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EFFECT OF DIFFERENT CONFIGURATIONS OF A GEOFOAM-FILLED BARRIER IN VIBRATION SCATTERING AND ITS OPTIMIZATION BY GENETIC ALGORITHM

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Abstract. *This paper deals with the effectiveness of various configurations of a geofoam-filled barrier including single, double and triangle wall trenches in isolating the ground vibrations induced by a harmonic load. A 3D finite element program (Plaxis) is used and the model is verified by the result of the analytical solution for the active scheme. Furthermore, a comprehensive parametric study is performed to evaluate the effect of geometrical factors including the depth, width and the length for all systems. The main assumption during the parametric study is treating each parameter as an independent variable and keeping other parameters constant. A genetic algorithm is a proper tool for optimizing all key parameters that can have mutual effects on the vibration attenuation since the vibration isolation is a non-linear problem. A genetic algorithm code is implemented with the help of Python Software and Finite Element Program (Plaxis) for all three systems and the optimized parameters for reaching 75% efficiency of the barrier are calculated. The result of the parametric study showed that the single wall system needs the lowest value of normalized depth for reaching the highest value of the efficiency. Also, the mutual study of all parameters proved that the results are very different from a single parametric study. The comparison of all systems demonstrated that a double wall barrier is the best system for different frequencies.*

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1 INTRODUCTION

The number of people who are interested in living in the big towns are increasing. This growth in population results in constructing more buildings and transport networks in and around the city [1]. Therefore, residence will have more vibration problems from the vibration sources like the passing train, machine foundation, traffic and other constructional activities. The body and Rayleigh waves produced from these sources results in ground-born vibration. The vibration is transmitted through the ground surface to the foundation of the building and create distress to the buildings and their inhabitants [2]. Mitigation measures are used to solve this problem, which include control of the vibration at the source, along the propagation path and at the place of immission. This paper deals with mitigation measure in the transmission path through installing a geofoam-filled barrier for attenuating the incoming waves.

Different approaches including experimental and numerical methods have been carried out to solve the problem of vibration isolation by trench. Since the experimental test is too expensive and the parameters to be assessed are fixed, a numerical model is an effective alternative method for assessing governing parameters in vibration isolation.

Woods conducted a series of field tests for evaluating the efficiency of the open trench and suggested that 75% reduction in incoming waves is enough to have a successful system [3]. Multiple rows of geofoam-filled trenches were applied for screening train-induced ground vibration and the results showed that increasing the depth of the barrier up to $1\lambda_{\mathrm{r}}$ is enough to reach the highest value of efficiency and further increase in depth does not have an effect on isolation capability [4]. A full experimental study was investigated to assess the efficiency of open and geofoam-filled barrier and the normalized depth of 0.6 was selected as an optimum depth for both open and geofoam-filled trench [5]. Mahdavisefat et al. [6] performed a full-scale field experiment to study the effect of open and sand-rubber mixture-filled trench and the normalized depth of 1.5 is recommended by the authors for reaching $60 - 70\%$ of attenuation of the incoming waves.

Tulika et al. investigated the efficiency of open and in-filled barrier by developing a numerical model and concluded that low-density material performs better than high-density [7]. Beskos et al. developed a BEM to study the efficiency of open and concrete filled in homogeneous and layered soils [8]. A FEM was used to evaluate the governing parameters of water and geofoam-filled barrier by [9] and they concluded that depth of the trench is a key parameter for assessing the efficiency of the trench. Ahmad and Al-hussain compared the screening efficiency of the stiff and soft trenches and developed a simple model for predicting the efficiency of the trench in the active and passive schemes [10]. Naghizadehrokni et al. [11] did a full experimental and parametric study and they suggested that the depth and width of approximately $1\lambda_{\mathrm{r}}$ and $0.2\lambda_{\mathrm{r}}$, respectively are enough to reach the acceptable amount of efficiency for the active isolation.

Most studies have mainly focused on one system like rectangular single wall and few researchers compared the efficiency of different configurations of the trench and only a few parametric studies investigated the optimization of different parameters together. Therefore, a full parametric study for assessing the effect of various configurations of geofoam-filled trench is missing. For this purpose, three different systems including the single, double and triangle wall systems are analysed and the efficiency of the systems are compared. There is also a need for mutual optimization of governing factors in evaluating of trench efficiency. It is not possible to treat each parameter as an independent variable in vibration isolation problem.

2 NUMERICAL MODEL

A wave barrier creates a finite material discontinuity for the incoming waves by intercepting, scattering, diffraction and refraction of wave propagation in soil, which can decrease the vibration amplitude beyond the obstacle. A time domain numerical model using the finite element package, Plaxis (2019) is developed to assess the effectiveness of different isolation systems as the wave barriers for the active isolation due to harmonic load in vertical direction. A $3D$ view of the vibration isolation problem and the soil and geofoam properties are illustrated in Fig. 1. Here, the depth D, width W and the length L of the trench are dimensionless values, which are in relation to the Rayleigh wavelength. The geofoam-filled trench is installed at the normalized distance of 1.25 for all three systems. A normalized distance of 7 beyond the trench is selected for calculating the average amplitude reduction ratio.

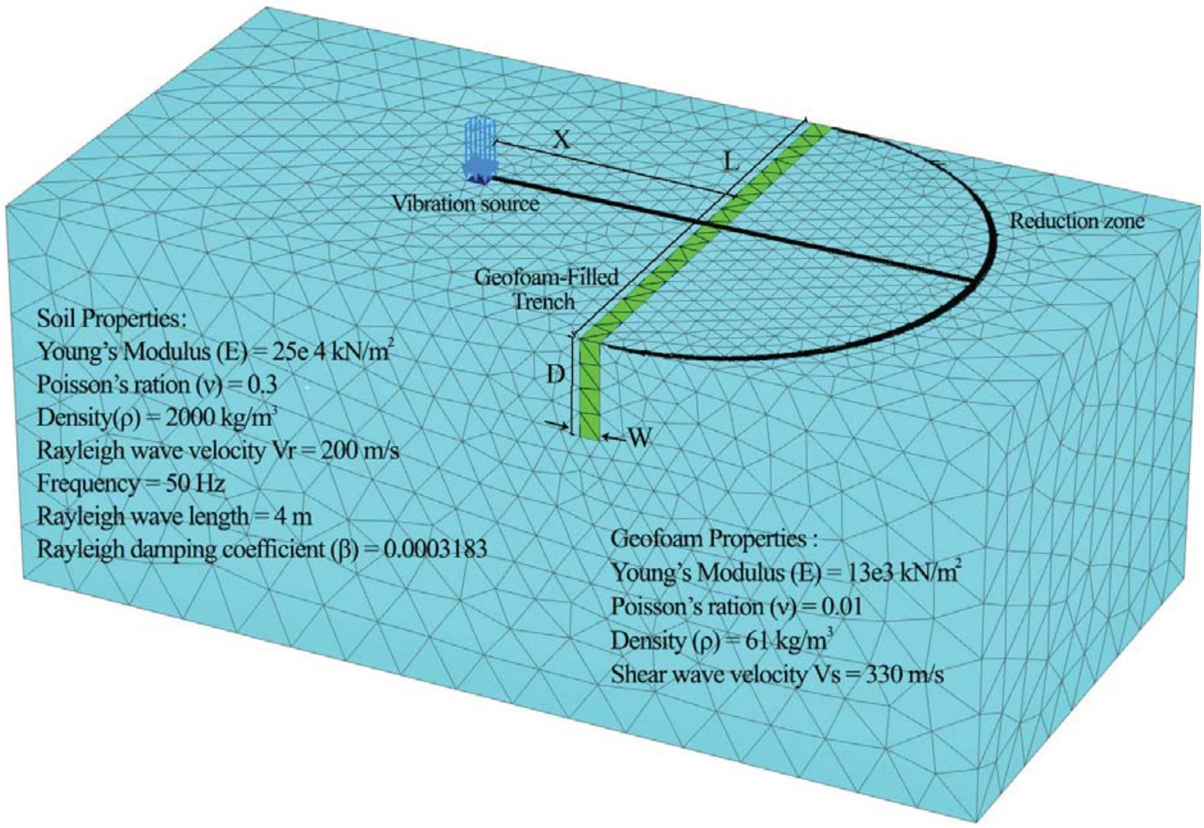

Figure 1: $3D$ model fir finite element analysis

3 ANALYTICAL VALIDATION OF FINITE ELEMENT METHOD

The developed model in Plaxis is verified by comparing the result of wave theory in terms of time of arriving to a specific point. There are two types of elastic waves in the elastic half-space theory including body and surface waves. Body waves are measured through equations 1 and 2.

$$V_p = \sqrt{\frac{E(1-\nu)}{\rho(1+\nu)(1-2\nu)}} \tag{1}$$

$$V_s = \sqrt{\frac{E}{2\rho(1+\nu)}} \tag{2}$$

The Rayleigh wave propagates along the surface of the half-space with a phase velocity, Vr, which is related to the shear wave velocity Vs and the poison's ratio. The Rayleigh wave velocity is calculated by:

$$K^6 - 8K^4 + (24 - 16\alpha^2)K^2 + 16(\alpha^2 - 1) = 1 \tag{3}$$

Where $K = Vr/Vs$ and $\alpha = Vs/Vp$.

Those equation are used just in an isotropic, homogeneous and elastic medium. For verifying the developed model for an open trench, a point at the location of $24\ m$ from the vibration source on the ground surface has been selected. The trench is located at the distance of $12\ m$ from the vibration source with the depth, width of and the length of 3, 0.25 and 10 m, respectively. Based on the equations of 1-3 the wave velocities are calculated as:

$$Vp = 406.6,\ Vs = 217.2,\ Vr = 200$$

Hence, the first time of arriving the waves to the selected point are measured as:

$$T_p = (24/406.3) = 0.059sec,\ T_s = (24/217.2) = 0.11sec,\ T_r = (24/200) = 0.12sec$$

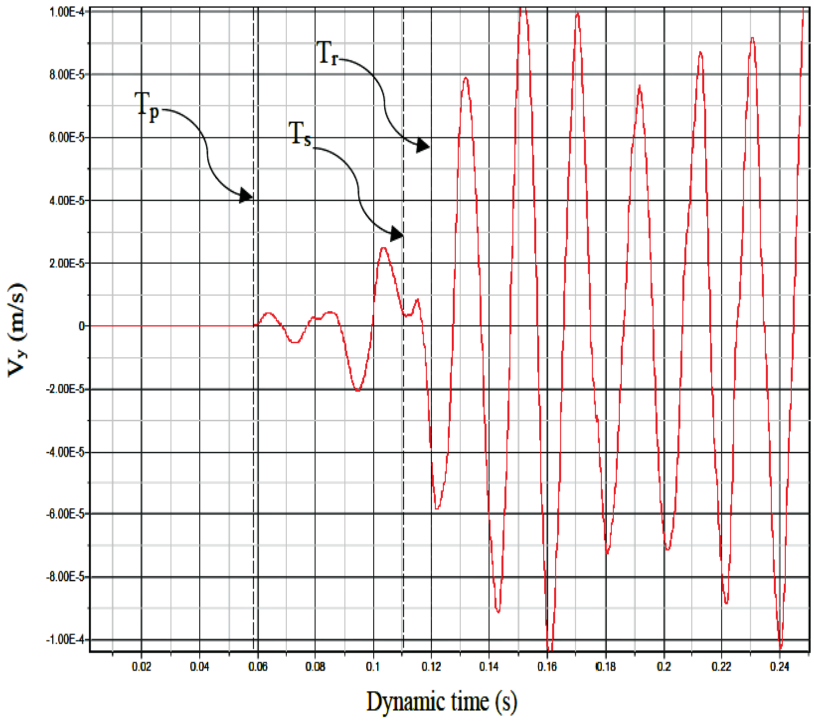

Figure 2: The motion of the selected point in homogeneous, isotropic and elastic soil media without damping

As it can be seen from Fig. 2 that the time of arriving of the body waves (P and S) to the selected point completely matches the analytical solution. The most important vibration will occur after arriving of the Rayleigh wave; that is 0.12 s and it is indicated as the third vertical dashed line. This confirms that the Rayleigh wave is the most important wave that should be considered in vibration isolation problem. Comparing the result of the developed numerical model and the analytical solution of the wave theory confirm the accuracy of Plaxis model.

4 SINGLE WALL SYSTEM

Fig. 3 shows the efficiency of an EPS Geofoam-filled obstacle as a function of normalized length. The average amplitude reduction ratio decreases dramatically with increasing the normalized length from 0.625 to approximately 2.5. It is apparent from the figure that the normalized length beyond around 2.5 does not create any further changes and $\overline{A}_r$ may be conservatively assumed to remind unchanged thereafter. Therefore, the normalized length of 2.5 is selected for the rest of the parametric study.

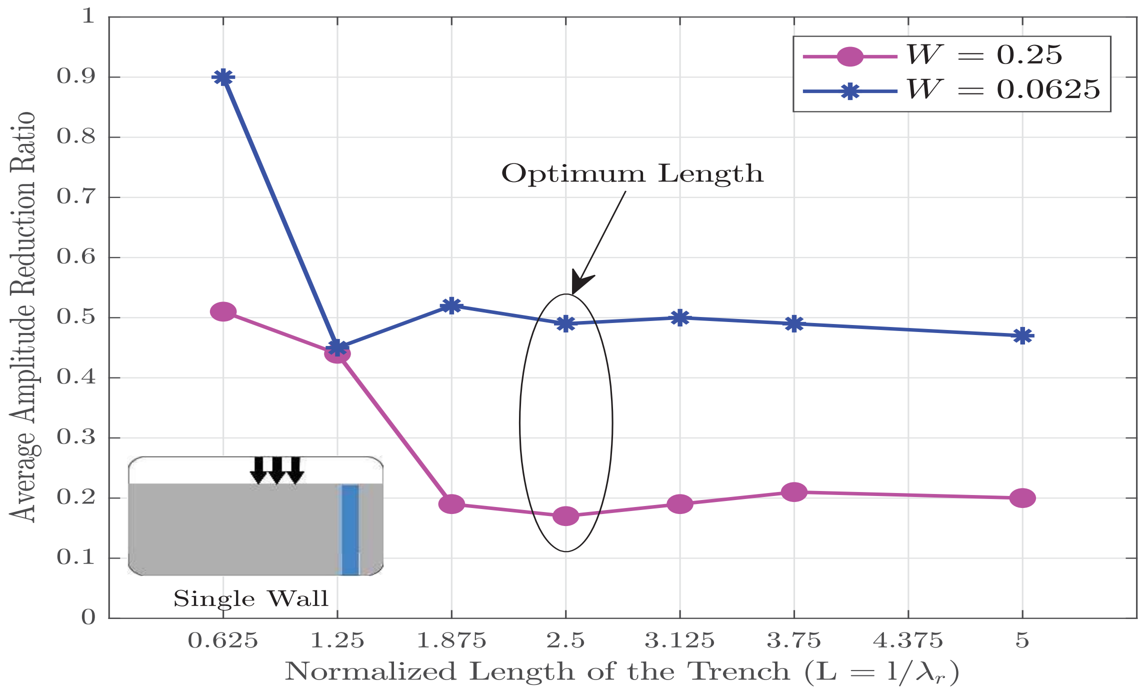

Figure 3: Influence of normalized length of the trench (normalized distance 1.25 from the vibration source, normalized depth of 1.25)

Fig. 4 illustrates the variation of $\overline{A}_r$ along the surface of soil domain for different trench depths. The effect of normalized trench depth is affected in a complex pattern with the effect of normalized trench widths. The efficiency of the trench reaches it's maximum value at D value around 1.25 for almost all widths. The optimum D has a close relationship with the width of the barrier and the efficiency of the trench increases gradually with increasing the normalized width for the same depth (optimum depth). Another important point in this figure is unexpected peaks and valleys in $\overline{A}_r$ value for various widths, which is caused by constructive and destructive interference of the barrier.

The importance of the normalized width on $\overline{A}_r$ is presented in Fig. 5. The width appears to play a significant role in screening efficiency of the trench. A reduction of approximately 50% is visible by increasing W from 0.0625 to 0.25 for almost all trench depths and it seems that $W = 0.25$ is an optimum width for achieving a reasonable amount of wave scattering. Increasing the normalized width means increasing the distance between two corners. The barrier bottom corners act as an additional geometric discontinuity and this issue results in mode conversation of incoming waves for converting part of the R-waves energy into the body waves

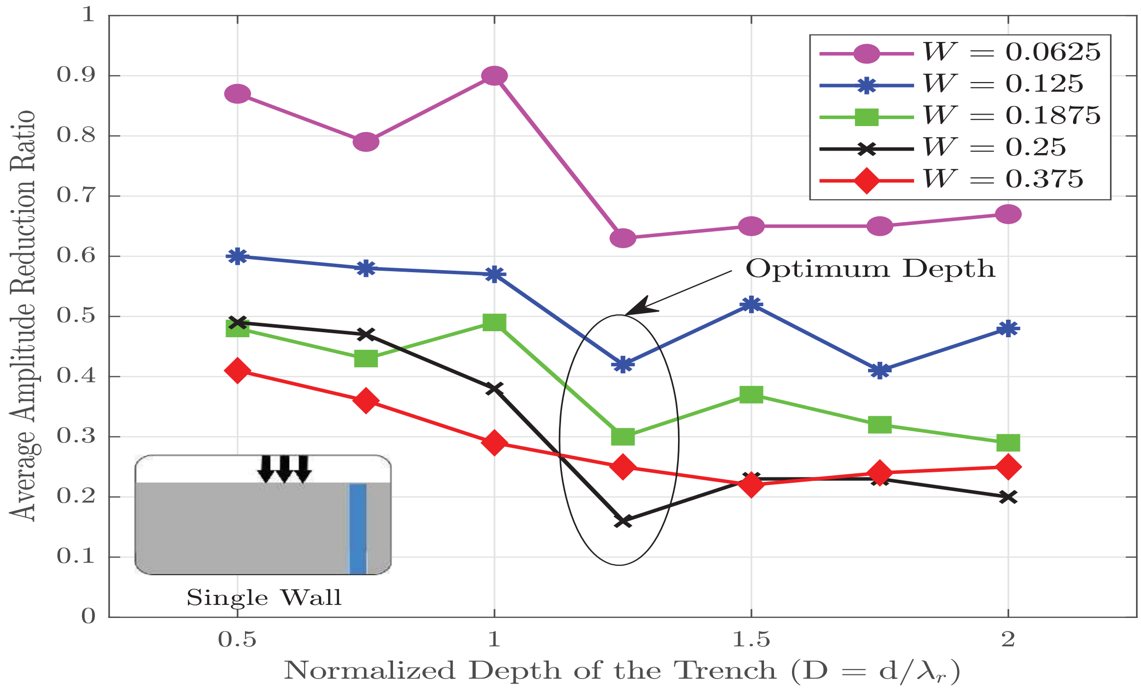

Figure 4: Influence of normalized depth of the trench

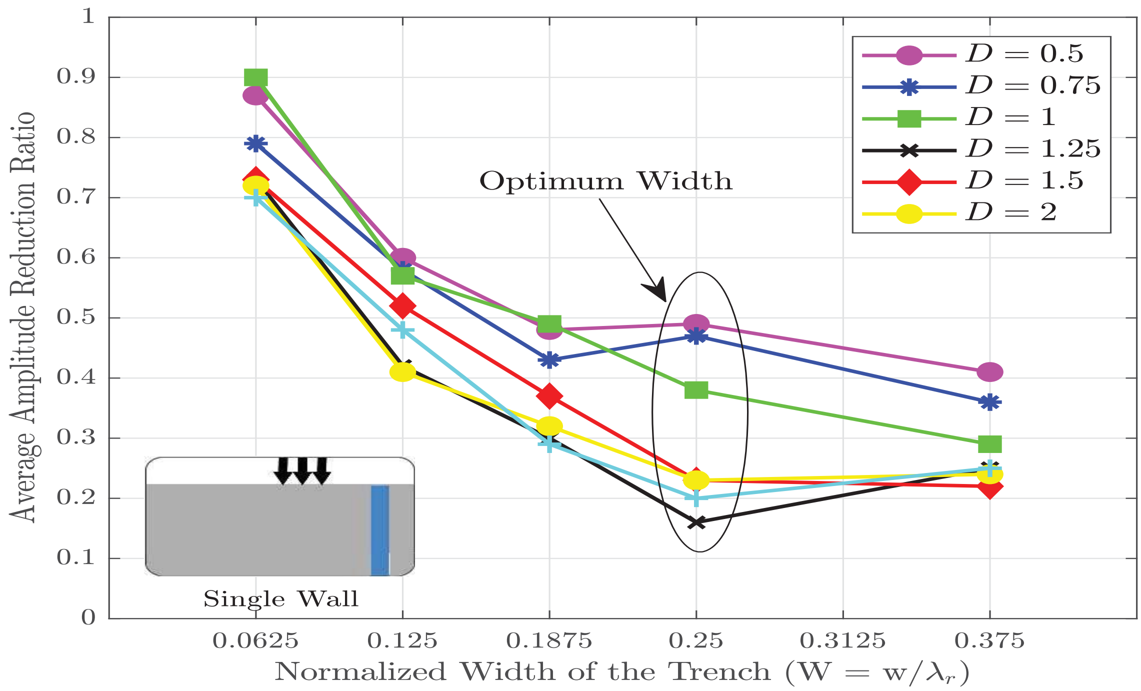

Figure 5: Influence of normalized width of the trench

5 DOUBLE WALL SYSTEM

The efficiency of the double wall system is compared with the single wall system with a thickness of $2W$, having the same width, depth and the length like the single wall obstacle. Hence, for this system the width of both barriers is considered as one width, which is W. This normalized width is the width for both trenches.

At the first step, a parametric study should be done for finding the optimum spacing between the barriers to achieve the best wave attenuation. The influence of spacing between trench walls is plotted in Fig. 6 with the constant normalized depth, width and length of 1, 0.25 and 2.5, respectively.

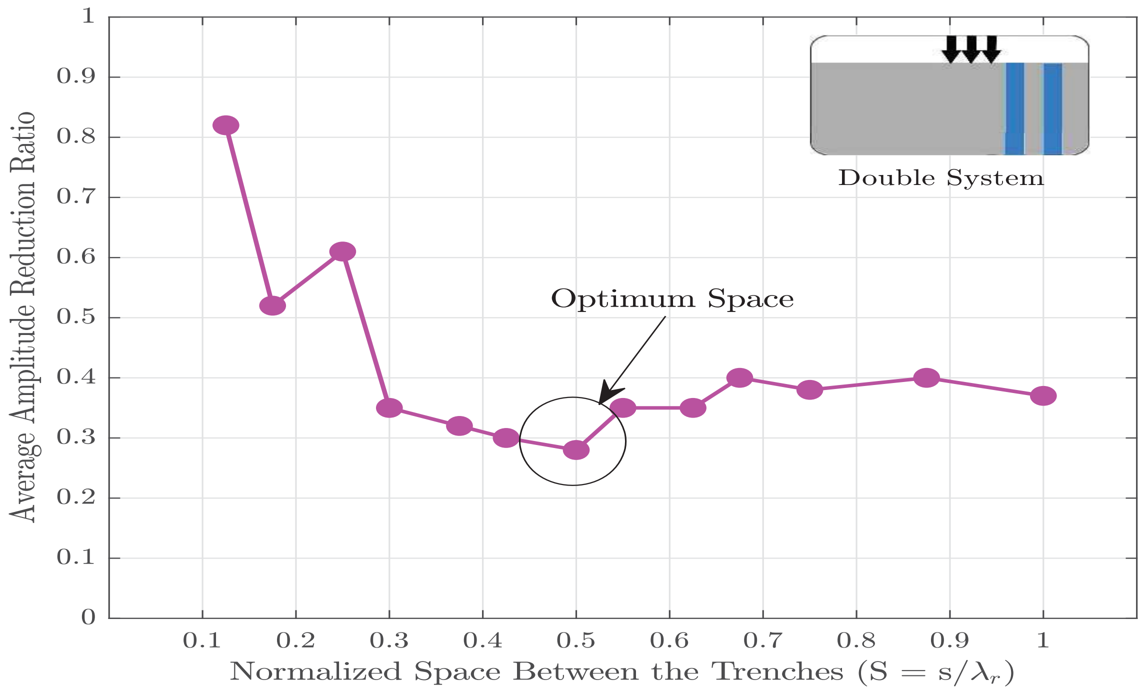

Figure 6: Influence of normalized space between the trenches

The normalized spacing (S) between the walls appears to govern the screening effectiveness of the trench. The efficiency of the double wall system is maximized at S value around 0.5. Therefore, the normalized optimum spacing between the wave barriers is considered as 0.5, which is compatible with the result of [5] for optimum spacing between trenches, for further parametric studies.

An investigation is done for finding the influence of the normalized length on wave attenuation like single wall system. The result of the parametric study doesn't show any specific change in comparison with the result of the single wall study. Therefore, to avoid the presentation of unchanged results, the normalized length of 2.5 is selected as the optimum length for this system.

Based on the information of Fig. 7, which is the calculated value of $\overline{A}_r$ as a function of the normalized depth, D for narrow trench ($W = 0.0625$) seems to govern the wave attenuation for the normalized depth between 0.5 and 1.5. For wider trenches, increasing the normalized depth of the barrier leads to blocking of more incident propagated waves until around $D = 1.25$, which is selected for the optimum depth of the trench for achieving approximately 80% of the barrier's efficiency for the wider trenches.

The effect of the width on $\overline{A}_r$ for an EPS Geofoam-filled barrier is presented in Fig. 8. It is obvious from the results that the value of average amplitude reduction ratio decreases dramatically with increasing the normalized width of the trench from 0.0625 to around 0.2 and thereafter, it remains at the constant value with increasing W to 0.375. An optimum width of almost 0.2 is enough for achieving the highest value of screening performance.

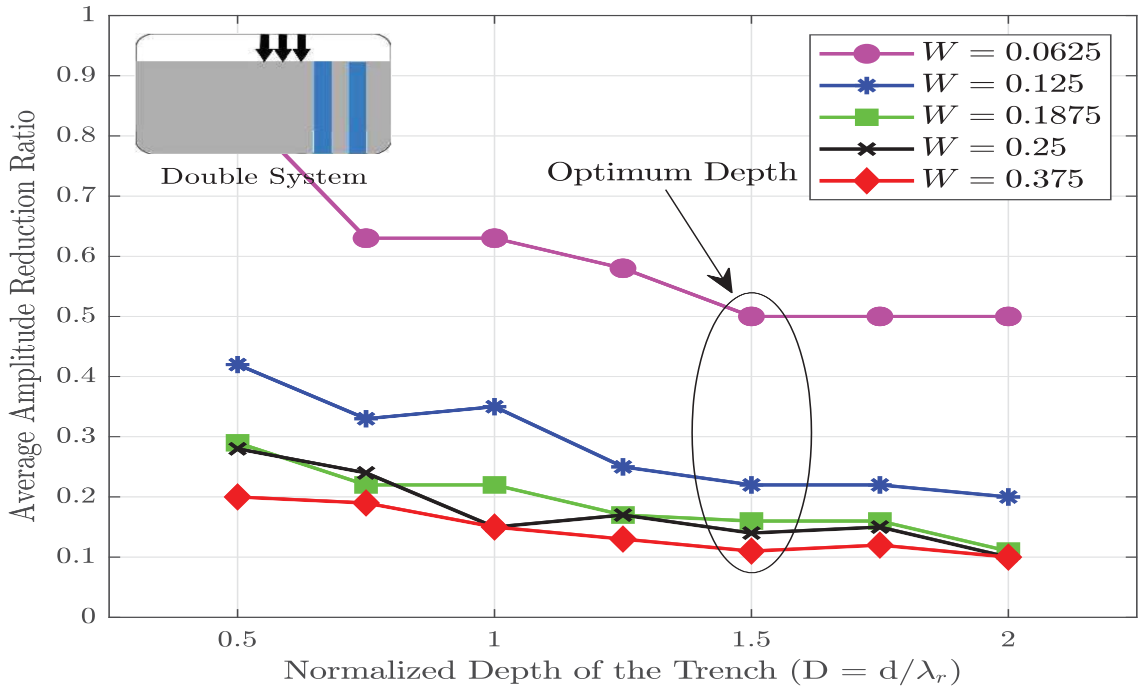

Figure 7: Influence of normalized depth of the trench

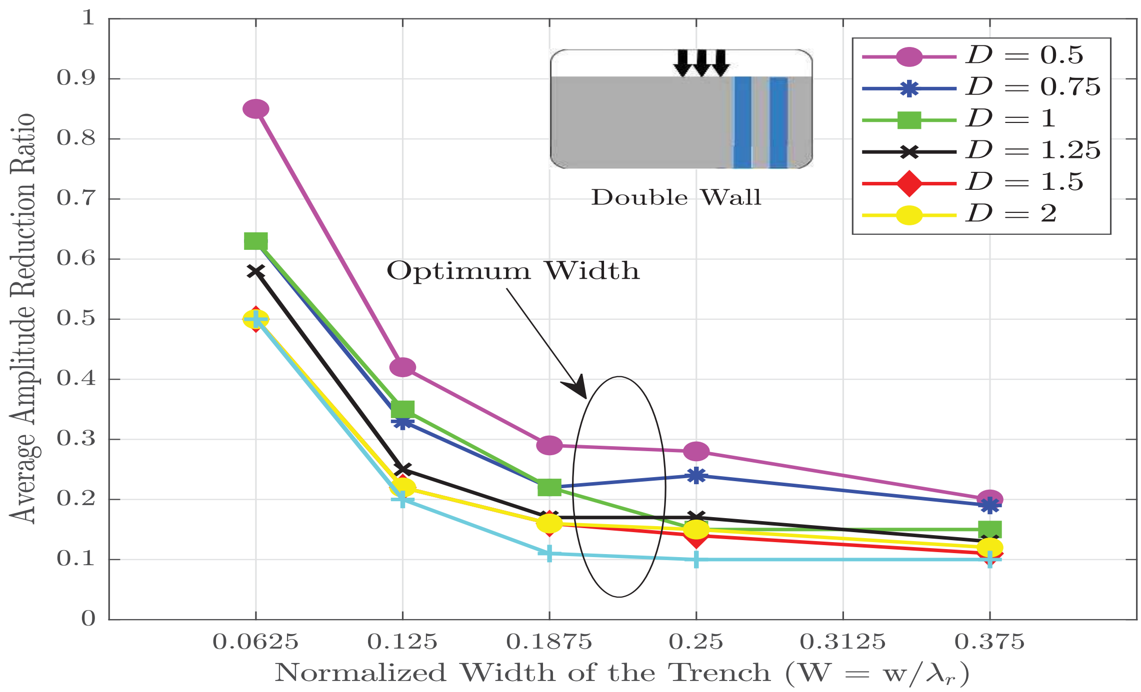

Figure 8: Influence of normalized width of the trench

6 TRIANGLE WALL SYSTEM AS WAVE BARRIER

For making a proper comparison with the single and double wall systems, triangle wall is considered with the same depth and the same area like single and double wall. However the width of the trench is different from those systems. Since increasing the width and the depth of the triangle trench leads to changing in the slope side wall of the trench, inclination angle is proposed as an alternative parameter for measuring the efficiency of the barrier. As a consequence, the value of inclination angle is calculated with keeping the width of the trench at ground surface constant and calculating the inclination angle through increasing the depth.

A parametric study is done for finding the effect of the length on the efficiency of the trench and to see how far the results match with the results of the single and double wall systems. The results show that an optimum length of 2.5 is enough for the triangle wall system like for previous systems.

The effect of the normalized depth on the wave attenuation performance is presented in Fig. 9. The results reflect that in general a normalized depth of almost 1.5 appears to be the maximum depth for achieving at least 70% of system's effectiveness except for the narrow trench ($W = 0.125$). An approximately 50% reduction for almost all barrier with different normalized widths is seen by increasing D from 0.5 to 1.5

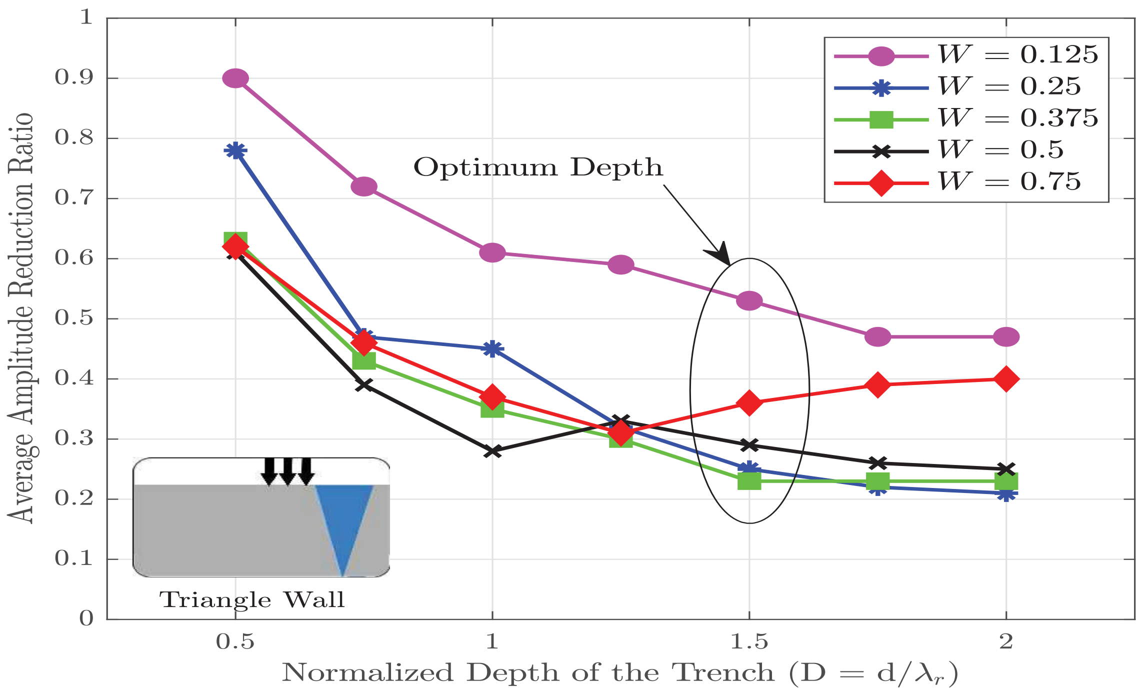

Figure 9: Influence of normalized barrier depth

The effect of varying the normalized width is studied by varying W from 0.125 to 0.75 which is the normalized width of the triangle wall system at the ground surface, while the normalized depth of the trench is varied from 0.5 to 4.

According to Fig. 10, vibration screening performance reaches the highest value when the normalized trench width is approximately 0.4 for shallow trenches ($D = 0.5$ to 1), which is considered as optimum W for shallow barriers. However, increasing the normalized depth ($D > 1$) leads to the highest value of wave attenuation when W is around 0.3. Therefore, a wider trench is needed (for $D < 1$) for reaching the highest value of screening performance, while by increasing the normalized depth of the trench ($D > 1$), a slender barrier is sufficient for reaching highest value of vibration isolation.

The performance of the trench inclination angle is investigated for $W = 0.125$ and three different normalized locations including 0.5, 1.25 and 2, respectively. Fig. 11 represent the effect of inclination on different situations.

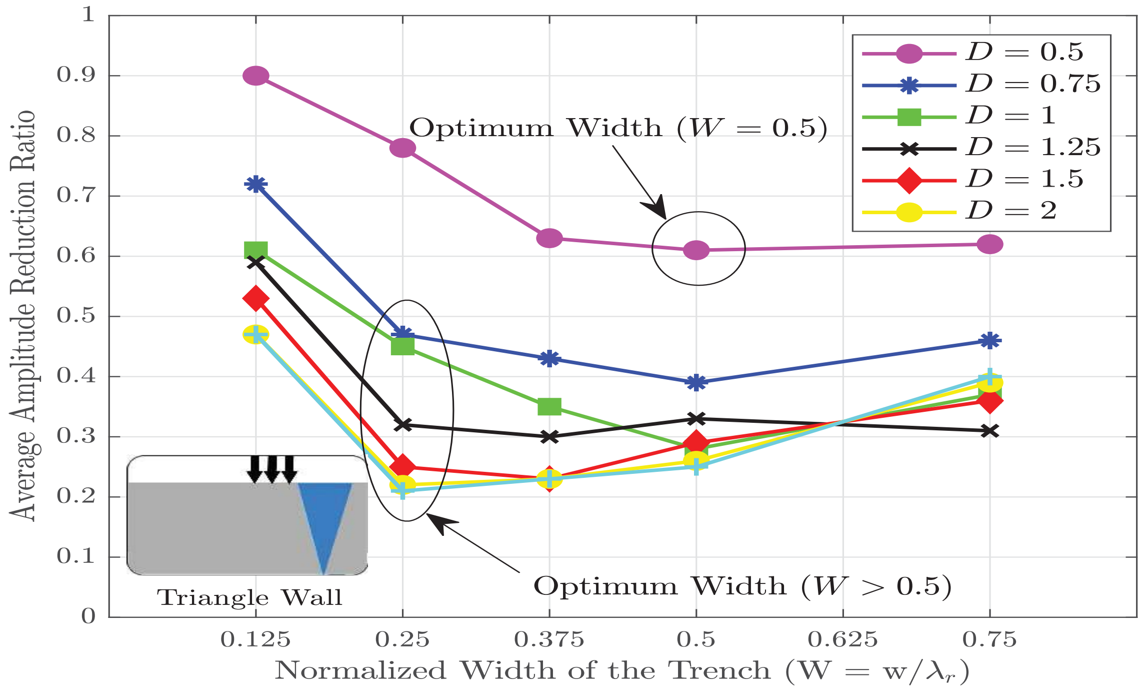

Figure 10: Influence of normalized width on the trench

It is observed that the average amplitude reduction ratio decreases dramatically with increasing the inclination angle from 35 to 60 degree. This angle is considered as the optimum angle for all locations.

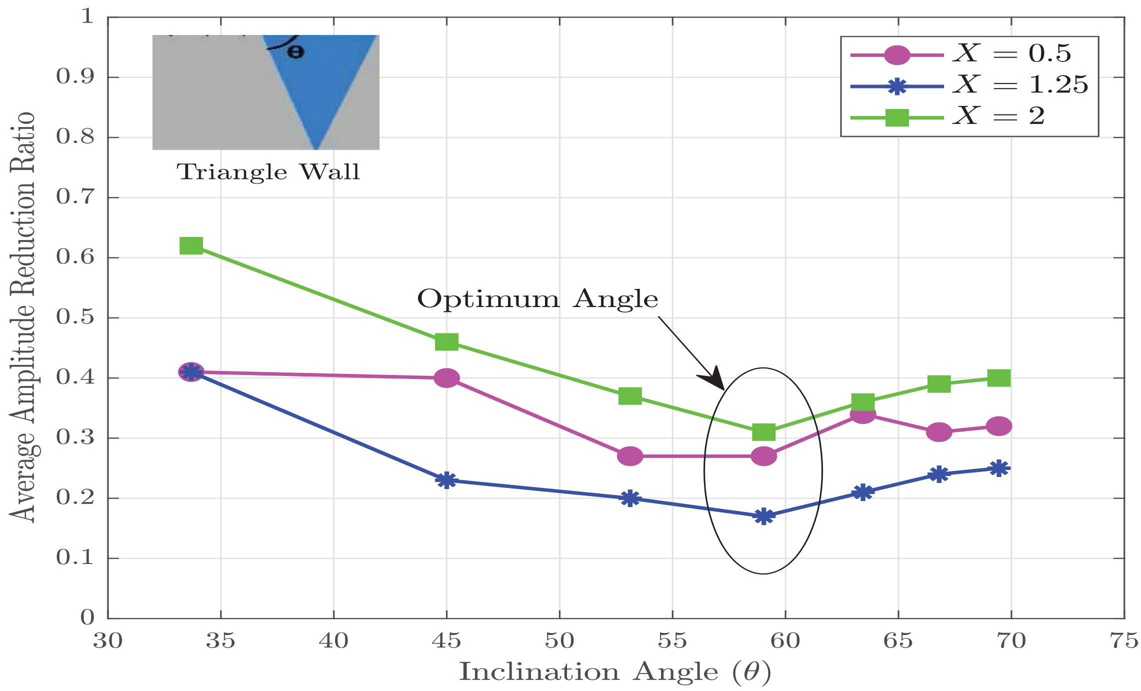

Figure 11: Influence of inclination angle of the trench with ground surface (normalized width 0.125)

7 COMPARISON OF DIFFERENT SYSTEMS

A comparison is performed between all proposed systems through calculating the screening performance as a function of D. The results are depicted in Fig. 12. The results show that the efficiency of the trench increases by increasing D for both widths ($W = 0.0625$ and 1). There is a considerable gap between the value of $\overline{A}_r$ for narrow and wide trenches that shows the significance of W.

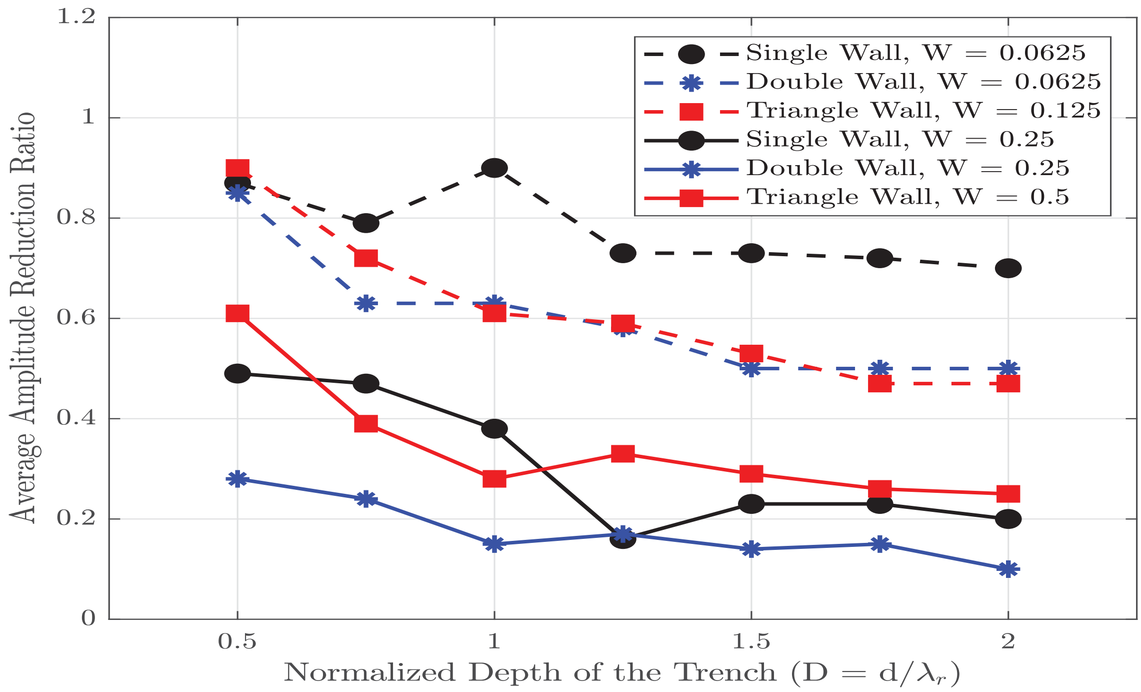

Figure 12: Comparison between different systems (normalized distance 2 from the vibration source)

Regarding the narrow trench, double wall systems has the highest value of screening efficiency for the normalized depth until 1. After this depth, double and triangle wall barriers have almost the same efficiency for all depths. However, the single wall system has the lowest value of efficiency in comparison with other systems.

As the width of the systems increases, the efficiency of all systems increases, too. However, the double wall system still performs better than the other systems in attenuating the incoming waves. There is a remarkable decrease in the amount of $\overline{A}_r$ for the single wall barrier which is the result of increasing the depth from 1 to 1.25. For making a comparison for the single and triangle wall system, it is divided into two different categories for shallower trenches ($D < 1$), in which triangle wall has better efficiency and deeper trenches ($D > 1$), in which single wall has more capability in blocking the incoming waves.

8 OPTIMIZATION PROCESS WITH GENETIC ALGORITHM

Until now, the problem of the vibration isolation has been solved for a specific parameter like depth, width, length or locations and keeping other factors constant. However, it is not reasonable to compute the wave barrier performance by allowing just one parameter to change since the parametric study proved that the dimensional and geometrical factors of a barrier are not independent and sometimes they may have an effect on each other. Therefore, it is imperative to study the mutual effect of all parameters including the dimensional and geometrical factors to implement a successful wave barrier through optimal combination of parameters. This aim has been achieved through a genetic algorithm optimization technique for three different configurations of obstacles including the single, double and the triangle wall systems, respectively. It was tried to adjust the parameters to reach the same value of cross-sectional area for each system. The first step in the implementation of a genetic algorithm is to randomly create an initial population. Through reviewing empirical studies carried out and doing some trial and error for the initial population, population size equal 30 is found to be optimal for the problems in vibration isolation. Since the vibration isolation problem is an inherent complex and non-linear problem, the finite element program (Plaxis) and Python programming language are utilized as a fitness function to calculate the quality of a chromosome as a solution. A remote scripting interface is an option for building a model automatically in Plaxis and this ability creates a possibility to use Plaxis as a fitness function in genetic algorithm. The code is developed for vibration isolation study and all analyses steps are automatized. Another important feature of this code is the changeability of the soil and geofoam material, the geometrical dimensions and the shape of the barrier.

Woods suggested that a successful wave barrier should reach at least 75% mitigation in scattering of incoming waves. On the other hand, reaching to a deep trench like 5 or 6 m is relatively tough and sometimes impossible in reality. All of these issues lead to create a restriction amount for $\overline{A}_r$ which is 0.75. In addition, we know that depth of the trench is one of the most important factors in achieving an acceptable efficiency for the wave mitigation. Therefore, defining a cost function for optimizing $\overline{A}_r$ value and simultaneously considering the depth of the barrier is a proper solution for increasing the importance of D in the optimization process. This is done by assigning two different constant coefficients including Alpha and Beta for $\overline{A}_r$ and the depth in a cost function, which are 0.995 and 0.005, respectively.

The next step is applying crossover, which is the genetic operator and uses to combine two chromosomes, or parents, to generate a crossover child for the next generation. Crossover is applied to the random selected parents with a crossover probability Pc of equal 0.8. The mutation operator is applied with a mutation probability Pm equal to 0.2. After completing the process of selection, recombination and mutation, the next population can be generated. This process of evaluation, selection, recombination and mutation is repeated until finishing the iteration number. A summary of implementation of the genetic algorithm for vibration isolation problem is presented in Fig. 13.

9 OPTIMIZATION OF DIFFERENT SYSTEMS

A genetic algorithm code with the above-mentioned properties is implemented in Python through writing a script for optimizing various parameters of the trench. It is mandatory to write a script that is readable by Plaxis for creating the model automatically including soil contour, borehole, soil model, structure, mesh, calculation phases, and calculating the efficiency of the trench.

A quantitative range for different parameters is defined for finding the optimal solutions of the problem. In order to make a proper comparison for all three configurations, the same depth and cross-sectional area is assumed for all three systems. For each system, different boundaries are defined as the maximum and minimum value for various variables, which are presented in Table 1.

A genetic algorithm is used for optimizing the important parameters of the barrier for the vibration isolation problem for reaching the efficiency of almost 75%. The variation of the parameters is assumed as the same value for having the equal cross-sectional area, while one of

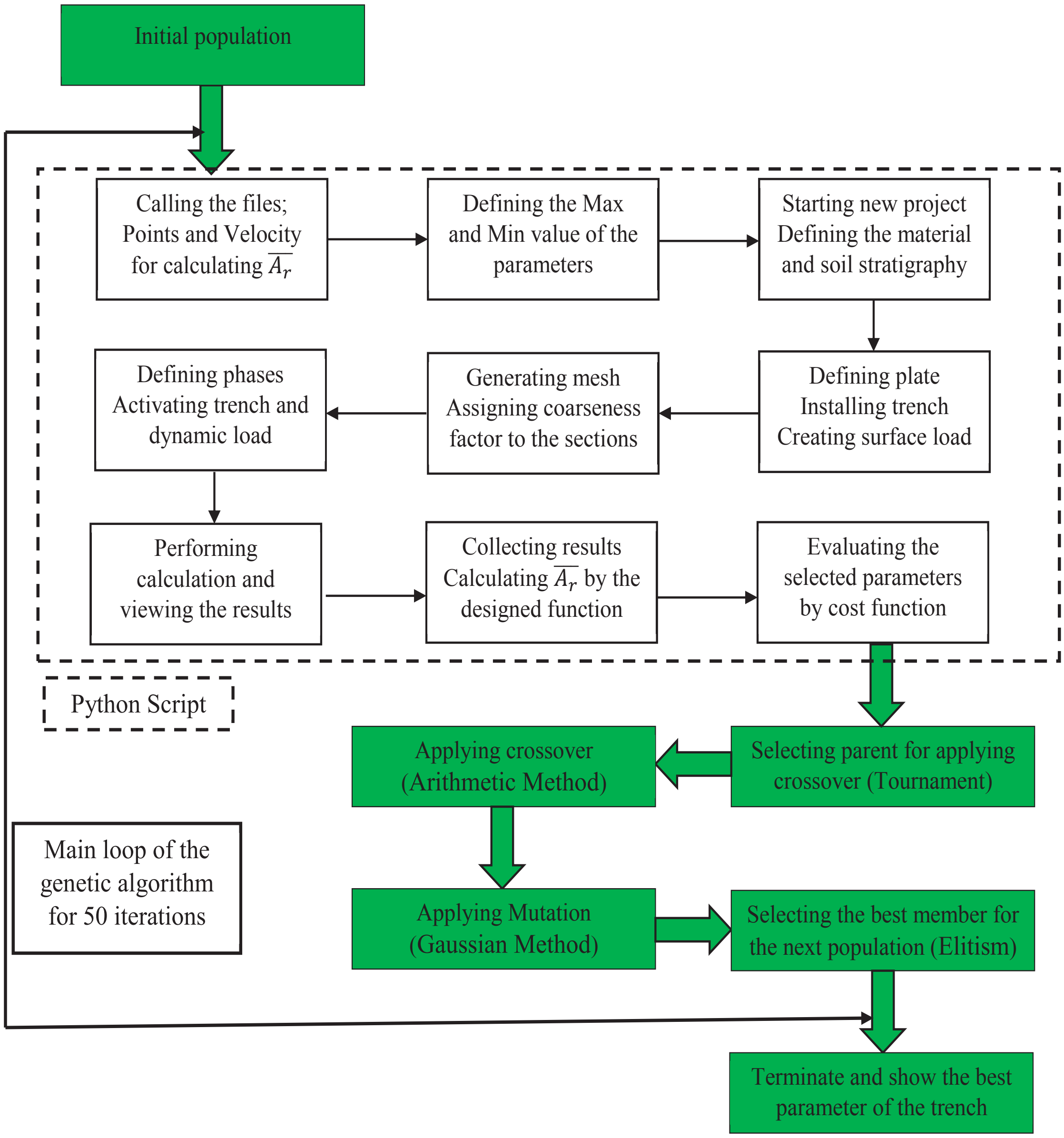

Figure 13: Implementation of the genetic algorithm for the vibration isolation problem

Type of system	Location (m)	Depth (m)	Width (m)	Length (m)	Distance (m)
Single	2-20	2-6	0.25-1	5-15	-
Double	2-20	2-6	0.25-1	5-15	2-4
Triangle	2-20	2-6	0.5-2	5-15	-

Table 1: Defined boundaries for different parameters in the genetic algorithm

the purposes of this study is evaluating the effect of the shape of the trench on mitigating of the incoming waves. The optimal parameters of geofoam-filled barrier for different systems in the case of active isolation and for the frequency of $50\ Hz$ is presented in Table 2.

The trench length for the single wall system is calculated with the same value of parametric study, so it is concluded that the length of $10\ m$ for the single wall system is suitable for reaching the desired efficiency. In addition, the space between the barriers for double wall system is in a

System	Location (m)	Depth (m)	Width (m)	Length (m)	Distance between trenches (m)	Efficiency (%)
Single Wall	5.38	2.96	0.95	10	-	78
Double Wall	4.06	2.6	1.2	6.05	2	78
Triangle Wall	2.18	2.98	1.92	8.15	-	74

Table 2: Optimized dimensions of the trench for different systems ($50Hz$)

good agreement with the result of parametric study.

An initial observation of the optimized parameters shows that the triangle wall system should be installed more near to the vibration source in comparison with other systems. In addition, the results show that the depth of the barrier is almost independent on the shape of the trench for the single and triangle wall systems, since the depth of the trench reminds almost has the same value for these systems. A pair of double wall barriers needs more width and lower depth in comparison with other configurations. Moreover, the length of the trench decreases in comparison with the other systems. Generally speaking, if reaching a depth of around $3m$ is difficult for a trench, double wall system is a good solution by having lower depth.

10 COMPARISON BETWEEN DIFFERENT SYSTEMS

Since the frequency of the applied load plays an important role in vibration isolation, a comparison has been done for different configurations with optimized parameters. By changing the frequency of the applied load, the average amplitude reduction ratio is calculated for the vertical response for the area beyond the trench and the results are illustrated in Fig. 14.

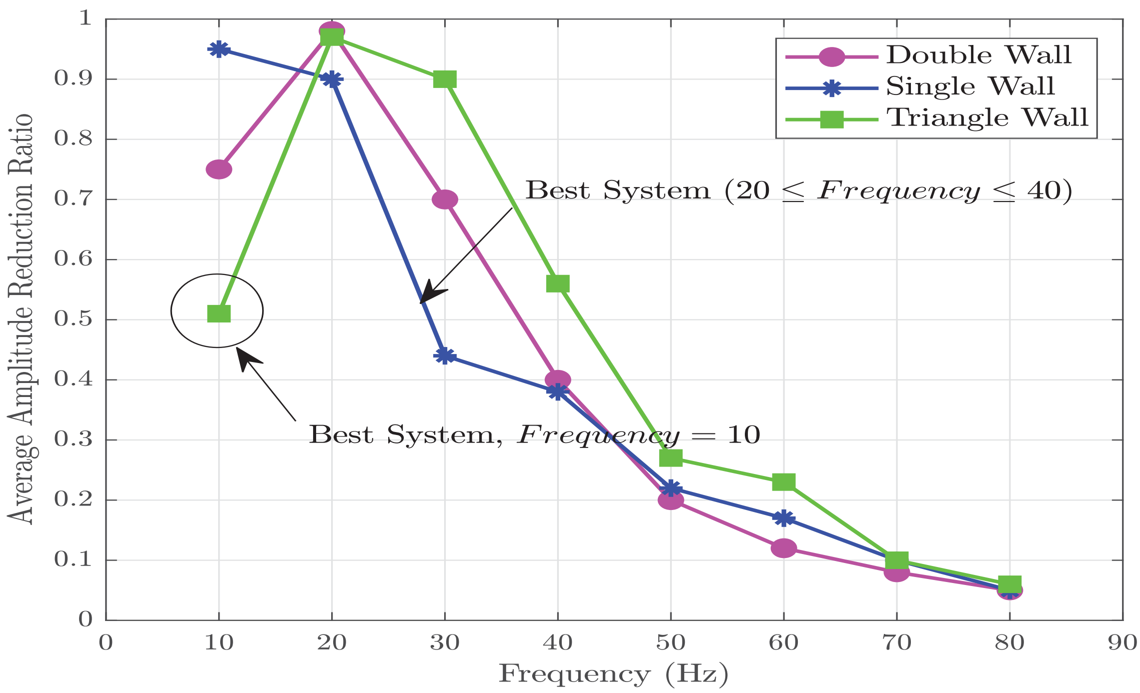

Figure 14: Influence of frequency of the applied load (Optimized parameters for all systems)

The results state that frequency of applied load plays a significant role in attenuating of incoming waves for various systems including the triangle, double and the single wall in orders.

Increasing the frequency of the load leads to a dramatic decrease in $\overline{A}_r$ value. For instance, increasing the frequency of the applied load from 20 to $70HZ$ results in reducing the average amplitude reduction ratios, which are approximately 85% for almost all systems.

11 Conclusion

The developed numerical model is verified by an analytical method. Then, a full parametric study is done for evaluating the effect of the governing factors including the depth, width and the length of the barrier in the active isolation and the results are compared. Three different systems including the single, double and the triangle wall are selected for assessing the effect of the shape of the trench on vibration isolation. Based on the results of parametric investigations:

- The normalized length of 2.5 is recommended for all three systems for having the highest amount of efficiency.
- The single wall system needs the lowest value of normalized depth for attenuating the incoming waves at an optimum depth, which is equal to 1.25. However, the optimum depth for double and triangle wall system is calculated to 1.5.
- The double wall system needs an optimum width of 0.2, which is the lowest width in comparison with other systems, whereas the optimum width of single wall system is calculated to 0.25. For triangle wall system, shallow trenches need more width ($W = 0.4$) to reach the highest value of efficiency in comparison with a deep trench, which is 0.3.
- The double wall is the best system for attenuating the highest amount of incoming waves in comparison with other systems.

Finally, the most significant finding of the research is the developed genetic algorithm code that can be used as a reference for geotechnical engineers for designing the barrier for achieving at least 75% mitigation in vibration amplitudes. In addition, the mutual study of all parameters demonstrated that the results are different to those of a single parametric study. The result of the comparison of all systems in the frequency domain revealed that the single and the double wall barriers are the best systems for the frequency in the range of $20-40\ Hz$ for the active isolation and the triangle wall system is highly recommended for the frequency of $10\ Hz$. However,

REFERENCES

[1] Kattis, S. E., D. Polyzos, and D. E. Beskos. "Modelling of pile wave barriers by effective trenches and their screening effectiveness." *Soil Dynamics and Earthquake Engineering* 18.1 (1999): 1-10.

[2] Haupt, W. A. "Wave propagation in the ground and isolation measures." (1995).

[3] Woods, Richard D. *Screening of suface waves in soils*. 1968.

[4] Pu, Xingbo, Zhifei Shi, and Hongjun Xiang. "Feasibility of ambient vibration screening by periodic geofoam-filled trenches." *Soil Dynamics and Earthquake Engineering* 104 (2018): 228-235.

[5] Alzawi, Ashref, and M. Hesham El Naggar. "Full scale experimental study on vibration scattering using open and in-filled (GeoFoam) wave barriers." *Soil Dynamics and Earthquake Engineering* 31.3 (2011): 306-317.

[6] Mahdavisefat, E., H. Salehzadeh, and A. A. Heshmati. “Full-scale experimental study on screening effectiveness of SRM-filled trench barriers.” *Géotechnique* 68.10 (2018): 869-882.

[7] Bose, Tulika, et al. “Efficiency of Open and Infill Trenches in Mitigating Ground-Borne Vibrations.” *Journal of Geotechnical and Geoenvironmental Engineering* 144.8 (2018): 04018048.

[8] Beskos, D. E., B. Dasgupta, and I. G. Vardoulakis. “Vibration isolation using open or filled trenches.” *Computational mechanics* 1.1 (1986): 43-63.

[9] Liyanapathirana, D. S., and Sanka D. Ekanayake. “Application of EPS geofoam in attenuating ground vibrations during vibratory pile driving.” *Geotextiles and Geomembranes* 44.1 (2016): 59-69.

[10] Ahmad, S., and T. M. Al-Hussaini. “Simplified design for vibration screening by open and in-filled trenches.” *Journal of geotechnical engineering* 117.1 (1991): 67-88.

[11] M. Naghizadehrokni and M. Ziegler and J. Sprengel. “A full experimental and numerical modelling of the practicability of thin foam barrier as vibration reduction measure.” *Soil Dynamics and Earthquake Engineering*, volume = 139, year = 2020, issn = 0267-7261, DOI: https://doi.org/10.1016/j.soildyn.2020.106416