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Numerical study of wave barrier and its optimization design

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ABSTRACT

A numerical investigation on the performance of wave barrier and a developed optimization design method for wave barrier are presented. Firstly, a two-dimensional (2D) numerical model is built in ABAQUS and the results are verified by previous publications. A comparative study of the 2D model and three-dimensional (3D) model is also carried out. Then, an extensive parametric study is committed to investigate the effect of each parameter on the barrier vibration isolation effectiveness, key parameters are identified. Unlike most of the previous work, an optimization design method has finally been developed to find out the barrier which has the best vibration isolation effectiveness. An example of optimization design for barriers made up of expanded polystyrene (EPS) geofoam is shown as well. This suggested method can provide useful guidelines for wave barrier design in practice.

1. Introduction

Ground vibration generated by vibratory sources, such as earthquake, explosion, high speed trains, subways or cars has detrimental influences on the nearby buildings and residents, ranging from causing annoyance to structural damage and loss of life. In the densely populated urban regions and buildings housing sensitive equipment, ground vibration must be strictly controlled. Up to now, various vibration reduction methods have been used, one of them is the installation of wave barriers, like open trenches, concrete or bentonite trenches, sheet pile walls, gas-filled cushions and expanded polystyrene (EPS) geofoam, which are considered to be able to prevent waves from transmitting wave energy into the protected areas. Generally speaking, the geometry, location and the composition of wave barriers are the most important factors that affect the screening effect. In the past few decades, a number of researches including analytical, experimental and numerical studies have been carried out to investigate the effectiveness of wave barriers. For the analytical approach, White [1] studied the scattering of plane compressional and shear elastic waves incident obliquely on a cylindrical discontinuity in a solid. Knopoff [2,3], Mal and Knopoff [4] and Thau and Pao [5] investigated wave diffraction by spherical, rectangular and parabolic obstacles, respectively. Lee [6] analyzed the 3D scattering and diffraction of plane waves by a hemispherical canyon in the homogeneous elastic half-space. Avillés and Sánchez-Sesma [7] presented a theoretical study on the usefulness of a row of rigid piles as barriers for isolating elastic waves, using cylindrical coordinate systems to solve the problem of multiple scattering for circular cross-sections. Since it is difficult to obtain closed-form solutions due to the mathematical complexity except for very simple geometries and idealized boundary conditions, the analytical approach is limited. Therefore, experimental and numerical approaches were pursued. Woods [8] conducted a series of field tests on vibration screening by installing open trenches which were close to the vibratory source (designated as active isolation) as well as far away from the vibratory source (designated as passive isolation). Based on the experimental results, he provided some recommendations for the rational design of open trenches. Aboudi [9] used a combined perturbation-numerical approach to solve the problem of wave propagation across a thin barrier embedded in an elastic half-space. Al-Hussaini and Ahmad [10,11] performed a rigorous boundary element (BEM) algorithm incorporating higher-order elements to examine the influence of geometrical and material parameters on the screening efficiency of a rectangular barrier, and a simple model was developed for the horizontal vibration screening effect. Massarsch [12] presented the gas cushion method and described its applications in full-scale projects, the efficiency of the gas cushion method was assessed in different soil conditions. Murillo et al. [13] conducted a centrifuge parametric study to investigate the influences of various parameters (barrier depth, width, location and input frequency) in reduced scale models made of EPS isolation barriers within Fontainebleau sand, the EPS geofoam isolation efficiency was examined and some useful suggestions about the practical design

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of wave barriers were provided. Lu et al. [14] developed a numerical model to analyze the isolation of moving-load induced vibration using pile rows embedded in a layered poroelastic half-space. They pointed out that better isolation efficiencies could be achieved when there were higher speed of moving loads and when pile rows were embedded in two-layered poroelastic half-space with a softer overlying layer. Alzawi and EI-Naggar [15] conducted a full scale field experiment to study the performance of both open and in-filled trenches with geofoam material, the effect of the geometry and location of trenches on the screening efficiency was examined. Alzawi [16] developed a model for the barrier design using Multiple Linear Regression (MLR), an artificial neural network (ANN) model was also developed to predict the geofoam barriers isolation effectiveness in different soil conditions.

To the best of the writers' knowledge, all the previous work which involved in parametric study mainly focused on the effect of single parameter on the barrier vibration isolation effectiveness. It is still unclear what will happen when mutual influences exist, while such mutual influences are very common in practice. The only exception is Wu [17] who used Taguchi method for the optimization of parameters of underground trench. However, his study was about the underground barrier, rather than surface barrier. Also, the investigation on the optimization of parameters in his work did not include the effect of barrier material, which is believed to play an important role in screening effect. To overcome these drawbacks, we carried out a numerical study using ABAQUS and PYTHON programming language, aiming to develop an optimization design method for wave barriers. Firstly, a 2D numerical model is created in ABAQUS and the result is verified by previous published literatures. Then, parametric study is committed to investigate the influence of each parameter on the barrier vibration isolation effectiveness, and key parameters are identified. Finally, Python scripts are drafted to optimize the combination of key parameters to find out the best barrier which is able to minimize the soil vibration. An example of optimization design for barriers made of expanded polystyrene (EPS) geofoam is shown as well. This developed method can be directly used in practice. For example, it is suitable to help optimize the barrier design for a particular site, which is one of the major research objectives in the ISVR (Institute of Sound and Vibration Research)'s project [18]: Mitigation measures-transmission-trench and buried wall barriers.

2. Numerical model and results

Fig. 1 shows a 2D plane-strain model constructed in ABAQUS. It has a length of 120 m and a depth of 24 m. A rectangle barrier is installed in a half space soil, its depth D, width W and inclination angle U are given as 5 m, 0.5 m and 90°, respectively. A dynamic load P, which is represented by a function $P = P_0 e^{iwt}$, is applied on the top surface of the soil and has a width of r. The quantities P_0, ω and r are specified as 1 kN, 100π rad/s and 1.25 m, respectively. The distance L_1 between the dynamic load and the wave barrier is 25 m, and L_2, which denotes the distance from the wave barrier to the point of interest (point a) on the ground surface, is assumed to be 25 m. There is no horizontal displacement along the left side of the soil and no reflection boundary is applied on the right side and at the bottom. Based on the elastic wave theory, Rayleigh velocity v_r in soil is derived as 250 m/s, so Rayleigh wavelength λ_r can be calculated as

$$\lambda_r = \frac{2\pi v_r}{\omega} = 5\ m \tag{1}$$

To perform the numerical modeling, explicit dynamic analysis procedure is adopted in ABAQUS. The soil and the barrier are modeled as homogeneous, isotropic and elastic media, using 4-node bilinear plane strain quadrilateral, reduced integration elements. The interface between them is assumed to be perfectly bonded. Table 1 provides the material properties of the model. It is noted that Rayleigh damping is adopted. To avoid reflected waves generated by soil boundaries, 4-node linear, one way infinite element is used to simulate the non-reflecting boundary conditions. In order to validate the convergence of numerical analyses, mesh convergence study is committed. Fig. 2 shows the amplitude of vertical displacement of ground surface beyond wave barrier with different element sizes. It is clear to see that models with crude meshes (corresponding element size: 1.0 m × 1.2 m and 0.75 m × 0.9 m) produce bad results. As the mesh becomes finer and finer, the results appear to gradually achieve convergence. The differences among the three curves (corresponding element sizes: 0.5 m × 0.6 m, 0.4 m × 0.45 m and 0.25 m × 0.3 m) are very small. Considering that the finer the mesh is, the longer time ABAQUS takes to finish calculations, element size in this study is taken as 0.5 m × 0.6 m, this agrees well with Kramer's suggestion [19] that the maximum element size should be less than one eighth of the shortest possible Rayleigh wavelength.

Table 1
Material properties of soil and barrier.

Material[a]	Density ρ (kg/m^3)	Poisson's ratio ν	Young's modulus E (GPa)	Damping ratio β
Soil	1750	0.25	0.33	6
Barrier	2397.5	0.25	11.30	30

[a] The density, Poisson's ratio, Young's modulus and damping ratio of soil and barrier are denoted as ρ_s, ν_s, E_s, β_s and ρ_b, ν_b, E_b, β_b, respectively.

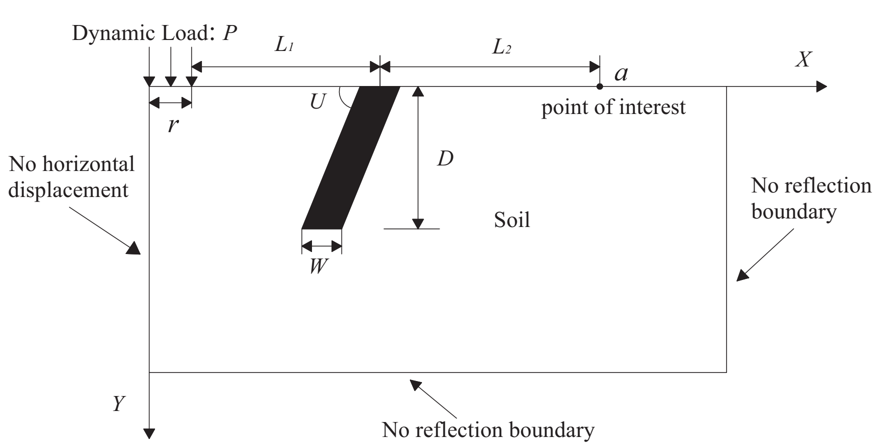

Fig. 1. Schematic diagram of 2D soil–barrier system.