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Numerical Investigations on Optimisation of EPS Geofoam-Infilled Vibration Barriers for High-Speed Railway Tracks

Ground-borne railway vibrations emanating from High-Speed Trains (HST) on ballasted railway tracks cause significant damage to infrastructure in the vicinity and structural vibrations that distress the residents. This study investigates the potential application of Expanded Polystyrene (EPS) Geofoam-infilled ground trenches as a mitigation measure for high-frequency ground-borne railway vibrations associated with HSTs, using full-scale ballasted railway track numerical models with a key focus on high-speed railway loading conditions and track vibrations. Evaluation of the results demonstrates the exceptional efficiency of EPS vibration wave barriers in attenuating Peak Particle Velocities (PPV) and propagation of ground vibrations away from the railway tracks. The efficacy of various geofoam wave barrier configurations, including different EPS density grades, trench dimensions, and placement locations, is analysed across a broad range of high train speeds. Results demonstrate that optimised trench dimensions, particularly those with low-density EPS infill and placed close to the railway formation, significantly enhance vibration attenuation. Furthermore, geofoam-infilled wave barriers exhibit greater effectiveness at higher, supercritical train speeds, substantiating their suitability for deployment in ballasted high-speed rail corridors to mitigate ground-vibration impacts.

Keywords: High-Speed Railways; Ballasted tracks; Ground vibrations; Geofoam-infilled trenches; Vibration mitigation

1. Introduction

The rapid global advancement of High-Speed Railway (HSR) systems in recent years, driven by an imperative to meet growing transportation demands, has made HSR a pivotal and

transformative mode of future transportation [1-3]. Conversely, ground vibrations and noise from these high-speed train operations pose a significant environmental sustainability issue, necessitating innovative strategies to mitigate the high-frequency ground vibrations. These vibrations adversely affect railway infrastructure, the integrity of nearby structures, and quality of life for nearby residents [3-6]. A study on train-induced vibrations in 1604 railway track sections across 16 countries [3] startlingly revealed that the prescribed ground vibration and noise limits were exceeded in 44% and 31% of the instances, respectively.

Rayleigh waves constitute the predominant energy form (67%) in the ground surface vibrations emitted by sources such as railway tracks. These waves are confined to a shallow depth within the elastic soil half-space, significantly impacting the surface structures due to their limited attenuation over distance, and resulting in substantial vibration-related damage and disturbances [7, 8]. The mitigation of railway-induced ground vibration primarily entails alterations to the rolling stock [9], the track infrastructure [10-14], or the vibration wave transmission pathway. The transmission of vibrations from the track onto the surrounding soil can be effectively controlled by soil stiffening [15, 16] and using wave barriers. Numerous approaches have been studied before for mitigating vibrations near HSR tracks, including the deployment of gabion walls [17], arrays of piles [18-20], lime cement columns [21], wave-impeding barriers [22], jet-grouted overlapping columns [23-25], concrete blocks [24], sheet pile walls [26], gas-cushion barriers [27], and composite isolating screens. Although soil stiffening techniques such as deep soil mixing, stone columns, deep vibro-compaction, jet grouting, and short soil binders exhibit notable efficiency in vibration attenuation, they are often economically unviable for railways, especially when longer stretches of sensitive track sections require vibration isolation.

In practice, vibration-impeding wave barrier trenches are strategically placed alongside the track at various distances from the railway embankment to mitigate vibrations, owing to their

cost-effectiveness and ease of deployment on high-traffic railway routes where retrofitting the track structure is cumbersome. An open trench (non-filled) can create a finite discontinuity at the ground surface, preventing the transmission of vibration energy. Conversely, in an infilled trench, a discontinuity arises from differences in material impedance between the in-situ soil and the trench, leading to energy dissipation through reflection, refraction, and wave damping. A series of field experiments [28] reveals that open trenches can be effectively utilised for vibration isolation, achieving a screening efficiency of up to 75%. Despite prior studies indicating that open trenches are more efficient at mitigating vibration than infilled trenches [29, 30], practical constraints on maintaining deep open trenches in situ for extended periods significantly limit their field applications.

Consequently, trenches are typically filled with construction materials that possess strong vibration-damping characteristics and sufficient stiffness, providing stability against caving and addressing maintenance concerns. An investigation of open trenches [31] revealed that trench depth predominantly influences screening efficiency. In contrast, both depth and width govern the effectiveness of infilled trenches in isolating vibrations [32]. Numerous studies have examined the effectiveness of infilled trenching methods employing various types of soft barriers, including gas cushions [33], soil-bentonite mixtures, water, rubber-asphalt mixtures [34, 35], and other stiffer alternatives such as concrete infill [36]. The insights from previous studies indicate that stiffer vibration wave barriers, such as concrete infills, exhibit notable efficiency at low frequencies (train speeds up to 50 m/s), while softer alternatives, such as rubber-chip-infilled barriers, demonstrate greater effectiveness at higher train speeds. This study, therefore, investigates the efficacy of softer EPS geofoam infills in attenuating vibrations resulting from high-speed railway loading conditions, a geosynthetic product primarily composed of closed-cell foam materials, such as polystyrene, that is highly suitable for mitigating ground vibrations [37]. Polystyrene geofoam exists in two primary variants:

Expanded Polystyrene (EPS) and Extruded Polystyrene (XPS). EPS is produced by heating or steaming polystyrene beads, which causes them to expand and fuse. In contrast, XPS is manufactured by melting the beads and extruding them through a die, resulting in a dense, closed-cell material. The present study explores the potential use of EPS geofoam as a trench infill material over XPS, given its cost-effectiveness, superior insulation properties, eco-friendly attributes, larger size options, resistance to moisture absorption, and enhanced recyclability.

The unique characteristic of EPS geofoam is its remarkably low density, typically 1% to 2% of soil density, while retaining a stiffness comparable to that of soil. These attributes make it well-suited for a wide range of geotechnical applications, including pavement construction [38], retaining wall backfill [39], seismic motion isolation [39], pipeline support [40], and expansive soil stabilisation [41]. The utilisation of EPS geofoam as a wave barrier to mitigate ground vibrations has also garnered significant attention in recent decades. Previous studies have demonstrated the efficacy of EPS geofoam wave barriers in attenuating ground vibrations induced by various surface sources, including shock loading [42] and blast loading [43, 44]. A centrifugal study [45] conclusively demonstrated that the effectiveness of the EPS geofoam wave barrier in mitigating traffic-induced vibrations depends primarily on trench depth. However, the width also has a notable influence, particularly at lower vibration frequencies for shallow barriers. Full-scale field studies [46] on geofoam infills estimated that the wave barrier trench could achieve a vibration screening efficiency of up to 68% when the Rayleigh wavelength-normalised depth (d/L_R) exceeds 0.6. The significance of d/L_R was also investigated in other field investigations [47, 48], which highlighted that even optimised geofoam wave barrier trenches can achieve screening efficiencies close to those of open trenches.

Optimising infilled trenches significantly improves their effectiveness in attenuating vibrations. Previous studies on the effects of trench infill material density [49] indicated that low-density materials with lower shear wave velocities than the surrounding soil are ideal. Additionally, experimental and numerical analyses [50] highlight that the shape of the infilled trench is also important (e.g., an inverted pyramid barrier shape can outperform a rectangular barrier). The screening efficiency of multiple rows of geofoam-filled trenches amplifies proportionally with the number of rows when surface wave frequencies align with the Attenuation Zones (AZ) [51]. Also, dual trenches offer a feasible alternative to single trenches, particularly when excavating a single deep trench is challenging or impractical [52]. Centrifugal investigations indicate that the screening efficiency of such dual geofoam barriers can exceed that of a single barrier by 14-35% and perform better even at lower frequencies [53].

An increase in train speed significantly affects the characteristics of ground-borne railway vibrations; consequently, the optimal configuration of vibration barriers for high-speed railway tracks must be explicitly identified. Limited studies have been conducted on mitigating high-speed train-induced ground vibrations using passive EPS geofoam vibration-isolation barriers, and, in particular, a structured approach to selecting optimal trench configurations for a higher (faster) range of train speeds is needed. The present study incrementally advances this understanding of the efficacy of EPS geofoam infill barriers in mitigating ground vibrations, with a key focus on high-speed railway loading conditions in ballasted track embankment sections that are not structurally reinforced with geosynthetics. Previous studies on the effectiveness of EPS geofoam barriers in mitigating ground-borne railway vibrations reported that geofoam with lower buffer stiffness demonstrated better screening efficiency [54]. It was also noted that the ideal slenderness ratio (d/w) for an EPS geofoam wave barrier is between 2.0 and 4.0 within the train speed range of 80-160 km/h, and that the vibrations on nearby

multistorey buildings could be reduced by about 57% using the geofoam barriers [55, 56]. Furthermore, it was recommended to maintain a separation distance of at least 10 m between railway lines and nearby buildings. Also, reinforced concrete buildings can be constructed as close as 20 to 30 m from railway tracks by incorporating single and double EPS geofoam trenches [57], given the potential adverse effects of vibrations on residents' health.

2. Numerical modelling of ballasted HSR tracks

The finite element modelling and analysis of the HSR tracks in this study were carried out using the commercial computational simulation package PLAXIS to quantify the dynamic track responses in the railway formation during high-speed train transit. The near-field vibrations along the lateral track directions were considered up to a distance of 20 m from the track centreline on both sides of the track, based on the vibration propagation estimated away from the railway track formation. As corroborated by previous field studies on railway tracks [58], longitudinal strains are negligible compared to lateral strains generated on the track, and plane-strain approximations are well-suited for modelling railway track sections. Numerous studies in the past (e.g., [59-61]) have also demonstrated the capability of such models to simulate lateral ground vibrations, with good convergence with field tests and measurements.

2.1 Model geometry

The track geometry of a double-layer ballasted railway section designed for carriage of trains with axle loads up to 25 T is modelled after [54], and in accordance with the field-scale track construction and design guidelines established by the Research Designs and Standards Organization (RDSO) [62]. A 'prepared subgrade' stratum of 50 cm thickness is provided above the embankment fill for the double-layer subgrade configuration. Fig. 1 illustrates the cross-sectional view of the railway track geometry, showing the various railway embankment strata and the underlying natural subsoil. Rails are simulated with an EI value equivalent to an

IRS-52 rail cross-section with a broad gauge spacing of 1.676 m. The rails are placed on sleepers that are 2.75 m long and 0.21 m high. The model assumes a uniformly stratified cross-section for the railway embankment along the track length. Fig. 1 also illustrates the potential deployment of EPS geofoam-filled trenches on either side of the railway embankment for attenuating ground-borne railway vibrations propagating away from the railway track.

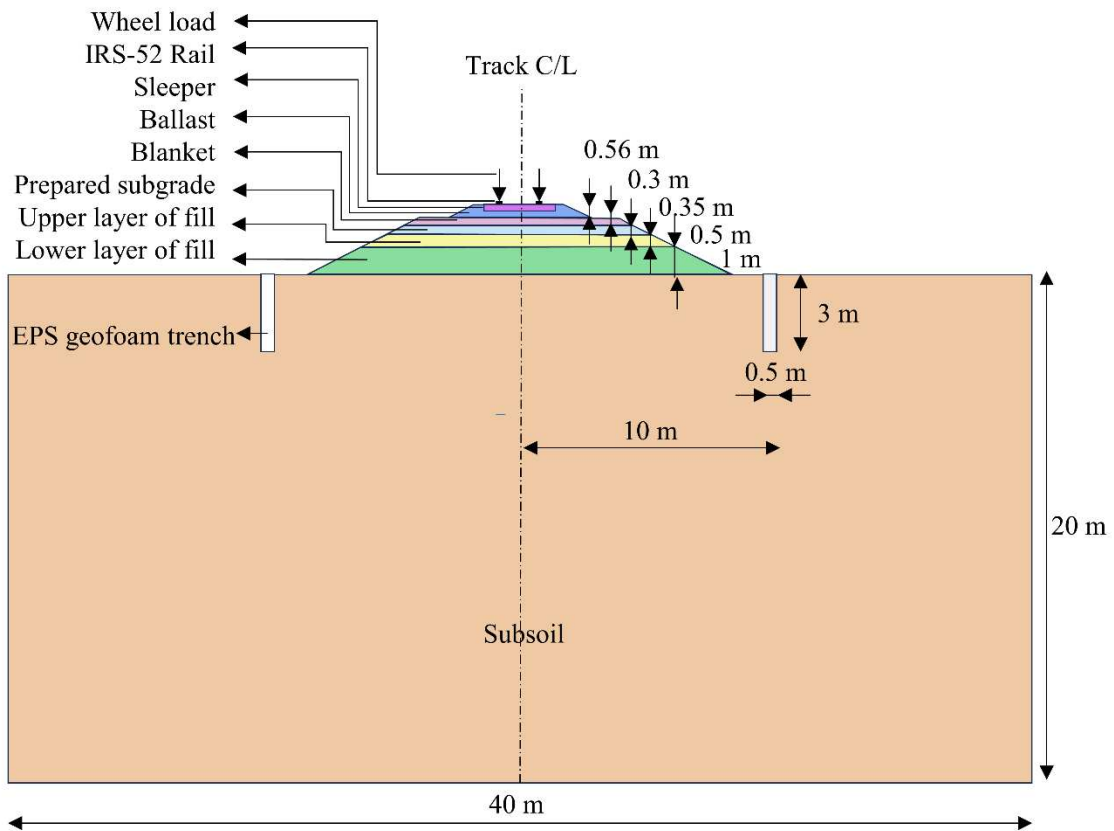


Fig. 1 Cross-section of ballasted HSR track with EPS geofoam vibration barriers

The bottom boundary (base) of the model is constrained for displacements in all directions, and the vertical model boundaries are constrained only for the horizontal displacements ($u_x=0$), facilitating any vertical displacements in the soil at these lateral model boundaries. A large analysis domain size was used to prevent the reflection of stress waves from the model boundaries back into the subsoil, along with the definition of viscous model boundary conditions to attenuate any incoming vibration wave energy.

2.2 Constitutive modelling of track substructure

In practice, railway track formation layers are preferably constructed using coarse-grained cohesionless soils to facilitate free drainage of water and prevent progressive shear failure under cyclic train loads. The presence of the groundwater table or the development of pore water pressures during cyclic loading were beyond the scope of the analyses presented in this study. The constitutive models and material properties for various track components were derived after Khan and Dasaka [54] and in accordance with the most recent RDSO guidelines for design of railway track formations [62], as summarised in Table 1. The damping ratios of the various soil layers [54] were specified as shown in Table 2. The Rayleigh damping parameters (α , β) were estimated by choosing the initial target frequency as the soil deposit's first natural frequency (f_1) and the second target frequency as the nearest odd integer higher than the ratio f_p/f_1 , where f_p is the predominant frequency of the input motion [63, 64].

The first natural frequency of a soil deposit is governed by the layer thickness (H) and the shear wave velocity (V_s), as outlined in eq. (1):

$$f_1 = \frac{V_s}{4H} \quad (1)$$

The equivalent damping response of the entire embankment was further calculated by accounting for the Rayleigh damping parameters for all the railway embankment soil strata [65].

212 **Table 1:** Constitutive modelling and material properties of track structure components (after [54])

Track Component	Material	Constitutive Model	Density ρ (kg/m ³)	Poisson's ratio ν	Elastic modulus E (kPa)	Effective friction angle Φ (°)	Dilation angle Ψ (°)	Cohesion C (kPa) (non-zero, for M-C numerical stability)
Rail	Steel	Linear Elastic	7850	0.30	2.0E+08	-	-	-
Sleeper	Concrete	Linear Elastic	2500	0.20	3.8E+07	-	-	-
Ballast	Gravel (medium dense)	Mohr-Coulomb (M-C)	1750	0.25	1.5E+05	44	0	1
Blanket	Sand (dense, well-graded)	Mohr-Coulomb	1900	0.40	1.0E+05	43	4	1
Prepared Subgrade	Sand (dense, well-graded)	Mohr-Coulomb	1800	0.38	6.0E+04	43	4	1
Top layer of the fill	Sand (medium dense, well-graded)	Mohr-Coulomb	1750	0.35	4.5E+04	42	3	1
Lower layer of fill	Sand (medium dense, well-graded)	Mohr-Coulomb	1700	0.35	2.5E+04	41	1	1
Subsoil	Sand (medium dense, well-graded)	Mohr-Coulomb	1700	0.35	2.5E+04	41	1	1

Table 2: Damping characteristics of railway embankment strata

Track Component	Material	Damping	Shear wave
		ratio ζ (%)	velocity V_s (m/s)
Ballast	Gravel (medium dense)	7.86	185.20
Blanket	Sand (dense, well-graded)	4.67	134.04
Prepared Subgrade	Sand (dense, well-graded)	4.35	105.19
Top layer of fill	Sand (medium dense, well-graded)	4.09	95.31
Lower layer of fill	Sand (medium dense, well-graded)	4.05	73.10
Subsoil	Sand (medium dense, well-graded)	3.14	73.10

214

215 The efficacy of EPS geofoam variants with three different densities [66] was analysed in this
 216 study, as shown in Table 3. Since the maximum strain levels expected in the material were
 217 small, on the order of 10^{-4} , linear elastic material response was considered suitable for
 218 modelling EPS geofoam within the small-strain range (below 1%), despite its inherent
 219 viscoelastic nature. Also, the interface between the geofoam infill and the surrounding soil was
 220 assumed rigid, with no relative displacement between the EPS geofoam and the surrounding
 221 soil.

222 2.3 Finite element mesh discretisation

223 A mesh sensitivity analysis was performed to determine the optimal mesh element sizes,
 224 quantifying the percentage variations in the estimated Peak Particle Velocity (PPV) of ground
 225 vibrations and track displacements for various sizes of mesh refinement. Finer mesh
 226 discretisations were assigned in the upper strata of the track in regions adjacent to train wheel
 227 loading to capture the load distribution and ensure accurate results. The sensitivity analyses
 228 indicated an optimal mesh element size of 0.35 m for the natural ground, beyond which the

mesh refinements produced minimal changes in the vibration PPV estimates and track displacements under train loads. The optimal mesh element sizes for various track components, determined through mesh sensitivity analyses, are given in Table 4. The finite element model of the railway track, discretised with the optimal mesh element sizes, is shown in Fig. 2.

Table 3: Material properties of various EPS geofoam grades

EPS geofoam type	Constitutive Model	Density ρ (kg/m ³)	Poisson's ratio ν	Elastic modulus E (kPa)	Damping coefficient α	Damping coefficient β
EPS25	Linear Elastic	25	0.14	3500	0.77	1.3E-04
EPS30	Linear Elastic	30	0.17	4514	0.78	1.27E-04
EPS35	Linear Elastic	35	0.20	6578	0.86	1.12E-04

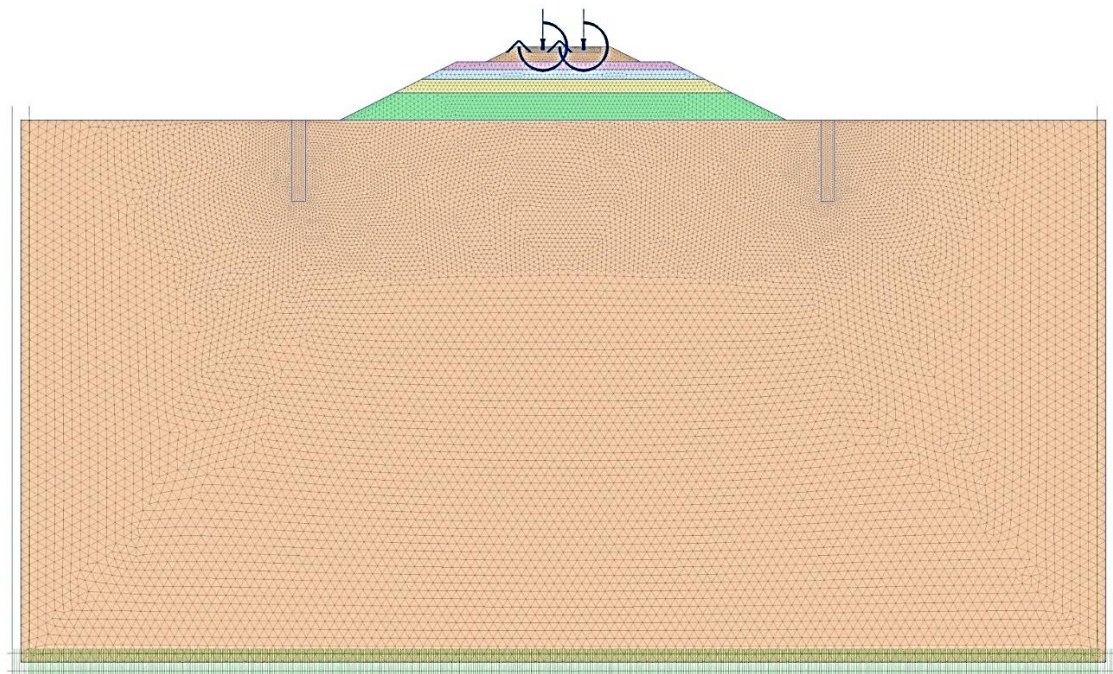


Fig. 2 Mesh discretisation of the finite element model of ballasted HSR track

Table 4: Optimal mesh element sizes for various track components

Track Component	Mesh element size (m)
Rail	0.045
Sleeper	0.10
Ballast	0.15
Blanket	0.20
Prepared Subgrade	0.15
Top layer of fill	0.15
Lower layer of fill	0.15
Subsoil	0.35

238

239 The HST loads were simulated through the definition of axle load-time histories, and the time
240 required for train wheels to traverse a specific cross-section was calculated by dividing the
241 inter-axle spacing in a bogie by the train speed. The PPV of vibration at a given point in the
242 railway embankment or subsoil is estimated as a resultant of the lateral (V_x), vertical (V_y) and
243 longitudinal vibration components (V_z), as shown in eq. (2).

244

$$PPV = \sqrt{V_x^2 + V_y^2 + V_z^2} \quad (2)$$

245 The vibration PPV at varying distances from the track centreline under HST loading was
246 validated for convergence [54], with the numerical errors well below 5-10% of the expected
247 track vibration levels.

248 3. Efficacy of geofoam-infilled barriers in high-speed rail track vibration mitigation

249 The effectiveness of geofoam-infilled trenches in mitigating high-speed train-induced ground
250 vibrations is characterised for various high train speeds ranging from 150 km/h to 250 km/h,
251 covering a slightly higher range of train speeds beyond the recommended maximum speed for
252 the traditional ballasted track embankment section (25 T) modelled in this study [62, 67].

Ground improvement measures, retrofitting of structural reinforcements such as geogrids into the track, and redesign of the track formation's cross-section can enable these slightly higher speeds by increasing the load-carrying capacity of the railway formation.

The Amplitude Reduction Ratio (ARR) is a widely used metric for evaluating the effectiveness of vibration isolation systems [49] and is defined as follows:

$$ARR = \frac{A_1}{A_0} \quad (3)$$

where A_0 represents the maximum amplitude of PPV before trench installation at a particular location, and A_1 represents the maximum amplitude of PPV after the installation of the trench.

In the present study, the efficacy of geofoam wave barriers in attenuating ground vibrations is quantified as the percentage reduction in PPVs after installing the EPS geofoam-infilled trench. It is represented as the Vibration attenuation efficiency, η (%), as given in eq. (4):

$$\eta = \frac{A_0 - A_1}{A_0} \times 100 \quad (4)$$

The PPV of ground vibrations are quantified at various locations on the surface of the natural ground (subsoil) at distances between 10 and 20 m from the track centreline, where the near-field vibrations are significant. The near-field vibrations are quantified and compared for both the track conditions with and without the EPS geofoam wave barriers, as shown in Fig. 3.

3.1 Near-field train-induced ground vibration levels

Fig. 4 portrays the near-field ground vibrations induced by HST at various speeds, before the installation of any vibration isolation barriers. For all train speeds, the PPV of ground vibrations decreases with increasing lateral distance (l) from the track centreline due to geometric damping. Additionally, increasing train speed from 150 to 250 km/h reduces near-field ground

vibrations, possibly due to dynamic amplification of ground vibrations at critical speeds approaching the Rayleigh wave velocity of the natural ground [68].

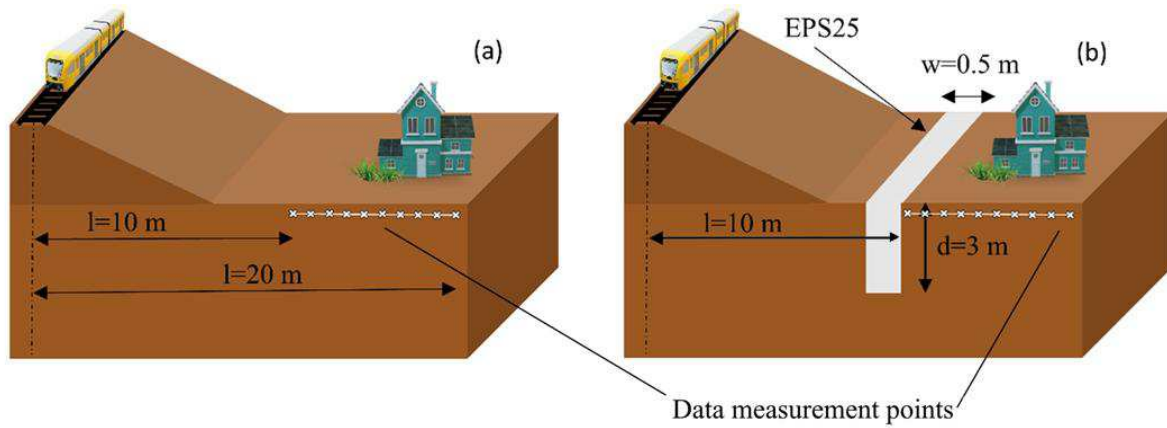


Fig. 3 Location of data measurement points (a) without wave barrier trench (b) after installation of EPS geofoam-infilled trench

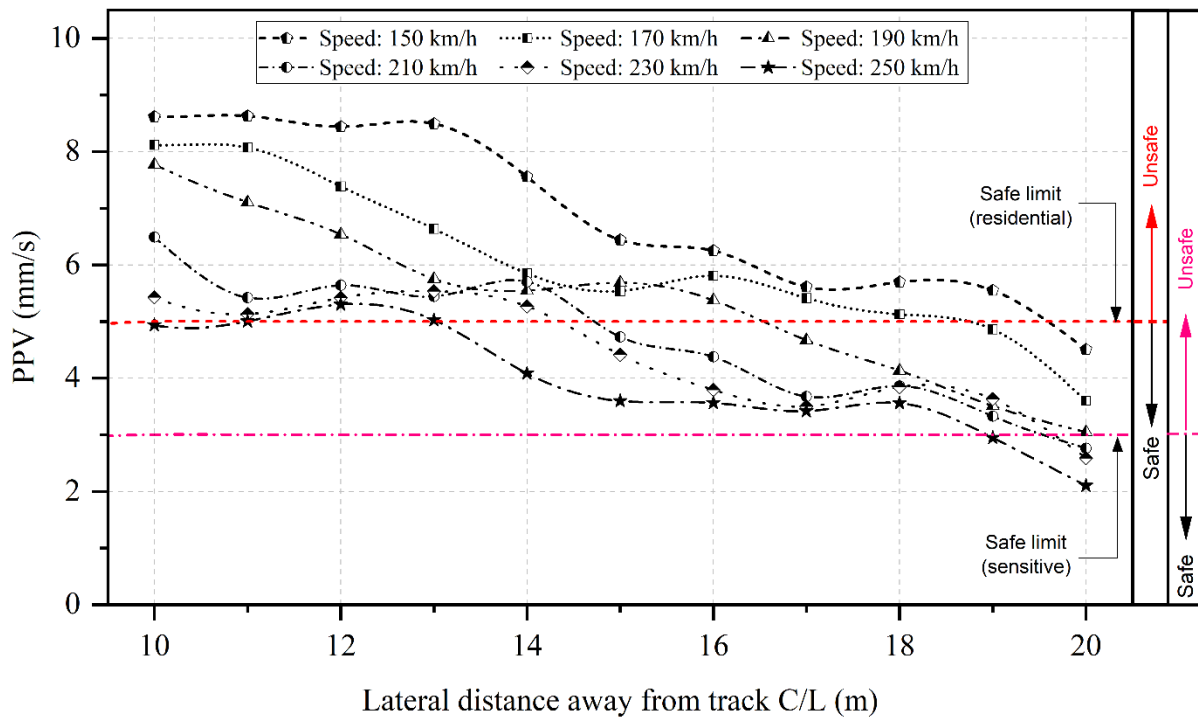


Fig. 4 Near-field vibrations induced by HSTs at various train speeds (without wave barriers)

Table 5 lists the vibration thresholds for different building structures, based on the German national standard DIN 4150 [69] and the Federal Transit Administration (FTA) guidelines [70]. The estimated data in Fig. 4 shows that the near-field vibrations from HST operations in a

conventional, untreated track exceed the established safety thresholds for residential buildings and sensitive structures in the vicinity. With cyclic load repetitions, ground vibration levels may even exacerbate further, as various defects develop in the rolling stock and the track structure over time. It is therefore necessary to implement appropriate measures to mitigate ground-borne railway vibrations to ensure the safety of vibration-sensitive structures in the vicinity, particularly on urban railway lines, where construction and residential occupancy are often close to the tracks.

Table 5: Vibration limits for buildings [69, 70]

Type of structure	Peak particle velocity (mm/s)	
	DIN4150 (2025)	FTA (2018)
Commercial structures	20	12.7-7.6
Residential structures	5	5
Sensitive structures	3	3

3.2 Mitigation of ground-borne railway vibrations using geofoam-infilled trenches

The potential use of EPS geofoam-infilled trenches to mitigate near-field ground-borne HSR track vibrations was further investigated. To begin with, a trial wave barrier trench of 3 m depth, 0.5 m width and infilled with EPS25 geofoam was placed at 10 m from the track centreline on both sides of the embankment, to understand its efficacy in mitigating the propagation of vibrations from a high-speed train at 200 km/h (with 125kN wheel load). Fig. 5 illustrates the vertical vibrations at a location (next to the trench, away from the track centreline) where the track configurations with and without geofoam wave barriers were evaluated. The maximum vertical vibration levels quantified before and after deployment of the EPS geofoam wave barrier trench were 3.70 mm/s and 1.29 mm/s, respectively.

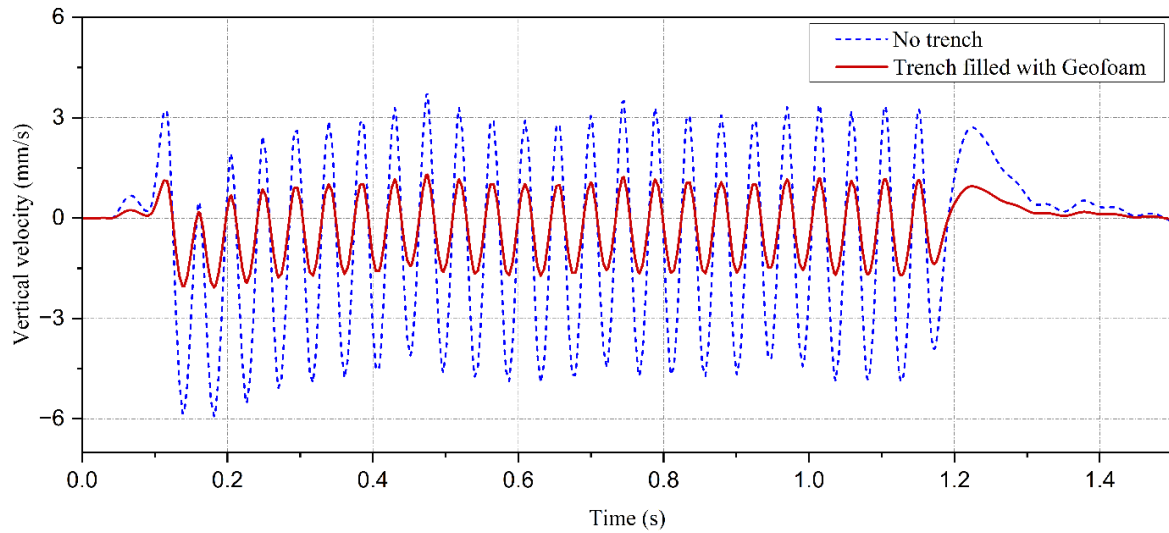


Fig. 5 Comparison of vertical vibrations at a lateral distance of 10 m from the track centreline before and after installation of an EPS geofoam-infilled trench

The attenuation of vibration PPVs at locations 10 to 20 m from the track centreline is illustrated in Fig. 6. It was observed that the vibration mitigation efficiency was highest in the immediate vicinity of the EPS-infilled trench, i.e., the attenuation decreased with increasing distance from the vibration isolation trench. A maximum vibration attenuation efficiency of 44% could be attained using the EPS25-infilled trench of 3 m depth and 0.5 m width (positioned 10 m away from the track centreline) for the HST transit at 200 km/h.

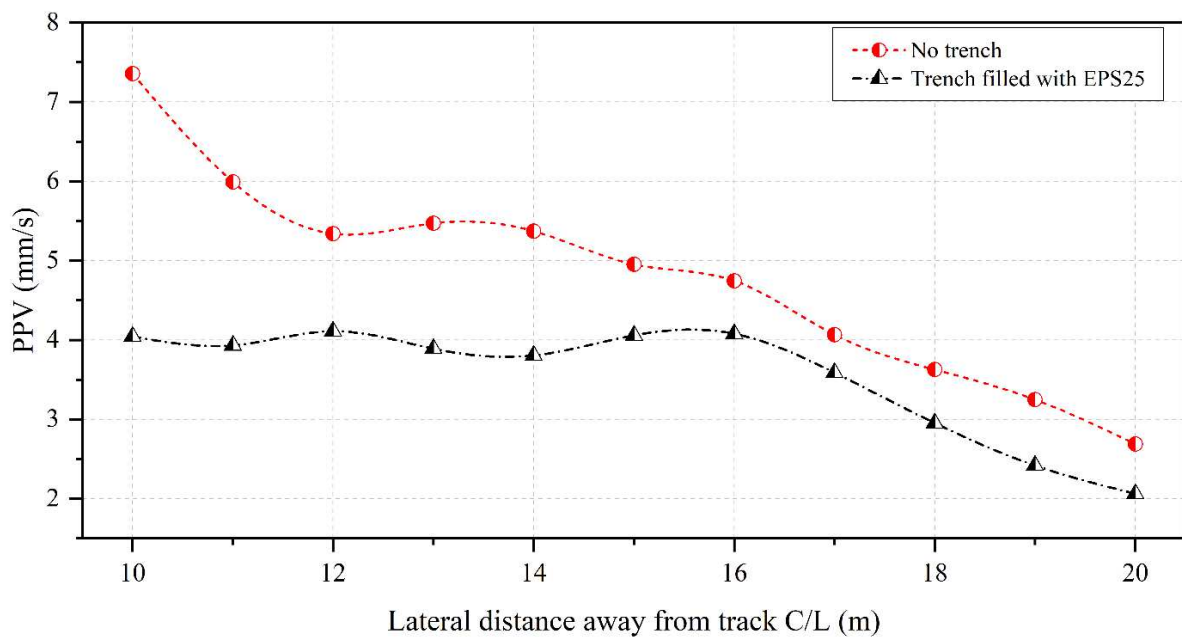


Fig. 6 PPV Comparison at varying distances from the track centreline

4. Parameters influencing the efficacy of geofoam-infilled vibration barrier trenches

The impact of various parameters, including the depth, width, and placement location of the geofoam-infilled trench, on the attenuation of ground-borne HST vibrations was systematically analysed across different EPS geofoam densities, with the key objective of identifying optimal EPS-infilled trench configurations that achieve maximum vibration attenuation efficiency.

4.1 Effect of trench location

The impact of trench placement location on the vibration attenuation efficiency was investigated for multiple lateral placement positions ranging from 10 to 14 m outward from the track centerline (Fig. 7). The trial analyses were conducted for an EPS25 infilled trench with dimensions of 3 m depth and 0.5 m width for a train speed of 200 km/h.

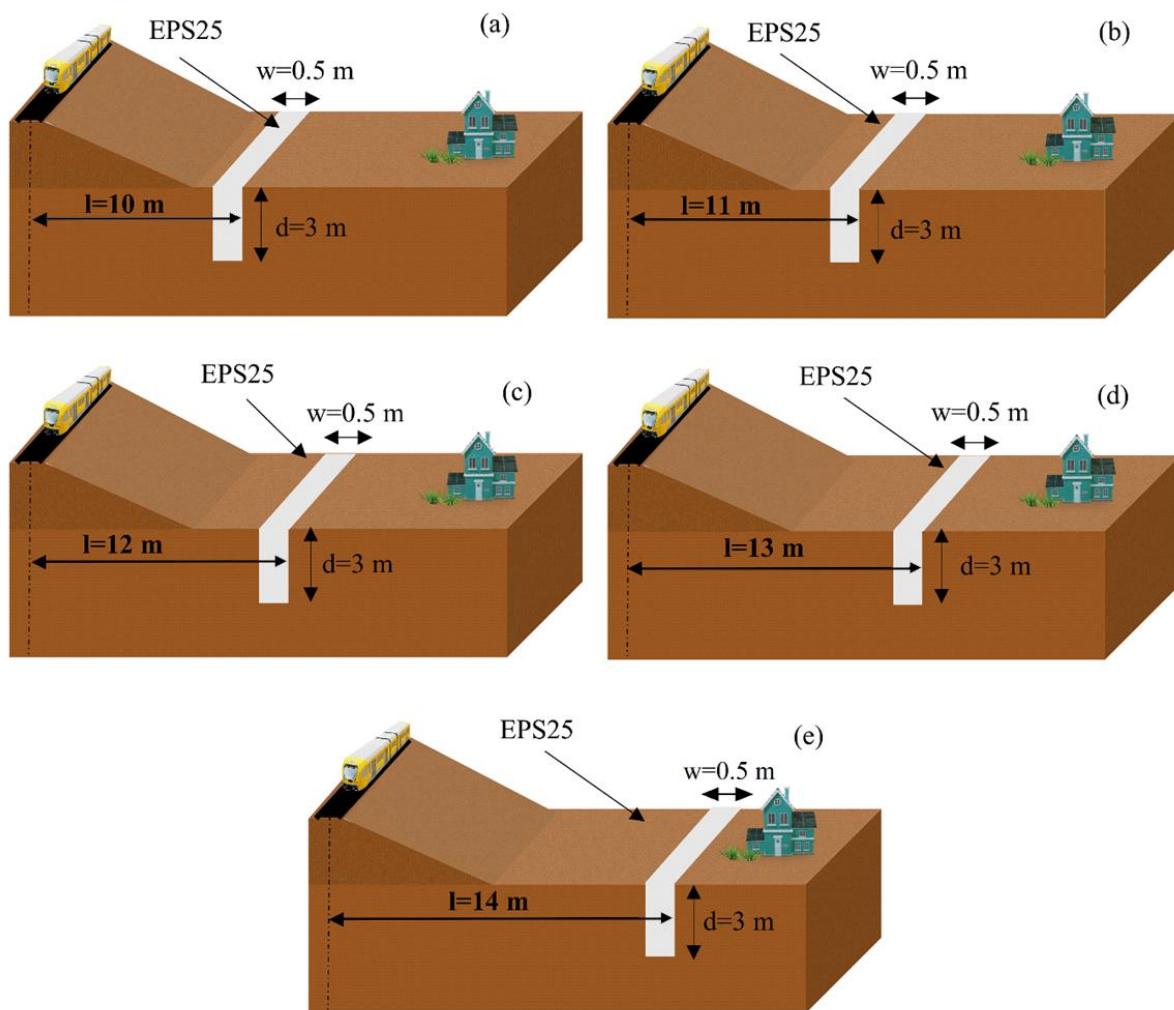


Fig. 7 Location of EPS-infilled trenches at various lateral distances from the track centreline

Results from the analyses (Fig. 8a) indicated that the maximum vibration attenuation was achieved when the wave barrier trench was positioned closest to the railway embankment. Hence, in this case, the optimal location of the geofoam trench was found to be at 10 m from the track centreline. An enlarged view of the estimated results (Fig. 8b) also revealed a minor amplification of the vibrations in the area between the railway embankment and the vibration isolation trench (near the trench), due to the slight reflection of vibration waves at the trench interface caused by a difference in stiffness between the soil and the infilled trench. This small amplification of vibrations near the trench was found to diminish with increasing distance from the track centreline.

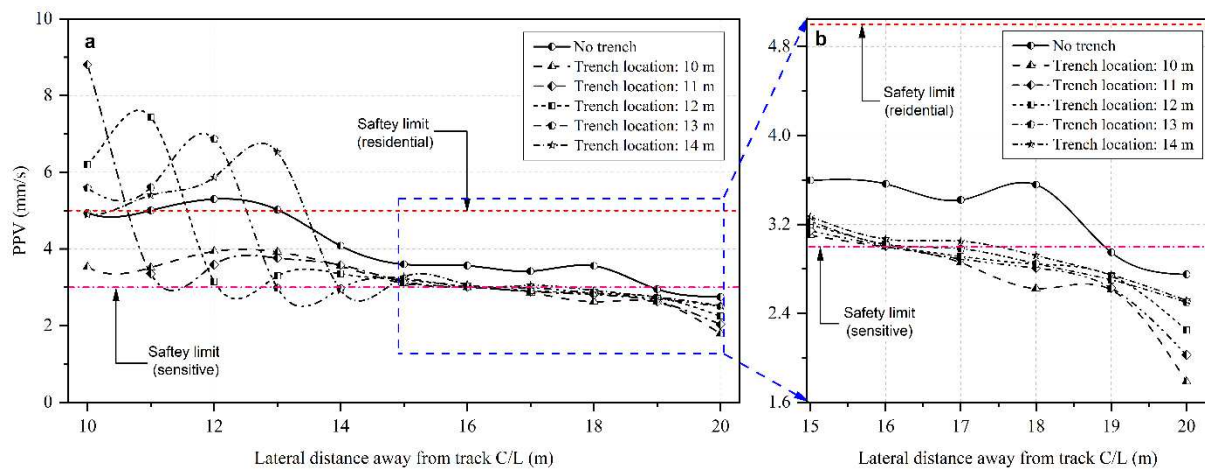


Fig. 8 Vibration PPVs observed after the deployment of trenches at various locations (a) in the distances from 10-20 m from track C/L, and (b) enlarged view for distances from 15-20 m

4.2 Effect of trench depth

The efficacy of EPS-filled vibration-isolation trenches shows a strong dependence on trench depth. Investigations were carried out using trenches with practical installation depths ranging from 1 to 4 m (as shown in Fig. 9, with a 0.5 m thickness and located 10 m from the track centreline) at train speeds of 150 to 250 km/h for various EPS geofoam densities. Fig. 10 illustrates the enhancement in vibration attenuation efficiency (VAE) facilitated by trenches with higher depths for the different grades of geofoam. Notably, there were no significant reductions in vibration PPVs when the trench depth was extended beyond 3 m (up to 4 m).

Considering both economic and practical aspects, the optimal trench depth was determined to be 3 m.

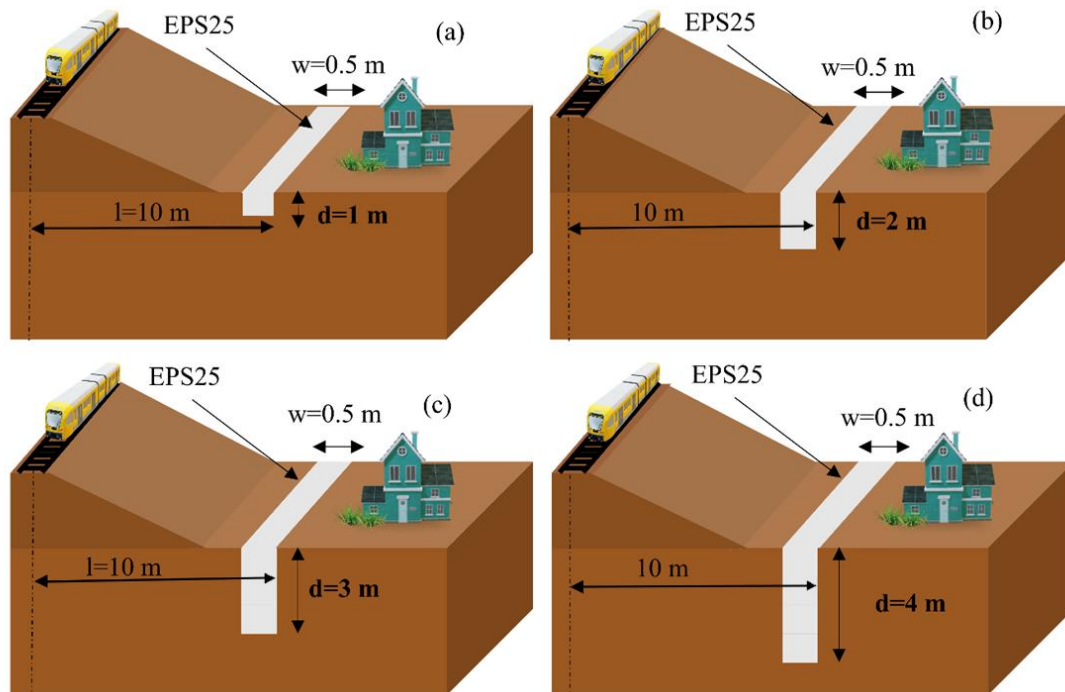


Fig. 9 Deployment of EPS-infilled trenches with depths varying from 1 to 4 m

4.3 Effect of trench width

The width of the geofoam-infilled trenches also plays a critical role in their effectiveness at mitigating vibrations. The effectiveness of various trenches with widths ranging from 0.25 to 1 m was investigated (as shown in Fig. 11), using 3 m-deep trenches located at 10 m from the track centreline, which were estimated to be the optimal trench width and placement location, as presented in Sections 4.1 and 4.2. The efficacies were estimated for various geofoam grades for a trial train speed of 200 km/h (HST).

The results in Fig. 12 indicate that the effectiveness of EPS-filled vibration isolation trenches increases significantly with increasing trench width.

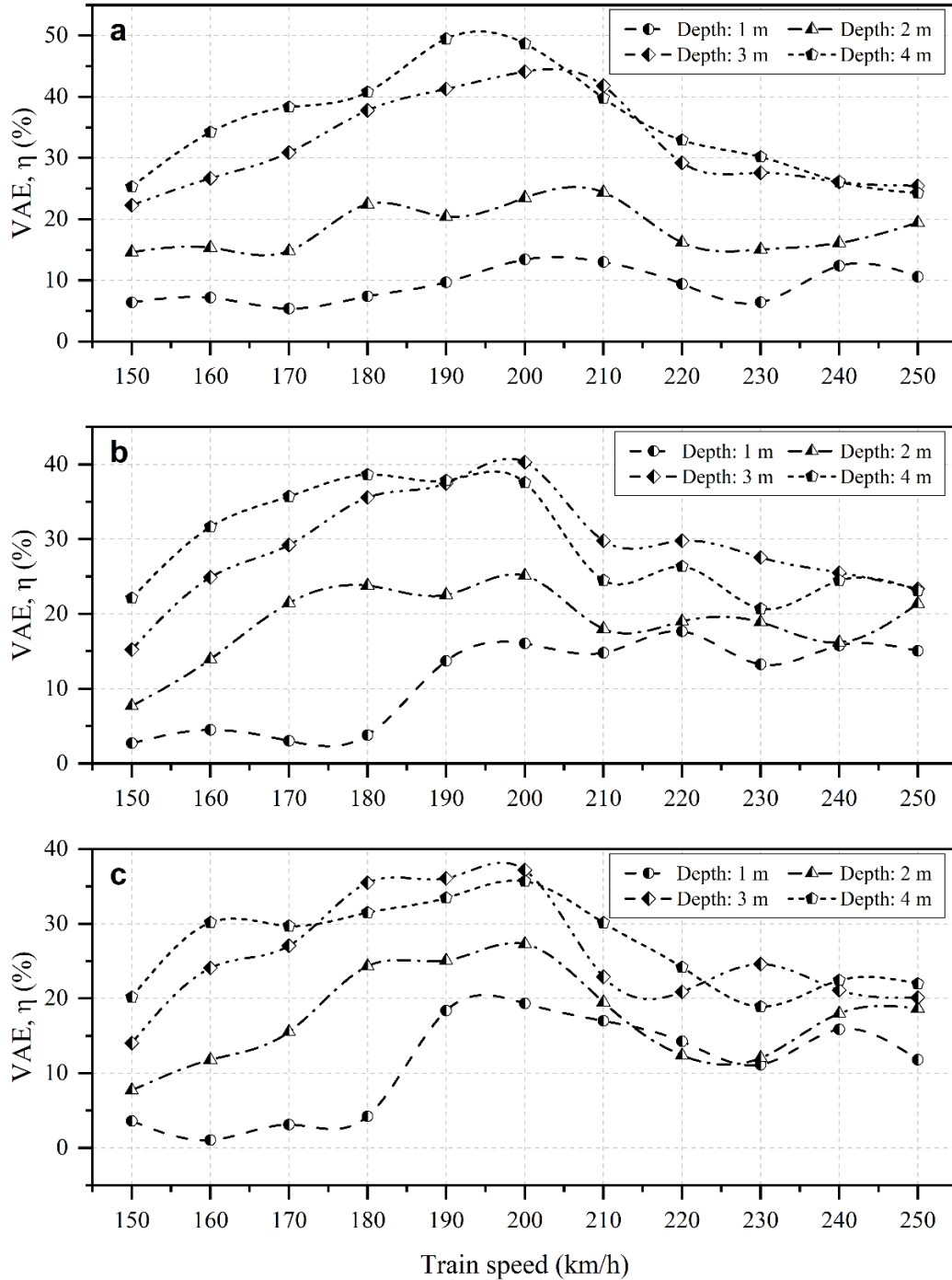


Fig. 10 The impact of trench depth on the efficacy of vibration attenuation for various geofoam grades (a) EPS25, (b) EPS30, and (c) EPS35

The vibration attenuation efficiency of a 3 m-deep EPS25-infilled trench, analysed at a train speed of 200 km/h, exhibited isolation performance ranging from 29 to 52 % for trench widths of 0.25 to 1 m, respectively. Notably, increasing the trench width from 0.25 m to 0.5 m resulted in a substantial 15 % reduction in the vibration PPVs (Fig. 12a). A further increase in the trench width from 0.5 to 1 m yielded only a smaller 8% improvement in vibration isolation efficiency

(Fig. 12b). The optimal trench width was therefore determined to be 0.5 m from the efficiency, economy and practicality standpoints.

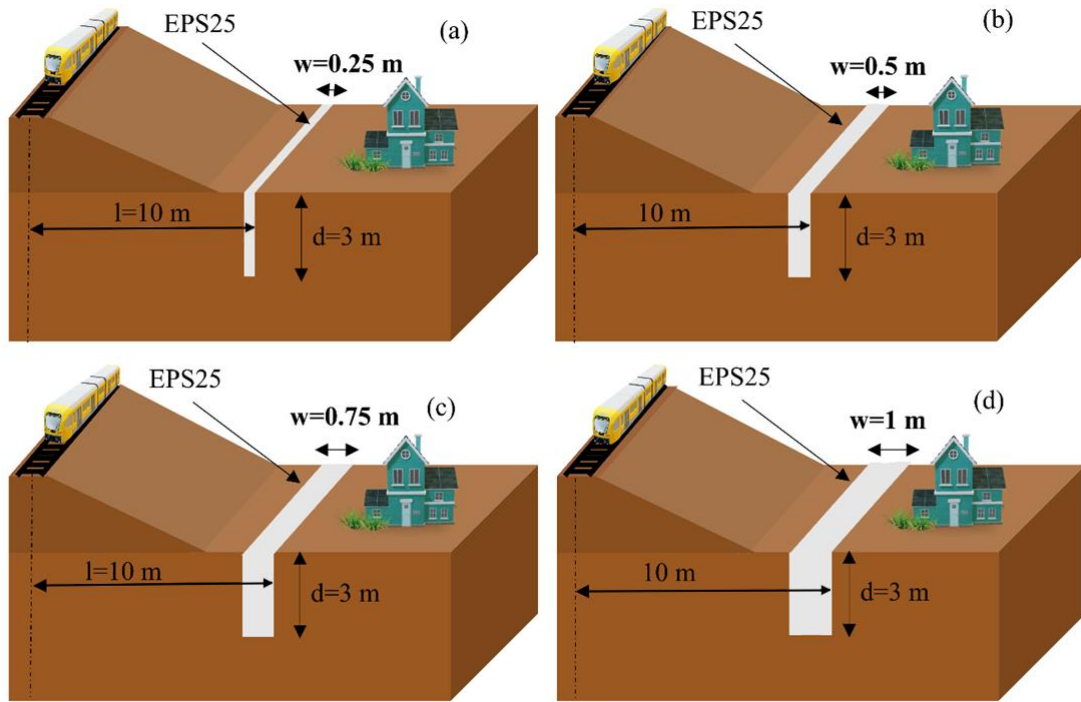


Fig. 11 Geofoam trenches with varying widths of 0.25-1 m

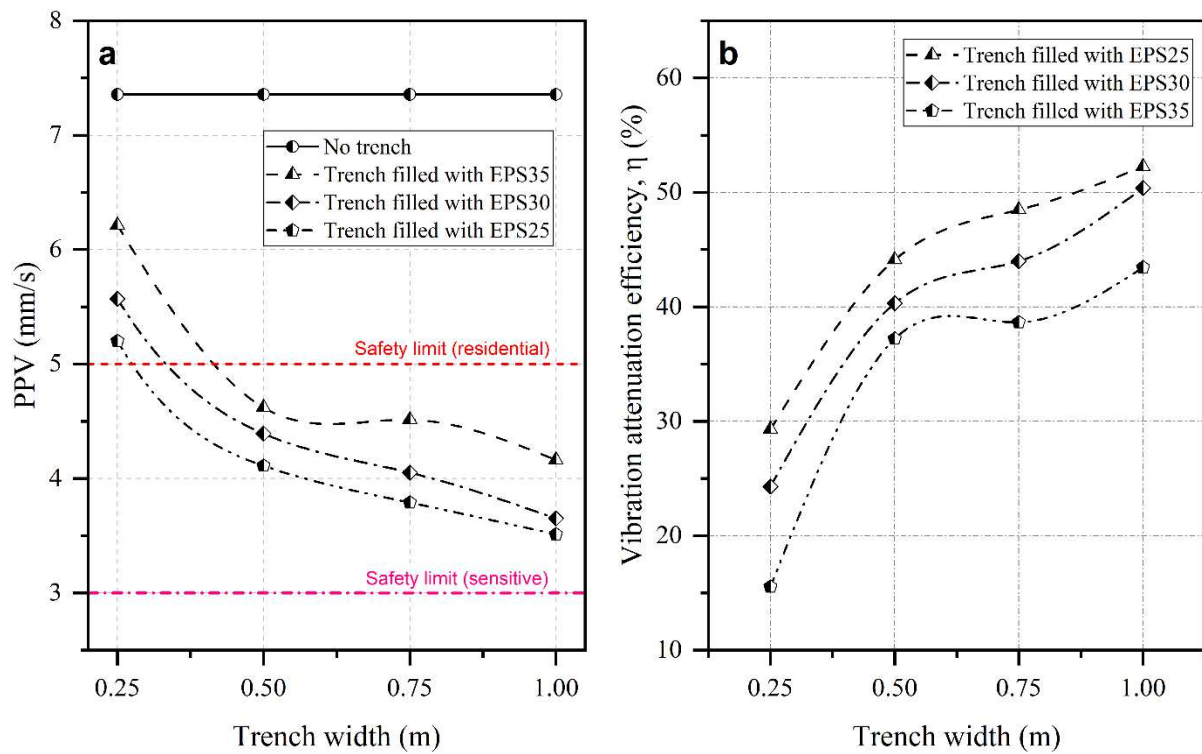


Fig. 12 Influence of trench width on (a) attenuation of HST-induced ground vibration PPV levels, and (b) vibration attenuation efficiency (%) of various EPS geofoam grades

4.4 Effect of EPS geofoam density

The density grade of the EPS geofoam infilled in the wave barrier trench highly impacts the vibration-damping potential of a wave barrier that is already geometrically optimised. The vibration attenuation efficiency of a 3 m deep and 0.5 m wide trench, utilising various grades of EPS geofoams, was estimated to be 37.20 %, 40.30 %, and 44.12 % for EPS35, EPS30, and EPS25, respectively (Fig. 12b) for the ground vibrations generated by an HST at 200 km/h. This clearly indicates that lower-density EPS geofoam has greater potential to mitigate ground vibrations. This observation also aligns well with previous laboratory centrifugal studies [35, 71, 72] and numerical investigations of EPS geofoam [54], which concluded that softer barriers outperform stiffer ones in mitigating vibrations.

4.5 Effect of train speed

Further investigations were conducted to assess the efficacy of wave barrier trenches filled with geofoam of various EPS density grades at operational train speeds of 150 to 250 km/h. The analyses were carried out using optimal trench dimensions of 3 m depth, 0.5 m width, and a placement at 10 m from the track centreline. The observed vibration attenuation facilitated by various EPS grades is illustrated in Fig. 13.

The observed data indicate that, for any given trench configuration, the vibration PPVs decrease with increasing train speed. This aligns with previous research findings (e.g. [73]) that attribute the increased effectiveness of infilled trenches in attenuating high-frequency vibrations [73]. A maximum vibration attenuation efficiency of about 44.12 % was quantified around the critical speed of 200 km/h for the track-ground system modelled, with the attenuation more pronounced at supercritical speeds than at subcritical speeds, consistent with previous studies [73, 74]. These results reinforce the suitability and effectiveness of EPS geofoam-infilled trenches for mitigating ground-borne railway vibrations generated by HSTs.

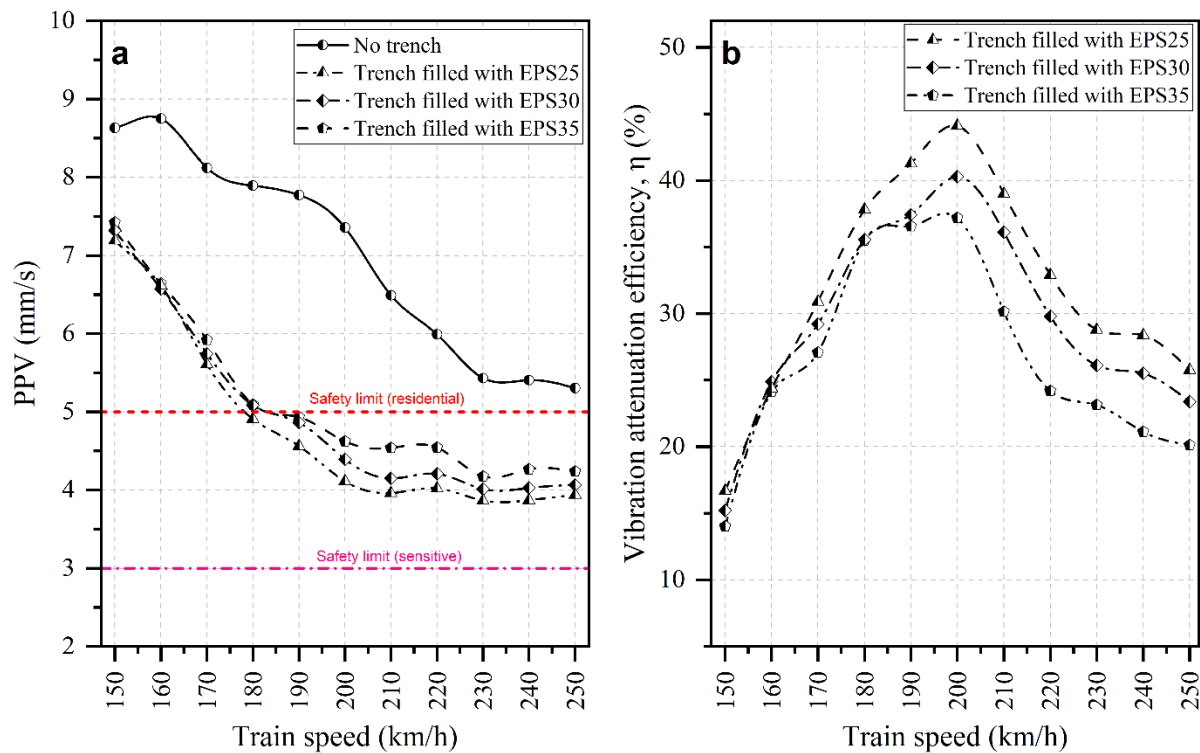


Fig. 13 Ground-borne HST vibrations at various train speeds (a) attenuation of vibration PPV levels, and (b) vibration attenuation efficiency (%) of various EPS geofoam grades

An overview of all analyses carried out on the double-layer ballasted railway track modelled in this study indicates that the deployment of an EPS25 geofoam-infilled trench, 3 m deep, 0.5 m wide, and positioned 10 m from the track centreline, is optimal for mitigating ground-borne vibrations from ballasted high-speed railway tracks. This trench configuration can attenuate ground vibrations induced by an HST with a 25 T axle load travelling at a critical speed of about 200 km/h by up to 44%.

4.6 Vibration intensification around the wave barrier

It was observed that the deployment of these passive vibration isolation trenches leads to a slight amplification of vibrations in the immediate vicinity of the railway embankment in the area adjacent to the trench. This amplification is attributed to wave reflection and refraction, which lead to interference and superposition with the incoming waves, resulting in higher vibration levels in front of the barrier [75]. For the various train speeds analysed in this study,

this amplification of PPVs was quantified at a distance of 8.5 m from the track centreline, before and after the installation of a trench at 10 m from the track centreline. Fig. 14 illustrates the minor vibration amplification of about 1-2 mm/s post installation of the geofoam-infilled trench.

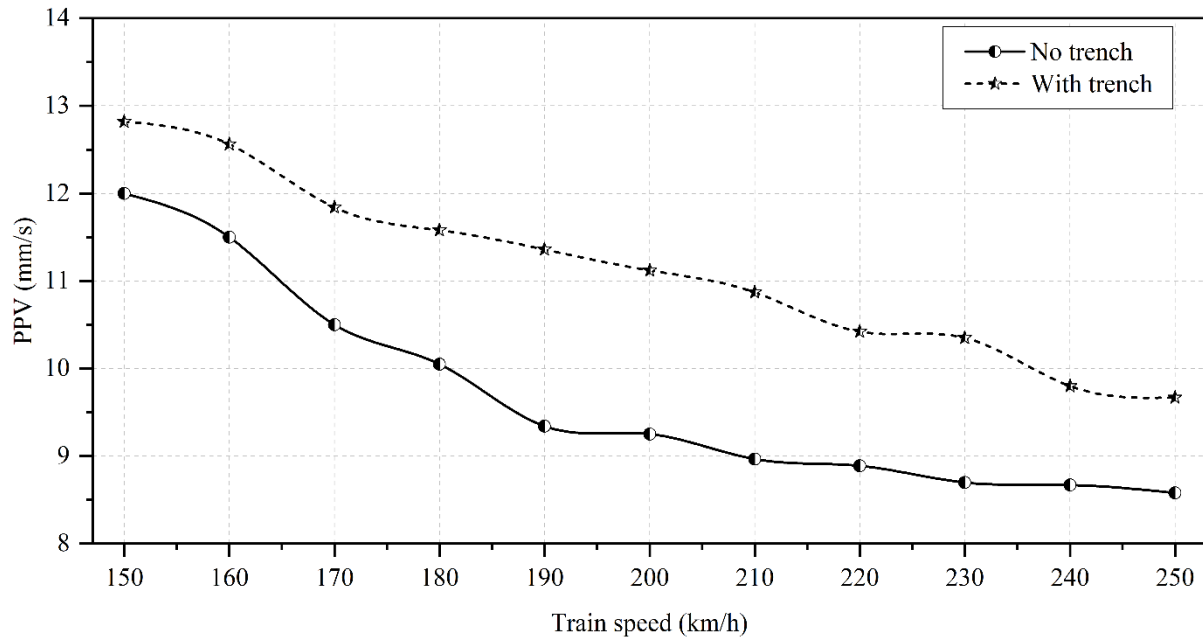


Fig. 14 Amplification of vibration due to geofoam trench

However, this trivial increase in vibrations is deemed not to cause a significant impact on overall track performance, compared with the significant benefits provided by EPS geofoam-infilled trenches in mitigating the propagation of vibrations away from the railway track onto structures in its vicinity.

5. Conclusions

The findings from this study demonstrate that EPS geofoam-infilled vibration-isolation trenches are highly effective at mitigating ground vibrations generated by high-speed trains on ballasted railway tracks. The influence of all key parameters, including the trench dimensions, density grade of infilled EPS geofoam, placement location of the trench and the impact of train

operation speed on the effectiveness of the vibration barrier, was analysed in detail, with the following inferences:

- EPS geofoam-infilled vibration isolation trenches are highly effective in attenuating high-speed train-induced ground vibrations. The vibration-isolation efficiency is higher at faster train speeds.
- For the ballasted railway track section analysed in this study, an optimised geofoam-infilled vibration barrier could attenuate the ground-vibration PPVs by 44% at the critical train speed.
- For a given EPS geofoam-infilled trench configuration, the vibration attenuation efficiency is found to be higher at super-critical speeds (about 25-28%) when compared to sub-critical train speeds (around 16-24%).
- The magnitude of vibration attenuation is the highest near a deployed trench. This efficacy drops by about 45-60% at locations about 4-5 m farther from the trench.
- Placement of the wave barrier trench close to the railway embankment is best recommended, since the overall vibrations propagating away from a track can be well-attenuated near the source itself. E.g., the overall vibration attenuation potential of a trench located at 10 m from the track centerline was found to be almost twice the efficacy of a trench located farther at 14 m from the track centerline.
- The use of lower-density grade EPS geofoam as trench in-fill material is found to yield the best results for attenuating the ground-borne railway vibrations. For example, the use of EPS25 infill resulted in a potential 21-44% reduction in vibration PPVs compared with 14-37% efficacy provided by EPS35 geofoam for the studied trench dimensions.

- Deeper and wider trench dimensions are both highly effective in improving the vibration attenuation potential of the wave barrier. For the investigated track cross-section, it was estimated that a trench depth of 3 m and a width of 0.5 m were optimal, from the efficiency, economy and practicality standpoints. The gains in efficacy were less than 10% beyond these trench dimensions.
- The deployment of passive vibration isolation trenches near the railway track is found to cause an inconsequential amplification of vibrations by about 1-2 mm/s in the area of ground adjacent immediately before the trench, due to interference and superposition of reflected and refracted vibration waves from the trench-soil interface with the incoming railway vibrations.

This study concludes that EPS geofoam-infilled vibration barrier trenches are highly effective in mitigating ground vibrations induced by high-speed trains. Their deployment can help safeguard vibration-sensitive structures and the population living near the tracks, especially in urban areas, where habitation and buildings are often close to railway corridors.

Limitations of the present study

The analyses carried out in this study are based on broad gauge track specifications, and smaller track gauges, including Standard Gauge, would render slightly different vibration wave interactions due to closer wheel spacing within a railcar axle. The study also assumes idealised soil conditions, neglecting environmental variables such as groundwater table fluctuations and the long-term creep behaviour of EPS geofoam under cyclic railway loading.

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