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Experimental study for performance evaluation of in-filled materials in trench wave barriers for vibration screening

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Vibrations which have been caused by non-seismic factors as high-speed rails, highway traffic, construction activities, machine foundations, blasting, underground explosions, etc. have not been considered safe for human life and structures around. Vibrations which have been generated by these sources have caused of occupant discomfort, settlement and shaking of building foundations, structural and non-structural damages to adjacent buildings, malfunctioning of ultra-sensitive medical equipment, etc. Vibration screeners in form of open or in-filled trench wave barriers have been used to reduce the effects of vibrations. This paper has described an experimental study for evaluating the performance of in-filled materials in trench wave barriers in an elastic, homogeneous and isotropic half space. The in-filled materials used are as rice husk, crumbed tyre rubber and sawdust. Key properties of the in-filled materials are have also been determined by geo-technical characterization to ascertain its suitability in terms of properties of in-filled materials. The important factors such as material damping and boundary conditions of soil have also been included. The effectiveness of geometric dimensions of the trench wave barrier, shear wave velocity and location of source from the barrier have also been investigated. In this study, a dimensionless approach have been used, where the geometrical parameters have been normalized by one of the characteristics i.e. wavelength of Rayleigh oscillatory wave in elastic half-space. The influence of parameters related to vibration isolation has been discussed in detail. Recommendations have been provided for the optimal selection of the geometry of trench wave barriers.

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

1 Introduction

Reducing the amplitude of wave propagation is a solution to mitigate the vibrational effects caused by non-seismic factors as rail, high speed traffic on highways, construction activities, machine operation, blasting, underground explosions, etc. The present research study comprises of amplitude as the significant characteristics feature in study wave propagation. The reduction of amplitude of wave propagation can be achieved by (a) Changing frequency of waves caused by source of excitation, or (b) Shifting of vibratory component and changing orientation, or (c) Increasing the dissipation of wave energy in soil, or (d) Obstructing wave propagation path moving towards structure to certain extent

The local subsurface dynamic propagation behavior can also be changed through wave scattering and reflection and change of mode of vibration in the proximity of source of vibration. This can be achieved by constructing anti vibration trench wave barriers in the wave's path propagating from source of vibration to affected structure. These wave barriers can be placed near the source of vibration is called active isolation (isolation near source) and if the barriers are placed near the structure or around the structure intended to protect from the propagating waves, this isolation is termed as passive isolation (isolation away source). Thus, either active or passive isolation can be used to shield vibrations.

Ashref Alzawi and M. Hesahm E.I. Naggar[1] investigated vibration scattering through a study at test site for determining the trench wave barrier's performance in terms of % age screening efficiency. Open trench barriers, trench filled with geofoam were used to provide some insight and framework of guidelines to implement in design. Experimental

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studies were conducted for a selected number and type of trenches. The experimental survey included the investigation of screening efficiency of geofoam as in-filled material. Conclusions obtained from the field investigation has suggested that geofoam filled trench wave barriers can have substantial effect in reducing the transmitted vibrations. Dr. Arnab Sur[2] has studied the problem in subways. Their work includes calculations of dynamic loads generated by a moving train and wave propagation through the tunnel lining and soil. Their study found that ground vibrations in open ground depend on parameters such as distance from the tunnel, speed of the train, stiffness of the soil and depth of the tunnel. Ground vibrations are proportional to distance from tunnel, stiffness of the soil and depth of tunnel inversely, whereas they are directly proportional to the speed of the train. Tunnels in soils with SPT values above 40 usually do not experience significant vibrations. In the affected portions, vibrations can be mitigated by increase in depth of tunnel or by reduction in speed of trains. Ashwani Jain and D. K. Soni[3] presented a review of vibration isolation techniques applied to machine foundations. The available vibration screening methods for active isolation and passive isolation were internal balancing within the machine, isolation from remote locations, soil stabilization, shielding from interference etc. Javier Aviles and Francisco J. Sanchez-Sesma[4] studied the problem of wave barriers in underground explosions, which included a theoretical study of isolating foundation from effect of vibrations utilizing solid piles as wave barrier in trench. Two models were suggested, one for piles of infinite length and the other 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. Deniz Ulgen and Onur Toygar[5] studied the performance of open trenches, paying special attention to active and passive vibration control systems. Field results show that trench barriers are effective in form of open trenches as alternative vibration control system to achieve moderate efficiency. Vibration amplitudes generated by impact loads reach an average reduction of 50% at a trench depth of 4.5m. Active isolation is more efficient than passive isolation. G.L. Shivakumar Babu *et al.*[6] conducted vibration study with a vibration test chamber. Ankurjyoti Saikia[7] studied the behaviour of softer in-filled trench wave barriers of rectangular in shape in an elastic, isotropic and homogeneous space. How the shear wave velocity ratio affects the degree of insulation, was demonstrated. The screening efficiency is affected by barrier location, depends also on geometrical dimension of barrier as well as the vibration components. Barkan reported that attempts to isolate buildings from vibration caused by traffic by using open trench method and sheet pile barriers ended in failure. In addition, he reported several other cases where the use of shielding devices such as slag-filled trenches and sheet piles did not produce positive results. However, it was first attempted realization that the screening efficiency of a trench wave barrier is not so much governed by geometrical dimensions of the trench, but on its dimensions normalized by with the wave length of the propagated waves. Seyhan Firat *et al.*[9] presented a detailed study on reducing foundation vibrations due to harmonic loads generated by electrodynamic shakers using trench barriers. The efficiency of screening in case of open or in-filled trenches as mitigation measures has been explained. Although the open trenches have more effectiveness than in-filled trenches. But the practical application has limitation of very low depths and is not suitable for soil stabilization. The study had the objective to provide recommendation for design of anti-vibration measures by using trenches. K. R. Massarsch[10] addressed the development and propagation of anthropogenic vibrations in the surface of earth. Impetus was given on a simplistic approach to evaluate important most influencing factors such as attenuation of waves, focusing refraction and amplification of vibration due to resonance. Practical guidelines were presented to help predict ground vibrations and settlements. Semi-empirical relationships are proposed to assess the tolerable vibration levels for buildings. Lastly, a newly developed method for isolating ground vibrations, barrier in form of gas cushion screen was introduced.

2 Materials and Methods

2.1 Methods

In the study of trench wave barrier screening, realistic cases are often considered. This work consists of several steps which are explained here. In this chapter, the experimental study involves generating vertical harmonic vibrations with a frequency range of from 10Hz to 50Hz with the help of an electromechanical oscillator called a vibration source (SOV) and obtaining the response at a particular observation point using a geophone. Two foundations are erected at a distance where the Rayleigh waves dominate. The first foundation is used for generating harmonic loads by the oscillator and the other one is used for recording by the geophone and vice versa. As part of this experimental study, several field cases have been performed out to evaluate the performance of in-filled materials. To this end, the shielding efficiency of in-filled trench wave barriers with materials such as rice husk, crumbed tyre rubber and sawdust (materials softer than soil) is determined. The shielding efficiency of these materials used in trench wave barriers is determined by field measurements while comparing field data with in-filled materials and without materials in trench barriers. Two different methods for vibration isolation have been considered; active isolation and passive isolation. In active isolation, vibration source was placed close to the trench, at a distance of 2.5m, 5.0m and 10m from the trench centre line on one side of the trench. In passive isolation, the vibration source was placed on the other side of the trench, at an additional distance of 23.75m from the trench center line on the other side. Active isolation is appropriate when there is limited space between the vibration source and the structure, such as a rail track or adjacent building. Passive insulation is appropriate when there is no space limit, but access to that space is restricted.

2.1.1 Test site selection and preparation

The test site is a flat area within the office premises of CSIR-Central Road Research Institute (CSIR-CRRI), New Delhi as shown in Fig. 1. The soil was characterized as a non-plastic silty soil based on previous work at the site and after carrying out several tests during the experimental study. Data show that the soil at this location is identified as silty clay, clayey silt and sandy silt with a hard fine grained layer underneath. This section describes the experimental field work performed out to study the performance of in-filled materials by measuring the screening efficiency of an empty trench and of the trench wave barriers in in-filled trenches with materials such as crumbled tyre rubber, rice husk and sawdust. Furthermore, the effect of trench geometry and location of the vibration source in the trench on the separation efficiency was investigated. Furthermore, experimental parametric studies were performed to investigate the effect of different ratios between barrier depth and location (i.e., to investigate the cases of both types of vibration isolation). The results obtained from experimental investigations were analysed, compared and suggestions for its application in the design are provided. Furthermore, a numerical investigation in form of finite element model was developed to simulate the field study operations and compare with the field operations. The finite element model created was calibrated based on the field test results to ensure its usefulness in conducting comprehensive parametric studies aimed at improving the conceptual understanding behaviour of in-filled trench wave barriers with available in-filled materials and filling conditions.

Fig. 1 — Aerial view of test site location at CSIR-CRRI, New Delhi.

Bender element tests were performed on in situ soils to investigate the shear wave velocity (VR) of Rayleigh waves, also known as the propagation wave velocity or phase velocity, according to ASTM D8295. The low strain shear modulus (Gmax) of the soil was measured. G_{max} is an important soil property that helps understand the elastic behavior of soils and evaluate their response to dynamic loading such as earthquakes, vehicle passage, and vibrations. Bending elements test is used to study the nature of propagation of ground waves through soil samples and measure their velocity depending on their elastic properties. Sine waves cause bending deformations in the same direction, which also causes soil particle movement. The motion of the particle generates a shear wave (S), propagates to the other side of the sample and reaches it after some time. When the shear wave arrives, the receiving element (the element on the top cap) deforms, generating a corresponding electrical signal that is many times weaker than the electrical signal that initiated the wave. The running time is determined by synchronizing with an oscilloscope and comparing the two electrical signals (the triggered signal and the signal generated in response). Thus, knowing that the travel time is the distance between the peaks between the two elements, the shear wave speed Vs can be determined as

V_R= L / t, where 't' is the travel time and 'L' is the distance, the wave travels. L can be considered as the distance between the tips of the two bending elements (transmitter and receiver). The average calculated shear wave velocity generated is V_R = 198.65 m/s. The low strain shear modulus Gmax is then calculated using the equation $G_{max}=\rho Vs$, where ρ is the bulk density of the soil and its value is G_{max} = 12.14 MPa. The wavelength (L_R) of the Rayleigh wave can be calculated using the relationship between the propagation speed V_R and the oscillation frequency f, the equation $L_R = V_R / f$. The value of L_R depends on the operating frequency. Rector Mechanical Oscillator.

2.1.2 Field test procedure

Dynamic excitation in form of sinusoidal vertical harmonic load was generated with the help of an electromechanical oscillator (SOV). The load is a quadratic function and is featured by a harmonic force proportional to square of driving frequency of generated ground waves of different wavelengths. The initial stage of the test was to excite the ground with loads of different frequencies of 10Hz, 20Hz, 30Hz, 40Hz and 50Hz and measure the ground motion at designated locations before constructing the trench as shown in Fig. 2. A staged excavation technique with a depth of 0.40 m was used when excavating the trench walls. A JCB excavator with the required bucket width of 0.250m was used to check and maintain the vertical stability of the trench wall while digging. In second stage of test i.e. in case of empty trench, the ground was excited after the construction of the trench and seismic motion measurements were collected at the same selected locations and at the same frequencies as in the first stage. In the third stage, the empty trench was backfilled with filler materials such as rice husk, crushed tire rubber and sawdust, which were gradually compacted to an optimum density. After completing the compaction of in-filled material in trench, a harmonic excitation induced and response during ground motion measurements were collected at same frequency and designated locations. To evaluate the effectiveness of the system, the recorded time course of vertical soil particle displacements at recording points were transformed into the frequency domain, analyzed and is presented in the subsequent text.

Fig. 2 — Formation of trench at test site location with JCB excavator.

2.1.3 Instrumentation and description of test setup

In this field study, vibration dispersion was investigated using empty and filled trench wave barriers in trenches containing rice husk, crumbed tyre rubber and sawdust. All test parameters and test results are presented in non-dimensional form. A trench of length 14m, width of 0,25m and depth of 1m was constructed. The width-to-depth ratio of the trench walls is very small, so it is entirely possible to excavate such narrow trenches using conventional technologies. The trenches were excavated in increment of 0.40m using a JCB excavator. Multiple stability checks showed that stability was maintained at the intended depth. The level of water table was quite below and the soil nature ranging from stiff sandy silt to silty clay, helped in maintaining stability without collapse of trench walls. This meant that soil could be stimulated and responses were collected while there is an empty trench which had further helped in comparing the screening effectiveness of open and in-filled trench wave barriers under the same profile and test conditions of ground. The excitation source, an electromechanical oscillator (SOV) consisting of a vibro motor with an RCC foundation base, a speed controller in the form of a variable frequency drive (VFD) and associated electrical connections. The vibro motor consists of a motor with eccentric masses at both ends of the rotating shaft. An eccentric mass in the engine creates a harmonic sinusoidal excitation. The oscillator was capable of generating a sinusoidal force of 23.50kN peak-to-peak which was driven by a 3.0HP 220V three phase motor. The speed of motor was controlled by an AC drive of variable frequency to provide a stable operating speed between 5Hz to 50Hz. The vibration motor was installed on top of a cubic RCC block measuring 0.50m x 0.50m x 0.70m. The device for mounting the vibration motor to the block was pre-embedded in the concrete and integrally welded to the reinforcement cage of the concrete block before pouring. Design calculations for the concrete block foundation were performed taking into account the required force generation. The oscillator was capable of running at the maximum speed of 3000rpm at no load. To simulate the oscillator foundation and maintain the acceleration of system below 1g during excitation, the vibration motor was placed at the center of the top of RCC concrete block foundation, as depicted in Fig. 3 and Fig. 4. Thus, center of gravity (CG) of the electromechanical oscillator (point at which dynamic load is applied) was exactly above the geometric center of pedestal base. The plates were anchored as a unit using four threaded steel bolts which were embedded during concreting. To ensure proper placement of electromechanical oscillator and contact on the ground, the concrete block foundation was buried in the ground at a depth of 0.30m relative to the ground. The portability of oscillator was ensured by a tripod handled manually throughout the tests.

Five events of loading with different frequencies were used in this experiment. Frequencies selected at 10Hz, 20Hz, 30Hz, 40Hz and 50Hz. All geometric parameters of the experiment were normalized with wavelength of Rayleigh waves (L_R), which is a function of the excitation frequency. The resulting Rayleigh wavelength, the dimensionless shape of the barrier, and the distance between the vibration source and the trench barrier were calculated which is listed in Table 1 and shown in Fig. 5. The geophones (10Hz) were installed at observation points with a distance gap of 2.5m on a line perpendicular to longitudinal central axis of the barrier. The experimental setup and the geophone numbers are depicted in Fig. 5.

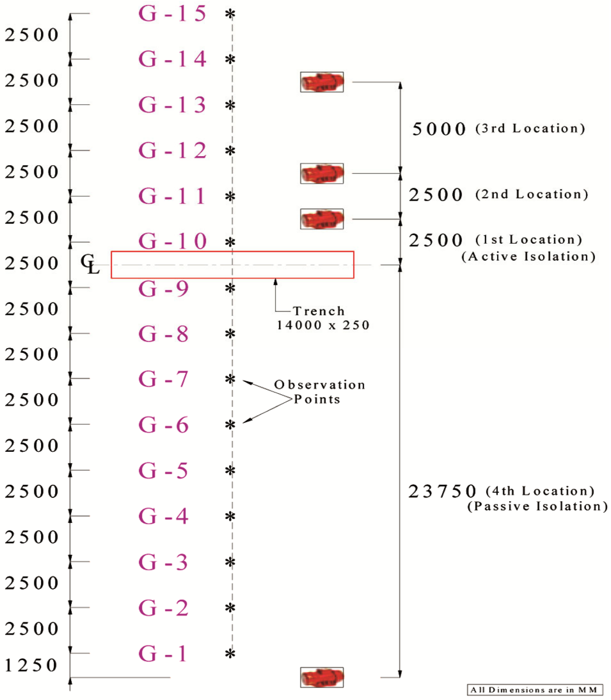

Fig. 3 — Experimental layout and instrumentation detail showing locations of source of vibration and geophones.

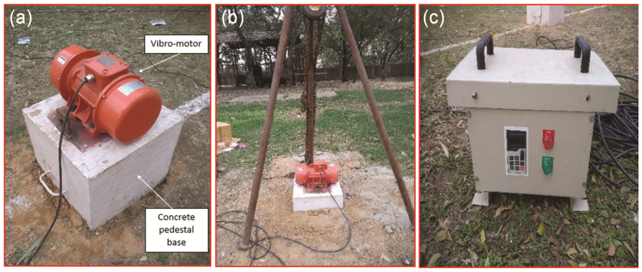

Fig.4 — View of (a) Electro-Mechanical oscillator, (b) tripod and (c) Variable Frequency Drive (VFD)

Table1 — Dimensionless geometrical parameters of experiment.

Frequency of exciter (Hz)	Rayleigh wavelength (m)	Barrier dimensionless or Normalized depth	Dimensionless distance between vibration source and wave barrier		
			1st location	2nd location	3rd location
	L_R	$D=d/L_R$	$X_1=x_1/L_R$	$X_2=x_2/L_R$	$X_3=x_3/L_R$
10	19.86	0.05	0.13	0.25	0.50
20	9.93	0.10	0.25	0.50	1.01
30	6.62	0.15	0.38	0.76	1.51
40	4.96	0.20	0.50	1.01	2.02
50	3.97	0.25	0.63	1.26	2.52

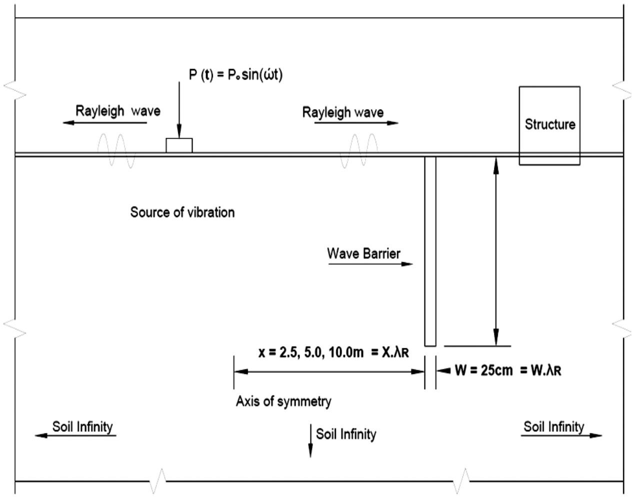

Fig. 5 — Schematic view of vibration screening system with geometrical parameters.

Geophones were communicated to a 32-channel OROS Data Acquisition system (DAQ). A laptop connected with DAQ was used to operate the acquisition system via NV Gate software. For each selected frequency, after the response had stabilized, soil particle amplitude and velocity measurements were recorded using the vertical component geophones for 5-10 seconds with a sampling interval of 1 milli second, resulting in 10000 data samples. To find the effect of proximity of interference sources to the screening system on its screening effect, three different locations were selected for the placement of the source of vibration i.e. at 2.5m, 5m and 10m from the center of the trench.

Measurements were performed at five excitation frequencies at each site under five conditions (no trench, empty trench, trench filled with materials such as rice husk, crumbed rubber and sawdust) as shown in Fig. 6 and Fig. 7. Table 2 shows the experimental parameters such as the geometric dimensions of the trench, the distance between source of vibration and interference source, frequencies of loading considered. Fig. 7 shows the trench after the trench formation was completed.

2.1.4 Measurements for vibration screening

Evaluating the performance of in-fill material in terms of screening efficiency depends on stiffness of the trench barrier in-filled material. It required a set of experiments were required to understand the nature of wave propagation and its characteristics. The test setup for both types of screening cases is shown in Fig. 8. The setup comprised of an electromechanical

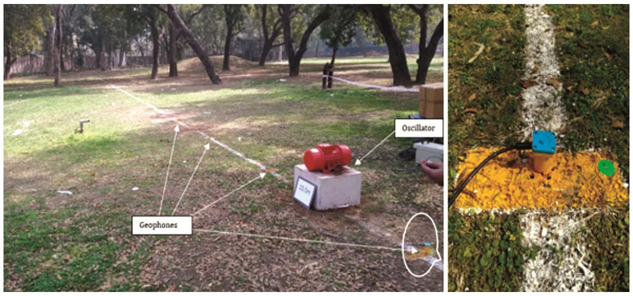

Fig. 6 — Instrumentation set up showing placement of Oscillator and installed geophones (inset).

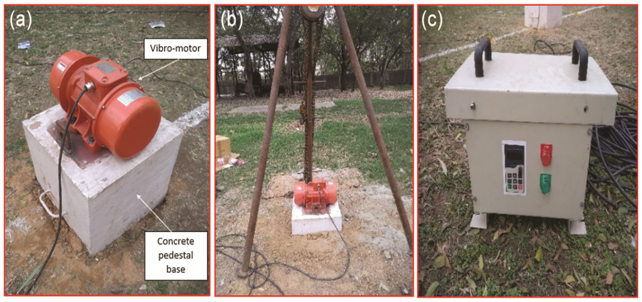

Fig. 7 — In-filled trenches with (a) Crumbed tyre rubber, (b) Rice husk and (c) Sawdust.

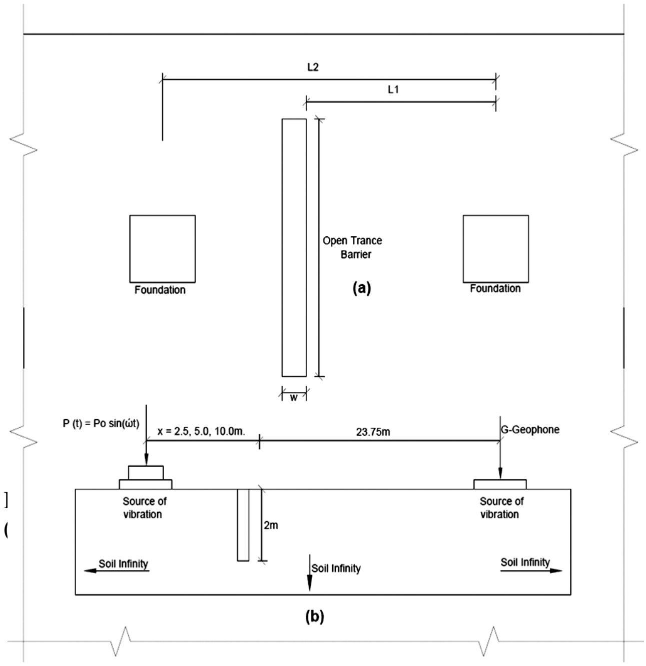

Fig. 8 — Experimental study model for both the isolation cases (a) Plan and (b) Sectional elevation.

Table 2 — Field test parameters.

Wave Trench Barrier width	w	0.250 m
Wave Trench Barrier depth	d	1.0 m
Distance of SOV and the trench	X	2.5 m, 5 m & 10 m
Operating Frequency	f	10, 20, 30, 40 & 50Hz

oscillator mounted on top of the RCC block foundation, the trench wave barrier, and 15 observation points on the centerline where geophones were installed to capture the response at these specific points. An electromechanical oscillator generating sinusoidal motion used in form of a steady source of vibration generating a maximum harmonic vertical force of 23.50kN and the practically range of frequency is of range from 10Hz to 50Hz. The excitation frequency was gradually increased in steps of Δf = 10Hz. The oscillator consists of a vibration motor mounted on an RCC block, placed in the center of a rigid rectangular foundation so that the vibration motor and the point i.e. center of gravity of the RCC block are coaxial, to excite only vertical vibrations. In this study, a rectangular trench of depth 1m, width of 0.250m and 14m long was excavated across the centerline. The power supplies installed in the foundation were installed at distances L_1 = 2.5m, L_2 = 5m and L_3 = 10m from the centerline of the trench for measurements in case of active isolation and passive isolation at a distance of L_4 = 23.75m across the trench. The response in vertical component of the harmonic vibrations is captured by a geophone located on the centerline, at a time interval of Δt = 0.0005s. The amplitudes and speed at exceptional remark factors are at once received from the obtained data. The screening efficiency of in-filled trench as compared to soil and the operating frequency range is investigated with the help of a screening barrier, particularly energetic and passive vibration isolation.

The energetic isolation instances had been investigated with the aid of using various the places of oscillator as 2m, 5m, and 10 m from the centre line of the trench barrier. The passive case has been studied with the aid of using the maintaining the oscillator at 23.75m from the centre line of trench. The parameters taken into consideration are depicted in Table 3. The time period of Rayleigh (L_R) wave of the produced vibration is important one element to decide the screening effectiveness of in-filled trench wave barriers, provided that minimal intensity of open trench ought to be at the least $0.6L_R$ at a factor $10L_R$ far from such trench for energetic isolation and 1.33 L_R for the passive while the size factor is placed at a distance among $2L_R$ and $7L_R$ from the wave barrier. The trench has constructed among $0.1L_R$ and $0.5L_R$ to perform such effective reduction in vertical displacement of soil[5,11,12]. The values of the implemented excitation frequencies on this take a look at and the combined Rayleigh wavelengths are given in Table 2 so that we can decide the most reliable geometric parameters of the barrier and common for a powerful safety and to keep away from the problems of their realistic packages including in-stability of soil excessive water table ranges and excessive cost.

2.1.5 Discussion for result

Geometry of the trench barrier has a significant effect on screening effectiveness, different tests were performed under the identical initial conditions and at the selected range of frequencies. The frequency of vibration is controlled using a variable frequency drive (VFD). To ensure that the accuracy and consistency of frequency of vibration at each of the test frequencies, the actual vibration frequency is checked with a vibrometer with an accuracy of about ±0.25 Hz before the response is recorded. Figure 9 shows time histories of soil particle displacements at frequency 30 Hz and the source of vibration is at 2.5m. The corresponding Fast Fourier Transform (FFT) of the signals received at the first stage on the ground at designated

Table 3 — Properties of In-filled material.

Property	Type of Materials			
	Rice Husk (RH)	Saw Dust (SD)	Crumbed tyre rubber (CR)	In-situ soil
Specific gravity	0.740	0.650	0.730	2.650
Field Density(kN/m^3)	3.857	2.976	4,215	15.230
Bulk density (kN/m^3)	3.300	2.300	3.700	13.200
Permeability (cm/sec)	0.010	0.016	0.031	0.006
Relative Density (%age)	19.210	40.440	36.080	28.783
Shear modulus (kN/m^2)	1214.00	1237.00	322.00	12140.00
Damping Ratio (%)	20.030	12.390	22.320	7.259
Poisson’s ratio	0.210	0.257	0.430	0.300
Young’s Modulus (kN/m^2)	3645.00	3712.00	10500.00	33200.00

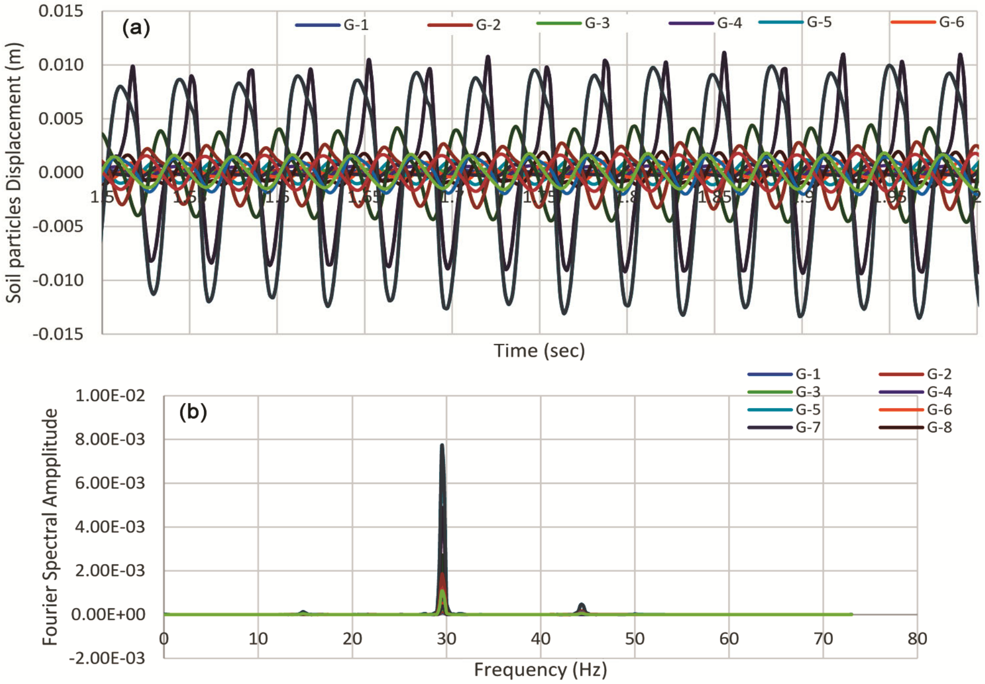

Fig. 9 — Displacement of soil particles during the 1st stage in time domain (a) Response at observation points in No Trench case when oscillator is at 2.5 m from trench and (b) corresponding FFT at exciting frequency of f = 30Hz.

observation points is also shown. The different channels used in the DAQ data acquisition system, shows the response at ground at locations of geophone on the specified points on center line. The results obtained shows signals of high quality for harmonic excitation at input of different frequencies, while the Fourier spectrum clearly shows that ground responses and the given dynamic load has the same dominant frequency.

2.1.6 Amplitude reduction ratio (A_r)

The oscillator simulating vibrations, resulting in a steady state response. The effectiveness of the screening system can be found out by observing displacement, velocity or acceleration in presence or absence of an anti-vibration trench wave barrier. In cases of published literature, the evaluation of effectiveness of the screening system is done based on reduced amplitude of soil particles. Generally, the impact of transmitted vibration is usually evaluated based on the soil particle velocity at the point of interest. Since a displacement transducer is used to measure the soil particle amplitude based on the vertical displacement, the effectiveness of the system can be represented by the reduction in the soil particle's amplitude. Thus, result is calculated in form of percentage of amplitude reduction (Ar). This is calculated by taking ratio maximum spectral amplitude after trench installation $(Ar)_{After}$ to the maximum spectral amplitude before trench $(Ar)_{Before}$. The maximum spectral amplitude can be found out from the Fourier curve created by applying Fast Fourier Transformation (FFT) to the time history record at point of interest. The % age of amplitude reduction is obtained from the following result:

$$\mathrm{Ar} = \frac{(\mathrm{Ar})\mathrm{After}}{(\mathrm{Ar})\mathrm{Before}} \qquad \dots (1)$$

To know the screening effectiveness of any particular type in-filled trench wave barrier system, the averaged amplitude reduction ratio (A_r) at a point of interest measured behind the wave barrier, can be calculated using the following equation:

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

The system effectiveness is then calculated by Equation 3.1 & 3.2 as follows:

$$\mathrm{Eff} = (1 - \mathrm{Ar}) \times 100 \qquad \dots (3)$$

2.1.7 Measurement of active isolation

The time series of vertical displacement as amplitude at observation points G1 to G15 for measurement of active isolation in the case when there is no trench, rectangular empty trench and in-filled trench with material whose properties are compared. Comparison of vertical displacement and time course for all cases at one of the observation points is considered in this paper. At G-8 for active isolation measures at excitation frequencies of 20Hz, 30Hz, 40Hz and 50Hz, when source vibrator is located 2.5m from Centre line of trench also is shown in Fig. 10. The pattern of wave propagation of transmitted vibrations is similar to those in the no-trench case for both the open and filled trench barriers. The amplitude reduction factor (A_r) is defined as the ratio of amplitude in vertical direction after the trench barrier to the amplitude without trench barrier. Effective shielding is present if the reduction factor calculated from experimental data for the applied excitation frequency is less than 0.6. The amplitude reduction factor A_r was calculated separately for all cases under different excitation frequencies. Spectral amplitude reduction factor (average) as a function of excitation frequency in case of active insulation with a vibration source at 2.5m.

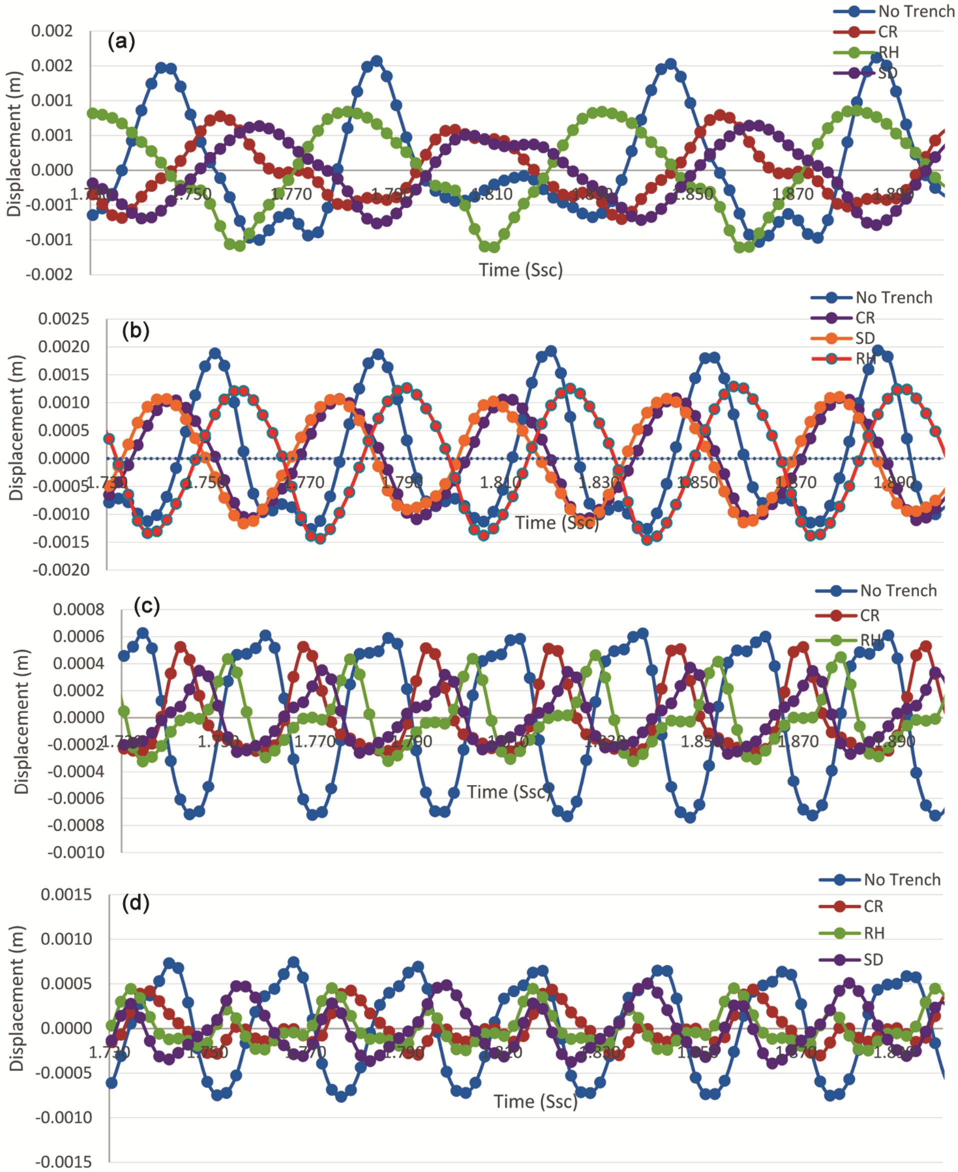

Fig. 10 — Vertical displacement vs time histories at observation point G8 in case of active isolation measurement due to frequency of (a) 20Hz (b) 30Hz (c) 40Hz and (d) 50Htz when the source of vibration is located 2.5m from centre of trench.

These reflects the change in vibration damping due to different filling materials. The average spectral amplitude reduction factor calculated as a function of excitation frequency of 10Hz, 20Hz, 30Hz, 40Hz and 50Hz with active isolation. Similar tests for location of source of vibration at 5m and 10m has also carried out and responses for the same has been collected.

2.1.8 Measurements for passive isolation

To perform measurements with passive isolation, the vibration source was installed on the other side of trench at a distance of 23.75m from the center of the trench. The observation points G1 to G15 are the same as for active isolation. The vertical response as amplitude over time at the observation points G1 to G15 for passive isolation measures without a trench, in a rectangular empty trench, and in trench barrier filled with material is compared. The comparison of vertical displacement vs. time history for all cases at the observation point G10 for passive isolation measures with operating frequencies of 20Hz, 30Hz, 40Hz, and 50Hz with the source transducer placed at a position of 23.75m from the trench center is shown in Fig. 11. Similarly, the comparison of vertical displacement vs. time for all cases at the observation point G11, G12 and G13 for passive isolation measures with operating frequencies of 20Hz, 30Hz,

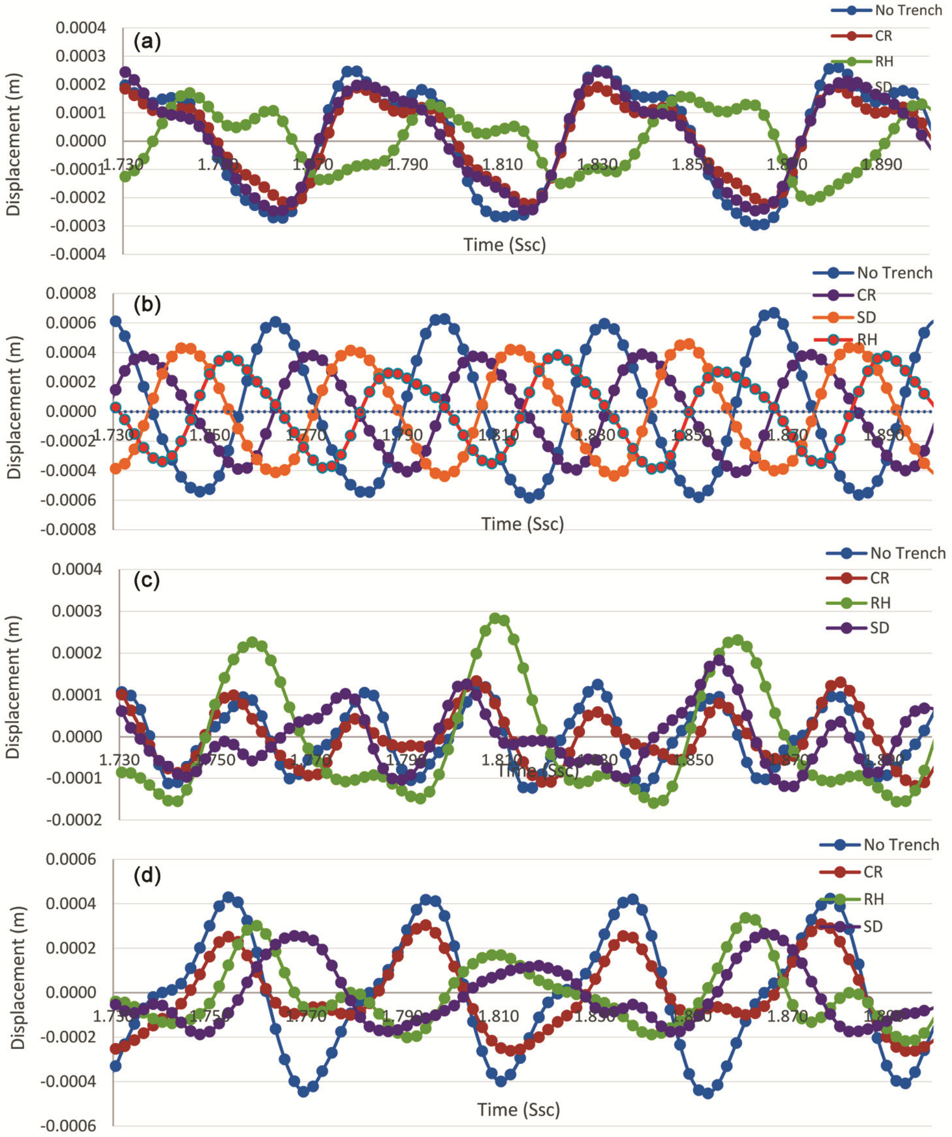

Fig. 11 — Comparison of the spectral amplitude versus time histories at observation point G10 in case of passive isolation measurement due to exciting frequency of (a) 20Hz (b) 30Hz (c) 40Hz and (d) 50Hz at the source vibrator location 23.75 m from centre of trench.

40Hz, and 50Hz with the source transducer located at a position of 23.75 m from the trench center. The wave propagation patterns of transmitted vibrations, both when the trench barrier is open and filled, are similar to that without a trench. The average amplitude reduction factor (Ar) under different excitation frequencies for the cases with and without a trench wave barrier with in-filled material were calculated separately.

2.2 Materials

Considering factors such as suitability for purpose, materials availability, type of waste, procurement, handling, etc., the following materials are selected for in-filled materials in present research work. The materials used for in-filled trench wave barriers are as shown in Fig. 12:

a. Crumbed Tyre Rubber (CR)
b. Rice Husk (RH)
c. Saw Dust (SD)

2.2.1 Crumbed tyre rubber (CR)

Crumbed Tyre Rubber (CR) is a black-coloured fibrous shaped recycled rubber in physical form that is produced using the scrapped car tyre. In the recycling process, its additives consisting of separating cord (fluff) of tyre with metallic wires, leaving rubber component with a fibrous granular consistency. In granulator, cryogenics or with the aid of mechanical means, the dimensions of debris are in addition reduced. Debris are separated further as consistent with length of fibrous grains and segregated at the fundamental standards which include color. The crumbed tyre rubber used on these studies observe has been gathered from recycled tyre manufacturing unit situated at Mayapuri Industrial area, New Delhi.

The manufacturing unit produces three distinct grades of the said crumb tyre rubber with a grading of 40, 20 and 16. The crumbed tyre rubber selected in present research work of the grade 20. Figure 13 shows generating process of crumb rubber from waste tyre while reducing into chipped tyre after which go through shredding. The form of this material is then sieved the usage of sieve device. By sieving, crumbed rubber and metallic cord are separated. In the present study, characterization of crumbed rubber has also been carried out to fix the suitability of material[9]. It is critical to notice that although the rubber from waste tyre is separated from its metal cord component, even some of metal dust might also additionally found in crumb tyre rubber under present process.

Due to the fact that tyres are an industrial waste product, researchers are interested in utilizing them: the improved energy dissipation and absorption properties of rubber can be used to manufacture barriers.

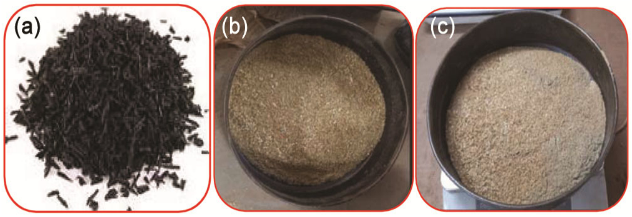

Fig. 12 — As in-filled material in trench wave barriers. (a) Crumbed tyre rubber (b) Rice husk and (c) Saw dust.

2.2.2 Rice husk (RH)

Rice husks are brown, flaky particles that cover rice grains. Rice husks are produced during process of rice milling and are already dried and collected at the mill or field. For a long time, rice husks were considered as a waste after rice milling operation and its disposal was a tedious task. Rice husks are easily, cheaply harvested and are therefore used as an energy source. They are made of hard organic materials such as lignin and silica that safeguards the seeds during the season of growing. Approximately 0.28kg of rice husk is produced from 1kg of milled white rice. In fact, rice husk is a by-product received after

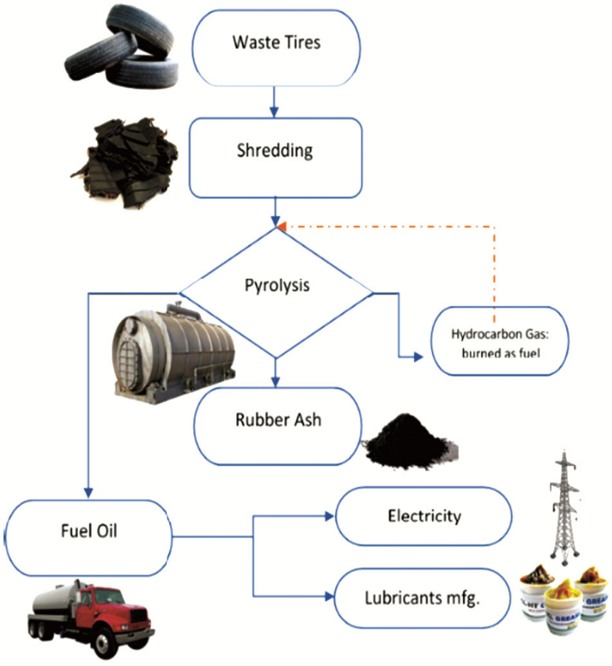

Fig. 13 — Typical layout for production of crumbed tyre rubber from scrapped tyre[13].

production of rice in milling operation. Common by products includes fuel (solid fuel, briquettes or pellets). Charred rice husk and rice husk ash are the by products resulting from combustion. Rice husk in its free state is primarily used for production of energy. With the compact form due to increased density of rice husk, rice husk briquettes or pellets are formed which have improvised combustion performance. Compressed rice husks are utilized in boilers which in turns helps in saving of fossil fuels.

2.2.3 Saw dust (SD)

Sawdust is dark brown in colour and angular in shape[14], is a waste or by-product of wood operations such as milling, sawing, sanding and planing. Most of the quantity is disposed off in the open which makes it an environmental pollutant[7]. It consists of small pieces of wood and fine wood powder. These operations are usually done with portable power tools or hand carpentry tools. In industries, sawdust may be a source of fire hazard and dust pollution in the workplace. The particles are the main component of chipboard. Swarf and dust, as explained above, are two waste products generated during wood processing. Dust is produced when wood cells are destroyed, whereas swarf is produced when an entire group of wood cells is destroyed. The more cells are broken, the finer the dust particles are produced[4]. For example, sawing and milling are mixed processes that destroy cells and produce chips, whereas grinding destroys cells almost exclusively. Therefore, using sawdust as a filler for anti-vibration trench barriers can improve the utilization rate of sawdust waste in the long term and contribute to some environmental conservation.

2.2.4 Geo-Technical Characterization of in-filled materials

Filling materials has a key role in the function as anti-vibration trench wave barriers in vibration screening. The use of trench wave barrier with such type of waste as in-fill material is an environmentally friendly and sustainable step in the service and application in geotechnical engineering. However, proper use of these materials in engineering application from the point of view of safety and stability is a major concern. To know its application as a fill material in vibration screening technology and its comparison with other materials, its geotechnical properties need to be determined. Geotechnical characterization of fill materials, i.e. rice husk, crushed tyre rubber and sawdust were taken in laboratory. Appropriate laboratory tests were performed out as particle size distribution, specific gravity, bulk density, relative density and permeability. In addition to these properties, the dynamic properties of the fill material were also important, since the trench wave barriers are subjected to dynamic loading. Dynamic properties such as shear modulus, elastic modulus, damping ratio, stiffness and shear stress were measured using a tri-axial cyclic loading test machine. It helps in determining the suitability of these types of waste materials as fillers used in trench wave barriers for vibration screening. The properties of the in-fill material observed after characterization are summarized in Table 3 and described in detail[6].

3 Results and Discussion

Since the field study comprises of several cases of vibration tests, it was not possible to present all the cases in this text. So only selected results are considered in a precise form. Following the characterization of the interference source, the impetus of factor as dimensionless barrier geometry on the screening effectiveness is discussed. Other factor such as effect of the barrier depth and proximity to the interference source. The results are exhibited as amplitude reduction factor (Ar). To evaluate the influence of the geometry of barrier on the screening effectiveness, tests were performed under identical initial conditions and vibration frequency. The vibration system is controlled using an AC frequency converter. To ensure accurate and consistent oscillation frequencies at each of the five phases, i.e., 10Hz, 20Hz, 30Hz, 40Hz and 50Hz of frequency levels, the actual oscillation frequency was measured with a vibrometer with an accuracy of approximately±0.25Hz before collecting the responses in data acquisition system. Figure 14 and Fig. 15 show normalized ground motion due to exciting frequency in active and passive isolation. The responses of the different channels G1 to G15 represent the ground responses during the specified observations at designated locations and the obtained results showed signals of high-quality corresponding to harmonic excitations at different operating frequencies. Meanwhile, the Fast Fourier Transform spectrum clearly shows that the response of ground has frequency as dominant as that of the applied dynamic load.

3.1 Attenuation of wave caused by barriers

Observations regarding attenuation by the barriers are as follows:

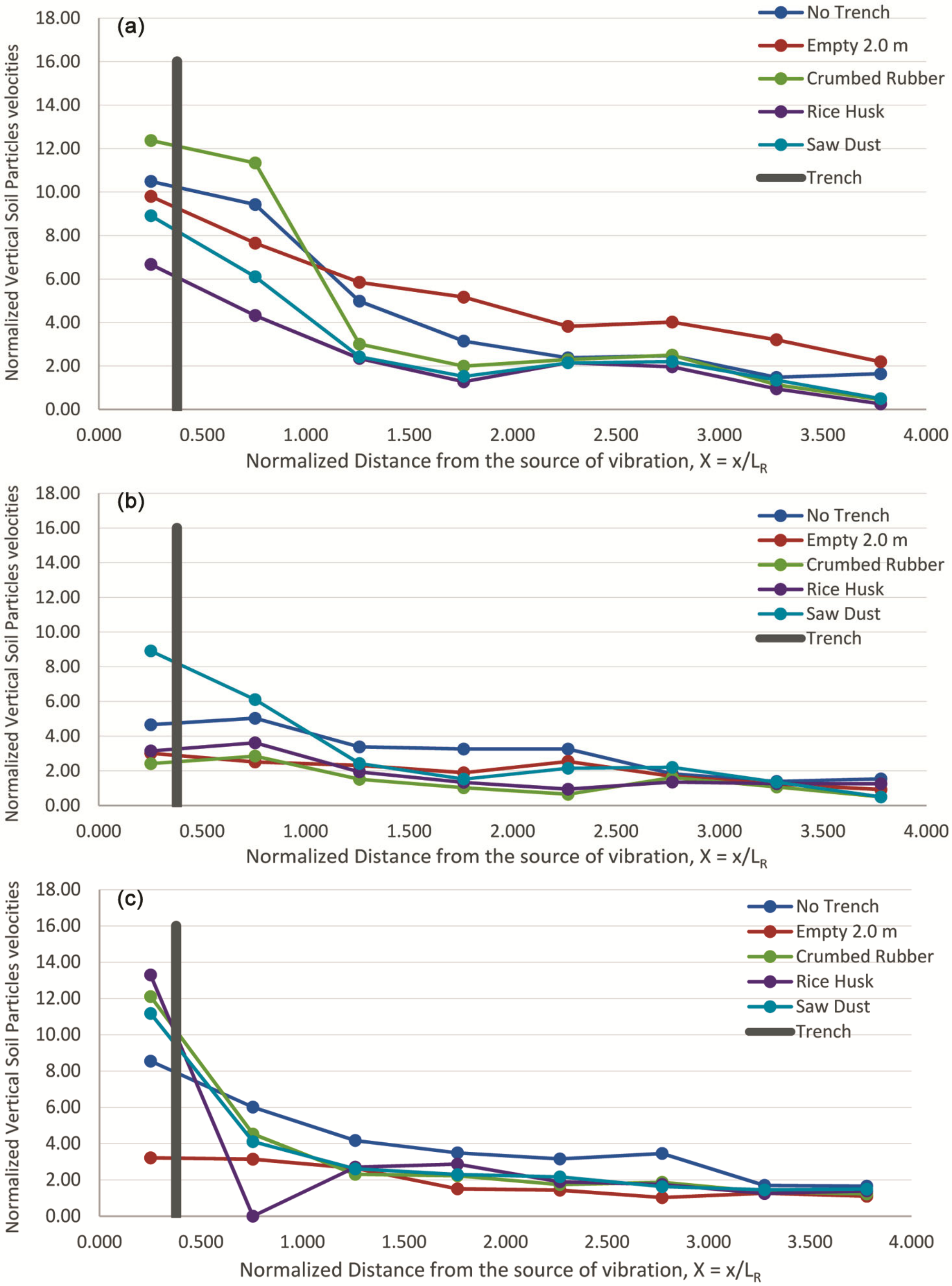

Fig 14 — Normalized ground motion (G10 to G3) due to exciting frequency of f = 40Hz when source of vibration at (a) 2.5n (b) 5.0m and (c) 10 m from center of trench in active isolation.

a Results at test site show that in-filled trench wave barriers may be considered as a viable alternative to scattering of waves and the %age efficiency of screening is found to be nearly up to 65%.

c. The screening effect of the trench wave barrier is governed by normalized depth of the trench barrier and distance of the barrier with respect to the source of vibration. In general, for both types of trench barriers i.e. open and in-filled trench barriers with in-fill materials such as rice husk, crumbed tyre rubber and sawdust, the barriers have proven at D ≥ 0.60 (i.e. the optimal normalized depth of barrier), the effectiveness is maximum. At x/d ratios of about 0.79, 1.63, and 3.29, the X

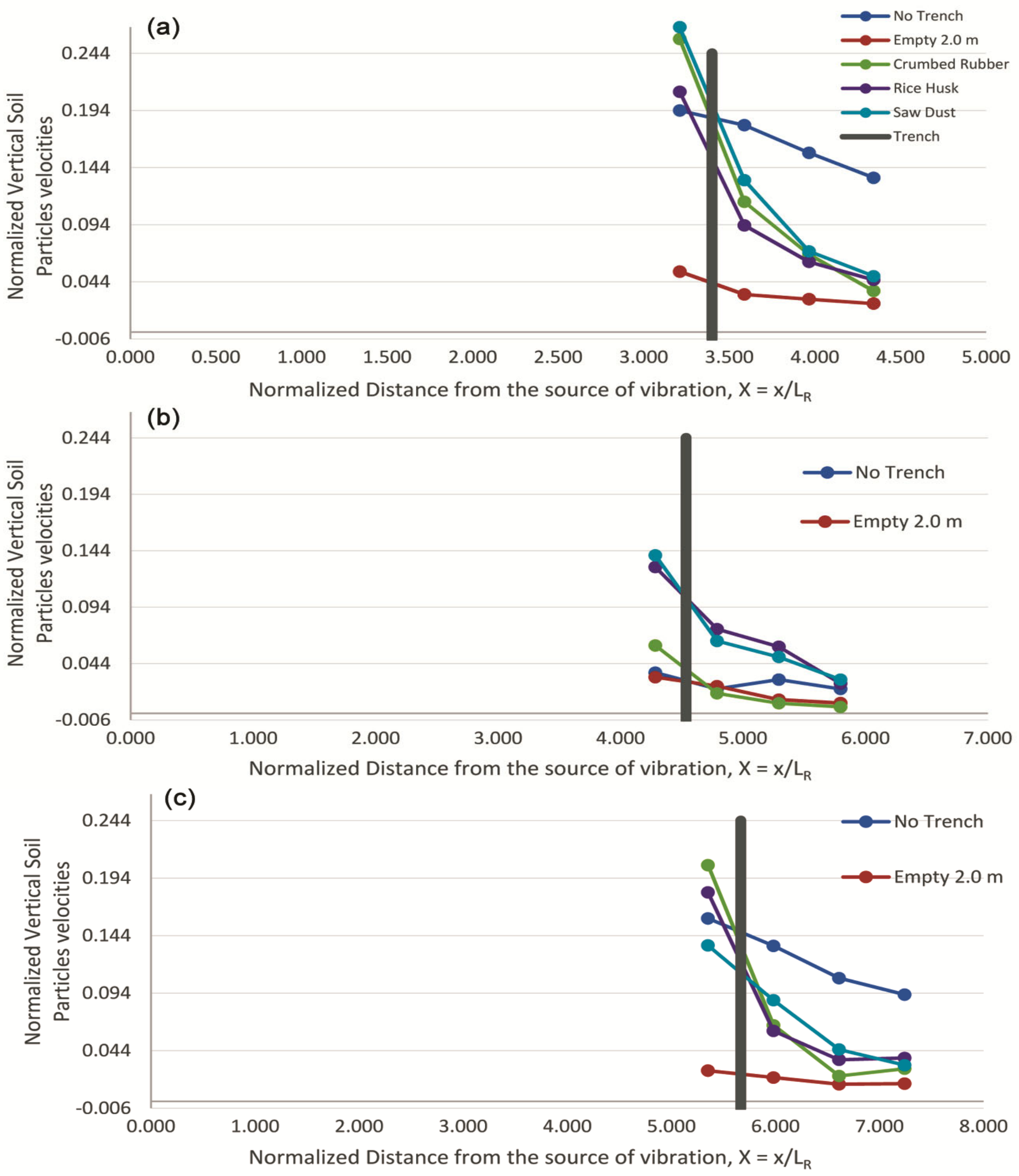

Fig. 15 — Normalized ground motion (G9 to G12) due to exciting frequency of (a) f = 30Hz (b) f = 40Hz, f = 50Hz when source o vibration at 23.75 m from Centre of trench in passive isolation.

(normalized distance) of 0.45, 0.92 and 1.64 are the optimum barrier locations corresponding to the optimum normalized depth D of about 0.60**.**

d. The results clearly show that with the increase in x/d ratio, trench with more depth is required to achieve the same system effectiveness. It is found that in case of open trenches, as the x/d ratio increases, the effectiveness decreased whereas in case of in-filled trenches, there is no significant changes observed in effectiveness of the screening system.

g. The field observations obtained in this study are applicable to all the types of soil profiles considered.

h. While validating the results of experimental result with the numerical one are comparable but with differences of about 10.65%, 17.86%, and 25.20% respectively for the open and filled trench barriers with filling materials such as crumbed rubber, rice husk, and sawdust. This discrepancy can be attributed to the heterogeneity of the soil as well as the incomplete bonding between the soil and the in-filled materials.

i. The validation of the experimental results is in agreement with the numerical and this basis can be used for carrying out parametric studies.

j. The soil particle velocities are measured (i.e., decay curves of soil particle velocity in vertical direction) at one of the observation points in case of no trench, empty trench and in-filled trench for normalized frequencies of 30Hz, 40Hz and 50Hz. The results are presented for all the locations of source of vibration, i.e., h. x = 2.5m, 5m and 10m. The measurements follow the trend which was expected for amplitude vs distance for all applied excitation frequencies. There was a rapid drop-off which indicates that damping is quite predominant. It also shows that ground motion is influenced by both the factors i.e. geometrical and material damping.

k. With the increase in frequency, the geometric damping also increases, resulting in more damping of the generated surface waves.

l. The calculated data shows that the observed response is significant at distances up to 18m from the source, but attenuates beyond 18m from the source of vibration. For ground conditions at this location, the amplitude is less than 4-5% than the source amplitude. Therefore, the study of A_r and barrier effectiveness is restricted to 18.0m from the source of vibration. This is because, even in case of no wave barrier, the amplitude is negligible at large distances. Therefore, the measured response does not allow a precise and reliable assessment of the barrier effectiveness at distant sites.

m. The calculated amplitude reduction ratios for three interference source locations at excitation frequencies of 10Hz, 20Hz, 30Hz, 40Hz and 50 Hz in case of no trench and in-filled trench. As can be seen, the amplitude reduction ratios change randomly (from 3.9 L_R to 5.7 L_R) when the distance from the trench exceeds about 15.0 m. There are two possible reasons for this. First, the reflected waves are in phase or out of phase at the interface of the soil layer where they pass under the barrier. Second, even in the case of no barrier, the amplitudes are negligible and response variations represent a large change in ratio.

n. Phase-in and phase-out behavior has caused due to phenomenon of minima and maxima. In other words, these are points where waves are most likely to be phase-in or out with each other, causing maxima and minima in A_r. This behavior has been explained by Woods[11] in field studies on open trenches, Baker[14] in experiments on backfilled trenches, and Beskos[15] on sheet pile barriers as vibration screeners. It was found that if distance to the principal minima decreases as increase in barrier depth i.e. by increasing excitation frequency. A similar behavior was also observed, as there is a clear minima just behind the barrier, resulting in a quiet region.

o. Available soil heterogeneity and high soil attenuation are possible reasons for the presence of many local maxima as one moves far from the barrier, leading to the unexpected nature of the calculated A_r. Rather, as the distance between the barrier and the source is increased, the vibration amplitude became much smaller, so that negligible velocity values were measured at the farther receivers, probably mixed with ground noise. Using these small values to calculate the amplitude reduction rate could lead to significant numerical errors. Therefore, high Ar values are considered to be suspicious, misleading and unreliable. Measurements from channels located within about 18.0 m from the source of vibration, are therefore only considered when calculating the average amplitude reduction.

p. In the passive isolation tests, it can be inferred from Fig. 15 showing the normalized vertical soil particle velocities that the amplitude reduction is very good, with performance in terms of efficiency ranging from 68% to 90% in the overall. case. This may be due to excessive reduction in amplitude at points far from the vibration source due to material damping. And with less energy, there is less impact on wave propagation. Overall, passive isolation performs better than active isolation.

3.2 Effect of barriers dimension and location on trench wave barrier performance

There is decrease in Rayleigh wavelength ($L_{R)}$ as excitation frequency increases. Hence, as the frequency increases, it leads increase in normalized barrier dimension and the normalized distance X, as the dimension are normalized by L_R. The distance 'x' remains constant for every location but changes as the disturbance source shifts from one to another location. Hence, we discussed the influence of the normalized depth of trench barrier and combined effect of the location of barrier on its depth. All experimental studies published so far have been carried out with a constant distance-to-depth ratio, and only a few studies have considered locations with varying distances. It means that the combined effect of location of barrier and its depth has not taken into account. The practical width proposed for constructing this type of wave barrier system in an in-filled trench is 0.25m, which has been shown to perform well in dispersing induced ground vibrations, as previously mentioned[1]. Therefore, the barrier performance is evaluated based on normalized depth and the ratio of distance between trench barrier and source of vibration to depth of barrier. The corresponding normalized barrier dimensions and barrier source distance are in Table 2.

As the normalized depth 'D' increases, the average amplitude ratio A_r (average) decreases. This indicates that the shielding performance is improving. The results indicate that remarkable effect can be obtained when the normalized depth is 0.25 or more. Therefore, a normalized depth of 0.25 can be assumed as optimal depth for all barrier types. As an overall reduction in amplitude is about 0.20 to 0.55 for all barrier types. As observed, the amplitude was reduced and the barrier effectiveness was 83% for the open trench, 61% for the rubber granules, 67% for the rice husk, and 57% for the sawdust trench barrier. There is effect of the barrier position normalized to depth on the effectiveness of the open barrier and all investigated barrier types. The assumed x/d ratios are 1.25, 2.5, and 5.00 for the 1st, 2nd and 3rd positions. It is found that on increasing the distance between the trench barrier and the vibration source, trench with more depth is required to attain a significant improvement in the system efficiency. For example, for the open trench barrier system with x/d = 1.25 (1st position), a significant improvement can be achieved by placing the barrier at a normalized distance of X ≥ 0.25 with D ≥ 0.15. For x/d = 5.00 (third position), a similar improvement can be achieved by placing the barrier at X ≥ 1.50 with D ≥ 0.25. A similar trend is observed for the trench wave barriers filled with rubber granules, rice husks, and sawdust. This means that average system efficiencies of 80%, 57%, 61%, and 57% (Table 4) can be achieved by placing the barrier at X = 1 to 1.5 for the open trench barrier and in-filled trench barrier. Second, for x/d = 2.50, average system efficiencies of 83%, 63%, 68%, and 53% can be obtained by setting the barriers for the open and in-filled trench cases at X = 1.64 to 2.75. The trench barriers are placed as follows: Furthermore, by setting the open and three filled barriers at X = 1.64 to 2.75, average system effectiveness of 85%, 63%, 70%, and 5% can be achieved for x/d = 5.00 and D = 0.50 to 0.84. A trench barrier can be installed. It can be concluded that the same improvement in system efficiency can be achieved with a flatter barrier as x/d decreases. The reason for choosing the current method to calculate A_r is that the trench is long enough (14m) and narrow, which means that effect of soft edges can be neglected, especially in case of high frequencies. Rather, according to the literature available, all field studies were performed using models of small scale, whereas the experiment carried out in present study include a full scale (complete) setup where soil stratification effects are anticipated to influence the results. Thus, a rigorous and direct comparison cannot be made between the present results and those published previously, especially at higher frequencies.

3.3 Validation with numerical study results

For each type of trench wave barrier, a numerical model was developed in Plaxis-3D and field test conditions were applied. The results obtained from numerical investigation and field study were compared. The trend of results obtained from Finite element model followed the same trend as of the experimental one. But in some locations the values are slightly higher and in others lower. This may be due to the Finite element model considering horizontal homogeneous soil layers, which may not be the case in the field. Another cause of probable discrepancies in results is due to presence of stone or rocky components at

Table 4 — Protective efficiency of barriers (% age).

S. No.	Trench Type	1st Location	2nd Location	3rd Location	Average
1	Open Trench	80.10%	83.00%	85.50%	82.86%
2	Crumbed Rubber	57.30%	62.80%	63.20%	61.10%
3	Rice Husk	64.10%	68.00%	69.60%	67.23%
4	Saw Dust	56.90%	54.30%	59.80%	57.00%

some depths in the soil composition. Nevertheless, it may be deduced that the Finite element model in PLAXIS 3D is able to adequately represent the vibration scattering phenomenon in both type of trenches i.e., open and filled and therefore the model find suitable and considered be reliable to extrapolate results and to conduct comprehensive parametric studies to gain a deeper understanding of rubber granule, rice husk and sawdust trench barriers.

3.4 Comparison with published data

As shown in Figure 5, the ground movement was monitored on the center line perpendicular to the axial line of trench. This was used to calculate the amplitude reduction ratio. In trench barriers filled with crumbed tyre rubber, rice husk and saw dust reduced the vibration amplitude (barrier effect) by 82.86%, 61.10%, 67.23%, and 57.00%, respectively. Meanwhile, available literature indicates that experimental studies were performed on models of small scale, whereas the experiment performed in present study include a full scale set up where the effects of soil stratification are expected to affect the results. Therefore, a strict and direct comparison cannot be made between the present results and those published in past. According to the results of Haput (1981), the amplitude reduction ratio (Ar) is in the range of 0.285–0.375, whereas according to the study based on the empirical formula of Ahmad and Al-Hussaini (1991), the results are in the range of 0.202–0.305. The results of the current field study exceed those published. This is probably due to the nature of the large-scale experiment, where real wave propagation problems can be simulated by taking into account real ground conditions such as soil heterogeneity and stratification, and the applied frequencies are the same as those occurring in the practice ground. Also, differences in the definition of Ar could be a source of variation, although the impact is small. However, the results follow the same general trend, i.e., better shielding efficiency is achieved as the normalized trench depth increases. With regard to the optimal normalized depth, the optimal normalized depth recommended in this study is consistent with the minimum normalized depth recommended by Woods[16] (D=0.6 for active insulation) and achieves a notable level of shielding. Furthermore, the materials used for the trench wave barrier in this study have low stiffness, which tends to result in high energy attenuation during wave propagation.

4 Conclusion

A comprehensive experimental study was performed to investigate the screening effect of open trench and in-filled trench wave barriers with in-filled materials as rice husk, crumbed rubber and sawdust, which help to disperse stationary vibrations caused by machine foundations, etc. An electromechanical oscillator was used to simulate the vibrations of machine foundations. A detailed study on reducing the intensity of vibrations due to harmonic loads generated by electromechanical oscillators using wave barriers in trenches has been presented. The protective effect of trench wave barriers was determined based on the reduction in amplitude of soil particles by varying the excitation frequency and the location of the vibration source. To verify results of field tests, a 3D finite element model was developed under the same experimental working conditions to numerically simulate the behavior of open and filled wave barriers during scattering of stationary surface waves. The effectiveness of using open or filled trenches as reduction measures has been determined through field measurement studies according to the results obtained. In this case, wave scattering and dissipation of wave energy plays a significant role. The open or in-filled trench wave barriers allows to significantly reduce the vibrations affecting the structure and the resulting internal forces. Open trenches are more effective than that of backfilled trenches, but in its practical application, the use is limited to relatively shallow depths. On the other hand, the use of softer backfill materials increases the effectiveness of the backfilled trench, allowing deeper trench depths without the need for supporting measures on the vertical trench walls. Furthermore, the waste material used in these trench barriers contributes to the economy of the application. At both measurement points, the barriers were found to be generally more effective for passive insulation than for active insulation.

However, it is remarkable to note that in many practical cases, it appears useful to carry out a more comprehensive study of the structure/ soil/ trench system in question, as was done in this paper. Planning of the optimal trench in terms of depth and width must be carried out for each individual case.

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