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Computation of Point of Application of Seismic Passive Resistance by Pseudo-dynamic Method

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Keywords: soil structure interaction, seismic passive resistance, retaining wall

ABSTRACT: Computation of seismic passive resistance and its point of application is an important aspect of seismic design of retaining wall. Several researchers in the past had obtained seismic passive earth pressures by using the conventional pseudo-static method. In this pseudo-static method, peak ground acceleration is assumed as constant and seismic passive pressure thus obtained shows the linear variation along the height of the retaining wall. There is hardly any scope to find out the point of application of seismic passive resistance by pseudo-static approach but to assume it to act at one-third height from the base of the wall. Rectifying these errors, in recently developed pseudo-dynamic method of analysis, all these factors are considered to compute seismic passive earth pressures. In this paper, an attempt has been made to compute the point of application of seismic passive resistance using limit equilibrium method of analysis with pseudo-dynamic approach. Effects of variation of parameters like wall friction angle, time period of earthquake ground motion, seismic shear and primary wave velocities of backfill soil, soil amplification and seismic peak horizontal and vertical ground accelerations on the seismic passive earth pressure are studied.

1 Introduction

Investigations of seismic passive resistance and its point of location are essential for the safe design of retaining wall in the seismic zone. Many researchers have contributed to this in the past and have developed several methods to determine the seismic passive earth pressure on a rigid retaining wall subjected to earthquake loading. The pioneering works on earthquake-induced active and passive earth pressure on a rigid retaining wall were reported by Okabe (1926) and Mononobe and Matsuo (1929) [see Kramer, 1996] using pseudo-static method. But this Mononobe-Okabe method using pseudo-static approach gives the seismic passive earth pressure value in a very approximate way.

To rectify the approximation involved in pseudo-static approach, Steedman and Zeng (1990) proposed the pseudo-dynamic approach to compute the active earth pressure behind a retaining wall. In this pseudo-dynamic method, the effect of phase difference in the shear wave as it propagates vertically upward through the backfill behind the retaining wall was considered. Again the recent research by Choudhury and Nimbalkar (2007) and Nimbalkar and Choudhury (2007) show the need of seismic design of retaining wall under passive earth pressure condition by considering the rotational and sliding stability of the wall respectively. However, these analyses didn’t cover in-depth discussion of effect of various soil and wall parameters on the point of location of seismic passive resistance. Hence in this paper, a complete closed-form solution for computing the point of application of seismic passive resistance using limit equilibrium method of analysis with pseudo-dynamic approach is adopted.

2 Method of Analysis

A fixed base vertical cantilever rigid wall of height H, supporting a cohesionless backfill material with horizontal ground is considered in the analysis as shown in Figure 1. The shear wave velocity, $V_s$ and primary wave velocity,
\( V_p \) are assumed to act within the soil media due to earthquake loading. A planar failure surface at an inclination of \( \alpha \) with respect to horizontal is considered in the analysis. In Figure 1, \( W(t) \) is the weight of the failure wedge, \( Q_h(t) \) and \( Q_v(t) \) are the horizontal and vertical seismic inertia force components, \( F \) is the soil reaction acting at an angle of \( \phi \) (soil friction angle) to the normal to the inclined failure wedge, \( P_{pe(t)} \) is the total passive resistance acting at height \( h \) from the base of the wall at an inclination of \( \delta \) (wall friction angle) to the normal to the wall.

Let the base of the wall is subjected to harmonic horizontal seismic acceleration with amplitude \( a_h = k_h g \) (where \( g \) is the acceleration due to gravity) and harmonic vertical seismic acceleration with amplitude \( a_v = k_v g \), the horizontal and vertical seismic accelerations at any depth \( z \) and time \( t \) with soil amplification factor \( f \) and exciting frequency \( \omega \), below the top of the wall can be expressed by equations (1) and (2) respectively as follows,

\[
a_h(z, t) = \left(1 + \frac{H - z}{H} \right) f \left( f - 1 \right) k_h g \sin \left( t - \frac{(H - z)}{V_h} \right)
\]

\[
a_v(z, t) = \left(1 + \frac{H - z}{H} \right) f \left( f - 1 \right) k_v g \sin \left( t - \frac{(H - z)}{V_v} \right)
\]

The mass of an elemental wedge at depth \( z \) is given as follows,

\[
m(z) = \frac{\gamma (H - z)}{g \tan \alpha} dz
\]

where, \( \gamma \) is the unit weight of the backfill.

The weight of the whole wedge is,

\[
W(t) = \frac{1}{2} \frac{\gamma H^2}{\tan \alpha}
\]

And, the total horizontal inertial force acting within the failure zone for passive case (Figure 1) can be expressed as,

\[
Q_h(t) = \int_0^H m(z) a_h(z, t)dz
\]

\[
Q_h(t) = \frac{TV_h \gamma k_h}{4\pi^2 \tan \alpha} \left[ 2\pi H \cos \omega \zeta + TV_h \left( \sin \omega \zeta - \sin \omega t \right) \right]
\]

\[
+ \frac{TV_h \gamma k_h}{4\pi^2 H \tan \alpha} \left[ 2\pi H \left( \pi H \cos \omega \zeta + TV_h \sin \omega \zeta \right) + \left( TV_h \right)^2 \left( \cos \omega t - \cos \omega \zeta \right) \right]
\]

And, total vertical inertial force acting within the failure zone for passive case (Figure 1) can be expressed as,

\[
Q_v(t) = \int_0^H m(z) a_v(z, t)dz
\]

\[
Q_v(t) = \frac{TV_v \gamma k_v}{4\pi^2 \tan \alpha} \left[ 2\pi H \cos \omega \psi + TV_v \left( \sin \omega \psi - \sin \omega t \right) \right]
\]

\[
+ \frac{TV_v \gamma k_v}{4\pi^2 H \tan \alpha} \left[ 2\pi H \left( \pi H \cos \omega \psi + TV_v \sin \omega \psi \right) + \left( TV_v \right)^2 \left( \cos \omega t - \cos \omega \psi \right) \right]
\]

where, \( \zeta = t - H/V_h \) and \( \psi = t - H/V_v \). As the horizontal acceleration is acting from left to right and vice-versa and the vertical acceleration is acting from top to bottom and vice-versa, only the critical directions of \( Q_h(t) \) and \( Q_v(t) \) are considered to result the minimum seismic passive earth pressure.
The total (static + dynamic) passive resistance, \( P_{pe}(t) \) can be obtained by resolving the forces on the wedge and considering the equilibrium of the forces and hence \( P_{pe}(t) \) can be expressed by equation (9) as follows,

\[
P_{pe}(t) = \frac{W(t) \sin(\alpha + \phi) - Q_v(t) \cos(\alpha + \phi) - Q_h(t) \sin(\alpha + \phi)}{\cos(\alpha + \delta + \phi)}
\]

(9)

The seismic passive earth pressure coefficient, \( K_{pe} \) is defined as,

\[
K_{pe} = \frac{2P_{pe}(t)}{\gamma H^2}
\]

(10)

Substituting for \( Q_v(t) \) and \( Q_h(t) \) in the equation (9), an expression for \( K_{pe} \) in terms of \( Q_v(t) \), \( Q_{vp}(t) \) and \( W_p(t) \) can be derived.

\[
K_{pe} = \frac{1}{\tan \alpha \cos(\delta + \phi + \alpha)} \left[ m \frac{TV}{H} \cos(\alpha + \phi) - m \frac{TV}{H} \cos(\delta + \phi + \alpha) - m \frac{TV}{H} \cos(\alpha + \phi) + m \frac{TV}{H} \cos(\delta + \phi + \alpha) \right] - \frac{k}{2\pi \tan \alpha} \left[ m \frac{(t-1)TV}{H} \cos(\alpha + \phi) - m \frac{(t-1)TV}{H} \cos(\alpha + \phi) \right]
\]

(11)

From equation (11), it is seen that \( K_{pe} \) is function of the dimensionless parameters \( H/TV_s, H/TV_p, t/T, f \) and the wedge angle \( \alpha \). By optimizing \( K_{pe} \) with respect to \( t/T \) and \( \alpha \), it is found that \( K_{pe} \) is a function of \( H/TV_s, H/TV_p \) and \( f \).

\[
p_{pe}(t) = \frac{k \gamma z}{\tan \alpha} \left[ \frac{\cos(\alpha + \phi)}{\cos(\delta + \phi + \alpha)} \right] \sin \left[ w \left( t - \frac{z}{V_p} \right) \right] + \left[ \frac{\gamma z}{\tan \alpha} \frac{k \gamma z}{\tan \alpha} \right] \sin \left[ w \left( t - \frac{z}{V_p} \right) \right] \sin(\alpha + \phi)
\]

\[
- \frac{k \gamma (f-1)}{\tan \alpha} \left[ \frac{\cos(\alpha + \phi)}{\cos(\delta + \phi + \alpha)} \right] \frac{TV}{2\pi} \left[ \cos w \left( t - \frac{z}{V_p} \right) - \cos w \left( t - \frac{z}{V_p} \right) \right] + \left[ \frac{TV}{2\pi \gamma z} \right] \left[ \cos w \left( t - \frac{z}{V_p} \right) - \cos w \left( t - \frac{z}{V_p} \right) \right] \left[ \cos w \left( t - \frac{z}{V_p} \right) - \cos w \left( t - \frac{z}{V_p} \right) \right]
\]

(12)

And the seismic passive earth pressure distribution \( p_{pe}(t) \) can be obtained by differentiating the total passive
resistance with respect to the depth of the wall as given in equation (12).

It may be noted that equations (11) and (12) are exactly same as those given by Choudhury and Nimbalkar (2005) for a specific case of \( f = 1.0 \), i.e. no soil amplification. Total seismic passive resistance can also be defined as

\[
P_{psd}(t) = P_{ps} - P_{psd}(t) + P_{pvd}(t)
\]

Where, \( P_{ps} \) is the passive resistance on the retaining wall due to vertical weight of the wedge, \( P_{psd}(t) \) is the passive resistance on the wall due to horizontal inertia of the wedge and \( P_{pvd}(t) \) is the passive resistance on the wall due to vertical inertia of the wedge.

The point of location of \( P_{psd}(t) \), i.e. \( h_d \) above the base can be found by taking moments about the base of the wall. Then, if \( M_d(t) \) is the dynamic component of the bending moment,

\[
h_d = \frac{M_d(t)(z = H)}{P_{psd}(t) \cos \delta} = \int_0^H \frac{P_{psd}(t) \cos \delta(H - z)dz}{P_{psd}(t) \cos \delta}
\]

\[
h_d = H - \frac{2\pi^2 H^2 \left[m \cos \omega \phi + n \cos \omega \psi \right] + 2\pi H \left[\lambda m \sin \omega \phi + \eta n \sin \omega \psi \right] - \lambda^2 H \left[ \cos \omega \phi - \cos \omega \psi \right] - \eta n \left[ \cos \omega \phi - \cos \omega \psi \right]}{2\pi^2 H \left[m \cos \omega \phi + n \cos \omega \psi \right] + \pi \left[\lambda m \sin \omega \phi + \eta n \sin \omega \psi \right] - \pi \left[\lambda m + \eta n \sin \omega \phi \right]}
\]

where, \( m = \lambda k_v \cos(\alpha + \phi) \) and \( n = \eta k_v \sin(\alpha + \phi) \)

Point of application of total passive resistance (static + seismic) is given by,

\[
h = \frac{P_{ps} \left[H \delta \phi \phi_0 + P_{psd}(t) \cdot (h_d)\right]}{P_{psd}(t)}
\]

3 Results and Discussions

Variations of parameters considered in the present analysis are as follows:

\( \delta = 20^0, 30^0 \text{ and } 40^0; \delta = -0.5, 0.0, \text{ and } 0.5; k_v = 0.0, 0.1, 0.2 \text{ and } 0.3; k_v = 0.0, 0.5k_v \) and \( 1.0k_v; f = 1.0, 1.2, 1.4; V_s = 100 \text{ m/s, } V_p = 187 \text{ m/s} \)

3.1 Effect of amplification factor (f)

The values of point of location of dynamic passive resistance increment (\( h_d \)) in nondimensional form are given in Tables 1, 2 and 3 for different values of amplification factors (f). It is evident that both the horizontal and vertical seismic accelerations with amplification effect show decrease in point of location of dynamic passive resistance increment (\( h_d \)). For example, when \( f \) changes from 1.2 to 1.4, for the case of \( \delta = 0^0, \phi = 30^0, k_v = 0.2 \) and \( k_v = 0.0, \) the value of \( h_d \) is decreased by 3 %. Again, when \( f \) changes from 1.2 to 1.4, for the case of \( \delta = 0^0, \phi = 30^0, k_v = 0.2 \) and \( k_v = 0.5k_v, \) the value of \( h_d \) is decreased by 17.6 % whereas for the case of \( \delta = 15^0, \phi = 30^0, k_v = 0.2 \) and \( k_v = 0.5k_v, \) the value of \( h_d \) is decreased by 25.4 %.

3.2 Effect of wall friction angle (\( \delta \))

Figures 2 (a) and 2 (b) show the plot of normalized distribution of seismic passive earth pressure with the normalized height of the retaining wall with \( \phi = 30^0, k_v = 0.2, k_v = 0.5k_v, H/k_v = 0.3, H/\eta_k = 0.16 \) for \( f = 1.0 \) and \( f = 1.2 \) respectively. From the plot, it may be seen that for the case of \( f = 1.0, \) the seismic passive earth pressure at the base of the retaining wall \( \delta = 0 \) and \( \phi/2 \) are about 48% and 59% greater than that for \( \delta = \phi/2 \) at the base of the retaining wall.  Also for the case of \( f = 1.2, \) the seismic passive earth pressure at the base of the retaining wall \( \delta = 0 \) and \( \phi/2 \) are about 25% and 83.2% greater than that for \( \delta = \phi/2 \) at the base of the retaining wall. Hence, similar to the static case, in seismic case also, passive resistance increases with increase in wall friction angle. Also the amplification effect also influences significantly the seismic passive earth pressure. The assumption of planar failure surface yields satisfactory results for the condition of \( \delta < \phi/2 \) (Nimbalkar and Choudhury, 2007). Hence in this paper, the results are restricted for this condition only.
Table 1. Point of location of dynamic passive resistance increment \((h_d/H)\) for \(f = 1.0\)

<table>
<thead>
<tr>
<th>(\phi) (deg.)</th>
<th>(\delta) (deg.)</th>
<th>(k_h)</th>
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--- Missing values are due to non convergence of solution, - Missing values are due to shear fluidization as per Richards et al., 1990

Table 2. Point of location of dynamic passive resistance increment \((h_d/H)\) for \(f = 1.2\)

<table>
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<th>(\delta) (deg.)</th>
<th>(k_h)</th>
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--- Missing values are due to non convergence of solution, - Missing values are due to shear fluidization as per Richards et al., 1990

Table 3. Point of location of dynamic passive resistance increment \((h_d/H)\) for \(f = 1.4\)

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</tr>
</tbody>
</table>

--- Missing values are due to non convergence of solution, - Missing values are due to shear fluidization as per Richards et al., 1990

It also reveals non-linear seismic passive earth pressure distribution behind retaining wall in a more realistic manner compared to the pseudo-static method. The basic equations discussed in the present paper (equations
12 and 15) also clearly show mathematically the non-linearity of the seismic passive earth pressure distribution.

3.3 Effect of vertical seismic acceleration coefficient ($k_v$)

Figures 3 (a) and 3 (b) show the plot of normalized distribution of seismic passive earth pressure with the normalized height of the retaining wall with $\delta = \phi/2$, $\phi = 30^\circ$, $k_0 = 0.2$, $H/\lambda = 0.3$, $H/\eta = 0.16$ for $f = 1.0$ and $f = 1.2$ respectively. From the plot, it may be seen that for the case of $f = 1.0$, the seismic passive earth pressures at the base of the retaining wall for $k_v = k_h$ and $0.5k_h$ are about 14% and 7.5% smaller than that for $k_v = 0$. Also for the case of $f = 1.2$, the seismic passive earth pressures at the base of the retaining wall for $k_v = k_h$ and $0.5k_h$ are about 18% and 9% smaller than that for $k_v = 0$. Thus the pronounced effect of amplification is also evident from these plots. Though the effect of vertical seismic acceleration on seismic passive resistance is hardly considered in the analysis by many researchers, the present study reveals the significant influence of vertical seismic acceleration on the seismic passive resistance.

4 Comparison of Results

Table 4 shows the comparison of the results of point of application of the total seismic passive resistance with those obtained by the previous researchers like Mononobe-Okabe (1926, 1929) [see Kramer, 1996] and Choudhury et al. (2004). From Table 4, it is clear that results of point of application of total passive thrust computed by pseudo-dynamic method compare well with the previously published data and current design recommendations. But present results cannot be compared for any generalized case with the influence of body waves and soil amplification on seismic earth pressures under passive earth pressure condition due to scarcity of results in literature.

<table>
<thead>
<tr>
<th>Methods</th>
<th>Point of application of total passive resistance (h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mononobe-Okabe (1926, 1929) [see Kramer, 1996]</td>
<td>0.333H</td>
</tr>
<tr>
<td>Choudhury et al. (2004)</td>
<td>0.332H</td>
</tr>
<tr>
<td>Present study</td>
<td>0.287H</td>
</tr>
</tbody>
</table>

Figure 2. Effect of wall friction angle ($\delta$) on seismic passive earth pressure distribution with $\phi = 30^\circ$, $k_0 = 0.2$, $k_v = 0.5k_0$, $H/\lambda = 0.3$, $H/\eta = 0.16$ for (a) $f = 1.0$ (b) $f = 1.2$
Figure 3. Effect of vertical seismic acceleration coefficient ($k_v$) on seismic passive earth pressure distribution with $\delta = \phi/2$, $\phi = 30^\circ$, $kh = 0.2$, $H/\lambda = 0.3$, $H/\eta = 0.16$ for (a) $f = 1.0$ (b) $f = 1.2$

5 Conclusions
The present study shows that the point of application of seismic passive resistance vary significantly with seismicity compared to a constant value proposed by pseudo-static method of analysis. It is also found that the point of application of seismic passive resistance is well below one-third from the base of the wall compared to the static value of one-third from the base of the wall. Amplification of body waves viz. shear and primary waves as they propagate vertically through the backfill soil significantly affects the point of location of seismic passive resistance. Also this location shifts towards the base of the wall with increase in interfacial soil-wall friction. The non-linearity of the seismic passive earth pressure distribution increases with seismicity compared to a linear pseudo-static seismic passive earth pressure distribution. But the conventional pseudo-static approach gives only linear earth pressure distribution irrespective of static and seismic condition leading to a major drawback in the design criteria. Thus the pseudo-dynamic method presented here describes well the change in the point of application of passive resistance under seismic loading which is required for the safe design of the wall under passive state of earth pressure conditions.

6 List of Notations

- $a_h, a_v =$ amplitude of horizontal and vertical seismic acceleration respectively
- $g =$ acceleration due to gravity
- $H =$ height of the retaining wall
- $K_{pe} =$ seismic passive earth pressure coefficient
- $k_h, k_v =$ seismic acceleration coefficient in the horizontal and vertical direction respectively
- $P_{pe} =$ pseudo-dynamic passive resistance
- $Q_h, Q_v =$ horizontal and vertical inertia force due to seismic accelerations respectively
- $t =$ time
- $T =$ period of lateral shaking
- $V_s, V_p =$ shear and primary wave velocity respectively
- $\alpha =$ angle of inclination of the failure surface with the horizontal
- $\gamma =$ unit weight of the soil
- $\phi =$ soil friction angle
- $\delta =$ wall friction angle
- $\omega =$ angular frequency of base shaking
- $\zeta =$ $t - H/V_s$
- $\psi =$ $t - H/V_p$
- $\lambda =$ $TV_s$
- $\eta =$ $TV_p$
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8 References


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