Modified Pseudo-dynamic Method for Seismic Passive Earth Thrust of Submerged Backfill

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Abstract. The accurate assessment of seismic earth pressure acting on a retaining wall is an important problem in earthquake geotechnical engineering. The existing calculations of pseudo-dynamic method mainly focus on the dry soil condition. To investigate the seismic passive earth thrust of submerged backfill, a general modified pseudo-dynamic method is established based on the limit equilibrium analysis. The derivation aims at a vertical gravity wall with a planar rupture surface retaining a horizontal, cohesionless and fully submerged backfill. Meanwhile the method assumes that the amplitude of the seismic acceleration increases linearly along the wall and the backfill is divided into two extreme cases of free water and restrained water conditions according to the permeability difference. Through the comparison with the previous work, the trend of seismic passive earth thrust for submerged backfill is basically consistent with that of the dry soil, but the submerged condition has a reducing effect on the passive earth thrust. Then a parametric study is carried out to investigate the influences of soil friction angle, wall friction angle, horizontal seismic action and vertical seismic action on the intensity distribution of seismic passive earth pressure. The results indicate that the passive earth pressure increases with the increase of soil friction angle and wall friction angle, but the impact of soil friction angle is more significant. The horizontal seismic acceleration is still the determining factor affecting the magnitude and distribution of the passive earth pressure rather than the vertical one.

Keywords: Passive earth pressure · Earthquake · Submerged backfill

1 Introduction

The determination of soil pressure acting on a retaining wall under earthquake actions is a fundamental problem in geotechnical seismic design. Many theoretical and experimental studies [1–3] on the seismic earth thrust have developed since the pseudo-static method was first introduced to solve this problem in the mid-1920s.

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Although the pseudo-static method is widely used in different codes of foreign countries, Steedman and Zeng [4] proposed a pseudo-dynamic method to overcome the drawbacks of the assumptions in the pseudo-static method. Then Choudhury and Nimbalkar [5, 6] extended the pseudo-dynamic method for both active and passive earth pressure conditions considering the effects of horizontal earthquake actions as well as vertical seismic action. Based on the pseudo-dynamic method, the seismic stability of retaining wall has also been improved [7, 8].

However, the existing calculations of pseudo-dynamic method mainly aim at dry soil condition, and a little literature on the seismic earth pressure considering the submerged condition by pseudo-dynamic method is found, although Bellezza et al. [9] tried to propose a more rational approach for this problem. On the other hand, during the last decades the effects of submerged or seepage conditions on seismic earth thrust have been paid attention to by some scholars. Matsuzawa et al. [10] improved the pseudo-static method for seismic active earth thrust of submerged backfill considering a restrained or free water condition exists in the soil. Ebeling and Morrison [11] used empirical coefficients to represent the ratio of the seismic excess pore pressure and the vertical effective stress, and then put forward the expressions of seismic earth and water pressure. Afterwards, Wang et al. [12, 13] calculated the seismic passive earth pressure with steady seepage conditions by using limit equilibrium analysis and pseudo-static method. As mentioned before, the pseudo-static method has some drawbacks, such as cannot describe the dynamic characteristics of earthquake actions and hardly considers the influence of the seismic acceleration magnitude on the earth resistance.

In order to improve the pseudo-dynamic method of submerged condition, a modified formula to calculate the seismic passive thrust of fully submerged backfill is proposed based on the limit equilibrium analysis in this work. The derivation takes into account the seismic acceleration amplification and the effect of phase change. Then the results of passive earth thrust between the submerged backfill and the dry soil are compared to verify this proposed method. Besides, a parametric study is performed to investigate the influences of soil friction angle, wall friction angle, horizontal seismic action and vertical seismic action on the distribution of seismic passive earth pressure.

2 Method of Analysis

2.1 Calculation Hypothesis

The interaction mechanism of the soil and water under earthquake action is complicated. In order to simplify the calculation model, some basic hypothesis should be made in this study. The gravity wall is vertical, retaining a horizontal submerged backfill, as shown in Fig. 1. The cohesionless soil behind walls is assumed to be homogeneous, isotropic and saturated. The friction angles, porosity, permeability, Poisson's ratio and elastic modulus of the soil are constant. Besides, the groundwater level is maintained on the surface of the backfill, and the seepage condition and excess pore pressure are ignored [9].

The retaining wall moves towards the backfill until the soil reaches the passive limit equilibrium state, and the planar rupture surface inclined at angle θ to the horizontal is assumed like the Coulomb's earth pressure theory. During the earthquake, the shear wave and the primary wave propagate through the backfill, and the soil vibrates in harmonic state on the basis of pseudo-dynamic method [5, 6]. The maximum amplitude of seismic acceleration increases linearly along the wall. The directions of horizontal and vertical seismic inertial forces are supposed as shown in Fig. 1.

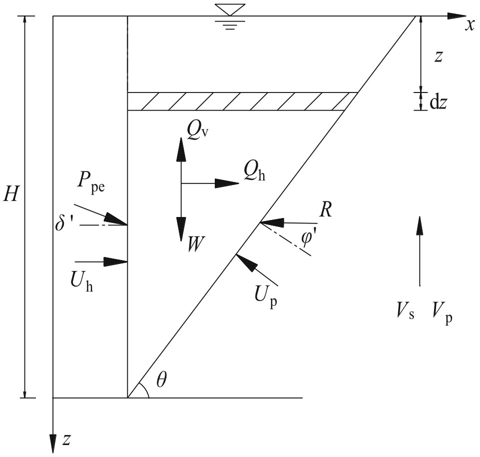

Fig. 1. Model of seismic passive earth thrust

2.2 Modified Pseudo-dynamic Method

Seismic Acceleration

Due to considering the amplification effects of seismic acceleration amplitudes, the relationship of the seismic acceleration coefficients between the top and bottom of retaining wall should be given as

$$k_{h,0}(z = 0) = f_a k_h(z = H),\ k_{v,0}(z = 0) = f_a k_v(z = H) \tag{1}$$

where k_h and k_v are the horizontal and vertical seismic acceleration coefficients at the wall base which represent the ratio of seismic acceleration to gravitational acceleration, z is the vertical depth, H is the wall height, and f_a is the amplification factor of seismic action.

Therefore, in the view of these previous assumptions, the seismic accelerations at any depth z and time t below the surface can be expressed as [14]

$$a_h(z, t) = \left[1 + \frac{H - z}{H}(f_a - 1)\right] k_h g \sin \omega \left(t - \frac{H - z}{V_s}\right) \tag{2}$$

$$a_{\mathrm{v}}(z,t) = \left[1 + \frac{H-z}{H}(f_{\mathrm{a}}-1)\right] k_{\mathrm{v}} g \sin\omega\left(t - \frac{H-z}{V_{\mathrm{p}}}\right) \tag{3}$$

where g is the gravitational acceleration, ω is the angular frequency of vibration, $\omega = 2\pi/T$, T is the period of vibration, V_{s} and V_{p} are the wave velocity of the shear and primary waves, respectively.

Seismic Inertial Force

The mass of the soil element at any depth z in Fig. 1 is given as

$$\mathrm{d}m = \frac{\gamma*}{g}\frac{H-z}{\tan\theta}\mathrm{d}z \tag{4}$$

where γ^* is the unit weight of backfill soil, the value of which depends on the seismic inertial forces and the soil permeability as illustrated in the following.

The total horizontal seismic inertial force on the soil wedge is given by the integral [14]

$$\begin{aligned} Q_{\mathrm{h}} &= \int_0^H a_{\mathrm{h}}(z,t)d\mathrm{m} \\ &= \frac{\lambda\gamma^* k_{\mathrm{h}}}{4\pi^2\tan\theta}[2\pi H\cos\omega\zeta + \lambda(\sin\omega\zeta - \sin\omega t)] \\ &+ \frac{\lambda\gamma^* k_{\mathrm{h}}(f_{\mathrm{a}}-1)}{4\pi^3 H\tan\theta}\left[2\pi H(\pi H\cos\omega\zeta + \lambda\sin\omega\zeta) + \lambda^2(\cos\omega t - \cos\omega\zeta)\right] \end{aligned} \tag{5}$$

where λ is the wavelength of the shear wave, $\lambda = TV_{\mathrm{s}}$, $\zeta = t - H/V_{\mathrm{s}}$.

Similarly, the total vertical seismic inertial force on the soil wedge is given by the integral

$$\begin{aligned} Q_{\mathrm{v}} &= \int_0^H a_{\mathrm{v}}(z,t)d\mathrm{m} \\ &= \frac{\eta\gamma^* k_{\mathrm{v}}}{4\pi^2\tan\theta}[2\pi H\cos\omega\psi + \eta(\sin\omega\psi - \sin\omega t)] \\ &+ \frac{\eta\gamma^* k_{\mathrm{v}}(f_{\mathrm{a}}-1)}{4\pi^3 H\tan\theta}\left[2\pi H(\pi H\cos\omega\psi + \lambda\sin\omega\psi) + \eta^2(\cos\omega t - \cos\omega\psi)\right] \end{aligned} \tag{6}$$

where η is the wavelength of the primary wave, $\eta = TV_{\mathrm{p}}$, $\psi = t - H/V_{\mathrm{p}}$.

With the consideration of the submerged soil condition in this study, the value of γ^* is somewhat different from that of the dry soil condition. Base on Matsuzawa et al. [10], the submerged backfill can be divided into two extreme types according to the permeability difference. For the highly permeable soil, ‘free water’ condition is defined in which the horizontal inertial force only acts on the solid portion of the soil element. Therefore, the value of γ^* in Eq. (5) equals the dry unit weight γ_{d} of soil, and Q_{h} is proportional to the dry weight W_{d} of the soil wedge. In the limit state without the seismic amplification, Eq. (5) can be given as

$$\lim_{V_s \to \infty} \left(Q_{h,F}\right)_{max} = k_h \frac{\gamma_d H^2}{2\tan\theta} = k_h W_d \tag{7}$$

For the low permeable soil, it is supposed that the solid portion and the water portion of the soil element behave as a unit subjected to the horizontal seismic action, which is defined as 'restrained water' condition. Thus Q_h is proportional to the saturated weight W_{sat} of the soil wedge. Similarly, it is easy to conclude that

$$\lim_{V_s \to \infty} \left(Q_{h,R}\right)_{max} = k_h \frac{\gamma_{sat} H^2}{2\tan\theta} = k_h W_{sat} \tag{8}$$

Meanwhile, as Matsuzawa et al. [10] suggested, it is important to note that the hydrodynamic water pressure should be added separately to the backfill side in the stability analysis for 'free water' condition, but there is no need to take this step for 'restrained water' condition. In addition, the calculation of vertical seismic inertial force depends on the submerged weight W' of the soil wedge, regardless of the situation in 'free water' or 'restrained water' condition. Consequently, the value of γ^* in Eq. (6) is the effective unit weight γ', and in the limit case Eq. (6) can be derived as

$$\lim_{V_p \to \infty} \left(Q_v\right)_{max} = k_v \frac{\gamma' H^2}{2\tan\theta} = k_v W' \tag{9}$$

Seismic Passive Thrust

When the soil wedge reaches the passive limit state, all the forces acting on the wedge include the total seismic passive earth thrust (P_{pe}), the self-weight of the soil wedge ($W = \gamma_{sat} H^2/(2\tan\theta)$), the horizontal and vertical seismic inertial forces (Q_h, Q_v), the hydrostatic pressure on both sides of the earth wedge (U_h, U_p) and the force from the backfill soil (R). The directions of all the forces in this derivation are illustrated as Fig. 1. The horizontal and vertical force equilibrium conditions of the soil wedge are expressed as

$$P_{pe}\cos\delta' + Q_h - R\sin(\theta + \varphi') + U_h - U_p\sin\theta = 0 \tag{10}$$

$$W + P_{pe}\sin\delta' - Q_v - R\cos(\theta + \varphi') - U_p\cos\theta = 0 \tag{11}$$

where φ' is the soil friction angle and δ' is the wall friction angle.

Substituting Eq. (10) into Eq. (11), the hydrostatic pressure on the both sides of the soil wedge is offset, therefore the total self-weight W of the soil wedge is replaced by the submerged weight W'. Then the seismic passive earth thrust of submerged condition is given as

$$P_{pe} = \frac{W'\sin(\theta + \varphi') - Q_h\cos(\theta + \varphi') - Q_v\sin(\theta + \varphi')}{\cos(\theta + \varphi' + \delta')} \tag{12}$$

Substituting Eqs. (5), (6) into Eq. (12), the modified pseudo-dynamic expression of seismic passive earth pressure can be expressed as

$$\begin{aligned} P_{\mathrm{pe}} = & \frac{1}{2}\gamma^{*}H^{2}\left\{\frac{1}{\tan\theta}\frac{\sin(\theta+\varphi')}{\cos(\theta+\varphi'+\delta')} - \frac{\cos(\theta+\varphi')}{\cos(\theta+\varphi'+\delta')}\cdot\left[\frac{k_{\mathrm{h}}}{2\pi^{2}\tan\theta}\frac{\lambda}{H}m_{1} + \frac{k_{\mathrm{h}}(f_{\mathrm{a}}-1)}{2\pi^{3}\tan\theta}\frac{\lambda}{H}m_{2}\right]\right. \\ & \left. - \frac{\sin(\theta+\varphi')}{\cos(\theta+\varphi'+\delta')}\cdot\left[\frac{k_{\mathrm{v}}}{2\pi^{2}\tan\theta}\frac{\eta}{H}m_{3} + \frac{k_{\mathrm{v}}(f_{\mathrm{a}}-1)}{2\pi^{3}\tan\theta}\frac{\eta}{H}m_{4}\right]\right\} \end{aligned} \tag{13}$$

where the value of γ^{*} is defined according to the seismic inertial action and the permeability,

$$m_{1} = 2\pi\cos\omega\zeta + \left(\frac{\lambda}{H}\right)(\sin\omega\zeta - \sin\omega t)$$

$$m_{2} = 2\pi\left[\pi\cos\omega\zeta + \frac{\lambda}{H}\sin\omega\zeta\right] + \left(\frac{\lambda}{H}\right)^{2}(cos\omega t - cos\omega\zeta)$$

$$m_{3} = 2\pi\cos\omega\psi + \left(\frac{\eta}{H}\right)(\sin\omega\psi - \sin\omega t)$$

$$m_{4} = 2\pi\left[\pi\cos\omega\psi + \frac{\eta}{H}\sin\omega\psi\right] + \left(\frac{\eta}{H}\right)^{2}(cos\omega t - \cos\omega\psi)$$

The intensity distribution of the passive earth pressure is $p_{\mathrm{pe}} = \partial P_{\mathrm{pe}}/\partial z$, and the passive earth pressure coefficient of submerged backfill is $K_{\mathrm{pe}} = 2P_{\mathrm{pe}}/(\gamma' H^{2})$. Through the derivation, it is demonstrated that K_{pe} is a function of the dimensionless expressions H/λ, H/η, t/T and the rupture surface angle θ. H/λ and H/η describe the ratio of the wall height to the seismic wavelength, which can be taken as constant when the material parameters of the backfill are determined. As a result, the minimum value of K_{pe} is obtained by optimizing it with respect to t/T and θ. The range of t/T is from 0 to 1, and the range of θ is from 0 to $\pi/2$.

3 Comparison

To illustrate the validity of the present method, the results calculated by the proposed formula are compared with those calculated by pseudo-static method and pseudo-dynamic method [14] in dry soil condition as shown in Fig. 2, where k_{h} = 0.2, k_{v} = 0.1, $\varphi' = 30°$, $\delta' = 15°$. From the figure, it can be seen that the distribution of passive earth pressure obtained by pseudo-dynamic method is a nonlinear form, while the results by pseudo-static method is linear. This discrepancy is mainly due to the difference of the basic hypothesis between the two kinds of methods. Meanwhile, it can also be drawn that the earth pressure intensity of the submerged backfill is lower than that of the dry soil, at the same time the nonlinear characteristic of the pressure distribution curve of the submerged condition is relatively more obvious than the dry one under the same earthquake.

Table 1 lists the comparison of the seismic passive earth pressure coefficients K_{pe} between the submerged backfill and dry soil conditions. It can be observed that the trends of K_{pe} between the two conditions are basically consistent, but the value of the submerged condition is somewhat smaller and the difference gets greater with the increase of seismic action. Thus, the groundwater has a certain role in reducing the seismic passive earth pressure.

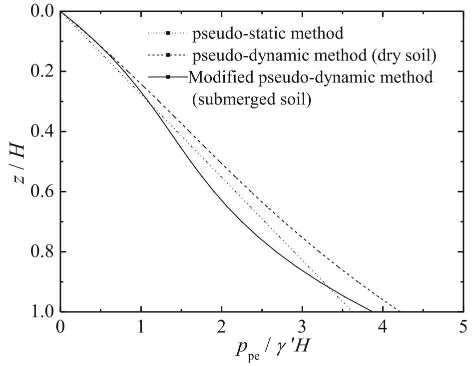

Fig. 2. Comparison of seismic passive earth pressure

Table 1. Comparison of K_{pe} between submerged soil and dry soil

$\varphi'/^\circ$	$\delta'/^\circ$	k_{h}	k_{v}	K_{pe} (submerged soil)	K_{pe} (dry soil)
20	10	0.05	0.025	2.292	2.441
		0.1	0.05	1.906	2.241
		0.15	0.075	1.344	2.032
25	12.5	0.05	0.025	3.118	3.301
		0.1	0.05	2.657	3.048
		0.15	0.075	2.130	2.787
30	15	0.05	0.025	4.402	4.638
		0.1	0.05	3.809	4.300
		0.15	0.075	3.175	3.957

4 Results and Discussion

In this section, the effects of seismic amplification factor, soil friction angle, wall friction angle, horizontal and vertical seismic actions on the distribution of seismic passive earth pressure of submerged backfill are analyzed. Only the restrained water situation is considered in this discussion. The values of the basic parameters are listed as follows: γ_{sat} = 19 kN/m3, γ' = 9 kN/m3, H/λ = 0.3, H/η = 0.16.

The influence of seismic amplification factor f_{a} on the distribution of passive earth pressure is shown in Fig. 3, where $\varphi' = 30^\circ$, $\delta' = \varphi'/2$, k_{h} = 0.2, $k_{\mathrm{v}} = k_{\mathrm{h}}/2, f_{\mathrm{a}}$ ranges from 1 to 1.3. From the figure it can be seen that the distribution of passive earth pressure calculated by the modified pseudo-dynamic method is curved. The seismic amplification has a certain increase effect on the passive earth pressure, and the growth rate of the pressure strength increase with the vertical depth. The magnification of the earthquake loading in the soil is objective and cannot be neglected in the seismic design, although a linear assumption is taken to simplify the effect. Accordingly f_a takes the value of 1.2 in the following calculation.

Figure 4 presents the influence of soil friction angle φ' on the distribution of earth pressure, in which φ' ranges from 15° to 30° with a step length of 5°, $\delta' = \varphi'/2$, $k_h = 0.1$, $k_v = 0.05$. It is seen from the figure that the soil friction angle has a significantly increasing effect on the seismic passive earth pressure, and the enlargement rate also gets higher with larger soil friction angle. The gap among the curves of p_{pe} becomes more remarkable with the wall depth. Besides, under the same earthquake action, the curve of earth pressure distribution tends to be linear with the increase of φ', which is demonstrated that the effect of soil friction angle will play a dominant role in seismic passive earth pressure with larger value.

Figure 5 depicts the effect of wall friction angle δ' on seismic passive earth pressure with $\varphi' = 24°$, $\delta' = 0, \varphi'/3, \varphi'/2, 2\varphi'/3$, $k_h = 0.1$, $k_v = 0.05$. From the plot, it is seen that the increasing influence of wall friction angle on p_{pe} is similar to that of soil friction angle, but the growth rate of p_{pe} with δ' is inferior to that with φ'.

Figure 6 illustrates the variations of p_{pe} with z/H under different horizontal seismic acceleration coefficient k_h with $\varphi' = 30°$, $\delta' = \varphi'/2$, $k_h = 0, 0.05, 0.1, 0.15, 0.2$, $k_v = k_h/2$. From the figure, it is shown that the passive earth pressure decreases with the increase of k_h. For example, the value of p_{pe} at the bottom of wall decreases about 12.8% when k_h changes from 0 to 0.1, and about 10.5% when k_h increases from 0.1 to 0.2. Moreover, as the backfill is assumed to vibrate in a harmonic form in the pseudo-dynamic analysis, the passive earth pressure distributes in a curve form under seismic action while the pressure distribution is linear without earthquake. The nonlinearity of the distribution curve becomes more obvious as the earthquake gets stronger.

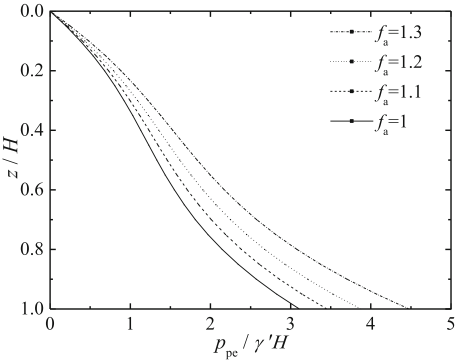

Fig. 3. Effects of f_a on seismic passive earth pressure distribution

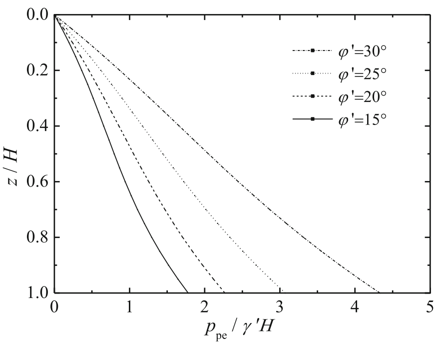

Fig. 4. Effects of φ' on earth pressure distribution

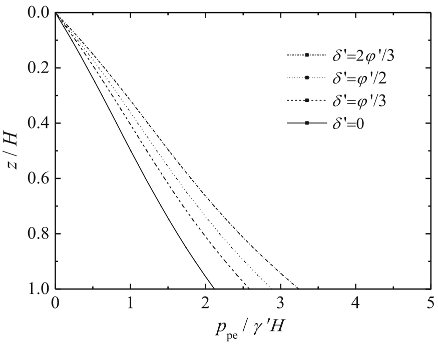

Fig. 5. Effects of δ' on earth pressure distribution

Figure 7 shows the seismic passive earth pressure under different vertical seismic acceleration coefficient k_v with $k_h = 0.15$, $k_v = 0$, $k_h/3$, $k_h/2$, $2k_h/3$. From the figure, the effect of vertical seismic force on passive earth pressure is much smaller than that of horizontal seismic force. In our calculation, the vertical seismic inertial force is supposed to be directed upward, thus the intensity of passive earth pressure decreases slightly with the increase of k_v.

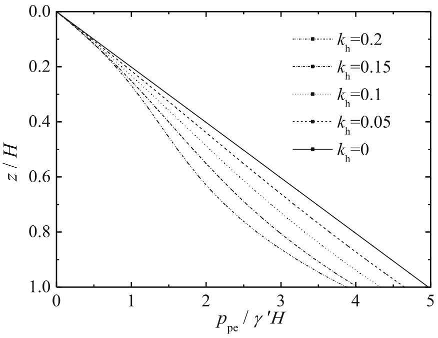

Fig. 6. Effects of k_h on earth pressure distribution

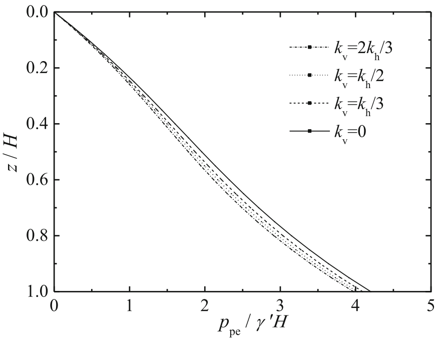

Fig. 7. Effects of k_v on earth pressure distribution

5 Conclusion

A modified pseudo-dynamic method to compute the seismic passive earth pressure for the submerged backfill is proposed in this study. The derivation is based on the limit equilibrium method with the assumption of planar failure surface, and it considers the influence of the groundwater condition and the earthquake amplification in the backfill on the seismic inertial forces.

The results manifest that the distribution of the seismic passive earth pressure by the proposed method is a non-linear form. Compared with the previous work, the trend of the earth pressure distribution of submerged backfill calculated by the proposed method is consistent with those obtained by the traditional pseudo-static and pseudo-dynamic approach of dry soil. Furthermore, it is worth noting that the submerged condition will reduce the passive earth thrust and the decreasing effect becomes greater with stronger earthquakes, which should be paid attention to in the seismic stability analysis of retaining walls.

Through the parametric study, the seismic acceleration amplification has a significantly increasing effect on the earth thrust, which cannot be neglected in the seismic design. The intensity of passive earth pressure increases with the increase of soil friction angle and wall friction angle where the former plays a more important role. The horizontal seismic action is still the key factor affecting the magnitude and distribution of the passive earth pressure rather than the vertical earthquake force.

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