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EFFECT OF WALL INCLINATION ON DYNAMIC ACTIVE THRUST FOR COHESIVE SOIL BACKFILL

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Abstract – Design of retaining walls under seismic conditions is based on the calculation of seismic earth pressure behind the wall. To calculate the seismic active earth pressure behind the vertical retaining wall, many researchers report analytical solutions using the pseudo-static approach for both cohesionless and cohesive soil backfill. Design charts have been presented for the calculation of seismic active earth pressure behind vertical retaining walls in the non-dimensional form. For inclined retaining walls, the analytical solutions for the calculation of seismic active earth pressure as well as the design charts (in non-dimensional form) have been reported in few studies for c-ϕ soil backfill. One analytical solution for the calculation of seismic active earth pressure behind inclined retaining walls by Shukla (2015) is used in the present study to obtain the design charts in non-dimensional form. Different field parameters related with wall geometry, seismic loadings, tension cracks, soil backfill properties, surcharge and wall friction are used in the present analysis. The present study has quantified the effect of negative and positive wall inclination as well as the effect of soil cohesion (c), angle of shearing resistance (ϕ), surcharge loading (q) and the horizontal and vertical seismic coefficient (k_h and k_v) on seismic active earth pressure with the help of design charts for c-ϕ soil backfill. The design charts presented here in non-dimensional form are simple to use and can be implemented by field engineers for design of inclined retaining walls under seismic conditions. The active earth pressure coefficients for cohesionless soil backfill achieved from the present study are validated with studies reported in the literature.

***Keywords*:** Inclined retaining wall, pseudo-static approach, cohesion, surcharge, seismic active earth pressure, wall inclination

1.0 INTRODUCTION

In the field under seismic conditions, seismic active earth pressure behind retaining walls can be calculated using explicit generalized expressions. The available generalized solutions take lots of time and effort and have a chance of error in the calculation of seismic active earth pressure. The pseudo-static approach was introduced to determine the seismic active earth pressure behind retaining walls by Okabe [1] and Mononobe and Matsuo [2], called the Mononobe and Okabe method. The soil backfill was assumed as cohesionless in their study. But in real field situations, the design of retaining walls encounters c-ϕ soil backfills for which the Mononobe-Okabe method cannot be used. A simple expression has been reported by Shukla et al. [3] for calculating the dynamic active thrust behind the vertical retaining wall with c-ϕ soil backfill, but wall friction and soil-wall adhesion were not considered in this study. Kim et al. [4] reported the calculations of total dynamic active thrust behind the retaining wall in terms of the inclination of failure plane by the hit and trial method. Due to the hit and trial method this study has limited application in real design practices. Using the pseudo-static approach, the effect of wall friction and soil-wall adhesion were incorporated in the analytical expressions presented by Shukla and Bathurst [5]. For sloping soil backfill, Shukla [6] obtained analytical expressions to calculate the seismic active earth pressure. Shukla [7] further extended the generalized explicit solution to calculate the dynamic active thrust behind the inclined retaining wall incorporating the sloping soil backfill. The expressions were associated the effect of wall inclination as well as the effect of soil cohesion, angle of shearing resistance, soil-wall adhesion, tension cracks, surcharge loading and the horizontal and vertical seismic coefficient. An expression for the critical inclination of failure plane (α_{cri}) was also presented in this study. Using the generalized expression by Shukla [7], the design charts for calculating the dynamic active thrust were developed by Gupta et al. [8] showing the effect of surcharge loading only. The present study has obtained the design charts for calculating the seismic active earth pressure considering the effect of wall inclination on the dynamic active thrust. The design charts reduce effort in calculation of seismic active earth pressure behind inclined retaining walls, and are very helpful for field engineers in the analysis of inclined retaining walls.

2.0 ANALYTICAL DERIVATION

Figure 1 shows a retaining wall A_1A_2. The height of wall H supports cohesive soil backfill with cohesion (c) and angle of shearing resistance (ϕ). An active trail failure wedge ($A_1A_2A_3$) is of weight W. The back face of the retaining wall is inclined at β with the horizontal. A_2A_3 is the assumed failure plane, passing through the bottom of the wall. A_2A_3 makes an angle α with the horizontal. The seismic inertial forces are k_hW and k_vW in the horizontal and vertical direction. k_h and k_v are the seismic horizontal and vertical seismic coefficient. A surcharge q per unit surface area is at the top of the sloping backfill. k_hqB and k_vqB are the seismic loads due to surcharge along the horizontal and vertical directions. The length of A_1A_3 is taken as B.

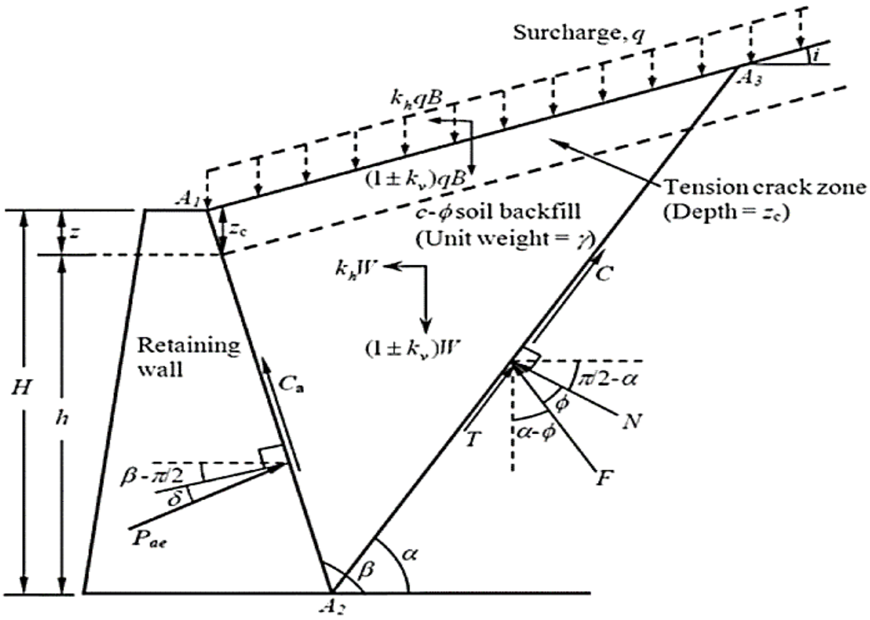


Figure 1 Forces in a trial failure wedge of an inclined retaining wall for c-ϕ soil backfill in active state (after Shukla [7])

The depth of tension crack is z_c from the top of the sloping soil backfill. The height of wall H is taken as the sum of z and h. On the failure plane, the frictional force is T and normal force is N. The force F is the resultant force of T and N. C_a is the total adhesive force mobilized along the soil-wall interface. Wall friction angle is δ and total cohesive force is shown by C. An angle i is made by the sloping backfill (A_1A_3) with horizontal.

Now, using the force equilibrium in the horizontal and vertical direction, the following equations can be obtained as:

$$P_{ae}\cos(\beta+\delta)+(1\pm k_v)(W+qB)-F\cos(\alpha-\phi)-\frac{\bar{c}\,H\sin(\beta-i)\sin\alpha}{\sin\beta\sin(\alpha-i)}a_f\bar{c}\,H=0 \quad (1)$$

$$P_{ae}\sin(\beta+\delta)-k_h(W+qB)-F\sin(\alpha-\phi)+\frac{\bar{c}\,H\sin(\beta-i)\cos\alpha}{\sin\beta\sin(\alpha-i)}a_f\bar{c}\,H\cot\beta=0 \quad (2)$$

Eliminating F from equations (1) and (2) and further simplifying, P_{ae} can be expressed as:

$$P_{ae} = \frac{1}{2}\left(\frac{a_1 \tan^2\alpha - b_1 \tan\alpha + c_1}{a_2 \tan^2\alpha - b_2 \tan\alpha + c_2}\right)\gamma H^2 \tag{3}$$

Here, a_1, b_1, c_1 and a_2, b_2, c_2 are the non-dimensional constants defined as follows:

$$a_1 = m_1 \cos\beta \cos(\theta - \phi) + m_2 \cos i \sin(\beta + \phi) + m_3 \qquad a_2 = \cos i \cos(\beta + \delta + \phi)$$
$$b_1 = m_1 \sin(\beta - \theta + \phi) + m_2 \cos(i + \beta + \phi) \qquad b_2 = \sin(\beta + \delta + \phi + i)$$
$$c_1 = m_3 - m_1 \sin\beta \sin(\phi - \theta) - m_2 \sin i \cos(\beta + \phi) \qquad c_2 = \sin i \sin(\beta + \delta + \phi)$$

$$m_1 = \left(\frac{1 \pm k_v}{\cos\theta}\right)\left[\frac{2q}{\gamma H} + \frac{\sin(\beta - i)}{\sin\beta}\right]\operatorname{cosec}\beta \qquad m_2 = a_f\left(\frac{2c}{\gamma H}\right)\left(1 - \frac{z_c}{2H}\right)\operatorname{cosec}\beta$$

$$m_3 = \left(\frac{2c}{\gamma H}\right)\left(1 - \frac{z_c}{2H}\right)\sin(\beta - i)\cos\phi \operatorname{cosec}\beta \qquad \theta = \tan^{-1}\left(\frac{k_h}{1 \pm k_v}\right)$$

$$z_c = \left(\frac{2c}{\gamma}\right)\tan\left(45^0 + \frac{\phi}{2}\right) \qquad \bar{c} = \left(1 - \frac{z_c}{2H}\right)c$$

For optimization, the following condition must be satisfied for the value of dynamic active pressure P_{ae}.

$$\frac{\partial P_{ae}}{\partial \alpha} = 0 \quad \text{or} \quad \frac{\partial P_{ae}}{\partial \tan\alpha} = 0 \tag{4}$$

$$(a_2 b_1 - a_1 b_2)\tan^2\alpha - 2(a_2 c_1 - a_1 c_2)\tan\alpha + (b_2 c_1 - b_1 c_2) = 0 \tag{5}$$

Equation (5) is solved for tanα to get the critical inclination of failure plane, $\alpha = \alpha_c$ as:

$$\alpha_{cri} = \tan^{-1}\left[\frac{(a_2 c_1 - a_1 c_2) \pm \sqrt{(a_2 c_1 - a_1 c_2)^2 - (a_2 b_1 - a_1 b_2)(b_2 c_1 - b_1 c_2)}}{(a_2 b_1 - a_1 b_2)}\right] \tag{6}$$

On substituting $\alpha = \alpha_{cri}$ into equation (3), P_{ae} is obtained as:

$$P_{ae} = \frac{1}{2}\left(\frac{a_1 \tan^2\alpha_{cri} - b_1 \tan\alpha_{cri} + c_1}{a_2 \tan^2\alpha_{cri} - b_2 \tan\alpha_{cri} + c_2}\right)\gamma H^2 \tag{7}$$

Or

$$K_{ae} = P_{ae}{*} = \frac{P_{ae}}{0.5\gamma H^2} = \left(\frac{a_1 \tan^2\alpha_{cri} - b_1 \tan\alpha_{cri} + c_1}{a_2 \tan^2\alpha_{cri} - b_2 \tan\alpha_{cri} + c_2}\right)\gamma H^2 \tag{8}$$

Where K_{ae} is the coefficient of seismic active earth pressure.

3.0 RESULTS AND DISCUSSION

According to the generalized analytical expression shown in equation (8), design charts can be presented to calculate total active earth pressure on retaining walls for different wall inclinations taken as -15º, 0º and 15º with vertical (β = 75º, 90º and 105º). $c*$ and $q*$ are as non-dimensional cohesion and non-dimensional surcharge defined in equation (9). We also consider the k_v is positive for the upward direction.

$$c^* = \frac{c}{\gamma H} \quad \text{and} \quad q^* = \frac{q}{\gamma H} \tag{9}$$

The design charts obtained from the present study are shown in Figures 2, 3, 4, and 5. Figures 2 and 3 present the design charts for calculating the seismic active earth pressure from *c*-ϕ soil backfill for the negative wall inclination as β = 75º and 90º respectively for surcharge loading q^* = 0.2. Figures 4 and 5 are showing the design charts for the positive wall inclination β = 105º for surcharge loading q^* = 0 and 0.2. Effect of surcharge is also showing in Figures 4 and 5. Variations of parameters considered are stated in Table 1.

Table 1 Variation of parameters considered in the present study

Description	Values are taken
Unit weight of soil backfill (γ)	18 kN/m^3
The height of retaining wall (H)	10 m
Non-dimensional soil cohesion (c^*)	0.0, 0.05, 0.1 and 0.2
Soil friction angle (ϕ)	5º, 10º, 15º, 20º, 25º, 30º, 35º, 40º, 45º and 50º
Non-dimensional surcharge (q^*)	0.0 and 0.2
Wall inclination with vertical (β)	-15º, 0º and 15º
Wall friction angle (δ)	0.5 ϕ
Coefficient of horizontal seismic acceleration (k_h)	0.0, 0.1, 0.2, 0.3 and 0.4
Coefficient of vertical seismic acceleration (k_v)	0.0, 0.25 k_h, 0.5 k_h and 1.0 k_h

3.1 EFFECT OF WALL INCLINATION DUE TO c AND ϕ OF SOIL ON K_{ae}

Figures 2, 3, 4, and 5 show that the calculated value of K_{ae} reduces with increase in c and ϕ of soil backfill. For example, at ϕ = 20º and c^* = 0.1, wall inclination angle β increases from (75º to 90º) and (75º to 105º), the value of K_{ae} increases about 69.8 and 159.5%. Yet, the successive percentage increment is reducing with respect to increase of inclination angle of back slope of retaining wall. The effect of the increment of ϕ for the same values of soil cohesion can be noticed from Figures 2 to 5. On increasing the value of ϕ with constant variation of cohesion of soil, the reduction in the value of K_{ae} is clearly observed. For example at c^* = 0 and k_h = 0 on increasing ϕ from 30º to 40º K_{ae} decreases by 45.1, 33.8 and 23.1% for different wall inclination as 75º, 90º and 105º respectively. The example is showing the reduction in K_{ae} when wall inclination moves from its negative to its positive value. The effect of increment of c value for the same values of ϕ can also be quantified from Figures 2 to 5. For example at ϕ = 30º and k_h = 0 when on increasing c^* from 0 to 0.1 the K_{ae} decreases by 67.6, 77.6 and 24.2% when the wall inclination angle changes from 75º, 90º and 105º respectively. From the example the small increment of active earth pressure on moving β from 75º to 90º and a large reduction in active earth pressure for β changes from 90º to 105º can be noticed.

3.2 EFFECT OF WALL INCLINATION DUE TO k_h ON K_{ae}

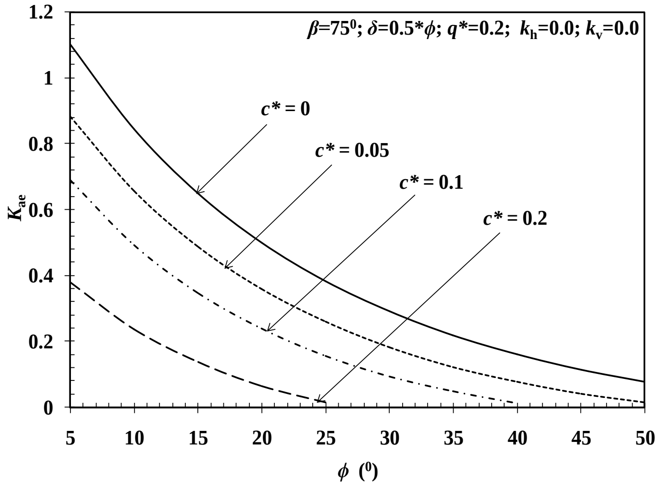
The effect of k_h on K_{ae} can be also quantified from Figures 2 to 5. It can be observed that the value of K_{ae} increases considerably when the value of k_h increases. On taking ϕ = 20º, c^* = 0.1, β = 75º and q^* = 0.2, the value of K_{ae} increases by about 46.2, 103.3, 177.6 and 286.3%, when k_h value increases from 0.0 to 0.1, 0.2, 0.3 and 0.4 respectively. For the respective increment of k_h the value of K_{ae} increases by about 26.2, 59.1, 102.6 and 168.3% (for vertical wall) and the percent increase in K_{ae} is 18.3, 41.8, 74.3 and 126.2 (for β = 105º). When k_h increases from 0.0 to 0.1, 0.1 to 0.2, 0.2 to 0.3 and 0.3 to 0.4, the percentage increase in the K_{ae} is about 46.2, 39.1, 36.6 and 39.2% (β = 75º) for ϕ = 20º, c^* = 0.1, and q^* = 0.2. The percentage increase in K_{ae} for the respective increment in k_h is 26.2, 25.9, 27.4 and 32.4 (for β = 90º) and 18.3, 19.9, 22.9 and 29.7 (for β = 105º). The value of K_{ae} increases for the same horizontal seismic coefficient in all three inclination angles (β = 75º, 90º and 105º) of retaining wall. While the successive percentage increment in K_{ae} reduces with respect to increase in wall inclination angle. From this we can easily say that the percentage increment is reducing with wall inclination angle.

3.3 EFFECT OF WALL INCLINATION DUE TO k_v ON K_{ae}

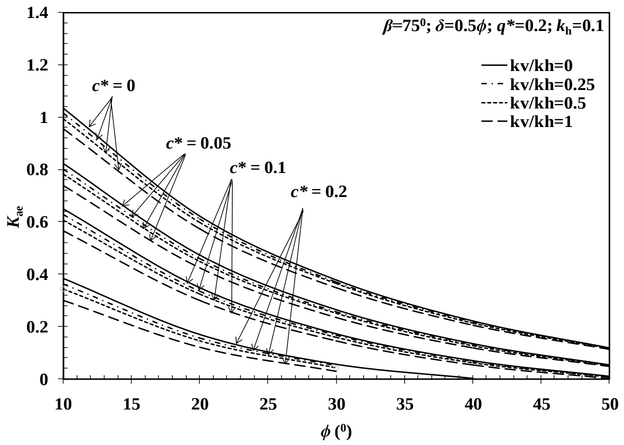
The effect of k_v on K_{ae} can be also quantified from Figures 2 to 5. It can be observed that the value of the K_{ae} increases marginally when the value of k_v increases. For example at $\beta = 75^o$, $\phi = 30^o$, $c^* = 0.0$, $q^* = 0.2$ and $k_h = 0.1$, on increasing the k_v from 0 to $0.25k_h$, $0.25k_h$ to $0.5\ k_h$ and $0.5\ k_h$ to k_h the respective values of K_{ae} decrease by 1.86, 1.88 and 3.83% respectively. On increasing the value of k_h from 0.1 to 0.3 for the respective increment of k_v, the increase in K_{ae} is 1.41, 0.82 and 1.93%. For the vertical wall at $\phi = 30^o$, $c^* = 0.0$, $q^* = 0.2$ and $k_h = 0.1$, on increasing k_v from 0 to $0.25k_h$, $0.25k_h$ to $0.5\ k_h$ and $0.5\ k_h$ to k_h, K_{ae} decreases by 2.0, 2.03 and 4.13% respectively. The respective percentage increase in K_{ae} is 2.1, 2.5 and 4.31 for $\beta = 105^o$. From the example, it is clearly observed that for all wall inclination (β = 75º, 90º and 105º) of retaining wall, the value of K_{ae} is reducing but the rate of reduction is very marginal.

3.4 EFFECT OF SURCHARGE ON K_{ae}

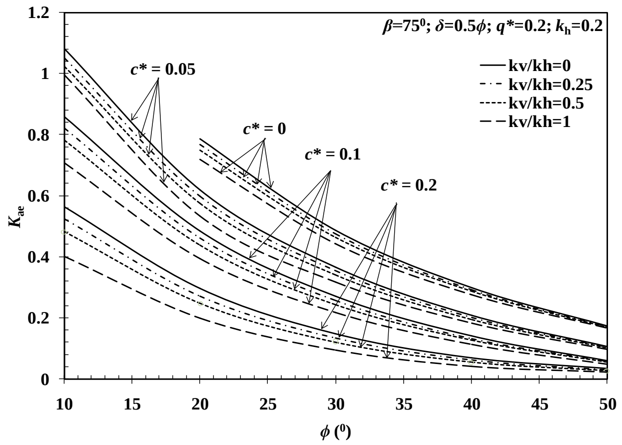
The effect of surcharge on the value of K_{ae} can be clearly noticed from Figures 4 and 5. From the developed design charts, it can be determined that the increment of surcharge affects the considerable increase on K_{ae}. For example, on increasing the value of k_h from 0.0 to 0.4 at $\beta = 105^o$, $\phi = 30^o$, and $c^* = 0.0$, when q^* increases from 0 to 0.2, an increment is of 40% in K_{ae}.



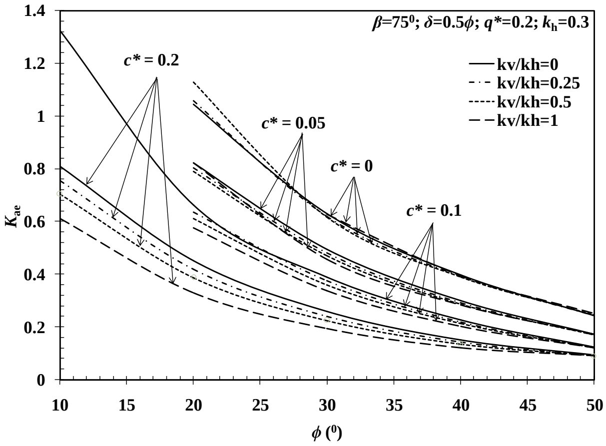
(a) $k_h = 0.0$



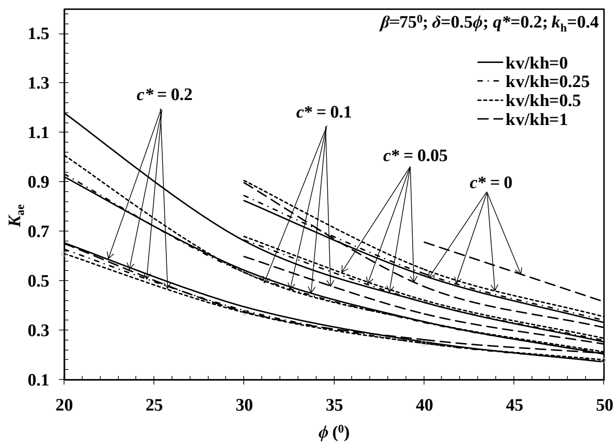
(b) $k_h = 0.1$



(c) $k_h = 0.2$

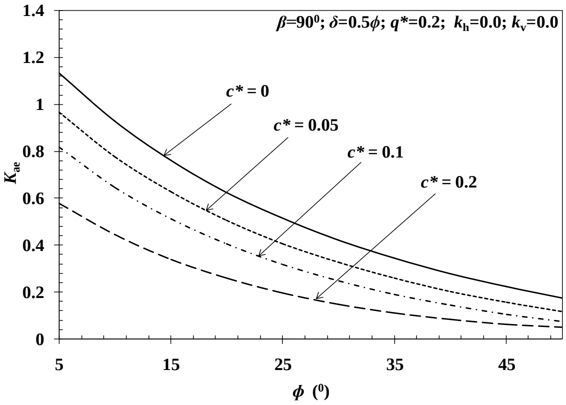


(d) k_h = 0.3

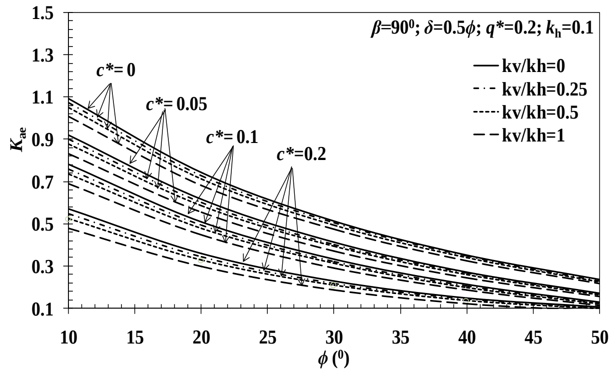


(e) k_h = 0.5

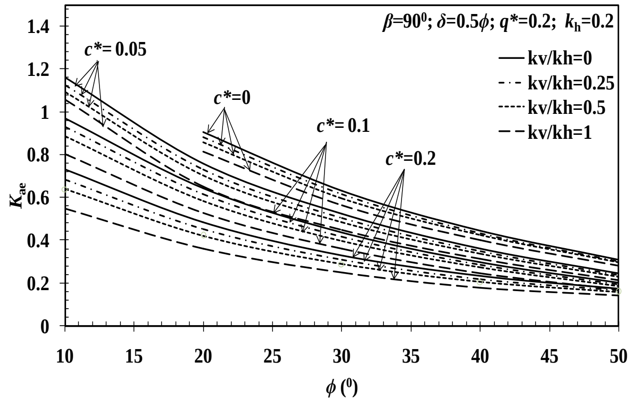
Figure 2 Design charts for K_{ae} for different values of k_h, k_v and $c*$ for wall with β = 75° and surcharge loading $q*$ = 0.2



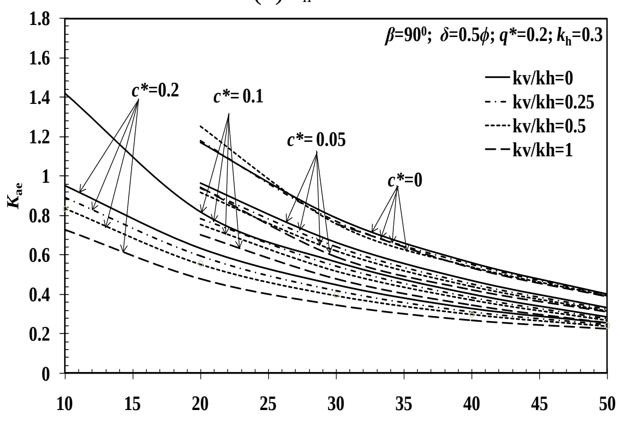
(a) k_h = 0.0



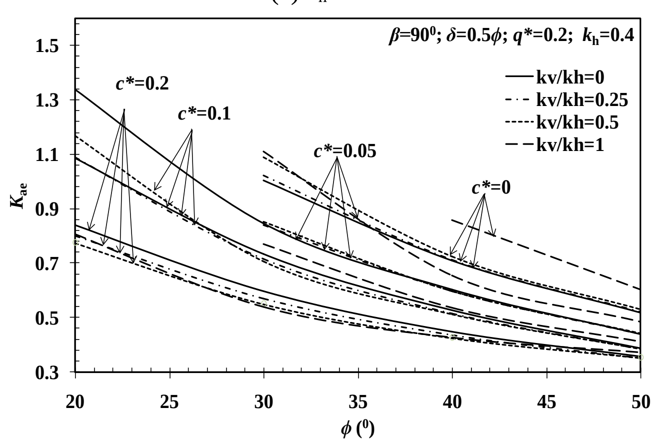
(b) k_h = 0.1



(c) k_h = 0.2

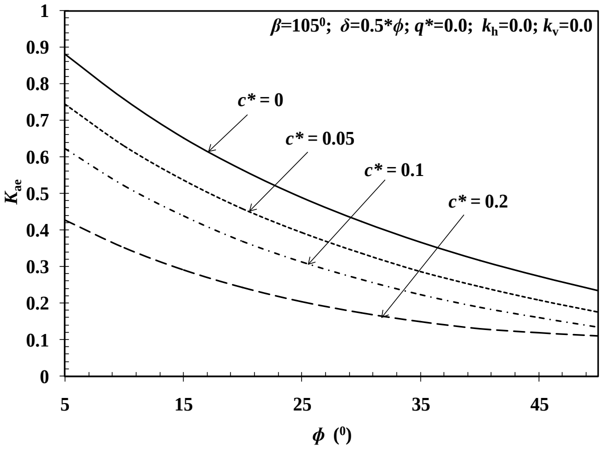


(d) k_h = 0.3

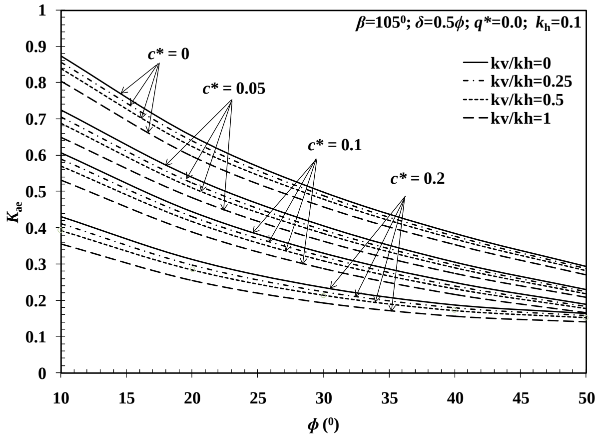


(e) k_h = 0.4

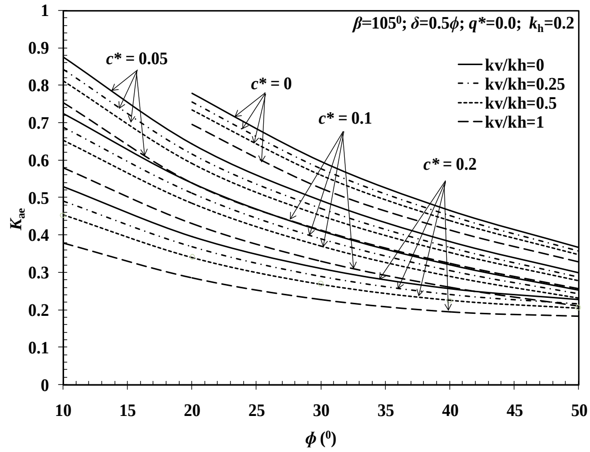
Figure 3 Design charts for K_{ae} for different values of k_h, k_v and $c*$ for vertical wall with surcharge loading $q*$ = 0.2



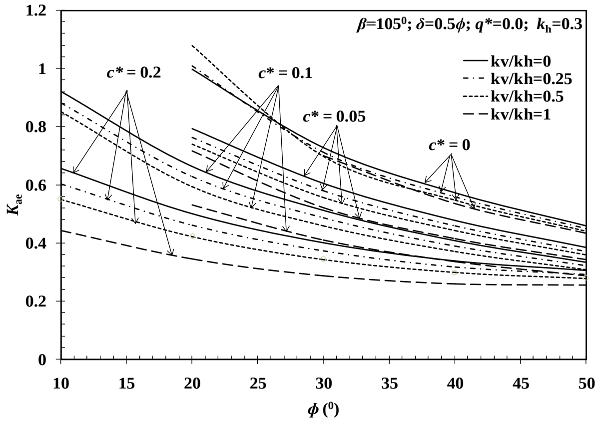
(a) k_h = 0.0



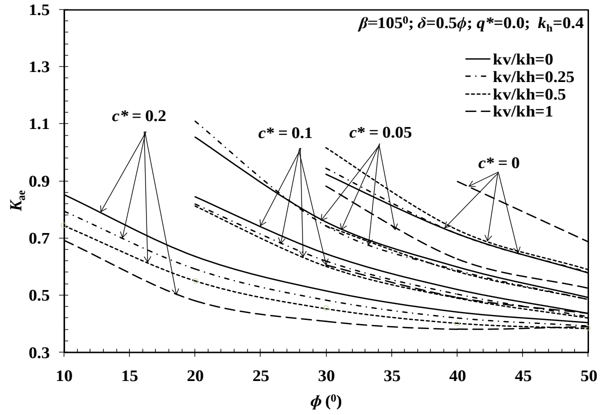
(b) k_h = 0.1



(c) k_h = 0.2

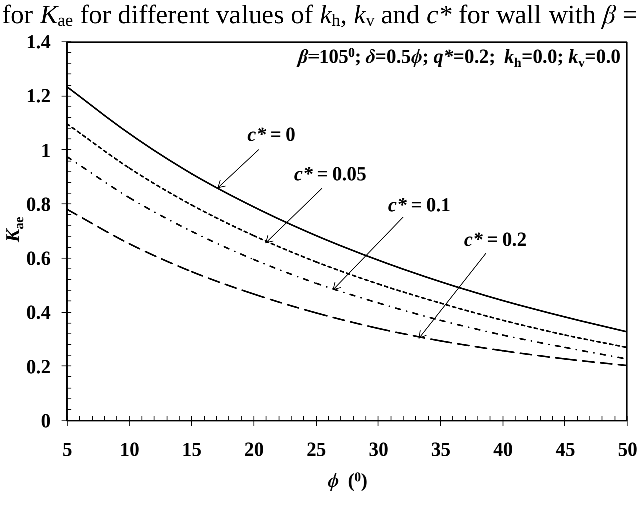


(d) k_h = 0.3

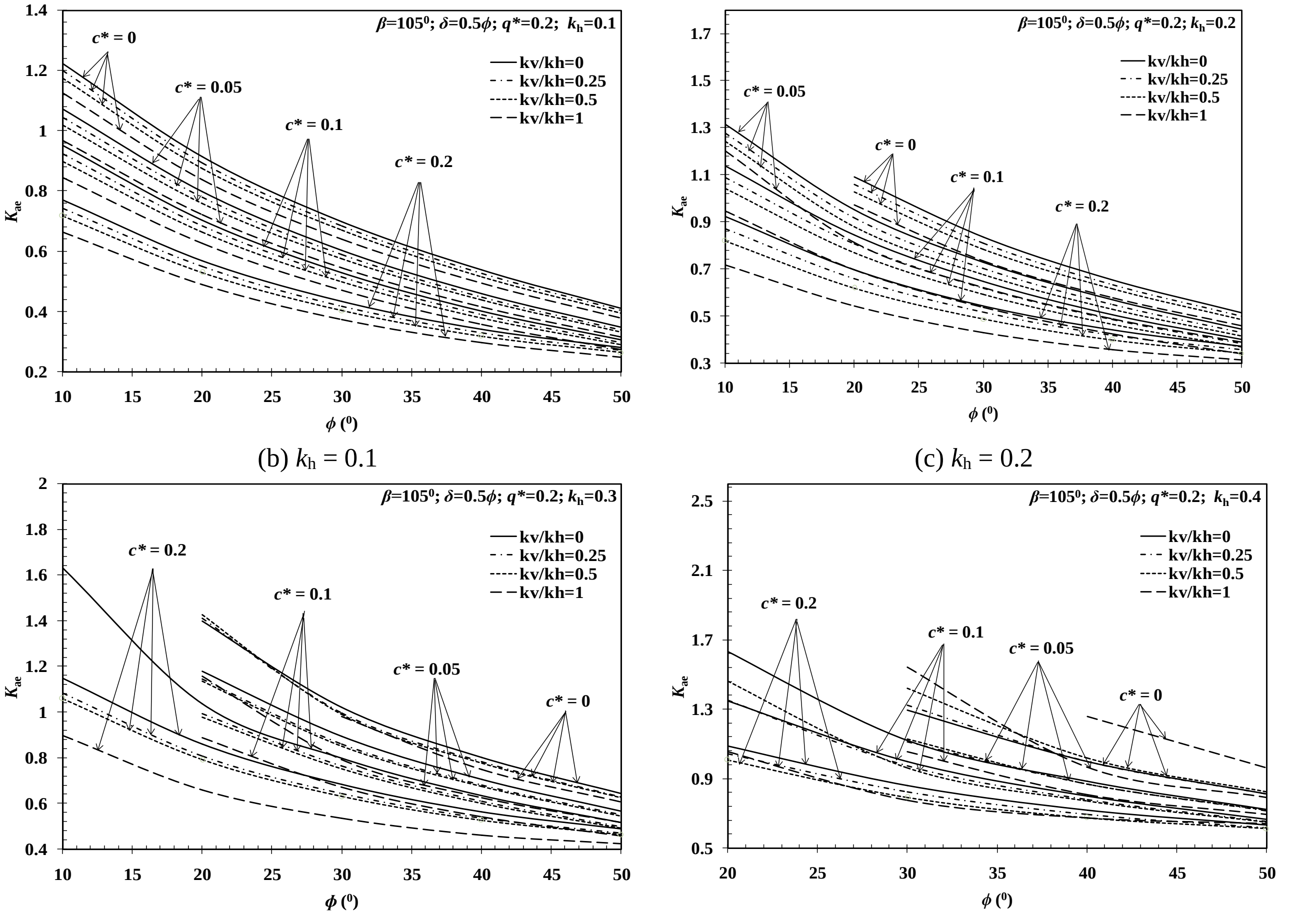


(e) k_h = 0.4

Figure 4 Design charts for K_{ae} for different values of k_h, k_v and c^* for wall with β = 105º without surcharge



(a) k_h = 0.0



(b) k_h = 0.1 (c) k_h = 0.2

(d) k_h = 0.3 (e) k_h = 0.4

Figure 5 Design charts for K_{ae} for different values of k_h, k_v and c^* for wall with β = 105º and surcharge loading q^* = 0.2

3.5 VALIDATION OF PRESENT WORK

The coefficient of seismic active earth pressure K_{ae} is compared with Mononobe and Okabe, Cheng [9], and Ghanbari and Ahmadabadi [10] in Table 2. For the given set of parameters, the values of K_{ae} show a good agreement.

Table 2 Comparison of results for calculation of active earth pressure coefficient (i = 0º; k_v = 0; c = 0; δ = (2/3)ϕ and β = 90º)

ϕ (º)	Mononobe and Okabe	Cheng [8]	Ghanbari and Ahmadabadi [9]		Present Study
			Based on Limit Equilibrium Method	Based on Horizontal Slice Method	
			k_h = 0.0		
20	0.438	0.426	0.438	0.440	0.438
25	0.361	0.346	0.361	0.362	0.361
30	0.297	0.279	0.297	0.299	0.297
			k_h = 0.05		
20	0.479	0.456	0.478	0.479	0.478
25	0.397	0.380	0.397	0.398	0.397
30	0.330	0.330	0.330	0.330	0.310
			k_h = 0.1		
20	0.525	0.511	0.526	0.526	0.525
25	0.438	0.419	0.438	0.438	0.438
30	0.366	0.344	0.366	0.366	0.366
			k_h = 0.2		
20	0.647	0.629	0.647	0.645	0.647
25	0.539	0.516	0.539	0.539	0.539
30	0.454	0.426	0.454	0.453	0.454

4.0 CONCLUSIONS

In the present work, design charts are developed to calculate the total active thrust from c-ϕ soil backfill for three different wall inclination angles from -15º to 15º (as β = 75º, β = 90º and β = 105º). The following points can be summarized:

1. The active earth pressure coefficient (K_{ae}) reduces with respect to increase in angle of shearing resistance of soil backfills and increase in cohesion (c), and irrespective of non-dimensional surcharge loading on backfills.

2. The value of K_{ae} increases marginally for negative value of wall inclination and reduces considerably for positive value of wall inclination.

3. The value of K_{ae} increases with increase in horizontal seismic coefficient (k_h), yet the percentage increment is marginally reduced with respect to the increment of k_h with the increase in wall inclination angle.

4. There is considerable increment in K_{ae} as wall inclination angle (β) increases from 75º to 105º, while percentage increment substantially reduces as the increment in the value of horizontal seismic coefficient (k_h) increases.

5. The value of K_{ae} increases marginally with increase in k_v. The rate of percentage increase is also very slow.

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