka, EPS Geofoam as a Wave Barrier for Attenuating High-Speed Train-Induced Ground Vibrations: A Single-Wheel Analysis, International Journal of Geosynthetics and Ground Engineering. (2020). https://doi.org/10.1007/s40891-020-00230-1.
[25] M. Majumder, P. Ghosh, Intermittent geofoam in-filled trench for vibration screening considering soil non-linearity, KSCE Journal of Civil Engineering. (2016). https://doi.org/10.1007/s12205-015-0267-6.
[26] M. Majumder, P. Ghosh, S. Rajesh, Numerical study on intermittent geofoam in-filled trench as vibration barrier considering soil non-linearity and circular dynamic source, International Journal of Geotechnical Engineering. (2017). https://doi.org/10.1080/19386362.2016.1215781
[27] M. Smith, ABAQUS/Standard User's Manual, Version 6.9, (2009). https://www.research.manchester.ac.uk/portal/en/publications/abaqusstandard-users-manual-version-69(0b112d0e-5eba-4b7f-9768-cfe1d818872e)/export.html (accessed August 22, 2020).

[28] S. Kramer, 1996, Geotechnical earthquake engineering. Prentice-Hall, Inc., Upper Saddle River, NJ, (n.d.).
[29] S. Valliappan, V. Murti, Finite element constraints in the analysis of wave propagation problems, (1984).
[30] J.-A. Zakeri, M. Esmaeili, S. Mosayebi, R. Abbasi, Effects of vibration in desert area caused by moving trains, Journal of Modern Transportation. 20 (2012). https://doi.org/10.3969/j.issn.2095-087X.2012.01.003.
[31] A. D6817-06, Standard specification for rigid cellular polystyrene Geofoam, (2006).
[32] G. Di Mino, M. Giunta, C.M. Di Liberto, Assessing the Open Trenches in Screening Railway Ground-Borne Vibrations by Means of Artificial Neural Network, Advances in Acoustics and Vibration. 2009 (2009) 1–12. https://doi.org/10.1155/2009/942787.