Simultaneous Estimation of Dynamic Active and Passive Earth Pressure on Retaining Walls

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Abstract. Estimation of generated earth pressure on retaining walls both in active and passive conditions, form an important area of research in civil engineering. Particularly in earthquake prone zones it is imperative to consider the effect of earthquake in possible extreme conditions on such earth pressure so that damage or failures of retaining walls are avoided. Failure of such walls not only causes stoppage of service of the wall connected with bridge, highways or basement walls, but also causes enormous problems for mitigation of disaster due to earthquake. Several works for estimation of dynamic earth pressure on retaining walls have been presented in recent few decades. In this paper, results of proposed analytical methods to estimate the active and passive earth pressure under earthquake conditions have been presented. The methods provide direct approach to establish the probable failure surface and corresponding developed pressure in both active and passive conditions. The basic assumption for developing the method is by considering plane failure surface and effects of earthquake have been considered in pseudo-static fashion. Some comparisons of results from the methods have also been made with results from some methods available in published literature.

Keywords: Effects of earthquake, Dynamic earth pressure, pseudo-static analysis, Close-form solution.

1 Introduction

The concept of seismic active and passive earth pressure is very much important for safe design of retaining walls in the seismic zone. During earthquake retaining walls are subjected to dynamic inertial forces. As a result, a retaining wall safe enough under static conditions may not be so under earthquake conditions. Excess seismic forces may cause the retaining wall to slide or tilt. Loss of ultimate bearing capacity of the subsoil may also cause the failure of the wall. Hence there is need to develop a rational and accurate method for prediction of lateral earth pressure under the seismic condition.

It is common practice to consider seismic acceleration in both horizontal and vertical directions due to earthquake in terms of equivalent static forces, called pseudo-static acceleration. Using the pseudo-static approach, many investigators have developed different methods to predict the seismic active and passive earth pressure on rigid retaining wall due to earthquake loading. The pioneering work on earthquake induced lateral earth pressure, acting on a retaining wall were reported by Okabe[1] (1926) and Mononobe and Matsuo[2] (1929), commonly known as Monobe-Okabe (M-O) method extending the Coulomb's[3] static earth pressure theory. This is generally used in practice to compute the earth pressure for both active and passive case in earthquake conditions. Prakash and Saran[4] (1966), Saran and Prakash[5] (1968) extended this method for estimating active earth pressure in earthquake conditions for c-φ soil for horizontal backfill and inclined face of the retaining wall. Recent work of Saran and Gupta[6] (2003), Choudhury and Singh[7] (2006), Shukla et at.[8] (2009), Ghosh[9] (2010), Ghanbari et al.[10] (2010), Ghosh and Saran[11] (2010), Mandal et al.[12] (2011), Jana[13](2017) and few others also considered pseudo static approach to evaluate the seismic active earth pressure behind a retaining wall. Also a number of investigations have been made by several researchers to predict the passive earth pressure under seismic conditions. Soubra[14] (2000) determined the seismic passive earth pressure considering the multi-block mechanism, using upper bound limit analysis. Kumar and Subba Rao[15] (1997), Zhu and Qian[16] (2000) adopted the method of slice to predict the seismic passive earth pressure coefficients. Kumar[17] (2001) computed passive earth pressure coefficient for an inclined wall in the presence of horizontal pseudo-static earthquake body force by taking the failure surface as a combination of arc and straight line. Recent work of Sukla[18](2013), John and Preethakumari[19](2014), Gupta and Chanadaluri[20](2016), Chatterjee and Chottopadhyay [21](2018) and few others also considered pseudo static approach to evaluate the seismic passive earth pressure behind a retaining wall

In this paper a close form generalized analytical solution to estimate dynamic active and passive thrust on retaining walls with a similar method, resulting from c-φ backfill when backfill surface is inclined, back of wall is not vertical and wall is rough is presented. The dynamic active earth pressure coefficients obtained from the present study for different values of horizontal seismic coefficient and the soil properties have been compared with those from an available theory reported in literature.

2 Definition of the problems

A rigid, non-vertical, retaining wall of height H is placed with a dry, c-φ inclined backfill is considered in the analysis of seismic active and passive earth pressure as shown in Fig. 1 and Fig. 2 respectively. The wall face (AB) on the backfill side is inclined at an angle α with vertical and has an wall friction angle δ. The backfill is sloped with the horizontal at an inclination β and has a unit weight γ and shear strength parameters c and φ. Angle of friction between the wall and backfill material is δ. Unit adhesion between the soil and the back of the wall is c_a. A sliding surface

BD is considered, from the heel of the wall B, making an angle θ, with horizontal and intersecting the backfill surface at D. Resisting forces at the failure surface BD, are F and C, where F is acting at an angle φ with normal to the surface BD and C acts along BD. The objective is to determine the active and passive earth pressure coefficient and distribution during seismic condition and by knowing the active resistance (P_{ae}) and passive resistance (P_{pe}) per unit length of the wall in the presence horizontal and vertical components of inertial force due to seismicity, F_h and F_v which act through the centroid of the failure wedge ABD. Considering that the weight of the failure wedge is W, the earthquake force F_h (= k_hW) and F_v (= k_vW) act as shown during seismicity. k_h and k_v being seismic coefficient in horizontal and vertical direction respectively.

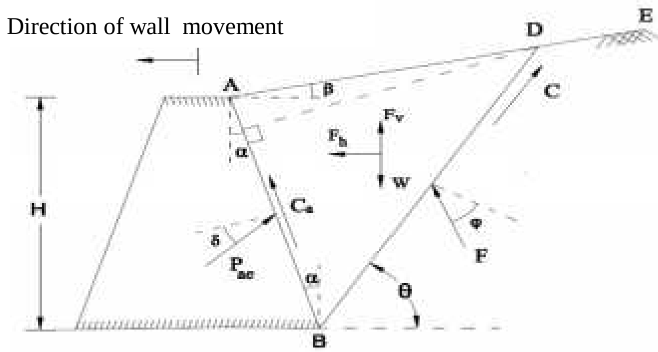

Fig. 1. Model retaining wall considered for computation of pseudo-static active earth pressure

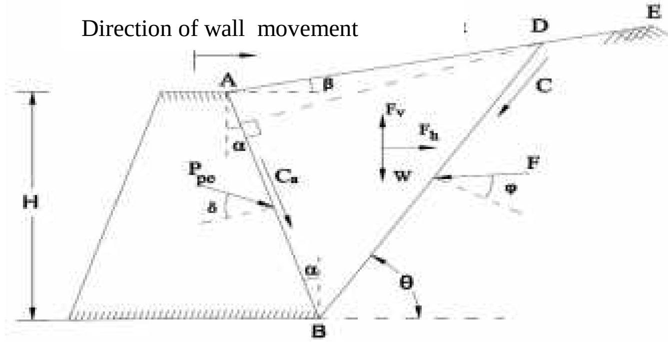

Fig. 2. Model retaining wall considered for computation of pseudo-static passive earth pressure

3 Analysis

In the pseudo-static method, horizontal and vertical acceleration are considered constant acting on the soil wedge with the neglect of time effect as shown below:
The inertia forces due to earthquake in horizontal and vertical direction are:

$$F_h = \frac{\alpha_h W}{g} = k_h W \tag{1}$$

$$F_v = \frac{\alpha_v W}{g} = k_v W \quad (2)$$

where, α_h and α_v are the horizontal and vertical pseudo static accelerations, k_h and k_v are the coefficient of horizontal and vertical pseudo static accelerations and W is the weight of the failure mass. In case of seismic active and passive resistance by the earthquake the total weight of the failure wedge, W is given by

$$W = \frac{\gamma}{2} H^2 sec^2\alpha \frac{\cos(\theta-\alpha)\cos(\alpha-\beta)}{\sin(\theta-\beta)} \quad (3)$$

Cohesive force, $$C = cH \sec\alpha \frac{\cos(\alpha-\beta)}{\sin(\theta-\beta)} \quad (4)$$

Adhesive force, $$C_a = C_a H \sec\alpha \quad (5)$$

3.1 Seismic active earth pressure condition

Application of equilibrium condition evaluation of active force, applying the force equilibrium condition $\Sigma H = 0$, $\Sigma V = 0$.

$$P_{ae}\cos(\delta+\alpha) + C\cos\theta - C_a\sin\alpha - k_h - F\sin(\theta-\varphi) = 0 \quad (6)$$

$$P_{ae}\sin(\delta+\alpha) + c\sin\theta + C_a\cos\alpha + k_v w - W + F\sin(\theta-\varphi) = 0 \quad (7)$$

By eliminating F from equation (6) and (7) and substituting the value of W, C, C_a one can get:

$$P_{ae} = \frac{1}{\cos(\theta-A)}[I\frac{\cos(\theta-\alpha)}{\sin(\theta-\beta)}\{(1-k_v)\sin(\theta-\varphi)+k_h\cos(\theta-\varphi)\} - \frac{E}{\sin(\theta-\beta)} + G\sin(D-\theta)] \quad (8)$$

Where,
$E = c.H\sec\alpha\cos(\alpha-\beta)\cos\varphi$, $G = c_a.H\sec\alpha$, $I = \frac{\gamma}{2}H^2\sec^2\alpha\cos(\alpha-\beta)$, $A = (\varphi+\delta+\alpha)$ and $D = (\varphi+\alpha)$

Now, if one goes through the details of equation (8) then it can be seen that for a particular retaining wall backfill system, all the parameters are constant except θ. The critical one following the critical $\frac{\partial P_{ae}}{\partial\theta} = 0$ will give the critical value of P_{ae} and that value is the corresponding active earth pressure. From this condition $\theta_{critical}$ or θc was found out.

$$\theta_{critical} \text{ or } \theta c = \tan^{-1}\left[\frac{-m_1 \pm \sqrt{m_1^2 + m_2^2 - m_3^2}}{(m_2+m_3)}\right] \quad (9)$$

Where,
$m_1 = [I\frac{(1-k_v)}{2\cos\psi}\{\cos(\alpha+\beta)\cos(\varphi-\psi-A) - \cos(\alpha-\beta)\cos(A+\varphi-\psi)\} + E\sin(A+\beta) + \frac{G}{2}\sin2\beta\cos(D-A)]$

$m_2 = [\mathrm{I}\, \frac{(1-k_v)}{2\cos\psi} \{\sin(\alpha+\beta)\cos(\varphi-\psi-A) - \cos(\alpha-\beta)\, \sin(A+\varphi-\psi)\} - E\cos(A+\beta) - \frac{G}{2}\, cos2\beta\, \cos(D-A)]$

$m_3 = [\mathrm{I}\, \frac{(1-k_v)}{2\cos\psi}\, \sin(\varphi - \psi - A + \alpha - \beta) - \frac{G}{2}\, \cos(D-A)]$

And, $\psi = \tan^{-1}\frac{k_h}{1-k_v}$

For the real values of $\theta_{critical}$, the expression under the radical sign in equation (9) must be positive and the denominator must not be zero.

i.e. $({m_1}^2 + {m_2}^2 - {m_3}^2) \geq 0$ and $(m_2+m_3) \neq 0$

Putting the value of $\theta_{critical}(\theta_c)$ in equation (8) Seismic Active Earth Pressure, P_{ae} can be found for known H, α, β, δ, φ, γ, c, c_a, k_h and k_v.

$$P_{ae} = \frac{1}{\cos(\theta c-A)}[\frac{\cos(\theta c-\alpha)}{\sin(\theta c-\beta)}\{(1-k_v)\sin(\theta_c-\varphi) + k_h\cos(\theta c-\varphi)\} - \frac{E}{\sin(\theta c-\beta)} + G\sin(\theta c - D)] \quad (10)$$

Co-efficient of seismic active earth pressure, K_{ae} will be-

$$K_{ae} = \frac{P_{ae}}{0.5\gamma H^2} \quad (11)$$

3.2 Seismic Passive earth pressure condition

Application of equilibrium condition evaluation of passive force, applying the force equilibrium condition ΣH = 0, ΣV = 0.

$$P_{pe}\cos(\alpha-\delta) - C\cos\theta + C_a\sin\alpha + k_h - F\sin(\theta+\varphi) = 0 \quad (12)$$

$$P_{pe}\sin(\alpha-\delta) - C\sin\theta - C_a\cos\alpha + k_v w - W + F\sin(\theta+\varphi) = 0 \quad (13)$$

By eliminating F from equation (12) and (13) and substituting the value of W, C, C_a one can get:

$$P_{pe} = \frac{1}{\cos(\theta+A)}[I\frac{\cos(\theta-\alpha)}{\sin(\theta-\beta)}\{(1-k_v)\sin(\theta+\varphi) - k_h\cos(\theta+\varphi)\} + \frac{E}{\sin(\theta-\beta)} + G\sin(\theta+D)] \quad (14)$$

Where, $E = c.H \sec\alpha \cos(\alpha-\beta)\cos\varphi$, $G = c_a.H\sec\alpha$, $I = \frac{\gamma}{2}H^2 \sec^2\alpha \cos(\alpha-\beta)$, $A = (\varphi+\delta-\alpha)$ and $D = (\varphi-\alpha)$

Now, if one goes through the details of equation (14) then it can be seen that for a particular retaining wall backfill system, all the parameters are constant except θ. The critical one following the critical $\frac{\partial P_{pe}}{\partial\theta} = 0$ will give the critical value of P_{pe} and that value is the corresponding active earth pressure. From this condition $\theta_{critical}$ or θc was found out (Chetterjee and Chattopadhyay[21], 2018) as:

$$\theta_{critical} \text{ or } \theta c = \tan^{-1}\left[\frac{-m_1 \pm \sqrt{{m_1}^2 + {m_2}^2 - {m_3}^2}}{(m_2+m_3)}\right] \quad (15)$$

Where,

$m_1 = [I \frac{(1-k_v)}{2\cos\psi} \{\cos(\alpha+\beta)\cos(A+\psi-\varphi) - \cos(\alpha-\beta)\cos(A+\varphi-\psi)\} + E\sin(A-\beta) - \frac{G}{2}\sin 2\beta$
$\cos(A-D)]$

$m_2 = [I \frac{(1-k_v)}{2\cos\psi} \{ \sin(\alpha+\beta)\cos(A+\varphi-\psi) + \cos(\alpha-\beta)\sin(A+\varphi-\psi)\} + E\cos(A-\beta) -$
$\frac{G}{2}\cos 2\beta \cos(A-D)]$

$m_3 = [I \frac{(1-k_v)}{2\cos\psi} \sin(A+\alpha+\psi-\beta-\varphi) - \frac{G}{2}\cos(A-D)]$ and, $\psi = \tan^{-1}\frac{k_h}{1-k_v}$

For the real values of $\theta_{critical}$, the expression under the radical sign in equation (15) must be positive and the denominator must not be zero.

i.e. $(m_1{}^2 + m_2{}^2 - m_3{}^2) \geq 0$ and $(m_2+m_3) \neq 0$

Putting the value of $\theta_{critical}(\theta_c)$ in equation (14) Seismic Active Earth Pressure, P_{pe} can be found for known H, α, β, δ, φ, γ, c, ca, k_h and k_v.

$P_{pe} = \frac{1}{\cos(\theta c+A)} [I \frac{\cos(\theta c-\alpha)}{\sin(\theta c-\beta)} \{(1-k_v)\sin(\theta_c+\varphi) - k_h\cos(\theta c+\varphi)\} - \frac{E}{\sin(\theta c-\beta)} + G$
$\sin(\theta c + D)]$ (16)

Co-efficient of seismic passive earth pressure, K_{pe} will be-

$$K_{pe} = \frac{P_{pe}}{0.5\gamma H^2} \quad (17)$$

4 Result and Discussion

Results are presented elsewhere Kundu[22] (2019) in the tabular and graphical form for seismic active and passive earth pressure coefficient along with different parameters for different values of k_h and k_v. Variation of parameters considered is as follows:
Soil friction angle, φ = 20°, 30° and 40°; Wall friction angle, δ = 0°, 10° and 20 °; Backfill inclination, β = 0°, 5° and 10°; Wall Inclination with Vertical, α = 0°, 5° and 10°; Horizontal Seismic Coefficient, k_h = 0.05, 0.1 and 0.2; Vertical Seismic Coefficient, k_v = 0, 0.05 and 0.1 In this study both cohesion, c and adhesion, c_a has been kept as 0 kN/m^2. And the angle of shearing resistance, φ and its dry density of backfill soil, γ were chosen from SN 670010B[23] as for φ vales of 20°, 30° and 40°, γ values were varied 18, 20 and 22 kN/m^3 respectively.

5 Comparison of the results

To check the validity of the value of K_{ae} and K_{pe} obtained in this study can be compared with the existing values proposed by other researchers. Comparisons are made between the results obtained from the present study and the pseudo static approaches of Mononobe-Okabe method (M-O method) (1929).

5.1 Seismic active earth pressure condition:

As there are few values of K_{ae} in the literature for different values of φ, δ, β, α k_h and k_v. For α = 0°, the obtained values of K_{ae} have been compared with the values reported by M-O method under pseudo-static condition using linear failure surface in Table 1.

Table 1. Comparison of seismic active earth pressure coefficient, K_{ae} for α =0°,β =0°,k_v =0.5k_h

φ	δ	k_h	K_{ae}	
			Present analysis	M-O method
20	0	0	0.490	0.490
		0.1	0.574	0.545
		0.2	0.701	0.631
	(1/2)φ	0	0.447	0.447
		0.1	0.537	0.510
		0.2	0.681	0.613
	φ	0	0.427	0.427
		0.1	0.526	0.499
		0.2	0.691	0.622
30	0	0	0.333	0.333
		0.1	0.400	0.380
		0.2	0.493	0.443
	(1/2)φ	0	0.301	0.301
		0.1	0.372	0.353
		0.2	0.474	0.353
	φ	0	0.297	0.297
		0.1	0.377	0.358
		0.2	0.498	0.448
40	0	0	0.217	0.217
		0.1	0.271	0.258
		0.2	0.343	0.309
	(1/2)φ	0	0.199	0.199
		0.1	0.256	0.243
		0.2	0.336	0.302
	φ	0	0.210	0.210
		0.1	0.279	0.265
		0.2	0.381	0.343

For graphical comparison, seismic active earth pressure coefficient, K_{ae} for different values of horizontal seismic coefficient (k_h) and soil friction angle (φ) with with α = 0°, β= 0°, k_v = 0.5k_h and δ = 0, δ = (1/2)φ, δ = φ respectively obtained from M-O method and present analysis have presented in Fig. 3-5.

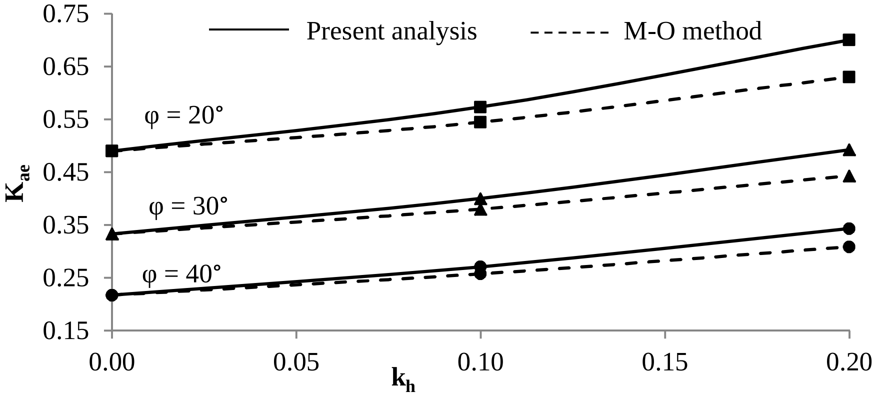

Fig. 3. Comparison K_{ae} for different values of k_h and φ with α = 0°, β = 0°, $k_v = 0.5k_h$ and δ = 0

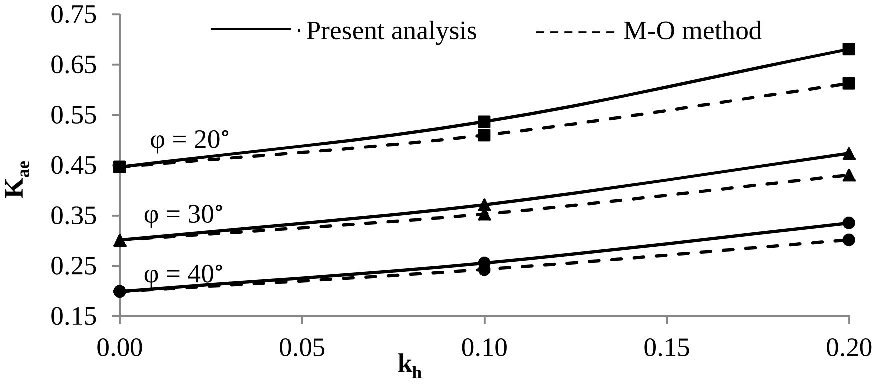

Fig. 4. Comparison of K_{ae} for different values of k_h φ with α = 0°, β = 0°, $k_v = 0.5k_h$ and δ = (1/2)

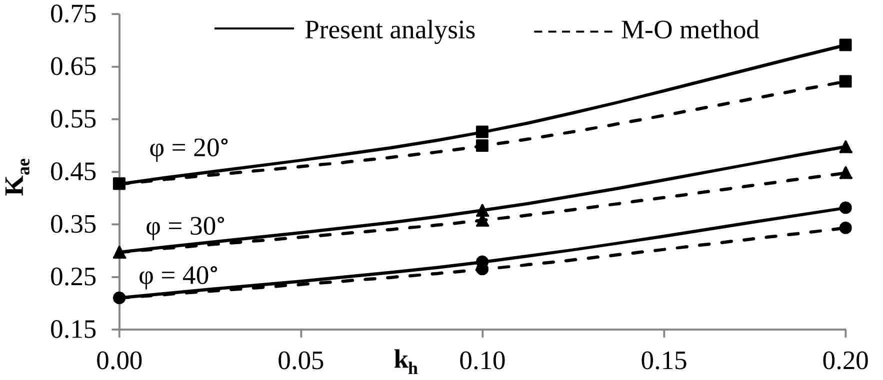

Fig. 5. Comparison K_{ae} for different values of k_h and φ with α = 0°,β = 0°,$k_v = 0.5k_h$ and δ= φ

From above figure it is observed that seismic active earth pressure coefficient, K_{ae} increases non linearly with increase of horizontal seismic coefficient, k_h value for each soil friction angle, φ values. When φ value increases K_{ae} values also decreases for each k_h value. It is evident that seismic active earth pressure coefficient, K_{ae} from present study is maximum as compared to M-O method which is desirable for design purpose.

5.2 Seismic passive earth pressure condition:

For α = 0° and β = 0 the obtained values of K_{pe} have been compared with the values obtained from M-O method under pseudo-static condition using linear failure surface in Table 2.

Table 2. Comparison of seismic passive earth pressure coefficient, K_{pe} for α = 0°, β = 0°, $k_v = 0.5k_h$

φ	δ	k_h	K_{pe}	
			Present analysis	M-O method
20	0	0	2.040	2.040
		0.1	1.786	1.880
		0.2	1.501	1.667
	(1/2)φ	0	2.635	2.635
		0.1	2.247	2.365
		0.2	1.818	2.020
	φ	0	3.525	3.525
		0.1	2.933	3.087
		0.2	2.290	2.545
30	0	0	3.000	3.000
		0.1	2.671	2.812
		0.2	2.326	2.584
	(1/2)φ	0	4.977	4.977
		0.1	4.312	4.539
		0.2	3.800	4.030
	φ	0	10.095	10.095
		0.1	8.515	8.963
		0.2	6.905	7.672
40	0	0	4.599	4.599
		0.1	4.150	4.369
		0.2	3.690	4.100
	(1/2)φ	0	11.771	11.771
		0.1	10.325	10.868
		0.2	8.863	9.848
	φ	0	92.586	92.586
		0.1	78.624	82.762
		0.2	64.639	71.821

For graphical comparison of seismic passive earth pressure coefficient, K_{pe} for different values of horizontal seismic coefficient (k_h) and Soil friction angle (φ) with $\alpha = 0°$, $\beta = 0°$, $k_v = 0.5k_h$ and $\delta = 0$, $\delta = (1/2)\varphi$, $\delta = \varphi$ respectively obtained from M-O method and present analysis, are presented in Fig. 6-8 .

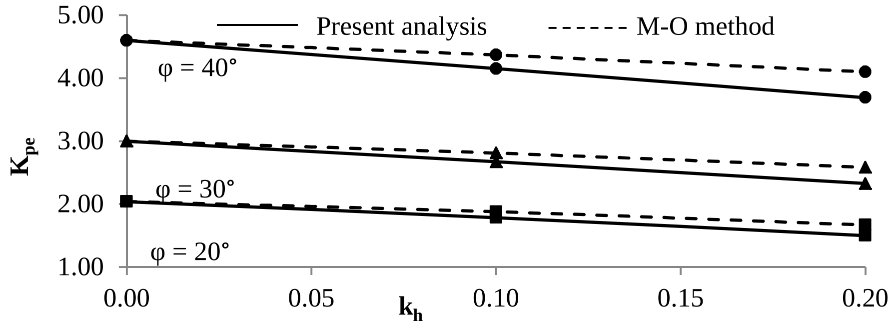

Fig. 6. Comparison K_{pe} for different values of k_h and φ with $\alpha = 0°$, $\beta = 0°$, $k_v = 0.5k_h$ and $\delta = 0$

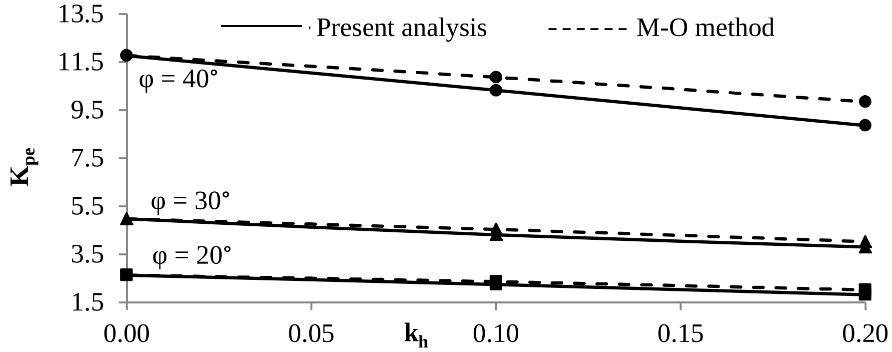

Fig. 7. Comparison K_{pe} for different values of k_h and φ with $\alpha = 0°$, $\beta = 0°$, $k_v = 0.5k_h$ and $\delta = 0$

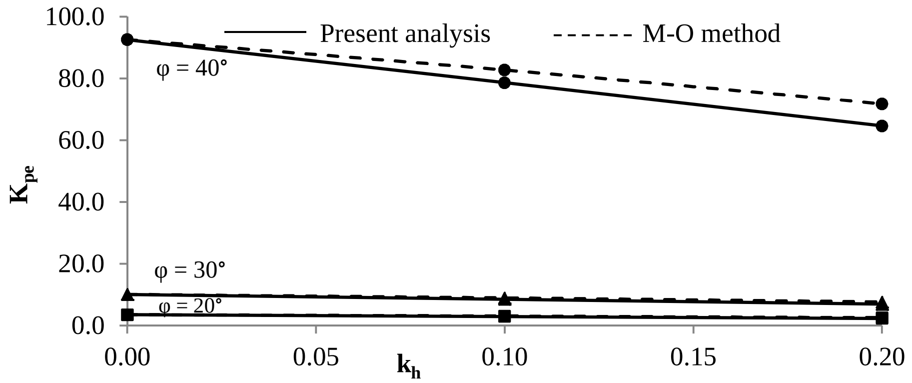

Fig.8. Comparison K_{pe} for different values of k_h and φ with $\alpha = 0°$, $\beta = 0°$, $k_v = 0.5k_h$ and $\delta = 0$

It is obtained from Fig. 6-8 that seismic passive earth pressure coefficient, K_{pe} decreases non linearly with increase of horizontal seismic coefficient, k_h value for each soil friction angle, φ values. When φ value increases K_{pe} values also decreases for each k_h value. It is evident that seismic passive earth pressure coefficient, K_{pe} from present study is minimum and thus proves to be safer as per design criteria as compared to M-O method which is desirable for design purpose.

6 Conclusions

Using pseudo-static approach with the assumptions of a planner rupture surface, to determine the seismic active as well as passive earth pressure coefficient behind the non-vertical rigid retaining wall supporting inclined backfill a closed formed solution have been made with the effects of the soil friction angle, wall inclination, wall friction angle, horizontal and vertical earthquake acceleration. In a same method with a generalized analytical solution is very helpful in practical purpose to find out the seismic earth pressure coefficient in both the cases. However the present method gives directly value of the estimated seismic active and passive earth pressure and also critical soil wedge angle (θ_c) directly. But M-O method requires trial and error to estimate the required value.

From the analysis, it is clear that both the horizontal and vertical seismic acceleration are significant for computation of seismic active as well as passive earth pressure moreover, there importance actually increases as the earthquake intensity increases. With increase of the horizontal seismic acceleration, seismic active earth pressure coefficient increases but seismic passive earth pressure coefficient decreases. The nonlinear distribution of seismic earth pressure increases with higher value of horizontal seismic acceleration. By applying pseudo-static method presented in this paper, seismic active earth pressure are more and seismic passive earth pressure are less as compared to those calculated by using conventional pseudo-static method of analysis.

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