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Vibration Screening in Layered Soil by Geofoam-filled barrier

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ABSTRACT

Studies on vibration isolation have attracted the attention of researchers for the last two decades because they can have a significant effect on the comfort of occupants of the buildings located near the source. A typical assumption for the study of ground-borne vibration is considering soil as homogeneous, which is unrealistic in many real cases. Therefore, the main focus of this study is to find the effect of soil layering on the efficiency of geofoam-filled trenches. An automated and comprehensive parametric study has been performed by coupling Plaxis, Python and Matlab programs. The results of this automated parametric study allow the identification of the main governing parameters, which are location (X) and depth (D) of the trench and shear wave velocities of the soil (V_s). Results showed that a depth of $D = 1$ and $1.25 \lambda_r$, is enough to have a successful active isolation system. In addition to this, the study shows that the trench is more efficient in soils with larger values of shear wave velocity (V_s). The use of this automated process can also assist with similar parametric studies for other applications and during design of similar installations.

Keywords: vibration isolation, layered soil, geofoam-filled trench, automated parametric study

INTRODUCTION

Ground-born vibration has been a challenge for large cities in recent years since it can affect surrounding buildings and other structures. The effects range from disturbance of occupants to visible structural damages. Some ground-borne vibration sources include pile driving, road traffic, and railway with different mechanisms of excitations and effects (Ben-Menahem & Singh, 2012; WA Haupt, 1995). The generated seismic waves by these vibration sources can be received by building foundations and are then propagated to other parts of the buildings where they may be amplified and may cause floors and walls to vibrate. This vibration has an impact on the occupants and any sensitive equipment inside a building and it can also damage it (Hao, Ang, & Shen, 2001).

Generally, mitigation measures can control vibrations at the source, in the propagation path, and at the receiver. The installation of a wave barrier between the vibration source and the building is one of these alternatives. The trench intercepts the traveling waves through a complex mode of wave interactions including reflection, refraction, diffraction, and wave interferences. This can result in a considerable reduction in ground motion behind the trench (Ahmad & Al-Hussaini, 1991; Naghizadehrokni & Ziegler, 2021).

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Several studies, including both experimental and numerical, have been carried out in the last few decades to improve our understanding of vibration scattering by wave barriers, e.g., (Alzawi & El Naggar, 2011; Liyanapathirana & Ekanayake, 2016; Naghizadehrokhni et al., 2020). However, an analytical method has rarely been used by researchers because of the complexity of deriving the equations for a vibration isolation system, especially in the case of layered soil (Mal & Knopoff, 1965; White, 1958).

(Woods, 1968) was one of the first to perform a full experimental test for evaluating the efficiency of open trenches. The field test was suited on a sand and silt deposit and water table was at the depth of 4.5 m. A harmonic load with a constant input excitation load of 80 N and frequency of 250 Hz was applied to the soil to generate the vibration. Finally, he introduced a normalized depth of 0.6 with regards to the Rayleigh wavelength (λ_r) to reach 75% reduction in the screening of incoming waves.

A series of field tests have been conducted by (Alzawi & El Naggar, 2011; Ulgen & Toygar, 2015) for finding the screening effectiveness of geofoam-filled obstacles as a soft barrier. The soil properties consisted of silty clay, clayey silt and sandy silt (Alzawi & El Naggar, 2011), and clayey sand over very stiff clay (Ulgen & Toygar, 2015). They used a harmonic load with frequencies in the range of 30-70 Hz. The results showed that the vibration amplitude can be reduced up to 68% by installing a geofoam-filled barrier. Moreover, they have found that the performance of a geofoam-filled trench is dependent on the normalized depth. The optimum depths are suggested as 0.6 and $1\lambda_r$ for active and passive systems, respectively. In addition, it was concluded that the screening efficiency of the geofoam-filled trenches decreases with increasing the distance between the vibration source and trench.

A FEM is developed in homogenous sandy soil with a density of 1955 kg/m^3 to evaluate the efficiency of geofoam-filled trenches by (Ekanayake, Liyanapathirana, & Leo, 2014; Liyanapathirana & Ekanayake, 2016). A single vertical vibratory force operating at frequency in the range of 30-50 Hz was applied to the driven pile. The influence of dimensional and geometrical parameters of the trench were investigated. They observed that the barrier efficiency can be improved by adopting passive isolation. The efficiency of EPS geofoam wave barriers increases significantly when the depth of the barrier is increased. However, an increase in the length of EPS geofoam wave barriers slightly improves the efficiency of the trench. While changes to the width of the wave barrier can either attenuate or amplify the ground vibrations.

The effectiveness of open, water-filled, concrete-filled, and geofoam-filled trenches is investigated by (Wang et al., 2009) in a homogenous soil with a density of 1000 kg/m^3 through numerical modeling. They used a blast load with frequency of 100 Hz as vibration source. The results demonstrated that open and geofoam-filled barriers performed well in reducing blast-induced stress waves in comparison with other systems and geofoam is a suitable alternative for filling a trench.

This brief literature review shows that, for given site conditions (soils, loads and receiving structure), the main governing parameters are depth, width, and distance to the source, and the material of the trench. Hence, in this paper, a comprehensive parametric study is performed to assess the efficiency of the geofoam-filled trench as a wave barrier using these parameters in layered soil. The range of parameters for the single parametric study is presented in the methodology section. The influence of different parameters of the barrier on screening the vibration is studied in the results section.

METHODOLOGY

A time-domain 2D numerical model is developed to assess the efficiency of the trench in attenuating the incoming waves. Since the model is largely affected by the transmitted and reflected waves from the boundary, it is important to keep the region of interest far enough from the reflecting boundary. (Naggar & Chehab, 2005; Yang & Hung, 1997) stated that a zone extending to a minimum distance of ($10\lambda_r$) from the vibration source is sufficient for wave barrier analysis. With regard to the minimum distance and crucial zone behind the trench, which is $7\lambda_r$, the dimensions of the model are selected as ($70 * 25 \text{ m}$) (Saikia, 2014).

Viscous boundaries are applied to the bottom and right sides of the model. A viscous boundary condition, which is introduced by (Kuhlemeyer & Lysmer, 1973) consists of viscous dampers applied in X and Y axis in a Cartesian coordinates system along the boundary. In this theory, the absorbed components by the damper are normal (σ_n) and shear stresses (τ), which are obtained by Equations 1 and 2 (Brinkgreve et al., 2010).

$$\sigma_n = -C_1 \rho V_p \dot{U}_x \quad (1)$$

$$\tau = -C_2 \rho V_s \dot{U}_y \quad (2)$$

where V_p and V_s are pressure and shear wave velocity respectively, \dot{U}_x and \dot{U}_y denote normal and shear particle velocities derived by time integration, ρ is material density, C_1 and C_2 are relaxation coefficients to change the effect of absorption. It is proved that applying the two relaxation coefficients equal to one leads to the highest efficiency in absorbing any waves reaching the boundary, which is sufficient for practical applications (Saikia, 2014).

The vibration source, which is illustrated in Fig. 1, is modelled as a vertical harmonic load with a magnitude of 1 kN, frequency of 50 Hz and a contact length of 0.36 m.

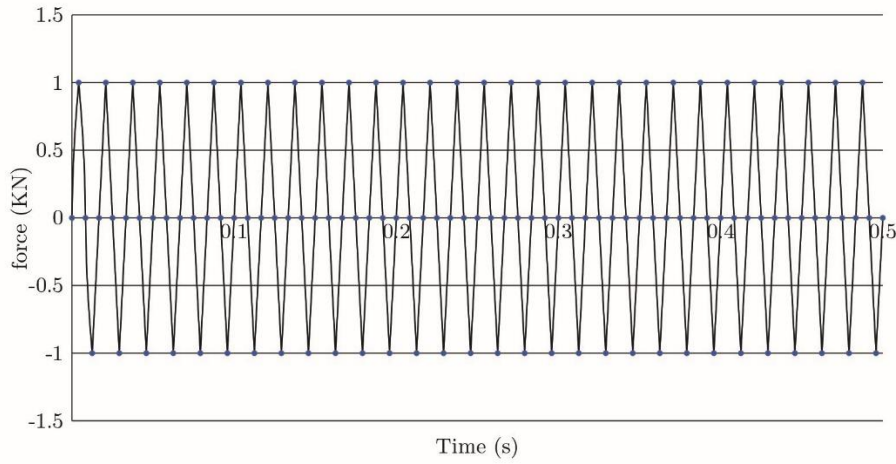


Figure 1. Proposed vertical harmonic load as vibration source

The properties of the soil and geofoam obtained from a full experimental test reported in the literature (Naghizadehrokn, Ziegler, & Sprengel, 2020) are used in Plaxis. The proposed FE model of the vibration isolation system and the defined parameters are presented in Fig. 2 (Saikia, 2014).

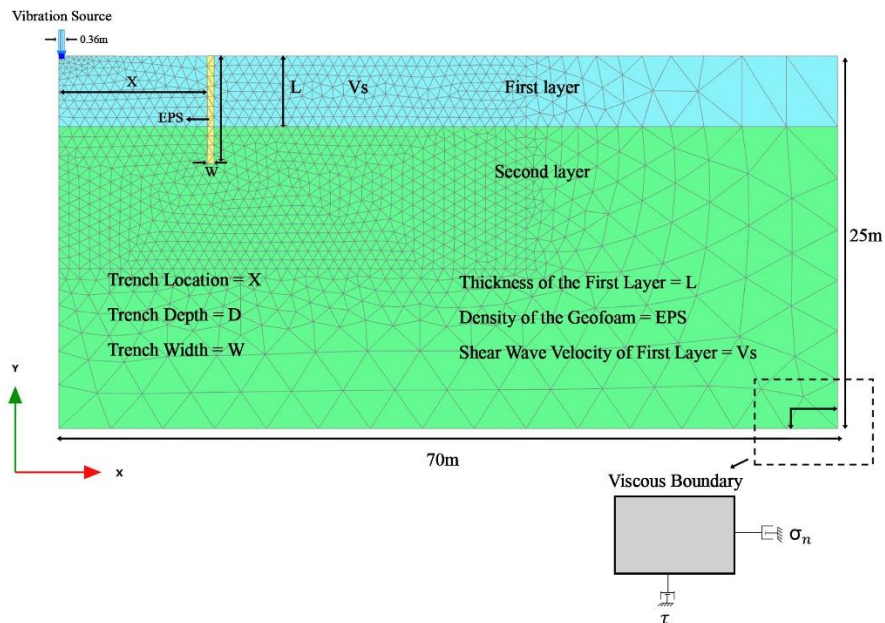


Figure 2. Proposed FE model and the defined parameters

A simplification for the non-homogeneity of the soil is done by considering a horizontal ground surface and soil layers. The shear wave velocity of the second layer is considered as $V_s = 400 \text{ m/s}$ (approximately equivalent to a dense sand). The ranges of parameters are presented in table 1. All parameters are normalized with the R-wavelength of the first layer, which is equal to $4m$. (WA Haupt, 1995) stated that the limit to distinguish between near (active) and far (passive) field conditions can be taken as 1.0 to 1.5 of the R-wavelength. Hence, the trench in this study is located at two locations, near ($0.75\lambda_r$) and far ($3.75\lambda_r$) from the source to be considered as an active and passive isolation system, respectively. Expanded polystyrene (EPS) geofoam material is selected for filling the trench. It has a density of 1% compared to the surrounding soil, making it appropriate for vibration mitigation. It is also accessible in different types with various dynamic properties that can be chosen by the designer for a specific application. In this investigation, EPS 15 with the density of 14.4 kg/m^3 and elastic modulus of 2500 kPa is selected for filling the trench (ASTM).

Table 1. Normalized ranges of different parameters in the parametric study

Parameters	The normalized value for the parametric study				
Location (X/λ_r)	0.75	1.5	2.25	3	3.75
Depth (D/λ_r)	0.75	0.75	1	1.25	1.5
Width (W/λ_r)	0.075	0.125	0.175	0.25	0.375
Thickness of first layer (L/λ_r)	0.5	1	1.5	2	2.5
Shear wave velocity (V_s) (m/s)	200	250	300	350	400

A parametric study can be time consuming, is prone to human error and requires saving large amounts of data. Altogether, the above parametric study results in 18750 models. Running of all models manually would take several months, even before collecting results and calculating the efficiency of the trench. The solution is automation.

For this purpose, a script is developed for coupling the finite element model (Plaxis) and Python programming language through Plaxis remote scripting interface in order to run the calculations automatically. All processes are done automatically through five computers for four weeks.

The general purpose of this research is to evaluate the screening effectiveness of the geofoam-filled trench through calculating amplitude reduction ratio (A_r) for different shapes and sizes. The step-by-step plan in numerical model was (1) to set up a harmonic load as a vibration source, (2) to determine the amplitude of vertical ground motion at the selected points with a normalized distance of $0.125\lambda_r$ at ground surface of the model before installing the trench (V_{before}), (3) to install the trench, (4) to determine the amplitude of ground motion at the same selected points after installing the trench (V_{after}). To evaluate the system effectiveness (screening effectiveness) of the wave barrier system on the ground surface beyond the wave barrier, the averaged amplitude reduction factor, \bar{A}_r , was calculated using Equation 3.

$$\bar{A}_r = \frac{1}{x} \sum_0^x A_r \quad (3)$$

$$A_r = \frac{V_{after}}{V_{before}} \quad (4)$$

Where x is the reduction zone beyond the trench which is equal to $7\lambda_r$ (Naghizadehrokhni et al., 2020).

Therefore, the system effectiveness, Efficiency (%), is calculated using Equation 5.

$$\text{Efficiency} = (1 - \bar{A}_r) * 100 \quad (5)$$

REULTS

A comprehensive parametric investigation is carried out to evaluate the effectiveness of the different parameters of the wave barriers for the active and passive isolation systems in the vertical direction. Results of the detailed parametric investigation are presented, and some applicable recommendations are suggested for designing the wave barriers in layered soil.

Influence of the Depth and Width of the Barrier

To investigate the effect of trench dimensions in screening the vibration, the influence of trench depth is investigated for different values of trench width for active system and the results are presented in Fig 3. The efficiency of the trench in the soft soil ($V_s \leq 250$ m/s) increases with deeper trenches until $D = 1.75$. In addition, it should be noted that the installation of the shallow trench ($D = 0.5$) does not have any practicability in attenuating of incoming waves for shear wave velocity of 200 m/s.

For stiffer soil ($V_s \geq 300$ m/s), increasing normalized depth improves the efficiency significantly up to $D = 1.0$ and 1.25, beyond this depth the improvement in efficiency is much lower. Owing the fact that as the trench reaches a certain depth, the deeper part of the trench can hardly affect the response of the soil on the free surface. However, this is not the case for the lowest shear wave velocities ($V_s \leq 250$ m/s) and this issue showed that deeper trenches are needed in softer soil ($V_s \leq 250$ m/s) for reaching the same screening effectiveness in comparison with the stiffer soil ($V_s \geq 300$ m/s).

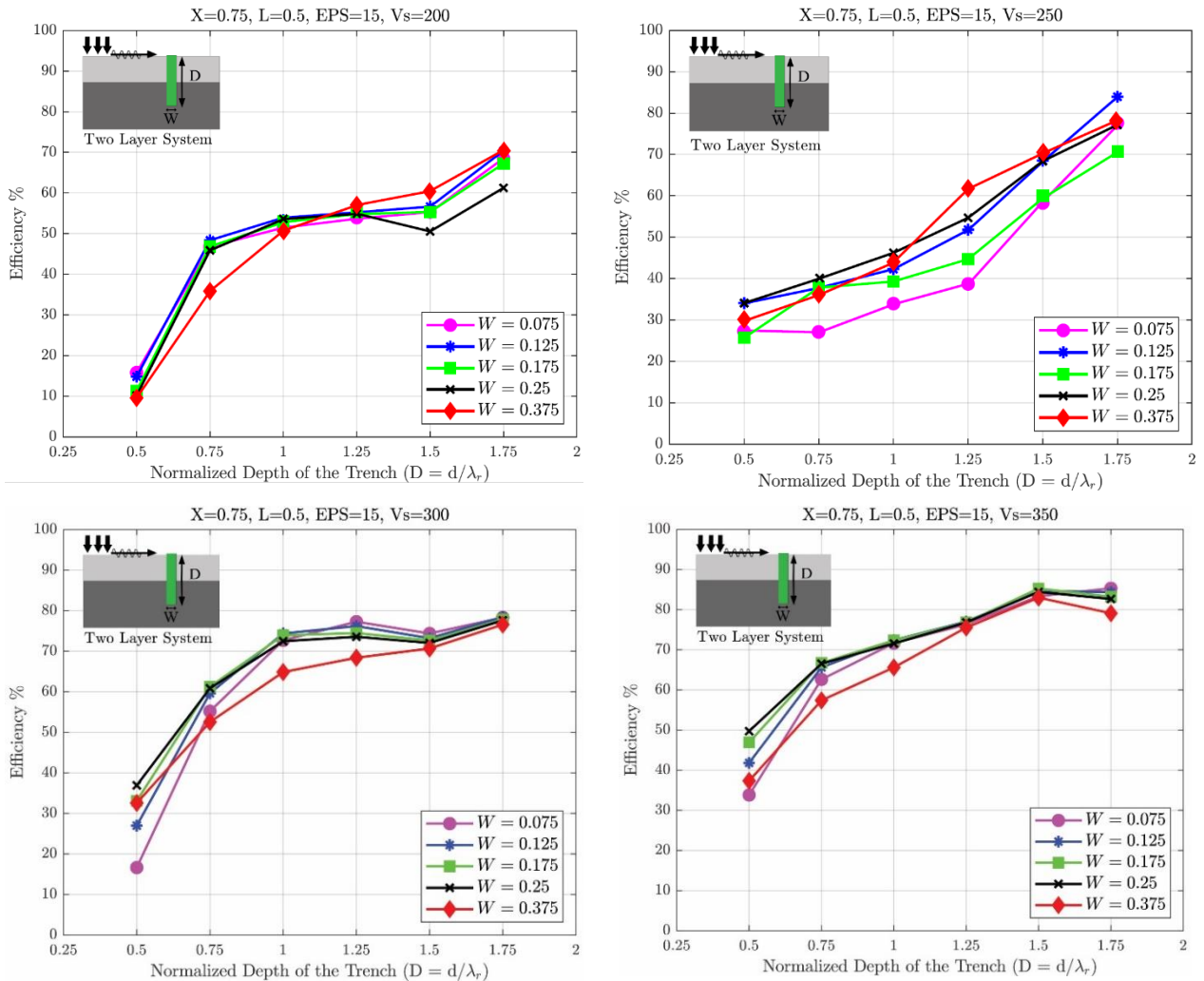


Figure 3. Influence of depth on the efficiency ($X = 0.75$, $L = 0.5$, $EPS = 15$)

The result of influence of the depth of the barrier for different values of the width are investigated through installing the trench at the normalized location of $X = 3$ for passive scheme and the results are illustrated in Fig 4. The efficiency of the trench increases gradually and continuously by increasing the depth of the barrier for approximately all widths, implying that D governs the screening influence. It should also be pointed out that installing a shallow trench with $D < 0.75$ in a layered soil should be ignored while it does not have any practicability (Efficiency $< 30\%$).

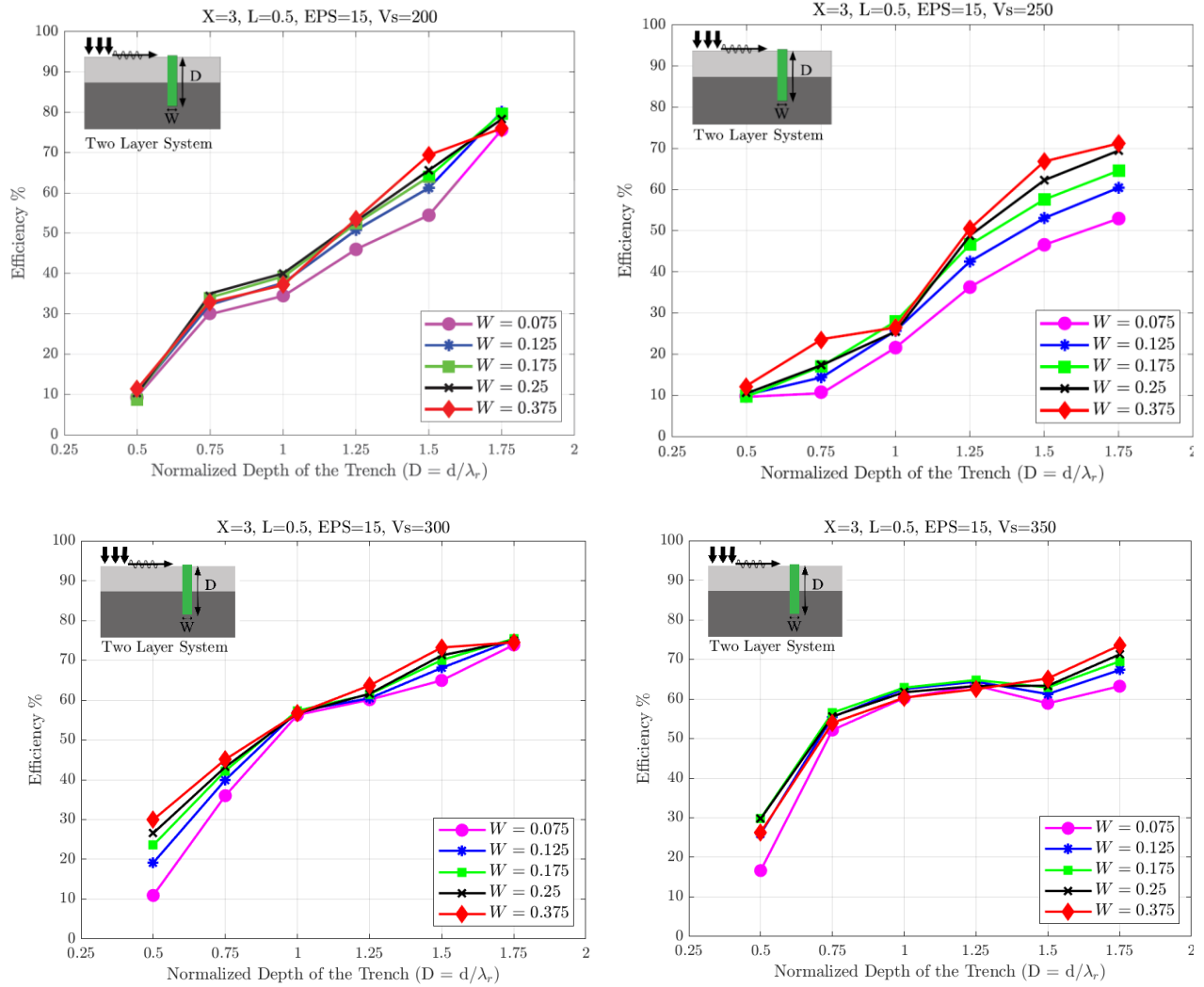


Figure 4. Influence of depth on the efficiency ($X = 3.0$, $L = 0.5$, $EPS = 15$)

A general comparison between active and passive ground vibration isolation with the same parameters showed that for softer soil with $V_s < 250$ m/s active system is more practical as passive one while a higher mitigation is reachable by installing deeper trenches. However, increasing shear wave velocity of the soil ($V_s > 250$ m/s) results in outperformin the active system as passive schemes.

It is also apparent from the result of active and passive systems that the efficiency of the trench is not affected by the width of the trench and even increasing depth and shear wave velocity of the first layer of the soil cannot create any change in the influence of W on screening effectiveness. Therefore, the normalized width of 0.075 is selected for the rest of the parametric study and the assumption has a good agreement with (Alzawi & El Naggar, 2011).

Influence of the Shear Wave Velocity of the First Layer

Fig. 5 shows the effect of shear wave velocity of the first layer of the soil on the trench performance as a function of D for active system ($X = 0.75$). The results clearly demonstrate the significance of V_s on

attenuation of incoming waves. As the value of V_s reaches 400m/s , the trench has the highest value of the efficiency for any given D , which means that the barrier has better screening performance in homogeneous soil (remember the bottom layer has a V_s of 400m/s) in comparison with the layered soil.

As already shown, the effect of the depth is also evident although for $D > 1.25$, the effect is much smaller. For $L = 0.5$ and 1.5 , a drop in efficiency is visible for $V_s = 250\text{m/s}$ for almost all depths, although for larger depths and layer thickness (L), the decrease is less evident.

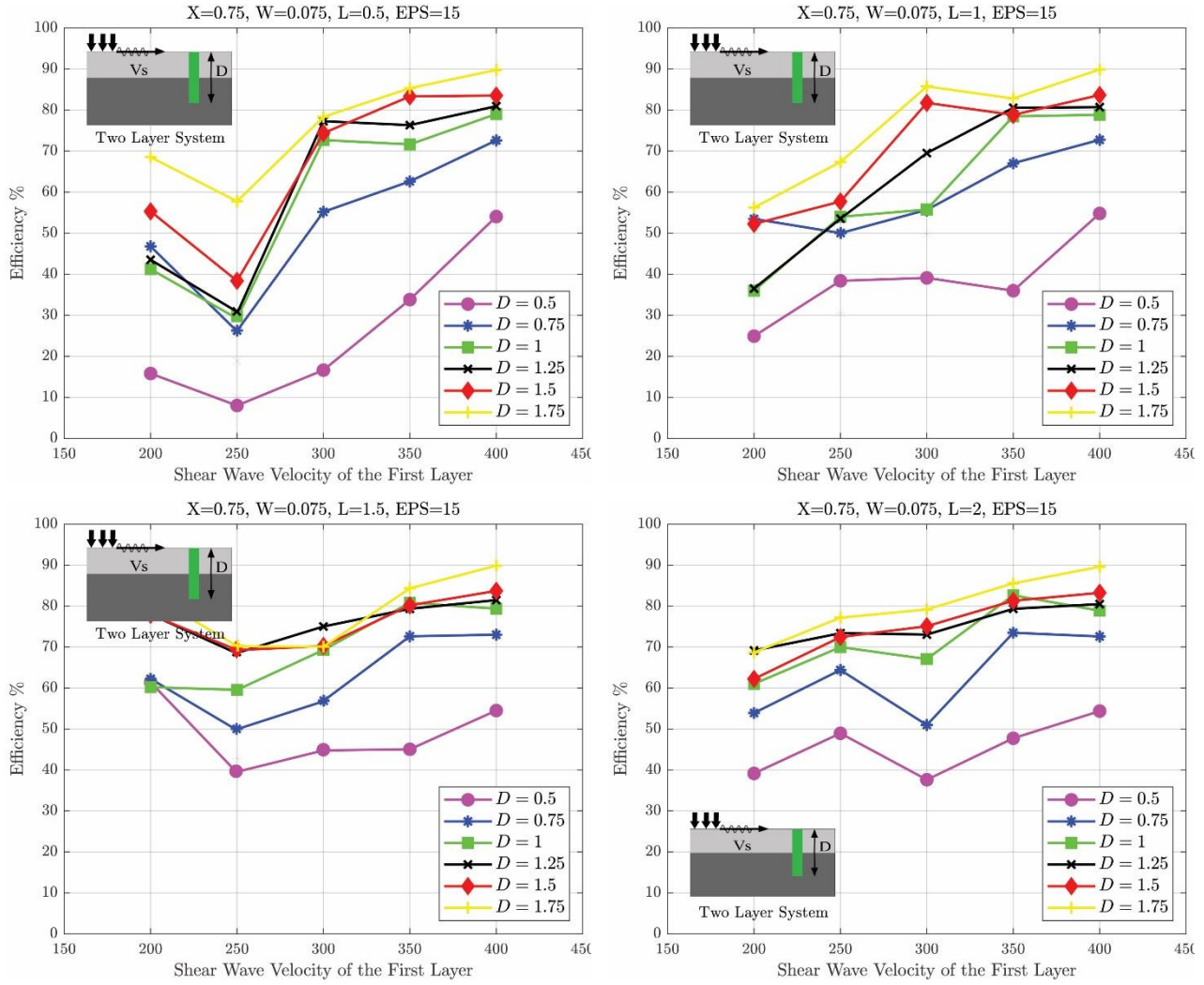


Figure 5. Influence of shear wave velocity of the first layer ($X = 0.75$, $W = 0.075$, $EPS = 15$)

(WA Haupt, 1977, 1995) stated that the body waves which radiate from a steady-state oscillation foundation at the surface to the interior of the half-space in layered soil are bent continuously upwards and return back to the surface. Therefore, a superposition of these body waves and the surface waves occurs yielding an amplification in the amplitude of the vibration that results in some irregularities in FE-calculations.

In addition, according to (Wolf & Oberhuber, 2006), the angle of incidence of the body waves to the interface in layered soil is an important parameter influencing the degree of amplification, as well as the propagation of waves at the surface of the layer. Furthermore, (Naghizadehrojni et al., 2020) observed that the destructive wave interference resulting from the phase difference between the waves is highest for $V_s = 250\text{m/s}$ which results in the drop of efficiency.

Fig. 6 shows the behaviour of the passive system. The results illustrate that for almost all values of L , the efficiency of the trench increases with increasing the value of V_s when $D > L$ (i.e., when the trench depth is greater than the thickness of the first layer) the behaviour is more non-linear showing the more complex interactions. For $D \leq L$, the system behaves more in a linear manner. This is confirmed for $L = 2.5$ that has

the lowest amount of fluctuations in the results for all values of D . It also indicates that this value is large enough for ignoring the effect of layering of the soil.

The results also show that for $V_s > 300\text{m/s}$, the effect of L is limited.

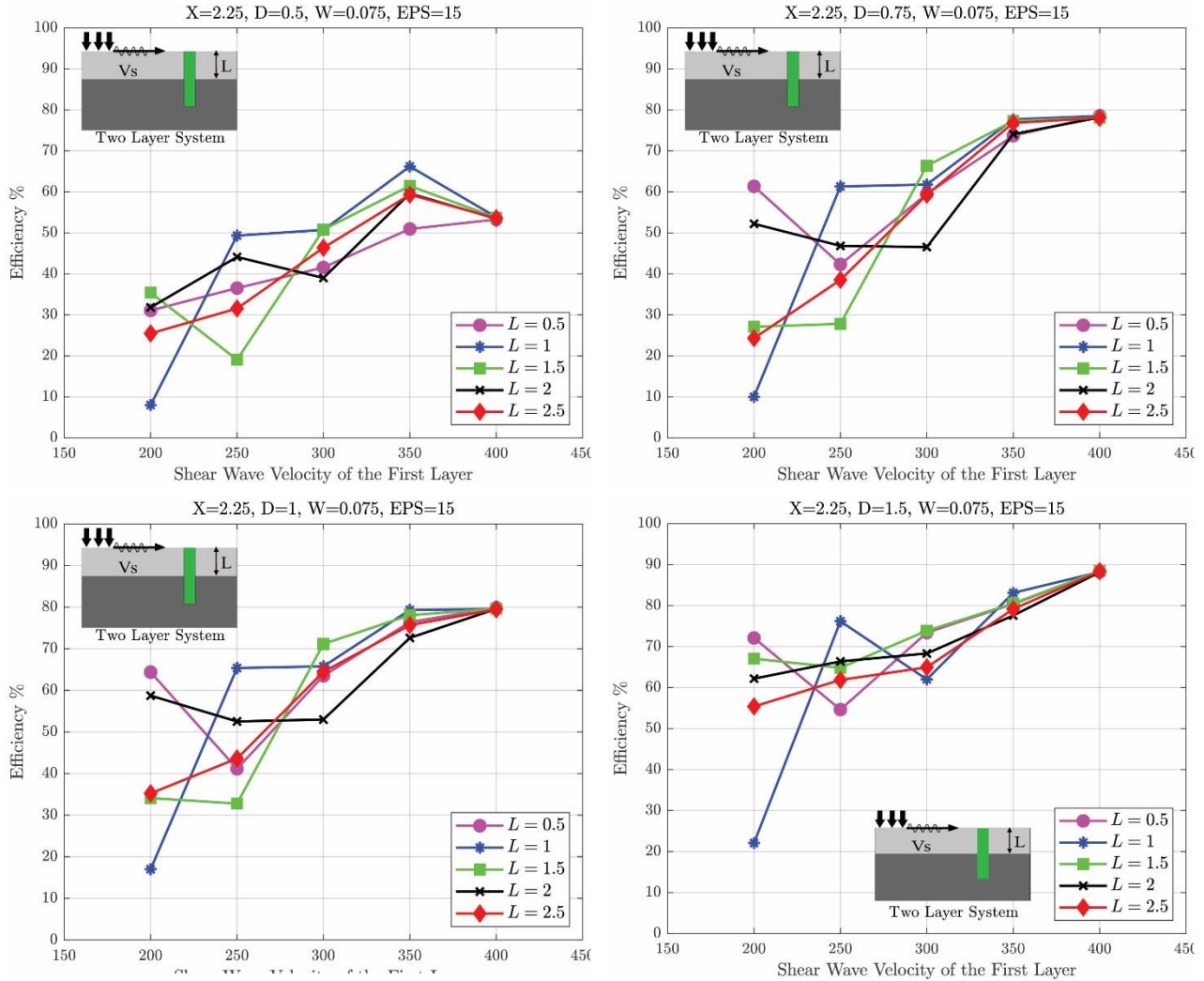


Figure 6. Influence of shear wave velocity of the first layer ($X = 2.25, W = 0.075, EPS = 15$)

Influence of the Thickness of the First Layer

The results of the soft soil with shear wave velocity of 200 and 250 m/s are presented in Fig. 7. As shown in the last section, there is not a significant influence of L on the efficiency for stiff soil ($V_s > 300$). For $X = 0.075$ the results show a general trend where the efficiency increase with thickness. For $X = 1.5$, the trend disappears. In general, though a singular point occurs for $L = 1.5$ except for $V_s = 250$ m/s for the reasons already explained. For $X = 1.5$ the nonlinear behaviour is clear for $D \leq L$ especially for low values of $V_s = 200\text{m/s}$.

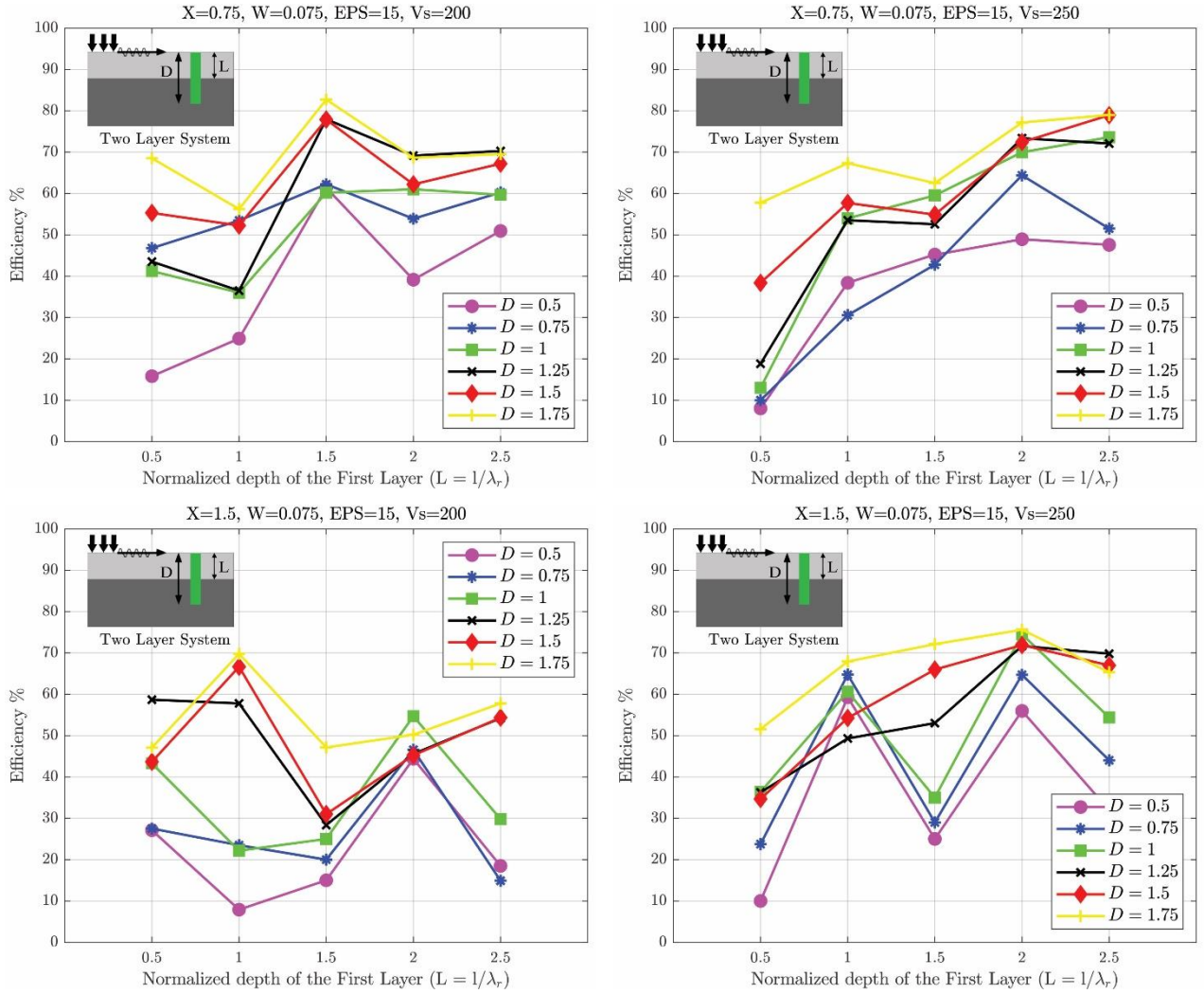


Figure 7. Influence of normalized thickness of the first layer ($W = 0.075$, $EPS = 15$)

Influence of the Location of the Barrier

Fig. 8 and 9 show the effect of normalized location of the trench as a function of D for soft soil ($V_s = 200m/s$) and stiff soil ($V_s = 350m/s$). As expected, the effect of layering is once again clear. For the softer layer the behaviour is much more nonlinear than for the stiffer soil which shear wave velocity is closer to the underlying layer. With only some exceptions, the efficiency does not seem to improve or change significantly for $X > 2.25$ for the softer soil, whereas the stiffer soil continues the linear trend where trench distance to the source reduces the efficiency. However, in the stiffer soil for $X < 2.25$, there seems to be also not significant differences in the efficiency, owing the fact that the position of the layer close to the barrier is not significant for all other parameters constant.

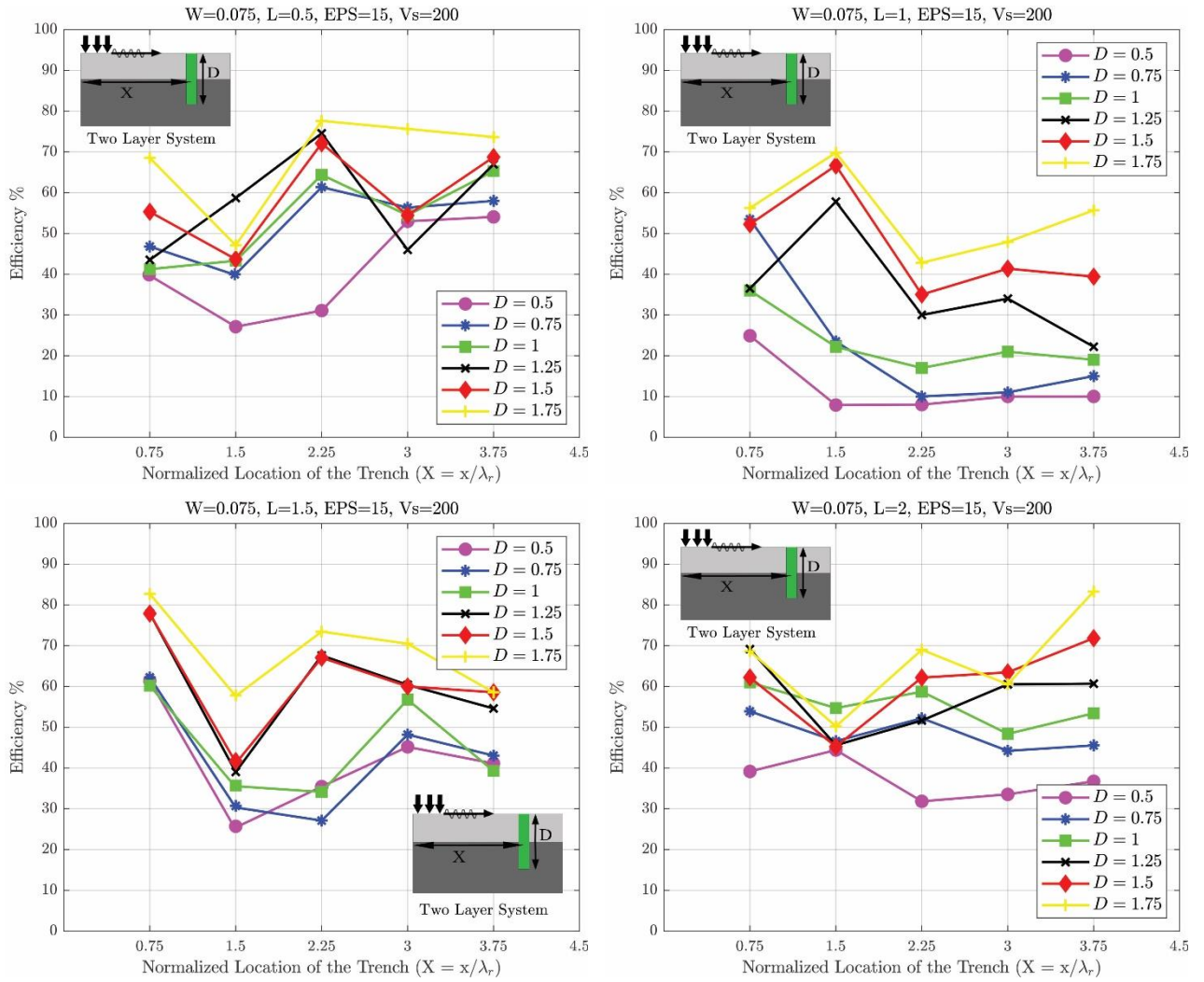
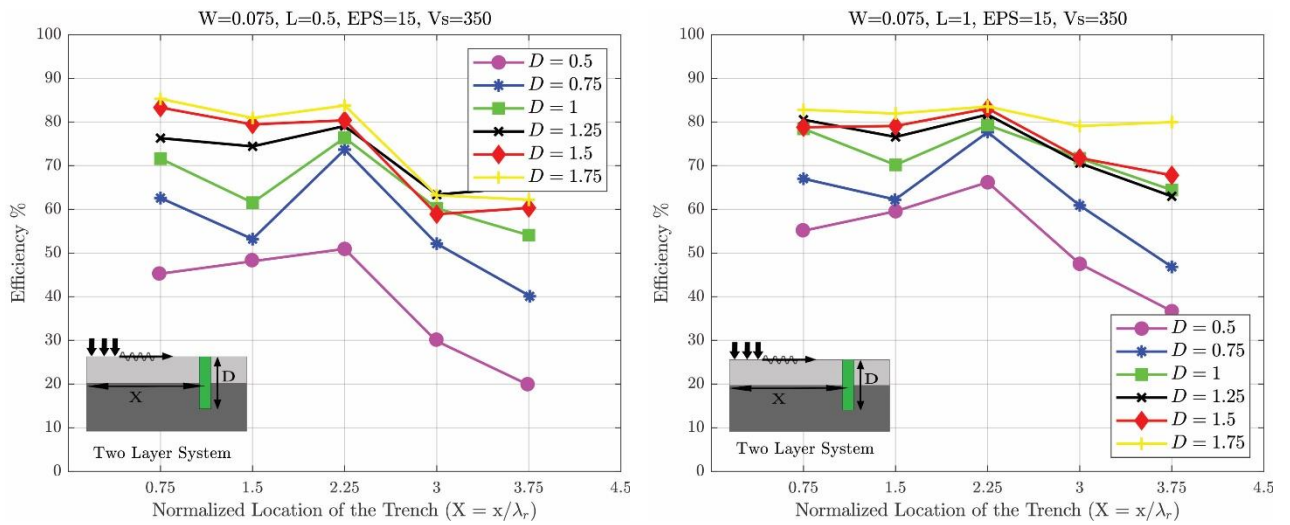


Figure 8. Influence of normalized location of the trench ($W = 0.075$, $V_s = 200$ m/s, $EPS = 15$)

The effect of X is smaller for deeper trenches than for shallow trenches.



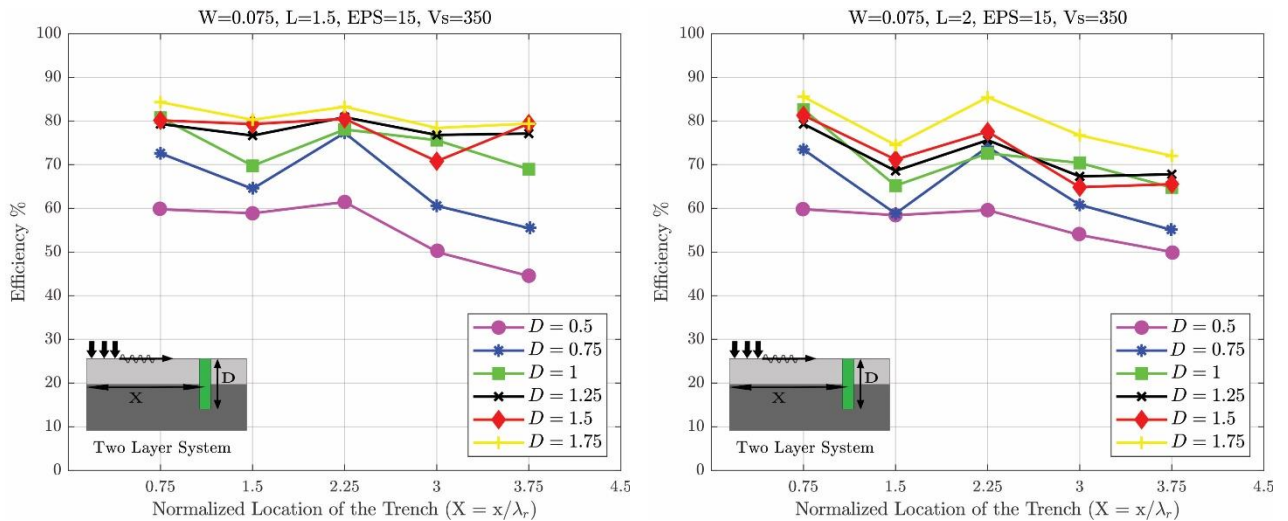


Figure 9. Influence of normalized location of the trench ($W = 0.075$, $V_s = 350$ m/s, $EPS = 15$)

After reviewing all depicted diagrams, it can be concluded that the highest attenuation of incoming waves is obtained when installing the barrier near to the vibration source ($X = 0.75 - 2.25$) regardless of the thickness of the first layer and normalized depth, which is in agreement with (Alzawi & El Naggar, 2011).

CONCLUSION

A parametric study has been performed for evaluating the efficiency of the geofoam-filled trench in layered soil using a combination of Plaxis, Python and Matlab program. Some of the most relevant results presented here and the conclusions can be summarized as follows:

- In layer soils, the depth of the trench compared to the layer thickness is a critical parameter that determines the behaviour of the system. It shows a significant non-linear behaviour when the soil layer is deeper than the trench, especially in the case of softer soils overlying stiffer soils. As the stiffness of the upper layer nears the bottom layer, these nonlinearities smooth out and the situation clearly resembles more of a homogeneous soil, as expected.
- In fact, the clearest trends appear on the influence of the shear wave velocity of the overlying layer, where, in general, the efficiency of the trench increases for increasing shear wave velocities for all other parameters, except when $D < L$.
- Analyzing the influence of D on the screening effectiveness based on the single parametric study showed that barriers with $D \geq 1$ and 1.25 is enough to have an optimum depth for active system as long as $D > L$. For passive system, the results do not show any optimum depth and the screening effectiveness increases gradually and continuously with increasing D .
- Concerning the location, the highest attenuation of incoming waves is shown when installing the barrier near to the vibration source ($X = 0.75 - 2.25$) regardless of the thickness of the first layer and normalized depth. For softer soils when $X > 2.25$ the efficiency does not change whereas for the stiffer soils ($V_s > 250$ m/s), the position of the trench is not greatly influential as long as $X < 2.25$.

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