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Numerical investigation for performance evaluation of In-filled materials in vibration screening

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Surface vibrations caused by human activities such as industrial activities, high-speed traffic (e.g. on highways and railways), Piling and blasting during construction and demolition works, usually reach limits where they have become problematic for people and buildings. Very often, it even reaches dangerous limits where they are no longer safe for human life. So many solutions have devised to mitigate effects of vibration and one of them is vibration screening by construction of trench wave barriers. This paper has focused on evaluating screening efficiency of in-filled materials and impact of different parameters of trench wave barriers on efficiency. This paper has presented a numerical study and subsequent validation, 3D finite element study of vibration screening in PLAXIS-3D against stationary surface vibrations using a trench wave barrier filled with an elastic, isotropic, homogeneous half-space. Key parameters have determined studied thereof. The results of numerical and experimental study have found in close agreement.

Keywords: Active Isolation, Amplitude reduction ratio, Efficiency of screening, In-filled materials, Normalized dimensions, Oscillator, Passive Isolation, Raleigh waves, Shear wave velocity, Trench wave barrier and Vibration screening

1 Introduction

Apart from the effects of earthquakes, high-speed traffic, construction and demolition works, vibrating machinery, blasting, underground explosions, etc. are also sources of ground vibration. Excessive ground vibration must be properly blocked or reduced, otherwise, it may cause inconvenience to residents, fatigue to structural and non-structural components of the structures and failure of high-precision equipment. To reduce the effects of vibration, vibration screening measures are an important development in vibration isolation. This measure consists in installing a trench wave barrier with filled materials in the propagation of surface wave from the source to the structure affected. The effect is that the amplitude of the incident wave traveling along the path is greatly reduced. Commonly used types of barriers to mitigate wave amplitudes include open trench barriers, filled trench barriers, gas cushion, solid, hollow, or sheet pile walls. There are two types of isolation, depending on location w.r.t. source of vibration and structure they are protecting. If trench barrier is located near to vibration source, it is called active isolation and if placed close to structure being protected, is called passive isolation. Energy generated by the surface source is dispersed, creating a combined waveform consisting of all three wave types: Primary waves, Secondary waves, and Rayleigh waves. Miller and Percy[1] generated vibrations by vertical vibration and determined the energy components of these waves in an elastic half-space. Rayleigh waves carry two-thirds (about 67%) of total energy of waves and travel in a half-space near earth's surface. For this reason, vibration screening measures focus on reducing the amplitude of Rayleigh waves. Among surface waves, Rayleigh waves have the property of having the largest amplitude compared to all other waves. This makes them the most destructive of all waves. In addition, Rayleigh waves decay more slowly than all other waves with distance from the vibration source. Here, we present as far as possible the contributions of researchers to the development of vibration isolation technology. According to Woods[2], the amplitude reduction was measured in rectangular trench of different depths and lengths. Experimental study to evaluate the performance of in-filled materials have already been carried out. Also, parametric study to determine effect of properties of in-filled materials and the screening efficiency in terms of dimension of trench wave barrier has also

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carried out. According to Woods[2], measurement for amplitude reduction factor on straight trenches with various depths and lengths has been observed. To validate the results of an experiment, a numerical investigation is the requirement for validating the outcome. In the context of above, a numerical study for validating the experimental work is present here.

Beskos *et al.*[3] found that the efficiency of passive isolation is lower than that of active isolation. The results are presented as a contour plot of the amplitude reduction ratio (A_r) and show that reduction in amplitude is highest just behind groove. Diversion of the surface wave at the edge of the groove creates a region of increased amplitude. Ashref Alzawi, M. Hesam A. Nagar[4] developed a numerical model to further study the performance of geofoam filled trench as wave barrier. 2-D and 3-D models were developed numerically in time domain using FEM software PLAXIS 3-D. Parametric study is performed by varying parameters viz. geometric dimensions of barrier, location and properties of soil. Due to soil dynamic properties, depth of barrier and its location were studied by varying independently. Properties such as density of soil, Poisson's ratio, damping, etc. were found to be of minor importance. To be effective, deeper trenches are needed as the disturbance approaches. The effectiveness of the barrier improves in stiffer soils (with high Vs values). Giuliano Bellinassi *et al.*[5] developed a numerical method based on direct boundary element method in frequency domain to solve vibration screening problems in homogeneous, elastic and isotropic media. This method allows investigations of different trench depths, lengths and widths. Analysing effect of the distance of source to trench in order to achieve better amplitude reduction or scenario of multiple trenches. Javier Aviles and Francisco J. Sanchez-Sesma[6] investigated the problem of wave barriers in underground explosions. This includes a theoretical investigation of isolating foundations from vibrations using massive piles as barrier. Two models were proposed, one for piles of infinite length and one for piles of finite length and different shafts. The study considered the effects of pile diameter, spacing and length and drew conclusions related to design guidelines. Baker[7] compared experimental and numerical results available in literature obtained using BEM and the equations from empirical design by Al-Hussaini (1992) but limited himself to the equations already derived.

G. L. Sivakumar Babu *et al.*[8] performed numerical 2-D analysis making use of FLAC 5.0, a finite difference tool and proposed an efficient vibration screening system. During this numerical analysis, the model was first calibrated w.r.t.properties of material, damping factor and boundary constraints to get results in the conditions of field tests. Theparametric study then carried out using this calibration to make decisions regarding the screening system. Kattis *et al.*[9] studied case of vibration screening numerically using set of piles in 3-D, using an advanced frequency domain BEM. Further, frequency domain BEM codeswas developed for dynamic analysis of complex 3-D elastic structural systems. The case of piles and trench is similar except the size of piles which is much larger but trenches are more effecting in vibration screening. In case of piles, factors such as pile length, spacing, overall width of piles, etc. affect the vibration isolation effect similarly to trenches. S. George Gazetas[10] numerically investigated the vibration behaviour of heterogeneous deposits as wave velocity increases. An analytical-numerical method was presented to investigate the dynamic behaviour of such deposits due to vertical shear waves or Rayleigh waves. Studies have shown that as the in homogeneity increases, the attenuation increases exponentially with depth. It has been found that the attenuation of Rayleigh wave-induced vibrations governed by shear wave velocity, percentage of in homogeneity and frequency.

Ankurjyoti Saikia[11] studied the behaviour of in-filled trenches in which soft in-filled materials were chosen. In this study, influence of shear wave velocity and location of trench barrier on screening efficiency had studied. In addition to location of barrier, width and depth of barrier has an impact on screening effectiveness. Tulika Bose *et. al.*[12] presented a numerical evaluation in PLAXIS to observe the behaviour of empty and in-filled trenches works as wave barrier to mitigate vibrations. The behaviour of trenches having extensive variation in geometrics of trench and in-filled material in trenches, forms of barrier and condition of loading have been analysed. The model developed was used to find out important elements influencing the screening efficiency of trench. Simulations in 2-Dhave been done so as to recognize the influence of geometrics of trenches and filled up materials in trenches on performance of wave barrier in response to vibration. C. Comina and S. Foti[13] achieved each active and passive surface wave taking an idea numerically, used to mitigate vibration. Characterization of vibration has been performed to acquiring Rayleigh wave length that is used for designing trench. Numerical simulations were made to evaluate the effectiveness of vibration screening. In a latest 2-D finite detail study[14] on barrier isolation, softer in-filled materials are proven to offer higher isolation effectiveness than stiffer obstacles.

2 Materials and Methods

The numerical investigation has carried out to calibrate and validate the experimental results obtained after operating the vibratory source at exciting frequencies with open trench and different in-filled materials. The properties of in-filled materials are utilized in developing conditions of filling as realistic during numerical study. The case is considered in this study with 3-D standpoint[15&16]. Numerical investigation comprises of various sub components such as numerical modelling, assumptions in study, etc. Geometrical dimensions of barrier are normalized with reference to Rayleigh wavelength in half-space so as to avoid dependency on frequency of excitation and parameters in elastic half space. Simplified procedure for analysing the model through Plaxis-3D is given in steps as follows:

a Assigning soil properties to elastic half space
b Creation of test site geometry
c Implying dynamic boundary conditions
d Assigning dynamic loads in terms of load multipliers
e Assigning material damping factor in form of Rayleigh damping
f Performing dynamic calculations

2.1 Methods

2.1.1 Numerical Modelling and Discussion

Finite Element method (FEM) of modelling has emerged as a principal tool for predicting behavioural reaction to vibration problem. The finite element (FE) modelling technique affords a greater particular device which is able to incorporating diverse components like soil continuity, dynamic load application, etc. Since FEM analyses require massive computational resources, the geometric dimensions of the numerical models are often kept to a minimal to lessen calculation time. PLAXIS 3D software program has been used in the subsequent research work and the test were simulated in FEM based PLAXIS 3D. These boundary situations have been simulated with the aid of using making use of the usual fixities to the geometry as supplied in program. In present study, vibration screening efficiency in case of effect of vibration at a point on ground and surroundings, is studied. Calculation time is considerably reduced by keeping the model simplest i.e. only one quarter of the whole geometry is studied by usage of symmetric boundary. Physical damping due to viscous impact also considered in terms of Rayleigh damping.

2.1.2 Geometry and elastic half space parameters in the study

The model has been assumed as a case of dynamic analysis of a source of vibration on an elastic foundation. The source of vibration is an oscillator installed on a RCC footing block of height 0.75m and base size of 0.50m x 0.50m size as shown in Fig. 1. The vibrational effect is created by the oscillator are then transmitted into the subsoil through the footing. The oscillations are simulated as a case of uniform harmonic loading. The amplitude of oscillator is 10 kN/m^2 in a frequency range from 10 to 50Hz at an interval of 10Hz. The effect of weight of footing and oscillator is considered as a uniformly distributed load of 8kN/m^2.

The boundaries of model are kept adequately far from the region of interest. This is done to ignore some of disturbances caused by possible reflections. Therefore, absorbent boundaries are assumed to avoidsuch spurious reflections. Model boundaries in dynamic analysis is taken far away than in static analysis, generally. The area under investigation is kept in form of rectangular size as x=40m and y=20m as geometry model is shown in Fig. 1 and Fig. 2.

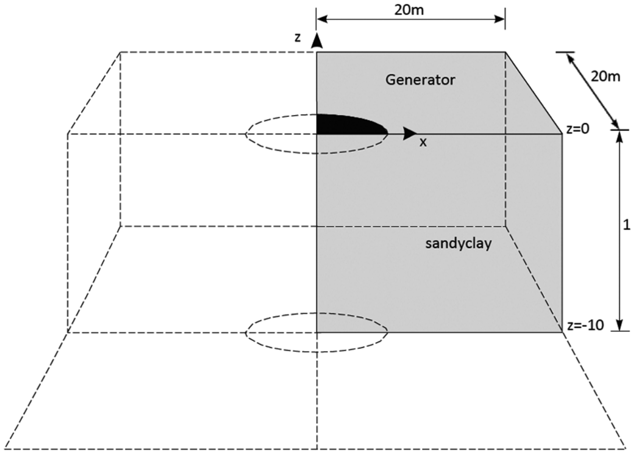


Fig. 1 — Source of vibration modelled in an elastic subsoil.

Table 1 — Soil layer properties

Parameter	Value
Material model	Linear, elastic
Element	10 Nodded
Model	Mohr-Coulomb
Drainage	Drained
Unit weight (Unsaturated)	16.00kN/m^3
Saturated Unit weight	16.15kN/m^3
Stiffness (E)	33.00 x10^3 kN/m^2
Poisson's ratio (ν)	0.30 (soil)
Strength of interface	Rigid
Damping ratio (ξ)	7.50
Shear wave velocity of soil (Vs)	88.22 m/sec

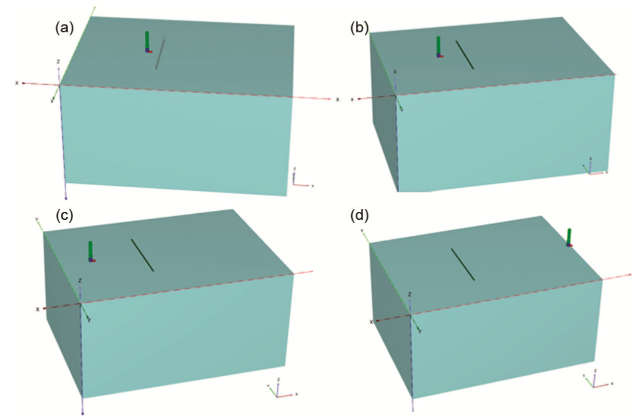


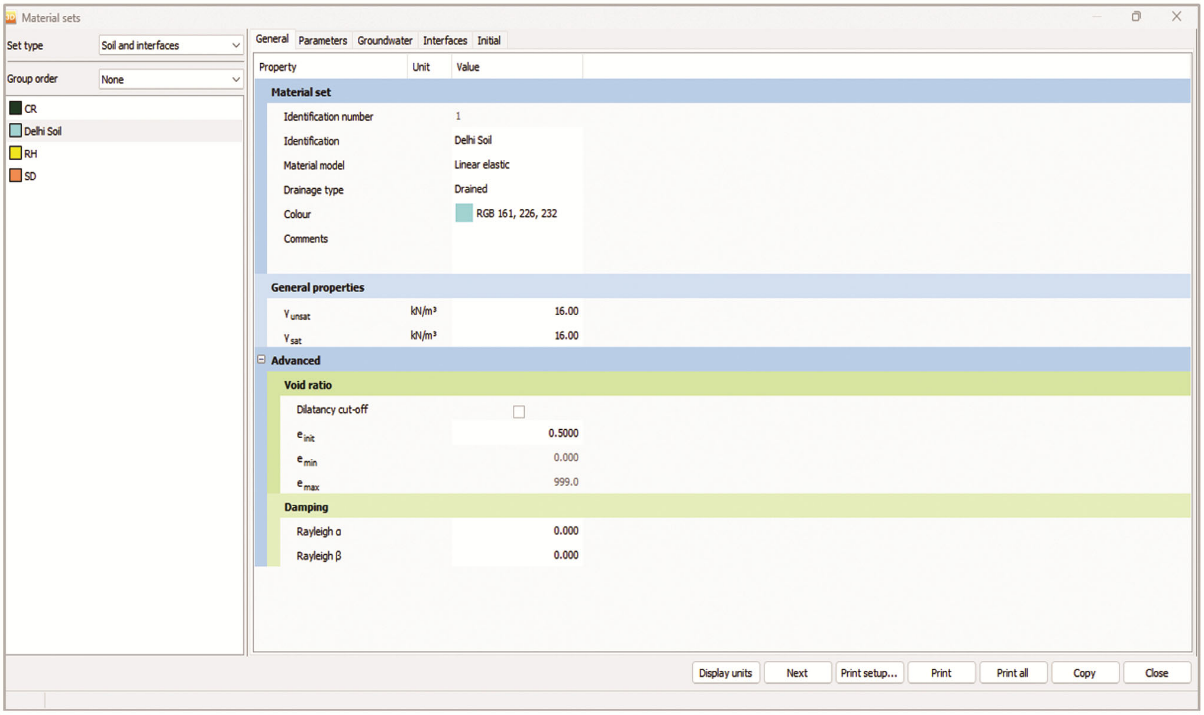
Fig. 2 — Model in Plaxis-3D for active isolation at (a) $X_1 = 2.5$m (b) $X_2 = 5$m (c) $X_3 = 10$m and Passive isolation (d) $X_{4} = 23.75$m

The depth of layer of subsoilis10m and the level of ground is kept a tz=10m. The data set related to material and half space elastic parameters are assigned as detailed in Table 1 and are assigned to subsoil layer and properties as depicted in Fig. 3. The water conditions are not considered.

Author's previous research[17] may be referred by readers for material parameter assumptions and properties. A sinusoidal varying vertical downward load of magnitude P_0=1kN and excitation frequency of 10Hz and amplitude of 10N/mm^2 is assumed to act on imaginary footing uniformly of width, B=0.50m. Footing mass is kept ignored as effect on isolation effectiveness of a barrier is not significant[16]. Parameters of Half-space, excitation frequency, shear wave velocity, Rayleigh wave velocity, Rayleigh wavelength of half-space, density, Poisson's ratio, material damping and elastic modulus of backfill materials are tabulated in Table 2[18].

2.1.3 Normalized dimension study

Geometrical parameters such as distance from the source to the centre line of trench (l), depth (d) and width (w) are expressed in terms of Rayleigh wavelengths as; l = L. L_R, d = D. L_R, and w = W. L_R as shown in Fig. 4. Here, 'l', 'd' and 'w' are dimensionless quantities. Hence, the ratio (V_b /V_s) is used to describe the effect on properties of the in-



Set type: Soil and interfaces
Group order: None

- ■ CR
- ■ Delhi Soil
- ■ RH
- ■ SD

Property	Unit	Value
Material set		
Identification number		1
Identification		Delhi Soil
Material model		Linear elastic
Drainage type		Drained
Colour		■ RGB 161, 226, 232
Comments		
General properties		
γ_{unsat}	kN/m³	16.00
γ_{sat}	kN/m³	16.00
⊟ **Advanced**		
Void ratio		
Dilatancy cut-off		☐
e_{init}		0.5000
e_{min}		0.000
e_{max}		999.0
Damping		
Rayleigh α		0.000
Rayleigh β		0.000

Fig. 3 — Material properties used in FEM model study.

Table 2 — Properties of Back filled materials

Name of backfill material	Density (g/cm^3)	Poisson's ratio	Damping %	Elastic modulus kN/m^2
Crumbed Rubber (CR)	0.37	0.45	22.00	10.53×10^2
Rice Husk (RH)	0.33	0.40	20.00	3.64×10^2
Saw Dust (SD)	0.23	0.37	12.40	3.71×10^2

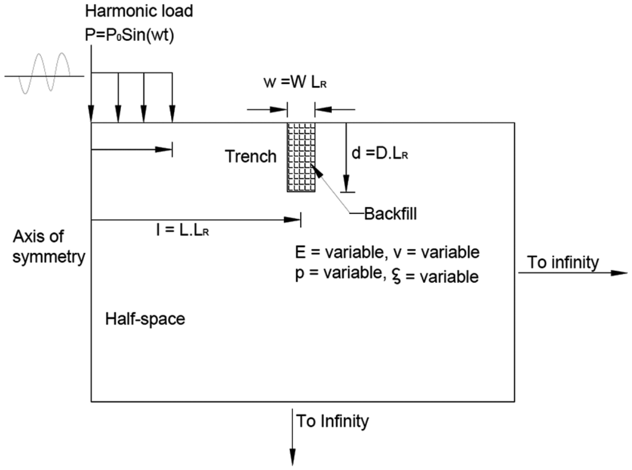


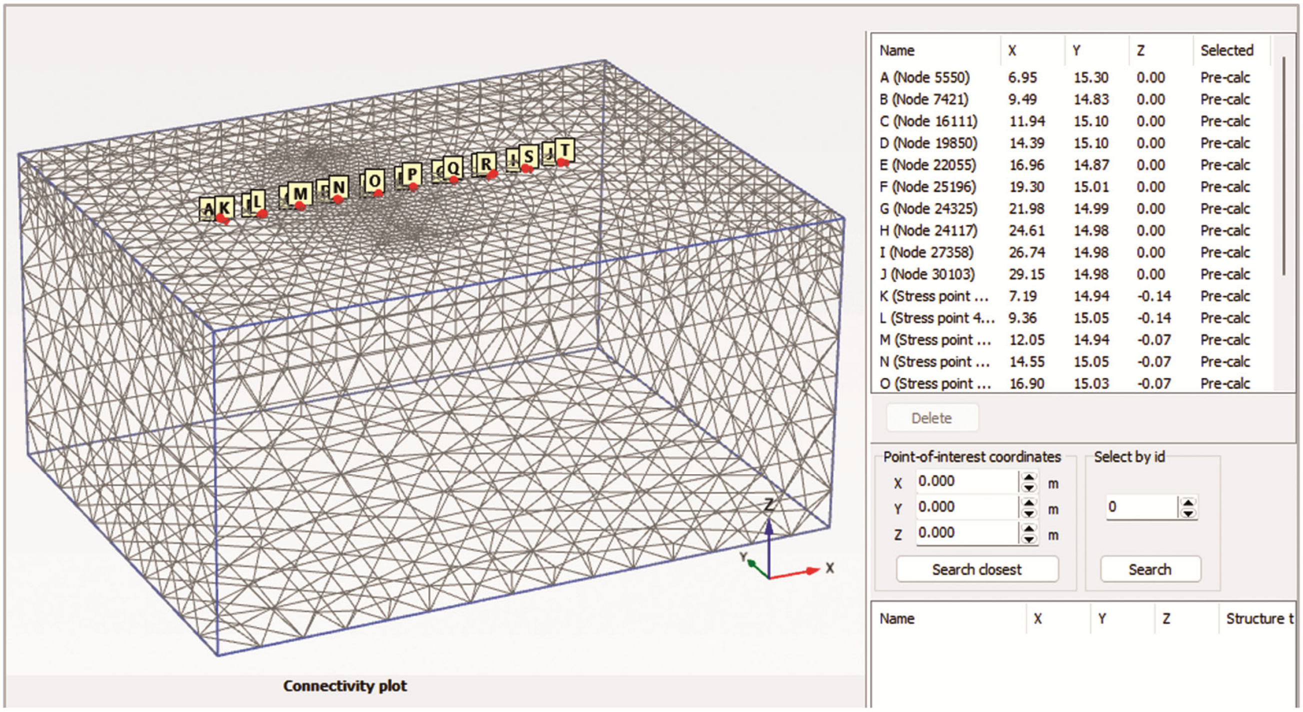
Fig. 4 — Schematic view of the case under consideration showing active and passive vibration screening by rectangular trench system and geometrical parameters.

filled materials under investigation. The factor, damping of the in-filled material is applied according to the availability of test results. The shear wave velocity depends on elastic modulus, density and Poisson's ratio. It means, change in parameters of these will change shear wave velocity. Shear wave velocity of in-filled materials is varied by varying its elastic modulus without changing the parameter of others.

2.1.4 Finite element model and Validation

The finite element model for the study was prepared in PLAXIS-3D in an area of dimension 40mx20m discretized with 10 nodded triangular mesh elements. The zone extending up to a distance of $10.L_R$ from the wave source is considered sufficient for the wave barrier analysis. For frequency-dependent Rayleigh wavelength, critical zone extends to 40m from source. This reason for choosing a slightly longer length for model is to avoid phenomenon of interference caused by reflection of waves at boundaries. The sufficiency of model dimension is based on a convergence study in which an undisturbed half-space is subjected to steady state excitation of known frequency and magnitude. Model tests are repeated with different dimensions. The convergence nature of plot of maximum particle displacement versus distance from the source gave the conclusion for adopting dimensions of 40m×20m finally. Standard fixations are assigned to model boundaries in which, horizontal fixations ($u_x = 0$) are applied to the symmetric edge and the right boundary and total fixations ($u_x = u_y = 0$) are applied to the bottom boundary. Special absorbing boundary conditions available in PLAXIS are applied to bottom and right model boundaries to allow for the absorption of dynamic stresses. The absorbing boundaries are associated with dampers by Lismer and Kuhlemeyer. On the basis of previous studies, wave relaxation coefficients assigned to these boundaries to adequately absorbing compression and shear waves are assumed to be $C_1 = 10$ and $C_2 = 0.25$. The convergence study also shows that wave relaxation coefficients applied to absorbing boundaries results sufficient wave absorption.

A linear elastic material is assumed in modelling soil and in-filled materials, where material type is considered drained. Material damping to the half-space and in-filled material is applied by taking Rayleigh mass and stiffness matrix coefficients (α and β). Meshing is performed through intermediate elements with local refinement along surfaces and within the in-filled materials. Local refinement tools allow further refinement of the mesh elements, ensuring higher accuracy. Since axi-symmetric model is used, a steady state excitation with magnitude of 1kN/m at frequency of 10Hz is applied over half the expected foundation width. Time interval of 0.5seconds is considered for dynamic analysis and integration time step (δt) remains at 0.0005 seconds with the calculations performed for a total of 1000 steps. The time interval selected is adequate for complete passage of the disturbance within study zone. Maximum surface displacement amplitudes are computed from the displacement time history at selected nodes with an interval of $0.5.L_R$after trench barrier. A schematic diagram representing the case and developed FE model with generated mesh, boundary conditions, dimensions, etc. are shown in Fig. 4 and Fig. 5.



Name	X	Y	Z	Selected
A (Node 5550)	6.95	15.30	0.00	Pre-calc
B (Node 7421)	9.49	14.83	0.00	Pre-calc
C (Node 16111)	11.94	15.10	0.00	Pre-calc
D (Node 19850)	14.39	15.10	0.00	Pre-calc
E (Node 22055)	16.96	14.87	0.00	Pre-calc
F (Node 25196)	19.30	15.01	0.00	Pre-calc
G (Node 24325)	21.98	14.99	0.00	Pre-calc
H (Node 24117)	24.61	14.98	0.00	Pre-calc
I (Node 27358)	26.74	14.98	0.00	Pre-calc
J (Node 30103)	29.15	14.98	0.00	Pre-calc
K (Stress point ...	7.19	14.94	-0.14	Pre-calc
L (Stress point 4...	9.36	15.05	-0.14	Pre-calc
M (Stress point ...	12.05	14.94	-0.07	Pre-calc
N (Stress point ...	14.55	15.05	-0.07	Pre-calc
O (Stress point ...	16.90	15.03	-0.07	Pre-calc

Point-of-interest coordinates
X 0.000 m
Y 0.000 m
Z 0.000 m

Select by id
0

Name	X	Y	Z	Structure t

Fig. 5 — View of deformed mesh with selected nodes and stress points for observation.

This modelling scheme is checked taking an example of an isolation as an open trench with2m depth, 0.25m width and 14m length. The dynamic load run for every case of an open trench, trench with Crumbed rubber, Rice husk and Saw Dust with 5 nos. of frequencies and 4 nos. of locations. The vertical dynamic load run with frequency of 10Hz, 20Hz, 30Hz, 40Hz and 50Hz. The source of dynamic load was located at 4different distances i.e. 2.5m, 5.0m, 10m and 23.75m from centre of trench. Amplitude reduction factors at these locations are in close agreement as found in experimental one[19]. Figure 6 showed the Colour contouring for deformation in in-filled trench with Crumbed rubber as a typical case example.

2.1.5 Effectiveness of vibration isolation

The efficiency of screening through trench wave barrier is calculated using amplitude reduction ratio (A_r). Amplitude reduction ratio is defined as the ratio of the surface displacement amplitude producing after the barrier ($A_{r(after)}$ to the surface displacement amplitude before the trench wave barrier ($A_{r(before)}$. As a whole, the screening level over the zone under study is expressed as the average amplitude reduction ratio, since the amplitude reduction ratio values are non-uniform over the zone. It may be defined as the weighted average of the A_R values measured at specified observation point along a line from the source (L) over the zone of interest. Low value of weighted average values indicates higher efficiency.

$$\mathrm{Ar} = \frac{\text{Displacement amplitude of ground surface after barrier}}{\text{Displacement amplitude of ground surface before barrier}}$$

$$\mathrm{Ar} = \frac{(\mathrm{Ar})\mathrm{after}}{(\mathrm{Ar})\mathrm{before}} \quad \ldots (1)$$

To calculate the screening effectiveness of trench wave barrier system, the averaged amplitude reduction ratio (A_r) overaline consists of observation points under consideration, can be calculated as:

$$\mathrm{Ar} = \frac{1}{x}\int \mathrm{Ar}\,dx \quad \ldots (2)$$

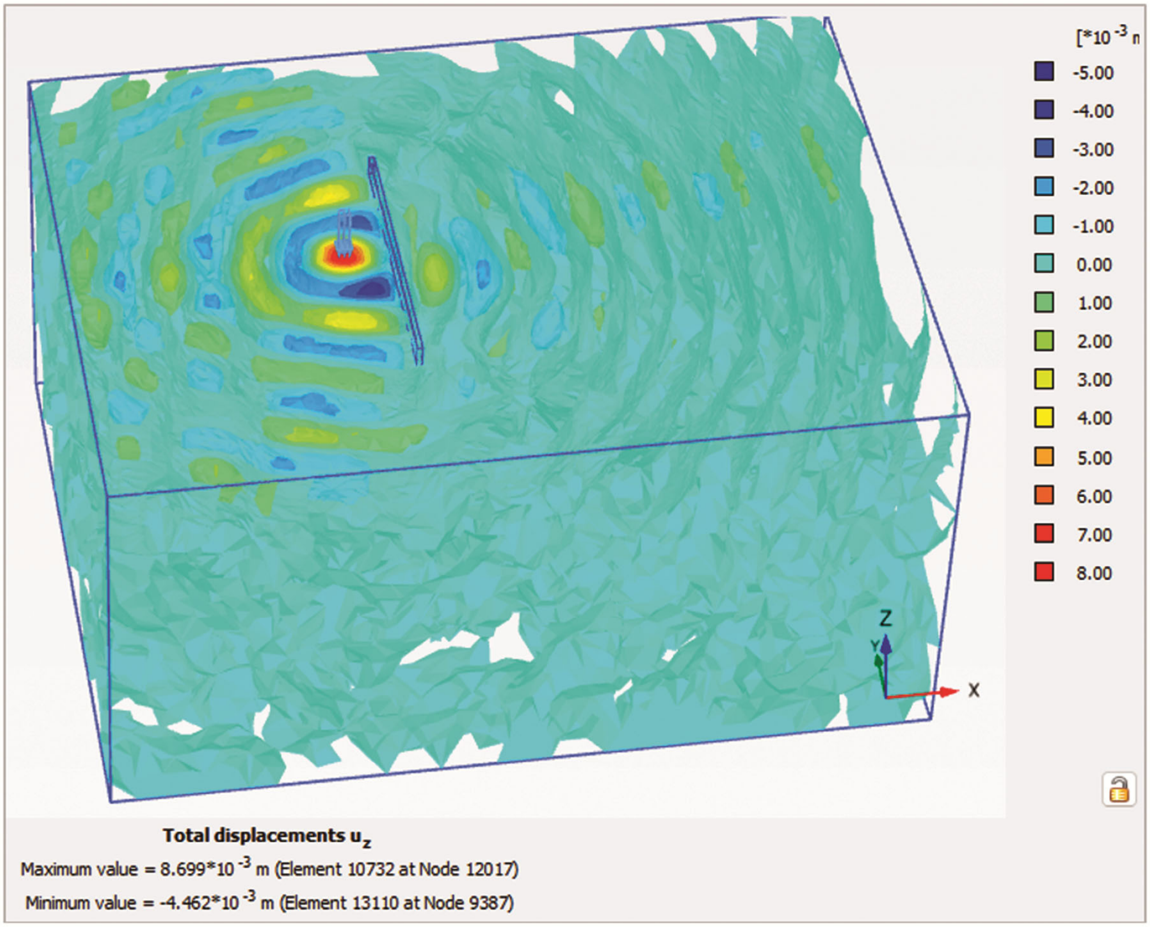
Thus, with the help of equation 3.3, efficiency of screening is calculated as follows:

$$\mathrm{Eff} = (1 - \mathrm{Ar})\ x\ 100 \quad \ldots (3)$$

2.2 Materials

2.2.1 Effects of various parameters on attenuation o wave motion

For performing a dimensionless parametric study, the geometrical properties are normalized with Rayleigh wavelengths. In the following sections, the notation U_x refer to represent the horizontal vibration



Total displacements u_z

Maximum value = 8.699*10^{-3} m (Element 10732 at Node 12017)

Minimum value = -4.462*10^{-3} m (Element 13110 at Node 9387)

Fig. 6 — Colour contouring for deformation in in-filled trench with crumbed rubber.

components and A_x to average amplitude reduction ratio of the respective component. As mentioned, in-filled geometrical properties and the shear wave velocity ratio are the parameters which determine screening efficiency of in-filled trench wave barrier. The influence of these parameters is discussed in the following subsections. Soft in-filled materials in wave barriers, with a shear wave velocity ratio less than 1, have shown to be much more effective than barrier with stiff in-filled materials.

The screening effectiveness of in-filled wave trench barrier chiefly depends on its wave attenuation properties. The wave attenuation properties are dependent on various factors as stiffness, density, specific gravity, particle size, degree of saturation. Dynamic properties such as damping ratio, shear modulus and shear wave velocity also affect the performance. Here, the case already explained in Fig. 3 is investigated for various factors affecting the screening performance. Unless otherwise stated, the soil properties and in-fill materials properties are as given in Table 2. There are few resources that provide much information on the dependence of factors on wave attenuation but here the influence of these factors on wave attenuation is discussed.

In the early phase of numerical investigation, the effect on overall area to be projected on the average amplitude reduction ratio is observed. Typical responses shown in Figure 9 and 10 convey the concept of normalized ground displacement amplitude. The variation between the amplitude curves subsequently indicates a significant reduction in amplitude achieved at subsequent observation points. For open and in-filled trenches of a given size with respect to normalized depth D and normalized width W, frequency range varied between 10Hz to 50Hz. Both in active and passive isolation, the propagated wave motion consists mainly of Rayleigh waves. Constructing trenches means producing a finite geometric or material discontinuity in wave path in undisturbed half-space. Available past researches, a qualitative description of the complex wave processes is discussed. Figure 7 describes Rayleigh wave propagating through trench. These waves when incident on trench, the following situation arises:

1. Reflected Rayleigh wave (R-wave)
2. Outward radiation of Body (P and S) waves from trench
3. Transmitted R-wave

Body wave propagation can be understood in dividing it in two sub-groups (a)Downward reflected body waves towards source of radiation and (b) Transmitted body waves which propagate away from source of radiation. Energy in transmitted R-waves and body waves (shown by double arrows) are responsible for vibration in ground across the trench. The conversion of the energy of the R-waves into other waveforms (P and S) due to scattering by wave barriers is called mode conversion. After the trench, body waves are partially converted into R-waves due to increase in distance between trench and transmitted body waves. The functional difference between different types of trenches, it is mainly in the capacity of filled trench to pass (transmit) the incident waves into the in-filled material and into the screening zone. This is not feasible in case of an open trench. This causes in quite different pattern of wave reflection and mode conversion. These two phenomena determine the vibration isolation.

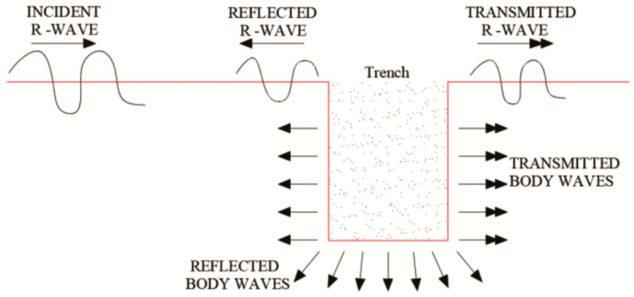


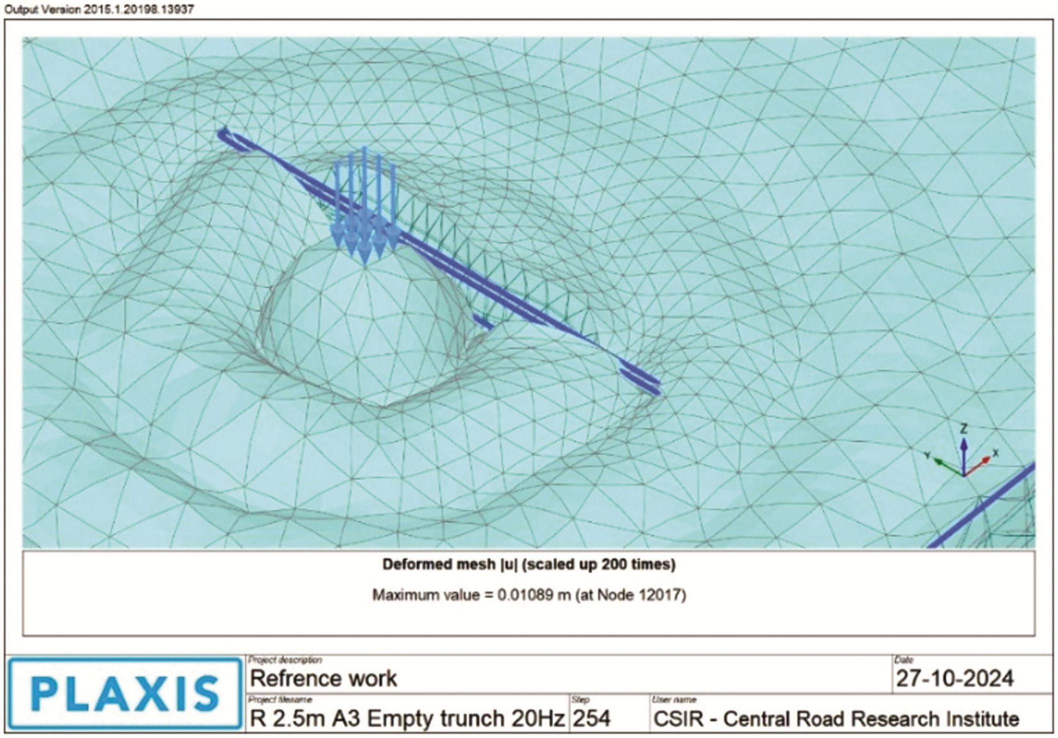
Fig. 7 — Generation of waves caused by incident Rayleigh Wave on Trench.

Figure 8 shows pattern of mesh deformed by dynamic load at $X_1 = 2.5$m.

As shown in Fig. 9, the comparison of displacement vs time histories at observation point G8 for active isolation at frequency (a) 20Hz (b) 30Hz (c) 40Hz & (d) 50Htz at the source vibrator location 2.5m from centre of trench is described as a case example. Also in Fig. 10, the Normalized ground motion (G10 to G3) due to exciting frequency of (a) f = 30Hz when source of vibration at (a) 2.5m (b) 5.0m and (c) 10m from centre of trench in active isolation is presented as a case example of the study.

3 Results and Discussion

In this study, an in-filled trench wave barrier rectangular in shape, in isotropic and homogeneous



Output Version 2015.1.20198.13937

Deformed mesh |u| (scaled up 200 times)

Maximum value = 0.01089 m (at Node 12017)

Project description: Refrence work

Date: 27-10-2024

Project filename: R 2.5m A3 Empty trunch 20Hz

Step: 254

User name: CSIR - Central Road Research Institute

Fig. 8 — Deformed mesh due to vibrational load $X_1 = 2.5$m.

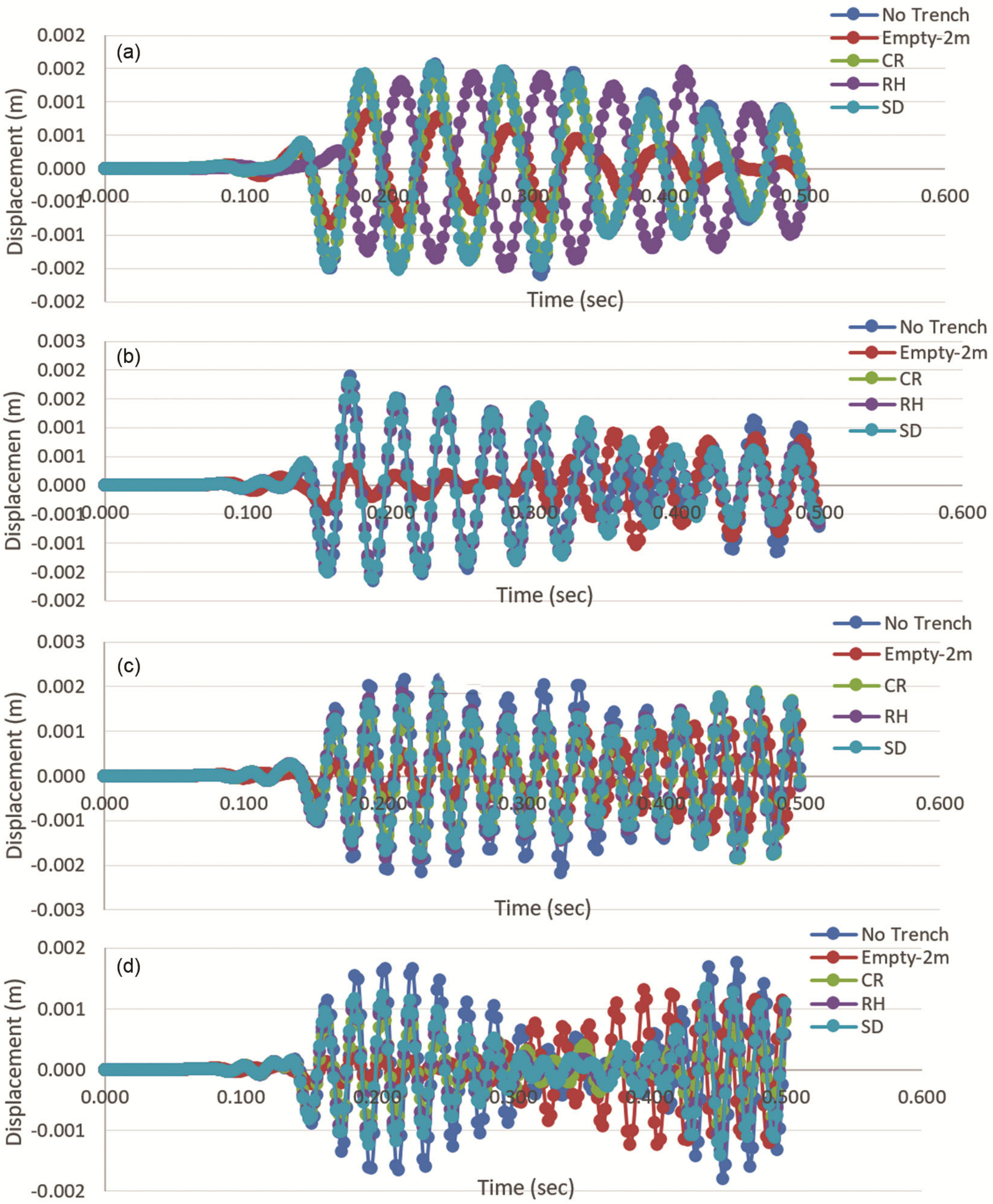


Fig. 9 — Comparison of displacement vs time histories at observation point G8 for active isolation at frequency (a) 20Hz, (b) 30Hz, (c) 40Hz, & (d) 50Hz at the source vibrator location 2.5m from center of trench.

elastic half-space in terms of amplitude reduction ratio is numerically investigated in a 3D context. Trench wave barriers with softer in-filled materials are considered under the study to provide a much better screening effect as compared to trench wave barrier with stiffer one. The important findings and outcomes of this study are presented here:

a An open trench can be observed to be special case of in-filled trench wave barrier with ratio of shear wave velocity of barrier with respect to soil i.e. $V_b/ /V_s \approx 0$. Attenuation of waves occurs only if there is a difference of stiffness exist either the in-filled material or soil in elastic half space. To obtain better screening effectiveness, shear wave velocity ratio $V_b/ /V_s$ of the in-filled to the surrounding soil be 0.3 or less. This may also be summarized that an in-filled trench wave barrier is capable of screening out vertical displacement amplitude with more efficiency.

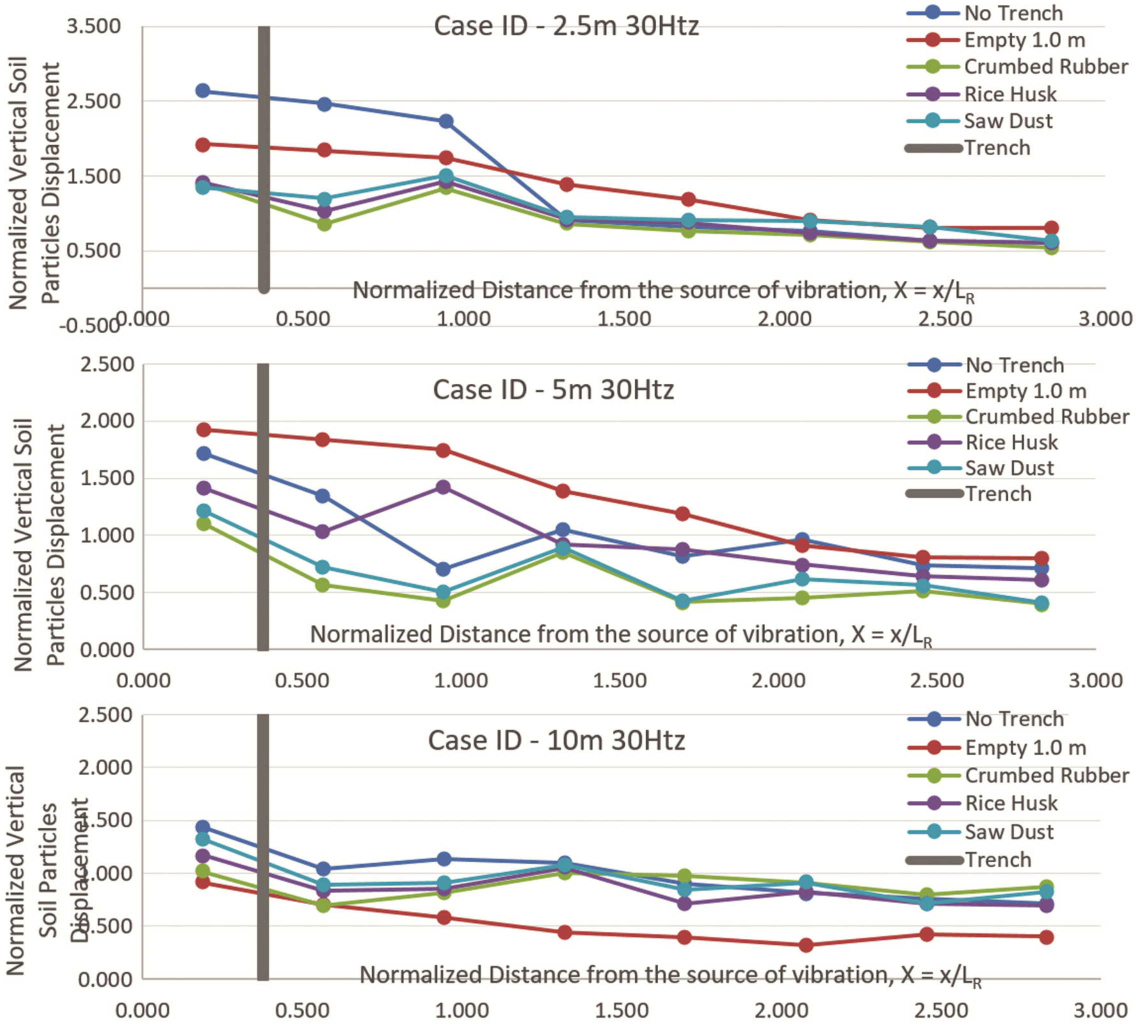


Fig. 10 — Normalized ground motion (G10 to G3) due to exciting frequency of (a) f = 30Hz when source of vibration at (a) 2.5m (b) 5.0m, and (c) 10m from center of trench in active isolation.

b Influence of location of the trench wave barrier on the screening efficiency depends on depth and width of the trench wave barrier and the vibration component considered.

c Decrease in amplitude cannot be achieved only by increasing barrier depth. To get the optimum screening efficiency, a specific trench depth must be associated with corresponding width and vice-versa. It confirms that D/W has a certain value around which a barrier with soft material produces optimum efficiency for both the cases of isolation whether active or passive.

d Based on the numerical study, three-dimensional colour contour map of the amplitude dissipation rates of the vibration.

e Response curves obtained after numerical investigation by using PLAXIS-3D show in agreement with the trend of experimental study.

f The results obtained from the finite element models are comparable to that of obtained experimentally with a difference of about 30% and 14% for open and in-filled trench barriers, respectively. The difference may be due to soil non-homogeny as well as imperfect bonding between the soil and the in-filled materials.

g Table 3 summarizes average protective effectiveness in case of open trench and different types of in-filled trench wave barriers as:

3.1 Comparison of Results

Past research shows documented results in case of softer trench barrier isolation are compared here with results obtained from the study and the charts as

Table 3 — Protective Efficiency of Barriers (%age) based on numerical study

Trench Type	1st Location	2nd Location	3rd Location	Average
Open Trench	44.41%	47.85%	48.28%	46.84%
Crumbed Rubber	54.11%	52.81%	52.96%	53.29%
Rice Husk	44.74%	49.98%	44.00%	46.24%
Saw Dust	49.68%	44.30%	43.55%	45.84%

Table 4 — Variable parametric values assigned in numerical modelling for parametric study:

S. No.	Properties	Parametric value-1	Parametric value-2	Parametric value-3	Parametric value-4
A	Open Trench:				
1	Poisson's ratio (ν)	0.300	0.400	0.480	-
2	Barrier Location (L)	2.500m	5.000m	10.000m	23.750m
3	Width (w)	0.250m	0.500m	0.800m	1.000m
4	Depth (d)	1.000m	2.000m	3.000m	4.000m
B	In-Filled Trench:				
1	Width (w)	0.250m	0.500m	0.800m	1.000m
2	Depth (d)	1.000m	2.000m	3.000m	4.000m
3	Stiffness (E)	25kN/m^2	20 kN/m^2	15kN/m^2	-
4	Barrier Location (L)	2.500m	5.000m	10.000m	23.750m
5	Shear wave velocity Ratio (V_b/V_s)	0.200	0.400	0.600	-
6	Poisson's ratio (ν)	0.300	0.400	0.480	-
7	Density ratio (ρ_s/ρ_b)	1.250	0.800	0.600	-
8	Damping ratio (ξ)	5%	10%	15%	-

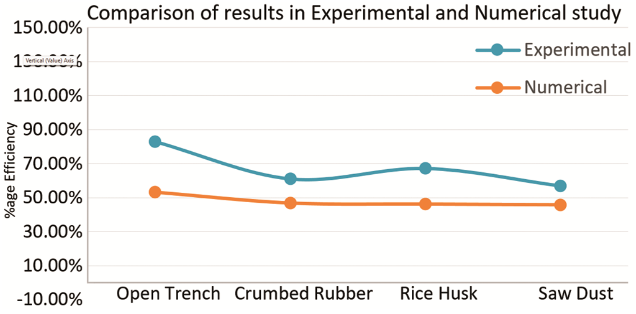


Fig. 11 — Comparison of results from experimental vs numerical investigation in determining the efficiency of in-filled materials.

refereedin Fig. 11. It is evident that the results provided qualitatively is in agreement with the published results. Fig. 11 shows that there is a variation of about 19-23% in the results of experimental and numerical study. The difference may be due to practical aspect of the ground the practices implemented during experimental study. Overall, both the result some similar conformity and validating both the studies.

3.2 Parametric Study

The case described in Fig. 4 is further subjected to parametric study by changing the values of key parameters used in above study which influences the performance of in-filled materials from major to minor extent. The dimensionless parametric study is performed where geometrical properties of the trench barrier are normalized with Rayleigh wavelength of oscillation in an elastic half space. This will eradicate dependency of the operating frequency and elastic half space parameters. Parameters were normalized as $L=l/L_R$, $D=d/L_R$ and $W=w/L_R$, where L, D and W are the dimensionless quantities represented with respect to Rayleigh wavelength and represents location of the source, depth and width of trench normalized against Rayleigh wavelength. The basic assumptions and the geometrical properties required in modelling, assigned as detailed given in Table 1 and Table 2. The parametric values assigned in parametric study to study the changes are tabulated in Table 4 as below:

In the succeeding sections, only vertical vibration components and average amplitude reduction factors of the respective component is taken into consideration. It has been found that as a whole, running of all the tests for all cases of trench wave barriers with in-filled materials at all operating frequencies range, is quite cumbersome and tedious. So, considering the permissible time, the case of Crumbed rubber is picked as in-filled material case with source of vibration located at 5m from centre of trench and the operating frequency applied is 30Hz.

The case studies considered for parametric study are subjected for the above only. This case is specifically chosen for parametric study in view of quality of responses collected and overall efficiency of the in-filled materials.

In this part, comprehensive parametric study including the in-filled material properties of in trench wave barriers, the dimensions, the location of source of vibration, the damping ratio, etc. has been studied to find the effect of these parameters on the screening efficiency of trench wave barriers. It is to be kept in mind that when one of the parameters is studied, the other parameters remained unchanged.

3.2.1 Open Trench

3.2.1.1 Effect of Trench Dimensions

Dimensions of trench i.e. depth, width and cross-sectional area have influence on screening efficiency. The trench depth has significant effect on screening efficiency as compared to the width of the trench and both the effects have been studied. Cross-sectional features of trench barrier have influence and is studied by considering variation of amplitude reduction in case of trenches of different depth (d = 1.5m, 2.5m and 3.5m) and width (w = 0.25m, 0.50m, 0.80m and 1.00m). The study considered particular barrier location i.e. distance between centre of trench and source of vibration, L=5.0m representing active case.

The instrumentation and layout of observation points in the parametric study are depicted in Fig. 12. The installation detail of Geophones and the layout of positioning of source of vibration is also depicted. The influence of normalized width on amplitude reduction is certain to cases. Increase in normalized width up to 0.5m causes a limited reduction in amplitude. The pattern is somewhat lower when width varies from 0.6 to 1m and may be looked as a maximum limit of width of trench barrier after which a further increase in width affects amplitude reduction unfavourably in case of shallow trenches for cases of active isolation in particular. For all other cases, if the width is increased beyond 0.6mdo not results in any beneficial effect on amplitude reduction. Generally, beyond this limit, the effect of width of trench has little effect in attenuation of vertical displacements and can be avoided in all practical cases.

3.2.1.1 (a) Effect of Depth of Trench

The optimum effectiveness in screening for open trench is obtained at shallow depth whereas for trench of more width, the same effectiveness can be obtained at more depth. This means that with a view to obtain maximum screening effectiveness, a particular depth should be followed to a particular width and vice-versa. The response at different observation points is as shown in Fig. 13 for which the range of depth varies from 1m to 4.50m. By observing the width to the depth relation, it is found that with increasing depth, amplitude reduction ratio decreases until reach an optimum value. The width variation has shown a different phenomenon as expected. It is noted that at the lower value of width, higher depths are more effective rather than the shallow depth. As the width increases, the effectiveness become less significant. The phenomenon can be understood by the fact that thin trench barrier permits are markable portion of waves to transfer through it without any obstruction, causing decreasing effect on isolation. But in case of wider trench, it allows adequate waves to propagate along with periphery while travelling into the soil. The conclusion is that barriers of more depth results in reduction of amplitudes too slender barriers are not effective. Limiting depth is also very helpful and further increasing the depth will have little improvement.

3.2.1.1 (b) Effect of Width of Trench

The effect of trench width on reduction of amplitudes is investigated and is found specific to some cases only. As shown in Fig. 14, an increase in width up to 0.5m causes reduction in amplitude. The trend is somewhat lower when width varies from 0.6 to 1m and can be looked as a maximum limit of width of trench barrier after which a further increase in width affects amplitude reduction unfavourably in case of shallow trenches for cases of active isolation in particular. For all other cases, if the width is increased beyond 0.6m, it has not shown any betterment on amplitude reduction. Generally, beyond this limit, the width has little impact on wave attenuating and can be avoided at all.

3.2.1.2 Effect of Poisson's ratio of soil

Figure 15 depicts influence of Poisson's ratio of soil (v) on the effectiveness of an open trench. The variations are limited to very low, but no significant conclusion may be derived from the responses observed as shown in Fig.15. For Poisson's ratio ν_s=0.30, the normalized depth can be increased up to 2.0 for higher efficiency of vibration screening, while taking ν_s=0.40, normalized depth may be taken as 1.75 and lastly for ν_s=0.48, a depth of 1.5 seems to be

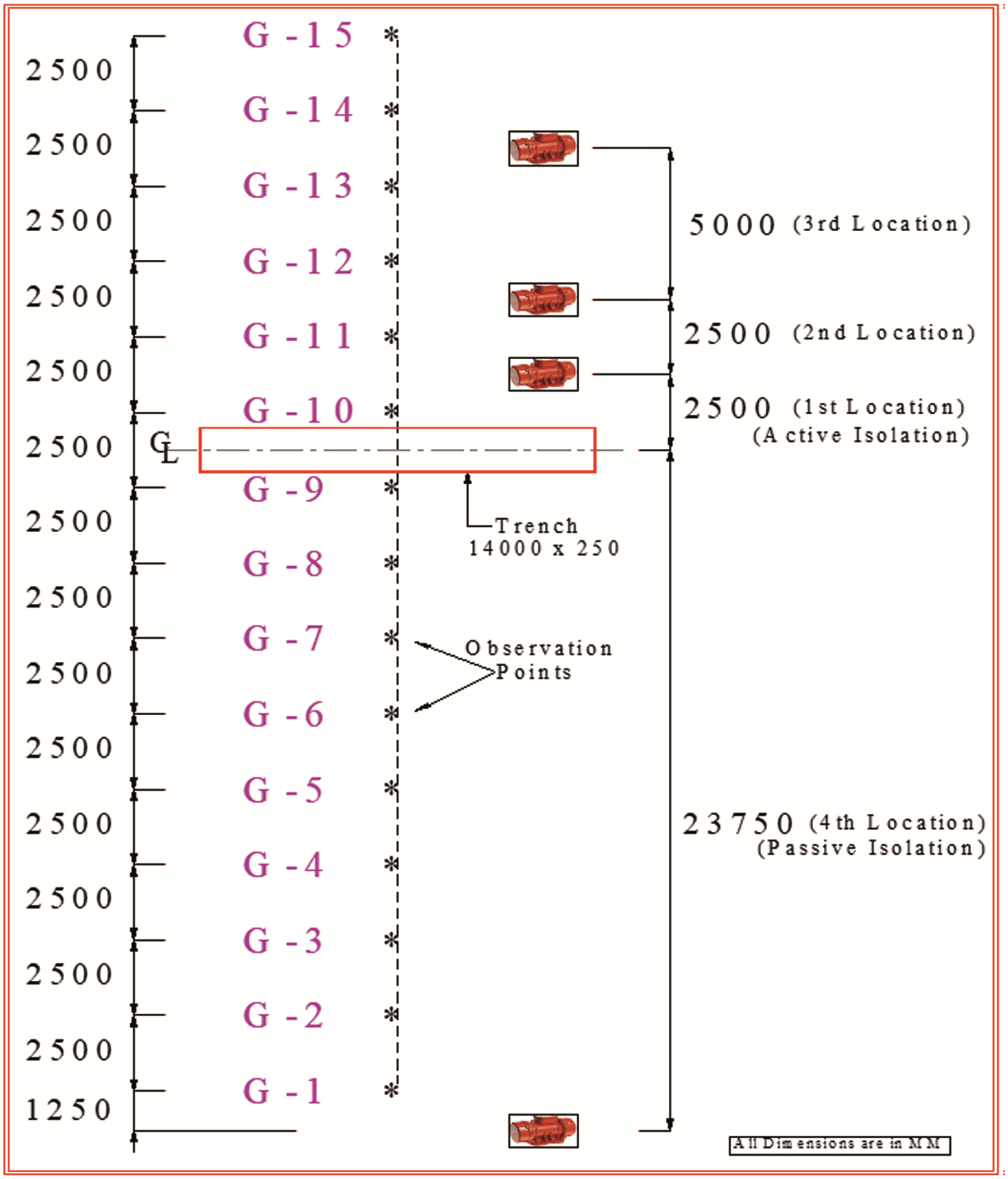


Fig. 12 — Layout and instrumentation detail showing locations of source of vibration and observation points.

the maximum one. The three values of Poisson's ratio taken in investigation, the reduction in amplitude reduction factor A_r varied up to 6%. Therefore, considering the soil's Poisson's ratio range from 0.30 to 0.48, the effect of v is ignorable.

3.2.1.3 Effect of location of barrier

The impact of source location i.e. distance between vibration source and centre line of trench is studied by amplitude reduction with reference to the responses as shown in Fig.16. The location of barrier from source is changed in case of active isolation from X=2.50m, 5.00m and 10.00m and in a passive case L=23.75m. The average amplitude reduction factors are observed at G6, G7, G8 and G9 location on centre line of layout. The variation of amplitude reduction ratio against barrier location (L) is shown in Figure 16 overall indicates that there is no monotonic variation for amplitude reduction while considering the active case locations at 2.5m, 5m and 10m. But while observing the response when location at 23.75m, it is found that the amplitude reduction is somewhat increased but not significant. This increase at 23.75m distance may be erroneous due to its farness where

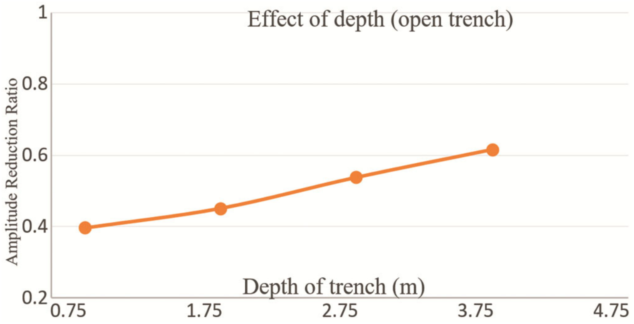


Fig. 13 — Effect of depth of trench barrier on amplitude reduction in open trench.

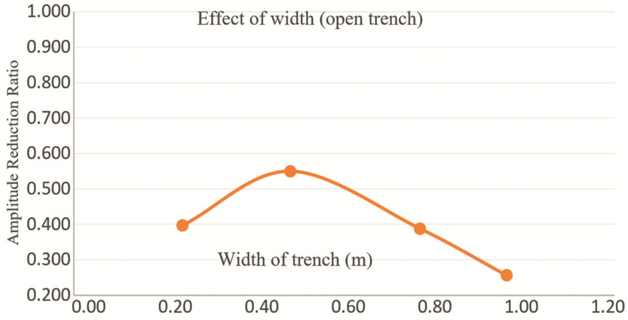


Fig. 14 — Influence of width on amplitude reduction ratio in case of open trench

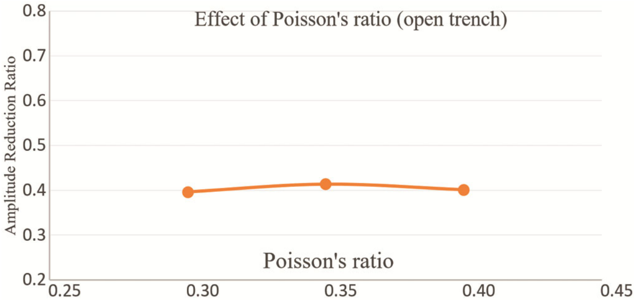


Fig. 15 — Effect of Poisson's ratio on amplitude reduction ratio for open trench.

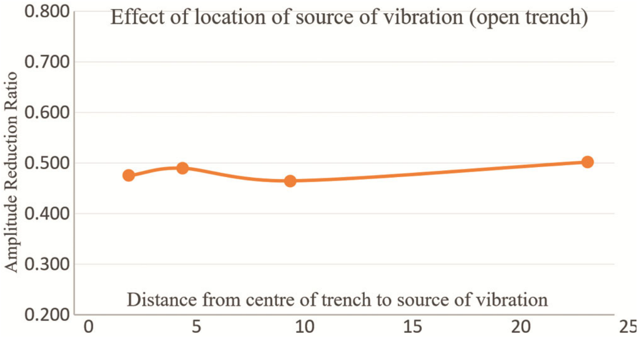


Fig. 16 — Effect of location of source of vibration on amplitude reduction ratiofor open trench

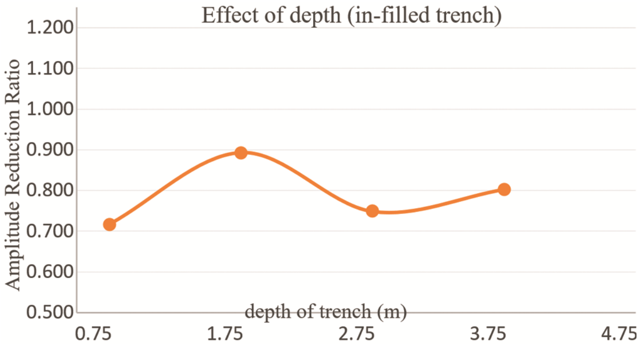


Fig. 17 — Effect of depth on amplitude reduction ratio.

some damping factors plays an important role in reduction of amplitude. It can be concluded that the location of source of vibration has no significant impact on amplitude reduction.

3.2.2 In-filled Trench

3.2.2.1 Effect of Dimension of Trench

Trench width and depth i.e. trench dimensions and related cross-sectional area is having effect on performance of the barrier for vibration screening. Depth of trench has significant influence on screening efficiency. The width of trench has lesser effect on screening performance of trench barrier and effects of both the parameters have been studied. The effect of in-filled trench barrier cross-sectional features with in-filled material as crumbed tyre rubber is studied. The trench with different depth and width (d=1m, 2m, 3m& 4m) and width (w = 0.25m, 0.50m, 0.80m and 1.00m) has been considered for the investigation. This study considers specific barrier locations i.e. distance between centre of trench and source of vibration which is X=5.0m representing active case.

3.2.1.1 (a) Effect of trench depth

Response in terms of amplitude reduction ratio in case of in-filled trench barrier with crumbed tyre rubber as in-filled material is shown in Fig.17. The effectiveness is observed at lower depth where as in case of wider trench, the same efficiency is achieved at higher depth. It states that to find out optimum screening effectiveness, a specific depth must be associated with specific width and in reverse. The vertical amplitudes at observation points G6, G7, G8 and G9 are shown and its inference is depicted in Fig. 17. The depth has been varied from 1m to 4m. By in sighting the relation of width to depth relation, with increase in depth, the amplitude reduction ratio decreases to an optimum value. The variation of width has shown a different aspect as was expected. It is found that at lesser width, higher depths are more effective as compared to shallow depth. With increase in width, the effectiveness decreases. This behaviour may be understood by the fact that narrow trench barrier permits a remarkable part of wave to propagate through it directly, causing low effectiveness. But for wider trench, it allows much more waves to travel along with boundaries during propagating into soil. Barriers with more depth contribute to higher efficiency.

3.2.1.1 (b) Effect of trench width

Effect of trench width on amplitude reduction is studied in case of in-filled trench wave barrier filled with material as crumbed tyre rubber and is found specific to some cases only. As shown in Fig. 18, an increase in width up to 0.65m causes reduction in amplitude significantly. The trend is somewhat lower when width varies from 0.70 to 1m and can be looked as a maximum limit of width of trench barrier after which a further increase in width affects amplitude reduction unfavourably in case of shallow trenches for cases of active isolation in particular. For all other cases, if the width is increased beyond 0.65m, it has not any benefit on amplitude reduction. Generally, beyond this limit, the effect of trench width has little significance in attenuating of waves results in amplitude reduction and thus, can be ignored at all.

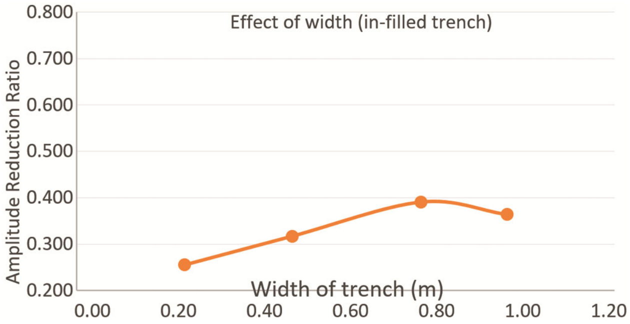


Fig. 18 — Effect of trench width on amplitude reduction ratio.

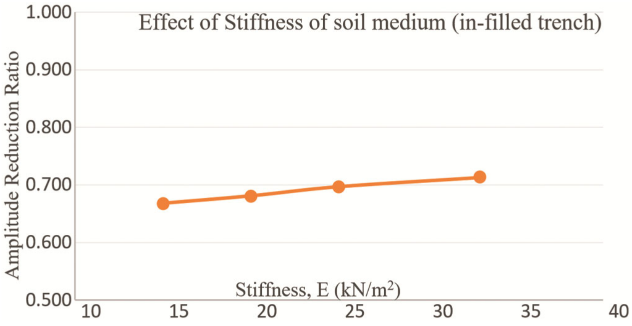


Fig. 19 — Effect of barrier Young's modulus on amplitude reduction ratio for in-filled trench.

3.2.2.2 Effect of Stiffness (Young's modulus) of in-filled materials

Figure 19 shows the responses and its inferences in case of in-filled trench barrier, received at observation points G6, G7, G8 & G9for determining active isolation performance when the frequency of the wave is at 30Hz and the source of vibration is kept at 5m from the centre of trench. Figure 19shows the effect of Young's modulus of material in barrier on vibration screening. The value of stiffness varied from 15 to 33 kN/m^2. It can be seen from the observation that when the value of stiffness is at lower value the reduction in amplitude is significant on higher side. It confirms with the conclusion that open trench barrier has the maximum isolation efficiency.

3.2.2.3Effect of barrier location

To investigate influence of location of barrier on amplitude reduction is varied in case of active isolation from X = 2.50m, 5.00m and 10.00m and X = 23.75m in a passive case and average amplitude reduction factors are calculated at G6, G7, G8 & G9. The change in amplitude reduction ratio against barrier location (X) is shown in Fig. 20. It indicates that, there is no monotonic variation for vertical response while considering the location at 2.5m, 5m and 10m. But while observing the response when location at 23.75m, it is found that the amplitude reduction is somewhat increased. This increase at 23.75m distance may be due to its farness where some other factors also play important role in amplitude reduction. It can be concluded that there is no significant impact of location of source of vibration on vertical amplitude reduction.

3.2.2.4 Effect of shear wave velocity ratio (Vb/Vs)

Stiffness of soil is defined by shear wave velocity. As soil's stiffness increases, the shear wave velocity also increases. Though, it has been expressed in past research that for better screening effectiveness, trench barriers should be softer than stiffer ones. Study of

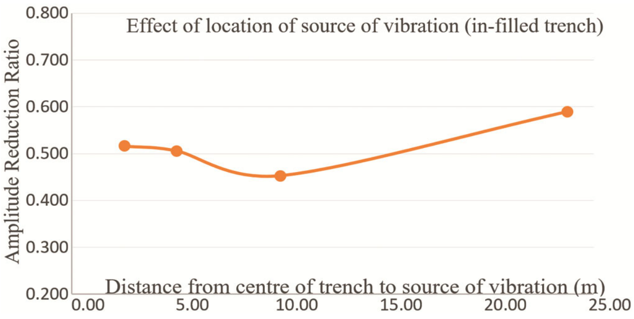


Fig. 20 — Effect of location of source vibration on amplitude reduction ratio.

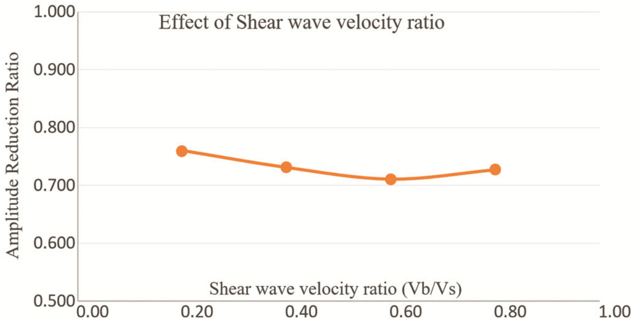


Fig. 21 — Effect of Shear wave velocity on amplitude reduction ratio for in-filled trench.

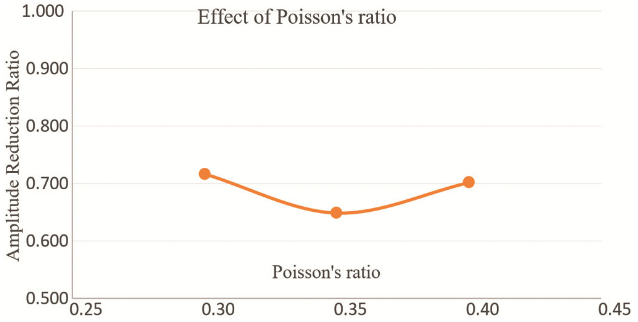


Fig. 22 — Effect of Poisson's ratio on amplitude reduction ratio.

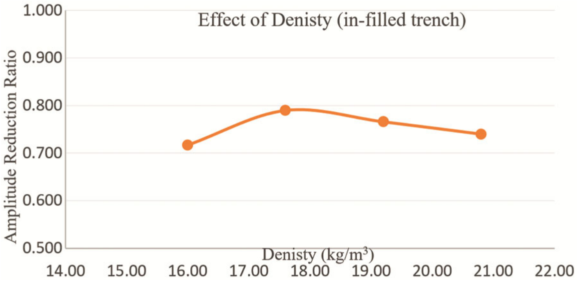


Fig. 23 — Effect of Density on amplitude reduction ratio for in-filled trench.

these cases has confirmed the selection of softer trench barriers in this investigation.

The trench considered, have a particular depth (d=1m), position (X=5m) and width (w=0.25m). As depicted in Figure 21, for softer barriers, shear wave velocity ratio (V_b/V_s) varies from 0.20 to 0.80. Shear wave velocity of in-filled materials is varied by changing stiffness while other parameters kept same. The influence of V_b/V_s on the amplitude reduction ratio is presented in Fig. 21. It is clear that to achieve attenuation of -waves, the backfill must have a different shear wave velocity and the material to be filled should softer than the half-spaces oil. This means that it is desirable that the barrier material's shear wave velocity be lower than that of the soil surrounding the trench. The amplitude reduction curve reaches a value of 1at $V_b /V_s = 1$, regardless of the trench geometries. This means that if the shear wave velocity of backfill is the same as that of half space, the insulation scheme will behave as if there was no trench barrier available barrier space. Other important finding is that vertical vibrations is screened more effectively. Nevertheless, screening efficiency of softer trench barrier is significantly higher than that of stiffer one. Therefore, softer in-filled materials with shear wave velocity ratio having value less than 1 is selected in this study. This is quite confirm that to achieve good degree of isolation, V_b /V_s of value taken about 0.30 is good choice.

3.2.2.5 Effect of soil's Poisson ratio

Figure 22 shows responses at observation points G6, G7, G8 and G9 and its inferences representing the effect of Poisson's ratio (ν_b) of the barrier on the screening effectiveness. This is clearly visible that vertical amplitude reduction ratio remains almost same as ν_b increases. The soil response at the observation point seems to be insensitive to the change in the Poisson's ratio of the barrier. To a conclusion, the effect of the Poisson's ratio of barrier on the vibration screening performance can be ignored.

3.2.2.6 Effect of density of soil

Fig. 23 depicts the responses at G6, G7, G8 and G9 observation points for indicating the impact of ratio of density ($\rho b/\rho s$, ratio of density of barrier to the soil) at the screening performance. The density of soil varies from 16kg/m^3 to 20.80kg/m^3. From Figure 23, it is found, in general, that the smaller the density of barrier is, the screening effectiveness of barrier is increased. On the contrary, the trench barrier with more density has a tendency to be effective up to a limit. When ρ_s is increased compared to ρ_b, the amplitude reduction ratio decreases to few extents. The reason may be that the vertical movement of barrier has a tendency to propagate the wave deep into the soil. Thus, more wave energy is utilized, causes good response in screening effectiveness. It is to be noted that in-filled material with high density will probable now no longer be considered, for example, whileρ_b is more than of ρ_s, it suggests that the barrier density is in excess of and such barrier in-filled material with huge density is not possible to achieve.

Table 5 — Protective Efficiency of In-filled barriers (%age):

Trench Type	In-filled materials	1st Location	2nd Location	3rd Location	Average
Open Trench	Open Trench	54.12%	52.80%	52.95%	**53.29%**
Crumbed Rubber	Crumbed Rubber	47.82%	44.40%	48.73%	**46.83%**
Rice Husk	Rice Husk	44.00%	49.97%	44.15%	**46.23%**
Saw Dust	Saw Dust	43.52%	44.30%	48.52%	**45.82%**

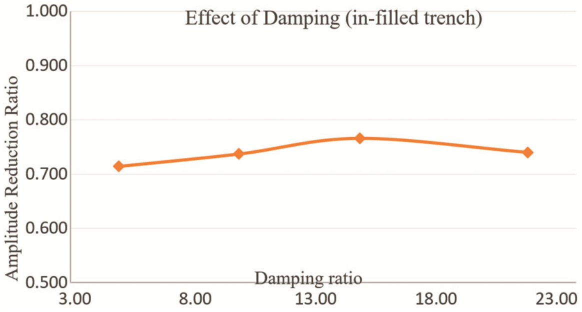


Fig. 24 — Effect of damping ratio on amplitude reduction ratio for in-filled trench.

3.2.2.7 Effect of barrier material damping

Figure 24 shows the responses due to effect of damping ratio (β_b) of barrier on the vibration screening effectiveness at observation points G6, G7, G8 and G9 and its inferences which indicates the effect of barrier damping ratio on the vertical amplitude ratio The behaviour observed in figures, amplitude reduces a little as β_b increases. Thus, influence of damping of material in barrier ratio can also be avoided.

3.3 Discussion

Vibration screening response of in-filled trench wave barrier, rectangular in shape in an isotropic and homogeneous elastic half-space is investigated numerically in PLAXIS-3D. Trench wave barrier is field with material as Crumbed tyre rubber, Rice husk and Saw dust as softer barrier taken into consideration offers higher screening efficiency than stiffer one. The observations are concluded as follows:

a An open trench can be considered as special case of in-filled trench wave barrier with $Vb/Vs \approx 0$. It is evident that attenuation of wave occurs only if the in-filled material is softer than the surrounding soils. To obtain better screening effectiveness, the shear wave velocity ratio V_b/V_s of the in-filled material be about 0.3 or lower. It can also be concluded that an in-filled trench wave barrier allows more effective screening.

b The influence of location of trench barrier on its screening effectiveness relies upon depth and width of barrier and the vertical vibration. Deeper (d ≥0.75) barriers have more effectiveness in passive isolation. The screening performance likely to decrease as width of trench barrier increases from 0.3m to 0.5m. Cases of exceptions exists for the shallow depth trenches (D=0.5) in which the amplitude varies in vertical is not realistic with location of barrier. And no firm remark can be made. Aside from D=0.5, the performance of screening will increase as much as L=2 to 3 and thus no change found.

c Based on the observation in vertical vibration, it can be assumed for the vibration in horizontal direction, in the passive isolation case, a better performance in screening is observed when there is a narrow trench (W=0.3), in such a case where the amplitude reduction ratio decreases with L, up to around 2 and remained unchanged afterwards. For trench with more width (W=0.5), the pattern is very irregular thus giving remark is difficult to present.

d When barrier depth is increased, the vertical amplitude does not necessarily reduce. A specific trench depth with width is associated are required to achieve optimal performance of screening against vibration in vertical direction and in reverse. There occurs a specific D/W ratio at which softer trench barriers, whether active or passive case yield optimum screening efficiency. It is found in most observation, this particular value of D/W is in the range of about 1.2 to 1.6. The influence of W is only noticeable in the active case and is almost meaningless in the passive case. In either case, W = 0.8 can be assumed as the maximum width of trench wave barrier, after which an increase has little or no effect on the amplitude.

e The %age efficiency of all the in-filled material derived is as shown in Table 5.

4 Conclusion

The Numerical validation for results obtained in experimental study is done and found that the variation is not beyond unreasonable limit. The effect of different parameters as frequency, amplitude reduction zone, trench dimension, location of trench barrier, Poisson's ratio of soil is studied. Properties of in-filled material as shear wave velocity, density and material damping has also investigated. Key findings are summarized as:

a For practical purposes, effect of Poisson's ratio of soil may be neglected.

b Influence of frequency of vibration is taken into consideration by normalizing dimensions of trench barrier with Rayleigh wavelength.

c In case of open trenches, depth is the deciding factor and the width is not so important if shallow depths trenches are considered.

d For in-filled trench wave barriers, depth and width both have equal significance.

e For in-filled trenches, influence of shear modulus and density of in-filled material also to be taken into consideration.

It is found in various practical cases, it may seem suitable to carry out a further detailed study of related trench barrier system. Optimum planning for depth of trench wave barrier w.r.t. depth must be carried out for each individual case.

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