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Research on the effect of the moving water table on passive isolation effectiveness using a multiple open trench barrier

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Abstract: Groundwater table might significantly fluctuate due to seasonal rainfall. In order to investigate the effect of the moving water table on the screening performance of multiple open trench barriers, a finite element model is developed to describe wave propagation in a layered ground, which is modeled as a dry layer resting on a saturated substratum. The effect of infiltrated water in trenches is considered in this model, and the vibration isolation efficiencies of multi-trench barriers with equal and unequal trench depth, multi-trench barriers with inclined trench wall and continuous undulating terrain barriers at different water levels are analyzed as comparable cases. Comparing with the corresponding single-phase elastic foundation, the numerical results show that a low permeability coefficient of the saturated substratum might have a significantly adverse effect on the vibration isolation efficiency for most of water tables. A triple trench barrier with a depth of $0.3L_R$ (L_R is Rayleigh wavelength) usually can achieve a satisfactory screening efficiency (i.e. 75% reduction), while the depth should be at least $0.6L_R$ at the critical water table, where the worst isolation efficiency occurs. A multiple trench barrier with decremental depth can effectively reduce the adverse effect of the resonance. The larger sloping sides are, the better isolation effect of a barrier is for the shallow trenches, while it is not important for deep ones. Moreover, a rolling terrain landscape can be an environment-friendly isolation measure, which would achieve a great vibration isolation efficiency.

Keywords: groundwater table; saturated soil; multiple open trench barriers; isolation effectiveness; COMSOL software

1 Introduction

With the development of the economy, various kinds of artificial vibration pollution has become more frequent. The vibration pollution, which has been recognized as one of the seven environmental hazards, will have more serious impact on residents' life. Therefore, the control of vibration pollution is an extremely urgent issue. Trench barrier possesses the advantages of low cost, convenient construction, and no impact on the vibration sources and the buildings. Engineering practice has proved that trench barrier is an effective treatment measure to control the vibration pollution. However, researchers found that the complaints about vibration pollution are related to seasons. Because the groundwater table fluctuates with the seasons[1], which changes the vibration level of the ground by altering the characteristics of the soil, such as changing soil layering, reducing soil stiffness, increasing soil density and so on, thus changing the vibration level of the ground. In view of this, it is necessary to study the effect of water level change on the barrier isolation effect.

The open trench is generally considered as the most effective isolation measures among all kinds of vibration trench barriers. The screening performance of the trench mainly depends on the Rayleigh wave (R-wave) length L_R. The trench depth should be at least $0.6L_R$ to obtain satisfactory vibration efficiency(i.e. 75% reduction)[2−3]. However, considering the soil stability and engineering cost, shallow trenches are generally designed. While a shallow trench is difficult to effectively shield incident waves with longer wavelengths. Fortunately, a multiple open trench barrier is an effective countermeasure as the depths of the multiple trenches is much smaller than that of a single trench to achieve the same isolation efficiency[4−6]. Younesian et al.[4] numerically analyzed the shielding effect of multiple trenches on train-induced ground vibration in dry soil. Results showed that trench depth is the most important parameter, while the effects of trench width, trench spacing and barrier position are relatively small. Hwang et al.[5] conducted an experimental study on the vibration isolation effect of a triple shallow trench barrier under impact load, but due to the small trench depth, no obvious isolation effect was observed. Moreover, as the in-filled trenches can effectively solve the problem of soil stability, some scholars have focused on the screening performance of multiple in-filled trenches[6−7].

It should be noted that in the above-mentioned studies, the foundation ground of open trench is commonly treated

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as single-phase elastic medium; while saturated foundations which consider groundwater are closer to reality with high water levels. Compared the isolation effect of open trench in elastic half-space with a fully saturated soil, Shi et al.[8] found that the screening effectiveness of the trench in elastic soil is better than that in a saturated medium. Gao et al.[9] investigated the train-induced vibration isolation effect by using an open trench in saturated soil and pointed out that the screening performance of trench in an elastic or saturated soil is similar. Cao et al.[10] studied the isolation effect of open trenches in saturated soil under the moving loads and found that the isolation effect in saturated soil is better than that in an elastic medium when the load speed is close to the Rayleigh wave velocity. However, due to the limitation of the above models, this research can only consider the case that the water level is equal to trench depth. It can be found that different studies on the vibration isolation effect of trench barrier in saturated foundation and elastic foundation have drawn divergent conclusions. Yuan et al.[11] found that the isolation effect of an open trench in the homogeneous saturated soil is worse than that in elastic soil, while it is better in the layered saturated medium. Besides, Xu et al.[12], Ba et al.[13], Bordón et al.[14] also studied the screening performance of open trenches in saturated ground.

It is worth noting that the studies of open trench in the abovementioned saturated soil didn't take the alternation of groundwater table into account. However, in fact, due to seasonal rainfall, the water table would fluctuate obviously in the rainy and dry seasons. For example, the monitoring of groundwater in the K144 landslide on the Dayu Expressway showed that the variation of water table is up to 4 m[15]. In some sandy area, the rise of groundwater table in spring and autumn also reached 2 m[1]. Yuan et al.[11] investigated the isolation effects of open trenches in three kinds of saturated soil models under moving loads, and found that the screening efficiency of open trenches increases with a decrease of water table and then it tends to stable when the water table is lower than the trench depth. On the other hand, the groundwater would infiltrate into open trenches when the groundwater table is higher than the bottom of the trenches. However, the above analyses did not consider the effects of the water in trenches on the screening performance of open trenches. In fact, the water, being a transmission medium, can propagate compression waves (P-waves), which may reduce the isolation efficiency of the trenches[16−17]. Therefore, it is necessary to study the effects of water table on the isolation effectiveness of open trenches.

Based on the wave equations of elastic medium, Biot's poroelastic medium and ideal water, a finite element model of open trenches in the layered ground with water influence is established. The influence of groundwater table fluctuation on the screening performance of multiple trenches in far-field is studied. The effects of permeability coefficients of saturated soil and geometric parameters of the barriers under different water tables are analyzed. Finally, the isolation efficiencies of several special-shaped multiple trenches are further analyzed.

2 Modeling and numerical method

2.1 Basic theory

As shown in Fig.1, the dry topsoil rests on the saturated subsoil, forming the layered ground. The mechanical parameters of the dry soil include Lamé constants λ^e, μ^e and density ρ^e. The Lamé constant and density of the saturated soil are same with the dry layer, i.e., $\lambda=\lambda^e$, $\mu=\mu^e$, $\rho^e=(1-n)\rho_s$ which is described by the density of soil particles ρ_s and the porosity n. When the water table rises, the material parameters of saturated soil are used for the submerged part. If the water table is higher than the bottom of open trenches, groundwater will infiltrate into the trenches, and the infiltrated water in trenches is assumed to change with the groundwater table simultaneously. The finite element method in frequency domain is used in present study. The following subsection will briefly introduce the wave equations of single-phase elastic medium, saturated porous medium and ideal liquids in the frequency domain.

2.1.1 The elastic wave equation

The elastic wave equation of the dry medium is

$$(\lambda^e+\mu^e)\nabla(\nabla\cdot\boldsymbol{u}^e)+\mu^e\nabla^2\boldsymbol{u}^e=\rho^e\omega^2\boldsymbol{u}^e \tag{1}$$

where $\boldsymbol{u}^e$ is the displacement vector of the dry soil; ω is the circular frequency; ∇ is the gradient operator.

2.1.2 Biot's poroelasticity wave equation

In the finite element software COMSOL, the Biot's $\boldsymbol{u}$-p formulation is applied to simulate the propagation of vibration waves in a porous medium. $\boldsymbol{u}$ and p_f are defined as the displacement vector of the soil skeleton and the pore pressure, respectively. The wave equation of saturated porous medium in the frequency domain can be written as[18]

$$\left.\begin{aligned}&\mu\nabla^2\boldsymbol{u}+(\lambda+\mu)\nabla(\nabla\cdot\boldsymbol{u})+\omega^2\left(\rho-\rho_f^2/\gamma\right)\boldsymbol{u}-\\&\qquad(\alpha-\rho_f/\gamma)\nabla p_f=0\\&\nabla^2p_f+\left(\omega^2\gamma/M\right)p_f+\omega^2(\alpha\gamma-\rho_f)\nabla\cdot\boldsymbol{u}=0\end{aligned}\right\} \tag{2}$$

where $\rho = n\rho_f + (1-n)\rho_s$ is the mixture density of saturated soil; ρ_f is the pore-fluid density; M and α are the first and second Biot's coefficients, which are constants and can be used to characterize the compressibility of pore fluid and soil particles; $\gamma = \tau_\infty\rho_f/n + \eta/(\mathrm{i}\omega\kappa)$; τ_∞ is the tortuosity of the pores; κ is intrinsic permeability coefficient(m^2); η is hydrodynamic viscosity, and η = 1.0×10^{-3} Pa·s for water.

2.1.3 Ideal compressible water

Assuming that the water in trenches is ideal liquid, and thus the wave equation of the fluid in the frequency domain is

$$\nabla^2 p_w + \left(\omega^2 / c^2\right) p_w = 0 \quad (3)$$

Where p_w is the fluid pressure; $c = \sqrt{(K_f / \rho_f)}$ is the compression wave velocity of the fluid; and K_f is the bulk modulus of water, $K_f = 2.19\times10^9$ Pa.

2.1.4 Boundary conditions

Assuming that the water table can feasibly rise and fall as the permeability of soil is high; and the water level in trenches is varied simultaneously with the groundwater table. Thus, there is no interface between the dry layer and the water in trenches. Therefore, two types of interfaces exist in the model: the dry topsoil–saturated subsoil interface and the saturated soil–water interface, both of which are summarized in Table 1.

Table 1 Interface continuous conditions

Soil	Dry soil	Water
Saturated soil	$\boldsymbol{n}\cdot\boldsymbol{u} = \boldsymbol{n}\cdot\boldsymbol{u}^e$	$\boldsymbol{n}(\mathrm{i}\,\omega)^2\boldsymbol{\sigma} = -\boldsymbol{n}(\nabla p_w / \gamma)$
	$\boldsymbol{m}\cdot\boldsymbol{u} = \boldsymbol{m}\cdot\boldsymbol{u}^e$	
	$\boldsymbol{n}\cdot\boldsymbol{\sigma} = \boldsymbol{n}\cdot\boldsymbol{\sigma}^e$	$\boldsymbol{n}\cdot\boldsymbol{\sigma} = -p_w$
	$\boldsymbol{m}\cdot\boldsymbol{\sigma} = \boldsymbol{m}\cdot\boldsymbol{\sigma}^e$	$\boldsymbol{m}\cdot\boldsymbol{\sigma} = 0$
	$p_f = 0$	$p_f = p_w$

Note: $\boldsymbol{n}$ and $\boldsymbol{m}$ are the normal and tangential vectors to the surface, respectively.

2.2 Dry soil–saturated soil–water combined finite element model

A two-dimensional plane symmetry model is established by using COMSOL as shown in Fig.1. The model size is 60 m × 50 m with a quadrilateral mesh and the element size is $0.1L_R$. Perfectly matched layers are applied to create absorbent boundaries[19].

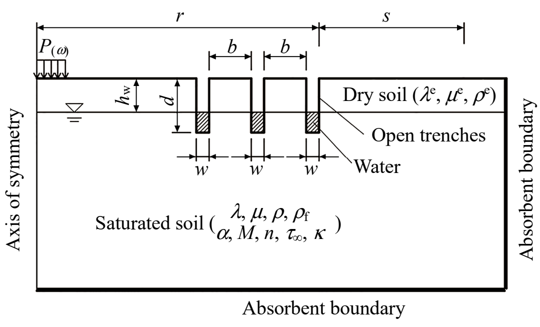


Fig. 1 Typical model of a multiple trench barrier

Ignoring the mass of foundation, harmonic load $P_{(\omega)}$ with frequency f = 36.5 Hz and load amplitude P_0 = 1 kN is assumed to act over a massless footing with a width t = 0.75 m[3]. The parameters of the saturated soil are shown in Table 2. The application of material damping of soil is realized by defining the complex form of Lamé constant, i.e., $\lambda_d = (1+\mathrm{i}\xi)\lambda$, $\mu_d = (1+\mathrm{i}\xi)\mu$, where ξ is the damping coefficient. For the selected parameters of soil, the velocities of the P-wave, S-wave and R-wave in the single-phase soil layer are: V_P=257.2 m/s, V_S=117.2 m/s, and V_R=109.9 m/s, respectively. Thus, the R-wave length can be calculated as $L_R = V_R / f$ = 3.0 m.

Vibration isolation by open trenches in far-field is mainly concerned with surface waves, and herein the geometric parameters are normalized with respect to the R-wave length L_R of the single-phase soil. Dimensionless barrier distance, post-trench measurement distance, water level, trenches spacing, the depth and width of hollow trenches are: $R = r/L_R$, $S = s/L_R$, $H_w = h_w/L_R$, $B = b/L_R$, $D = d/L_R$ and $W = w/L_R$, respectively. Without special instructions, the geometric parameters in this study are respectively taken as: R = 5.0, S = 5.0, B = 1.0, D = 0.3, W = 0.1, and the number of trenches Q = 3. The dimensionless analysis makes this study more general as it is independent of load frequency[3, 19–20].

According to the formation hypothesis, the water in trenches would be established in the model only when the water level is higher than the bottom of open trenches (i.e., $H_w<D$).

2.3 Model validation

2.3.1 Verification of vertical displacement in saturated half-space

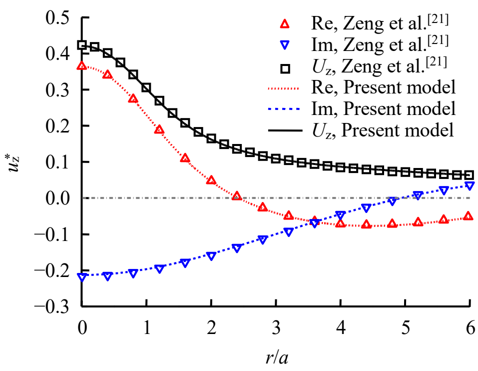
Firstly, the saturated porous medium in this study is verified. Applying a harmonic load over a rigid disk embedded in the saturated half-space, the vertical displacement of the free surface, including real part (Re), imaginary part (Im) and amplitude (U_z), is calculated by the two-dimensional model, in which the thickness of the dry soil layer is taken as a small value (0.1 m). As shown in Fig. 2(a), the numerical results are in good agreement with the analytical solutions[21], where $u_z^* = \mu u_z / (P_0 a)$ is the normalized vertical displacement, u_z is the vertical displacement, and a is the radius of the disk.

Table 2 Mechanical parameters of saturated soil

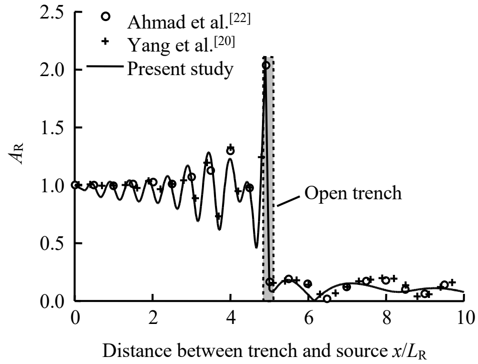
Parameters	λ/(N • m^{-2})	μ/(N • m^{-2})	ρ_s/(kg • m^{-3})	ρ_f/(kg • m^{-3})	n	M/(N • m^{-2})	α	κ/m^2	τ_∞	ξ
Values	6.2×10^7	2.2×10^7	2 670	1 000	0.4	5.1×10^9	0.99	10^{-13}	1.2	0.05

2.3.2 Verification of isolation effect of open trench in degraded single-phase elastic soil layer

Since the previous models of trench isolation in saturated sites did not consider the influence of water, the degradation model was used to verify the isolation effect of open trench isolation in single-phase elastic sites. If the related parameters (ρ_f, M, α and κ) of (pore) fluid are set to be small enough, the porous medium and water can degenerate into a quasi-elastic medium and the air, respectively. Based on the degraded model, it is



(a) Verification of the model of saturated half-space



(b) Verification of the open trench in the degraded model

Fig. 2 Verification of model

assumed that the open trench with depth $d = 1.0L_R$ and width $w = 0.1L_R$ is located at the distance $r = 5L_R$ from the vibration source. The vertical displacement amplitude reduction factor A_R (A_R is defined as the ratio of displacement amplitude with and without barriers) along the free surface is calculated and compared with the previous works[20, 22], as shown in Fig. 2(b) (x is the distance from measurement point to the source). It can be observed that the results are in good agreement. Thus, the above two verification examples demonstrate the correctness of the present model.

3 Multiple open trenches with equal depth

As the A_R values beyond the barrier are unequal. In order to facilitate the evaluation of vibration isolation effect of the trenches, the average amplitude reduction factor AA_R is introduced, which is defined as

$$AA_R = \frac{1}{s}\int A_R(x)\mathrm{d}x \tag{4}$$

Obviously, the smaller the AA_R value, the better the vibration isolation effect is.

3.1 Effect of water table

It can be observed from Fig.3 that, with a decrease of the water level H_w, the average amplitude reduction factor AA_R first rapidly increases to the maximum value, then rapidly decreases, and finally approaches a stable value. The stable value is determined by the vibration isolation effect of the same trench in single-phase soil. Meanwhile, the AA_R values reaches the maximum values when H_w = 0.6–0.7 under different trench depths. In addition, the limiting water table is as high as $10L_R$, which means that the impact of groundwater on the isolation effect of the multiple open trenches can be completely negligible only if the water table is below this limiting water table. When the water table is above the limiting water table, the existence of groundwater usually has an adverse effect on the barriers. On the contrary, the shallow multiple trench with high water levels (such as $D = 0.3$ and $H_w \leqslant 0.4$) may be beneficial to the vibration isolation effect.

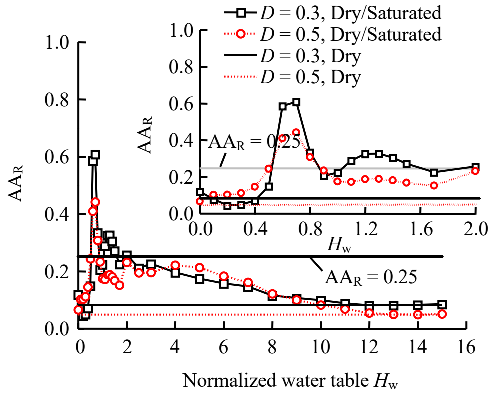


Fig. 3 Effects of water table change on isolation efficiency using multiple trenches

Comparing the isolation effect of the barriers with the two trench depths in far-field, it can be found that the isolation effect of the deeper trenches (D=0.5) is better than that of the shallower ones (D = 0.3) at most water tables. However, for H_w<0.5, the shallower trenches have a better isolation effect. It might be because the water in deeper trenches can propagate more P-waves thought the barrier, resulting in an increase of displacement amplitude beyond the trenches. This subsection illustrates that neglecting the influence of the water in trenches may overestimate the isolation effect of the barrier. Therefore, the water in trenches should be considered in similar problems.

In particular, when H_w=0.6–0.7 the isolation efficiency of the multiple open trenches is the worst, which is due to the resonance of the overlying single-phase layer at this water table. The causes of resonance will be expatiated in Section 3.2. For D=0.3 or 0.5, the isolation efficiency is about 40% ($AA_R \approx 0.6$) and 60% ($AA_R \approx 0.4$), which is far lower than the satisfactory screening efficiency of the open trench(75% reduction). Therefore, designers should pay attention to the problem of barrier failure where the resonance of the dry layer may occur.

The groundwater has a great impact on the isolation efficiency of the multiple open trenches at high water tables ($H_w \leqslant$ 1.0). When H_w > 1.0 the AA_R gradually decreases to the isolation efficiency of the trenches in the single-phase soil. Therefore, the cases of $H_w \leqslant$1.0

will be mainly discussed in the following sections, and the case of $H_w = 1.0$ can be taken as the representative case of the water table below the trench depth.

3.2 Effect of the permeability coefficient of saturated soil

Figure 4 shows the influence of the permeability coefficient κ of saturated soil on the isolation performance of multiple open trenches in far-field. As can be observed that the groundwater has little impact when κ is large ($\kappa \geqslant 10^{-9}$ m^2) and thus the saturated soil can be simplified to dry soil. While the groundwater has a significant influence on isolation efficiency when κ is small ($\kappa <$ 10^{-9} m^2), the influence of groundwater is large, especially at H_w=0.6, AA_R value increases rapidly and then gradually stabilizes with decreasing κ. This is due to the fact that with the decrease of κ, saturated soil gradually changes from a drained two-phase medium to an equivalent undrained single-phase medium, and the dynamic characteristics of the soil also change from high-frequency behavior to low-frequency behavior[23]. The equivalent single-phase medium can be equivalent to the mixed single-phase soil with ice formed by pore water in saturated soil, and its equivalent Lamé constant are $\lambda_{eq} = \lambda$, $\mu_{eq} = \mu + K_f/n$. Thus, the equivalent P-wave velocity of the soil $V_{p,eq}$ = 1 669.6 m/s, which is much larger than that in overlying single-phase soil (V_p = 257.2 m/s), inducing much P-wave reflects at the interface. The reflected P-wave would interfere with the incident waves, resulting in resonance phenomenon in the single-phase soil at the critical water table $h_c = V_p/(4f)$[1, 23]. For a given load frequency f = 36.5 Hz, the critical water table can be obtained i.e.h_c = 1.8 m, H_c = 0.6.

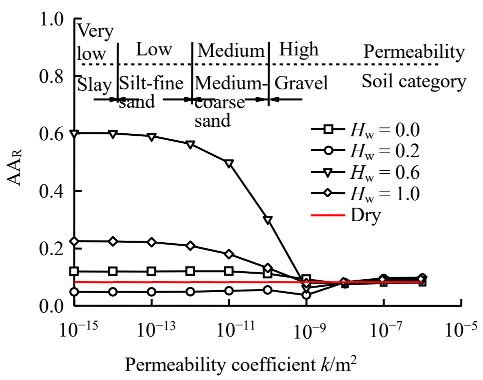


Fig. 4 Effects of hydraulic permeability coefficient on isolation efficiency using multiple trenches

The different permeability coefficients are generally corresponded to different soils. Given a load frequency f = 36.5 Hz in the present study, for the soil with high-frequency behavior (such as gravel), the presence of groundwater has little impact on the isolation effect of open trenches. In this case, a dry soil model can be used to investigate the screening performance of the trenches. While for soils with low-frequency behavior (such as sand, silt, etc.), groundwater has a significant impact on the isolation effect of the trenches and usually has an adverse effect, which should be paid attention to. Thus, a lower permeability coefficient $\kappa = 10^{-13}$ m^2 is adopted to investigate the screening efficiency of multiple open trenches in saturated soil with low-frequency behavior in this study.

3.3 Effect of the number and geometric dimensions of multiple open trenches

Since the influence of trench width is small[2–3, 6], the trench width is set as a constant value, i.e. W = 0.1.

3.3.1 Number of open trenches

According to Fig.5, the AA_R value rapidly decreases with increasing number of open trenches Q at most water tables when $Q \leqslant 3$. However, further increasing Q has no benefit to the isolation efficiency of the barrier, and even has a few adverse effects. It indicates that the triple open trenches barrier can be used as the optimal scheme in the saturated ground with high water levels. For comparison, a double trenches barrier is suggested in singlephase elastic soil because the AA_R value basically reaches the minimum value when Q = 2. Particularly, the isolation efficiency cannot significantly decrease with an increase of Q at critical water level H_c (H_c=0.6), which means that increasing Q cannot effectively eliminate the adverse effects of the resonance in the overlying single-phase layer.

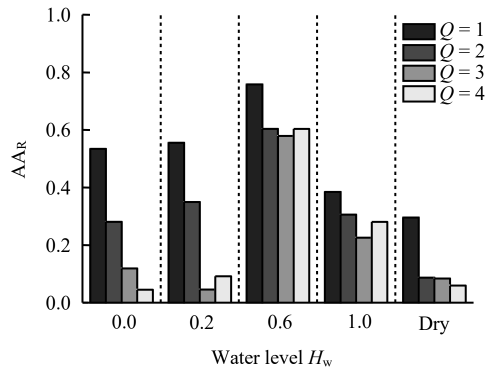


Fig. 5 Effects of the number of trenches on isolation efficiency using multiple trenches

3.3.2 Space between empty trenches

The effect of trench spacing B on the isolation efficiency of multiple open trenches is shown in Fig. 6. As can be observed, B has a little effect on the screening performance of the trenches, which is similar to the previous work[4]. The AA_R shows an obvious fluctuation with B in the saturated soil and it reaches a minimal value when B = 1.0 at most water tables (except H_c). This may be because more R-waves will diffract from the adjacent trenches to the areas beyond the barriers when B<1.0. However, the coupling isolation effect of the adjacent trenches is weakened when B > 1.0. Besides, the AA_R value also shows a certain periodic change at H_c. In practical engineering, the trench spacing is suggested to be 1.0L_R.

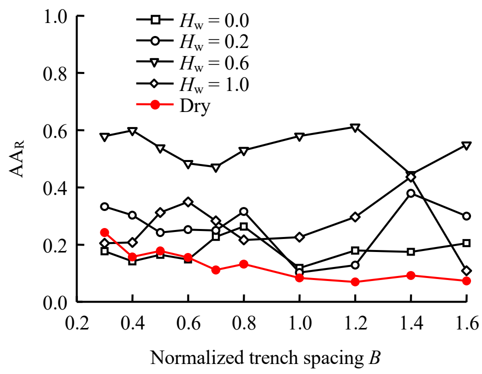


Fig. 6 Effects of the trench spacing on isolation efficiency using multiple trenches

3.3.3 Trench depth

It can be observed from Fig.7 that satisfactory screening efficiency(75% reduction or AA_R = 0.25) can be obtained when the dimensionless trench depth D reaches 0.3 at most water tables (except H_c), which is similar to that in a full dry half-space. While the AA_R value gradually decreases with an increase of trench depth at H_c and it is less than 0.25 when $D \geqslant 0.6$. The multiple open trenches barrier can effectively eliminate the adverse effects of the resonance in the overlying dry layer; and a satisfactory screening efficiency(75% reduction) can be obtained when the trench penetrates the dry layer (i.e., $D \geqslant H_c$).

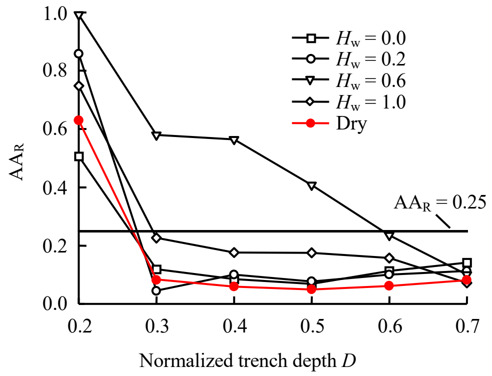


Fig. 7 Effects of the trench depth on isolation efficiency using multiple trenches

4 Special-shaped open trenches

In Section 3 the isolation effects of rectangular multiple open trenches with equal depth in far-field are studied. However, the trenches with inclined slope sides may be excavated for stability reasons; each trench depth may be different due to site constraints. Besides, in order to improve the practicability of the barrier, the multiple trenches may be designed to combine with the drain or landscape, such as a green barrier that is formed by a rolling terrain landscape. The isolation effects of these barriers in far- field will be studied in this section.

4.1 Multiple open trenches with inclined slopes

The effects of the angle of sloping sides θ under different trench depths are shown in Fig. 8. As can be observed from Fig. 8(a) that the screening efficiency of the shallower trenches (D = 0.3) decreases with decreasing θ for all cases. By comparing Figs. 9(a) and 9(b), it is found that, for shallow trenches a small θ is adverse to the conversion of surface waves into body waves (the propagation directions of the main vibration waves are qualitatively marked by the arrows in Fig. 9 when the incident waves pass through the barrier). For deeper trenches (D = 0.5), the influence of the angle of sloping sides is small at most of the water tables (except H_c) as shown in Figs. 8(b) and 9(c). For the deeper trenches, most surface waves are converted into body waves when diffusing from the bottom of the trenches. At the resonance water table, only low isolation efficiency can be achieved when $60^\circ < \theta < 75^\circ$. Previous studies[24] showed that the angle of sloping side θ has little effect on the isolation effect of the open trench. However, the above analysis shows that the impact of θ is related to the trench depth, and when the trench is relatively shallow the reducing θ would be adverse to the screening performance of open trenches.

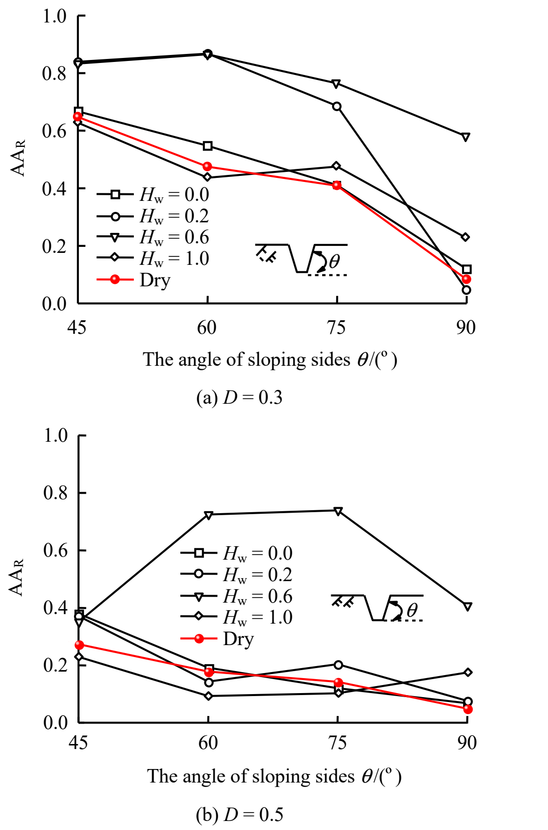


Fig. 8 Effects of the angle of sloping sides on isolation efficiency using multiple trenches

4.2 Multiple open trenches with unequal depths

Previous studies were mostly focused on multiple trenches equal depth[4–5], while a multiple trenches barrier with unequal depths may be more cost-effective considering the cost, construction, and site conditions in engineering. As shown in the schematic diagram in Fig.10, this section will investigate the isolation effects of two types of

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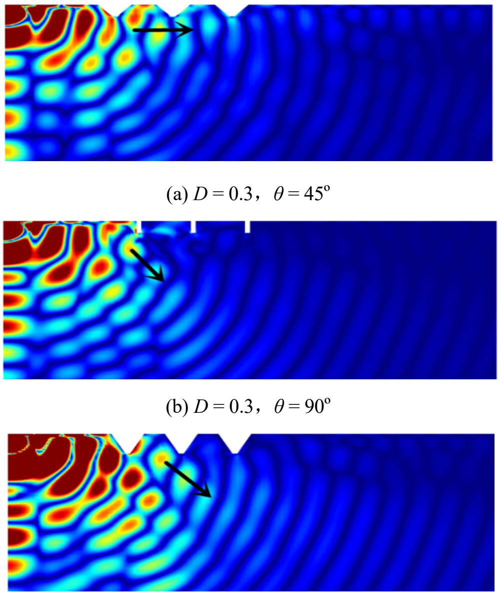

(a) $D = 0.3$, $\theta = 45^{\circ}$

(b) $D = 0.3$, $\theta = 90^{\circ}$

(c) $D = 0.5$; $\theta = 60^{\circ}$

Fig. 9 Stress contour near multiple trench barriers

multiple trenches with unequal depths(Case 1 and Case 2 are the multiple trenches with incremental and decremental depths, respectively). The barrier with equal depth is taken as the comparative case, terming as Case 0. For the sake of comparison, the total excavation area A is kept constant ($A = 3\times0.1\times(D_1+D_2+D_3) = 0.12$) and the second trench depth($D_2 = 0.4$) keeps unchanged. Only the depths of the first and third trenches are changed(D_1, D_3). The difference between the adjacent trench depths $\Delta D = D_{m+1} - D_m (m = 1, 2)$ is equal. Thus, $D = 0$ in Case 0, $D>0$ in Case 1 and $D<0$ in Case 2.

As showed in Fig. 10, at most water tables (except H_c) and in single-phase soil foundations, the AA_R value increases with the increase of absolute value $|D|$, which indicates that unequal trench depths may be adverse to the isolation effect of multiple trenches, but the effect is relatively small. However, at H_c, the AA_R value of Case 2 significantly decreases with the decrease of D, and AA_R decreases to 0.21 when $D = -0.3$. It demonstrates that the multiple trenches with decremental depths can effectively eliminated the adverse effect of the resonance of the dry layer and obtain a satisfactory isolation efficiency ($AA_R < 0.25$). However, at the same time, the AA_R value of Case 1 does not change that much. Therefore, multi-trench barrier with decreasing trench depth is more cost- effective in high-water level area where overburden resonance is likely to occur.

4.3 A rolling terrain barrier

The multiple open trenches can be incorporated into the drain or landscape, such as a rolling terrain landscape, in order to improve the practicability of the barrier. Therefore, the isolation effect of a rolling terrain barrier with geometric dimensions as shown in Fig.11 is investigated at different load frequencies and the result is compared with the single trench.

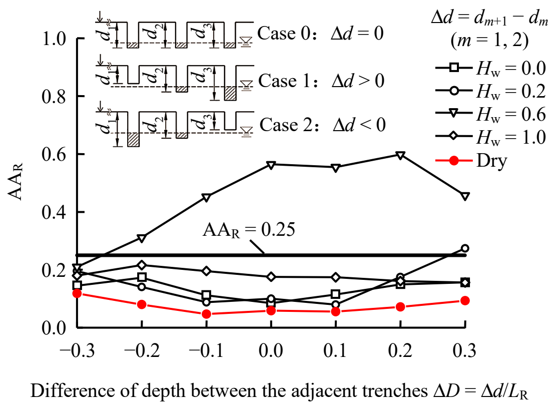

Fig. 10 Isolation efficiency of multiple trenches with unequal trench depths

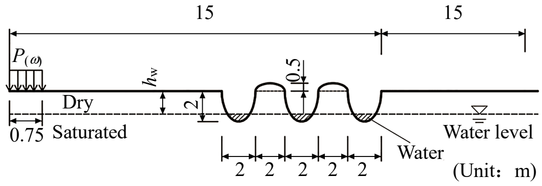

Fig. 11 Typical model of a rolling terrain barrier

It can be seen from Fig.12 that the isolation efficiency of the rolling terrain barrier is much higher than that of a single trench, especially for the low frequency(10 Hz < f <30 Hz). In single phase foundation and the sites with different water levels, the rolling terrain barrier can achieve a better isolation effect, that is, the barrier can reduce ground vibration by more than 70% with frequency $f \geqslant 15$ Hz. In addition, it can be calculated from Section 3.2 that, the resonant frequencies corresponding to water tables $h_w = 1.0$ m and 3.0 m are $f = 64.3$ Hz and 21.4 Hz, respectively. Figure 12 shows that the multi-trench barrier can effectively contain the adverse effects of resonance and achieve higher vibration isolation efficiency.

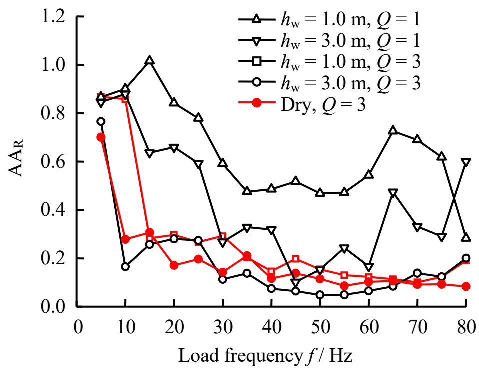

Fig. 12 Effects of loading frequency on isolation efficiency using rolling terrain barrier

5 Conclusions

Based on COMSOL, this study established a hollow trench finite element model for overlying single phase saturated foundation and investigated the effect of the moving water table on the isolation performance of multiple open trenches in far-field. Finally, several special-shaped multiple trenches were proposed and their screening performances at different water tables were analyzed. The main conclusions are as follows:

(1) High permeability coefficient of the saturated soil has a little effect on the isolation performance of the multiple open trench barrier. However, the saturated soil with low permeability, which shows the low-frequency behavior of the medium, can be equivalent to a mixed single-phase medium with a greater P-wave velocity. At this point, a large amount incident wave will be reflected at the water table interface, which will adversely affect the isolation efficiency of multiple trenches.

(2) For the soil with a low permeability coefficient, the existence of groundwater is usually detrimental to the isolation effect of the multiple open trench barrier, and the most adverse effect occurs at the critical water table (H_c = 0.6 in this study). The limiting depth of influence of water table can reach up to 10 times the Rayleigh wavelength L_R.

(3) Double trench barrier is recommended for the full dry half-space, while the triple trench barrier is preferred in the sites with groundwater. Generally, the triple trench barrier can obtain a satisfactory isolation efficiency(75% reduction) when trench depth D=0.3. However, at resonance water level H_c, the trenches should penetrate the dry layer (i.e., $D \geqslant H_c$) to obtain 75% reduction. The trench spacing is recommended to be $1.0L_R$.

(4) For the shallower open trenches, the smaller the angle of the sloping sides is, the better the isolation effect will be, while the angle have small influence for the deeper trenches. A multiple trench barrier with decremental depths can effectively reduce the adverse effects of the resonance in the overlying single-phase layer. A rolling terrain landscape can be used as an effective green barrier to achieve a great vibration isolation efficiency.

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