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TECHNICAL NOTE

Seismic Active Earth Pressure Coefficients on Battered Retaining Wall Supporting Inclined c – ϕ Backfill

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ABSTRACT: This paper provides an analytical solution for total active force on the retaining wall backfilled by c – Φ soil considering both horizontal and vertical seismic coefficients. The effect of tension crack is also taken into account. The results are presented in tabular form so that one can easily determine the seismic active earth pressure.

KEYWORDS: c – ϕ backfill, seismic loads, active force, pseudo-static, cracked zone

Introduction

The estimation of active earth pressure on retaining wall due to backfill soil is an essential feature. Mononobe – Okabe analysis (Okabe 1926; Mononobe 1929) has provided the solution for dynamic active earth pressure considering that the retaining wall is backfilled only by ϕ soil. They extended the Coulomb's wedge theory to find out the seismic active earth pressure by introducing seismic acceleration as inertia forces. Seed and Whitman (1970) also provided the solution for seismic active earth pressure considering the friction nature of backfill.

The very recent analysis is given by Shukla et al (2009), which is an extension of Rankine (1857). Further analyses to evaluate the seismic active earth force on retaining wall supporting c – ϕ backfill were done by Saran and Prakash (1968), Saran and Gupta (2003), Ghosh and Saran (2007) and Ghosh, et. al. (2008). In their analytical approach, pressure due to weight, surcharge and cohesion are optimized separately and large number of charts are provided. Applicability of those analyses is further restricted due to the fact that the analyses (which were made for c – ϕ soil) are applicable only for $\delta = 2\phi/3$ and $\alpha_v = \alpha_h/2$.

In this paper, a further extension of all the above said works is done to evaluate the seismic active earth pressure for any value of angle of wall friction upto 2/3rd of angle of internal friction of soil and for all possible combinations of vertical and horizontal seismic coefficients considering maximum value of horizontal seismic coefficient as 0.40.

The results are given in tabular form and for intermediate portion a linear interpolation is suggested. The inclination of failure surface is also mentioned in the Tables that one can get the idea about the wedge surface at failure.

Analysis

Forces Acting on Retaining Wall - Soil Wedge System during Active State of Equilibrium

Let us consider a retaining wall is inclined at an angle 'α' with the vertical retains a backfill of height 'H', angle of internal friction 'ϕ', cohesion c and unit weight 'γ', the top surface of which is inclined at an angle 'i' with the horizontal. On the top of the backfill a surcharge load of intensity 'q' per sqm is acting. At any time during active state of equilibrium if 'θ' is the wedge angle then Figure1 shows the forces acting on the retaining wall – soil wedge system. In the assumed model, the weight of the tension crack zone (height H_0) is considered to act along with the weight of the surcharge and cohesive and adhesive resistance in the tension crack zone is neglected.

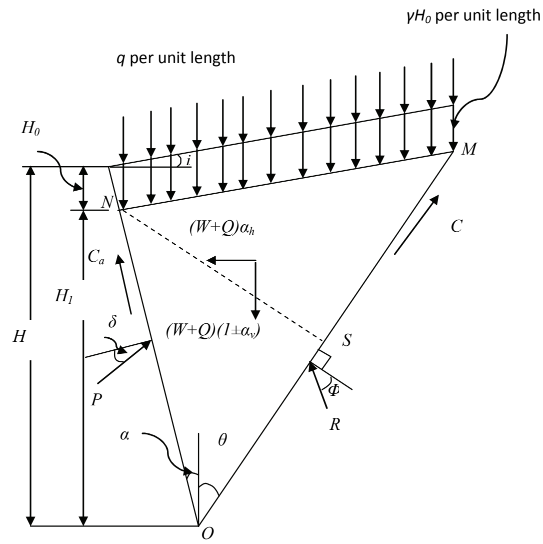

Fig. 1 Forces Acting on Retaining wall – Soil Mass System during Active State of Equilibrium

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'P' is the force acting on retaining wall at an angle 'δ' to the normal of the wall and '*R*' is the reaction due to retained soil on the sliding soil whereas '*W*' and '*Q*' are the weight due to wedge soil and surcharge respectively. '*C*' is the cohesive force acting on the wedge surface and 'C_a' is the adhesive force acting on the wall surface.

Derivation of Formulations during Active State of Equilibrium

Geometrical Parameters and Various Force Components

Depth of the tension crack zone = $H_0 = \frac{2c}{\gamma}\sqrt{N_\phi}$ (1)

where

$$N_\phi = \frac{1+\sin\phi}{1\sin\phi} \quad (2)$$

So, $H_1 = H - H_0$ (3)

For sliding triangular wedge OMN,

<ONM = 90°- α + i = a, <NOM = α +θ = b, <NMO = 90° - i – θ = d

$$OM = H_1\frac{\sec\alpha}{\sin d}\sin a \quad (4)$$

$$NM = H_1\frac{\sec\alpha}{\sin d}\sin b \quad (5)$$

SN (to OM) = $H_1\sec\alpha\sin b$ (6)

$$W = \frac{1}{2}\gamma\ .SN\ .OM = \frac{1}{2}\gamma H_1^2\ sec^2\alpha\sin a\frac{\sin b}{\sin d} \quad (7)$$

$$Q = (q+\gamma H_0)H_1\frac{\sec\alpha}{\sin d}\sin d \quad (8)$$

$(W+Q)\alpha_h$ and $(W+Q)(1\pm\alpha_v)$ are horizontal and vertical inertia forces due to earthquake where α_h and α_v are horizontal and vertical seismic coefficients.

$$OM = H_1\frac{\sec\theta}{\sin d}\sin a \quad \text{and} \quad ON = H_1\sec\alpha \quad (9)$$

$$C = cH_1\frac{\sec\theta}{\sin d}\sin a \quad \text{and} \quad C_a = c_a H_1\sec\alpha \quad (10)$$

Application of Equilibrium Conditions and Evaluation of Active Force

Applying the force equilibrium conditions ∑H = 0, ∑V = 0

$$C_a\cos\alpha + C\cos\theta + R\sin(\phi+\theta) + P\sin(\alpha+\delta) - (W+Q)(1\pm\alpha_v) = 0 \quad (11)$$

$$-C_a\sin\alpha + C\sin\theta - R\cos(\phi+\theta) + P\cos(\alpha+\delta) - (W+Q)\alpha_h = 0 \quad (12)$$

On solving of Eqns. (11) and (12), substituting the values of C, Ca, W, Q (as calculated above) and assuming ***c*** **=** ***c$_a$***, we get

$$P = \frac{\gamma H_1^2}{2}\left[\frac{\sin(\alpha+\theta)\cos(\alpha-i)}{cos^2\alpha\cos(\theta+i)}\frac{(1\pm\alpha_v)\cos(\varnothing+\theta)+\alpha_h\sin(\varnothing+\theta)}{\sin(\alpha+\delta+\varnothing+\theta)}\right]$$
$$+(q+\gamma H_0)H_1\frac{\cos\alpha}{\cos(\alpha-i)}\times$$
$$\left[\frac{\sin(\alpha+\theta)\cos(\alpha-i)}{cos^2\alpha\cos(\theta+i)}\frac{(1\pm\alpha_v)\cos(\phi+\theta)+\alpha_h\sin(\phi+\theta)}{\sin(\alpha+\delta+\phi+\theta)}\right]$$
$$-cH_1\frac{\left[\frac{\cos(\alpha+\phi+\theta)}{\cos\alpha}+\frac{\cos(\alpha-i)\cos\phi}{\cos\alpha\cos(i+\theta)}\right]}{\sin(\alpha+\delta+\phi+\theta)} \quad (13)$$

$$P = \frac{\gamma H_1^2}{2}(1\pm\alpha_v)K_\gamma + (q+\gamma H_0)H_1\frac{\cos\alpha}{\cos(\alpha-i)}(1\pm\alpha_v)K_\gamma - cH_1K_c \quad (14)$$

$$K_\gamma = \left[\begin{array}{c}\frac{\sin(\alpha+\theta)\cos(\alpha-i)}{cos^2\alpha\cos(\theta+i)}\text{x}\\ \frac{\cos(\phi+\theta)+\frac{\alpha_h}{(1\pm\alpha_v)}\sin(\phi+\theta)}{\sin(\alpha+\delta+\phi+\theta)}\end{array}\right] \quad (15)$$

$$K_c = \frac{\left[\frac{\cos(\alpha+\phi+\theta)}{\cos\alpha}+\frac{\cos(\alpha-i)\cos\phi}{\cos\alpha\cos(i+\theta)}\right]}{\sin(\alpha+\delta+\phi+\theta)} \quad (16)$$

On scrutiny of the Eqn.(13), it can be concluded that the seismic component of the earth pressure does not depend on the cohesion of the supported backfill and the cohesion of the soil has always a tendency to reduce the earth pressure on the retaining wall.

On review of the Eqns (13), (15) and (16), it can be seen that for a particular retaining wall backfill system, all the terms are constant except *θ*. Thus, for different values of *θ* one will get different values of the respective earth pressure coefficients. To evaluate the seismic active earth pressure, one has to consider maximum value of K_γ but minimum value of K_c satisfying the conditions, $\frac{dK_\gamma}{d\theta} = 0\,and\,\frac{dK_c}{d\theta} = 0$. These maximum value of Kγ and minimum value of K_c are designated as $K_{a\gamma}$ and K_{ac}. Thus, for seismic active earth pressure, the Eqn 14 becomes

$$P_{act} = \frac{\gamma H_1^2}{2}(1\pm\alpha_v)K_{a\gamma} + (q+\gamma H_0)H_1\frac{\cos\alpha}{\cos(\alpha-i)}(1\pm\alpha_v)K_{a\gamma} - cH_1K_{ac} \quad (19)$$

$$P_{act} = P_{a\gamma} + P_{aq} - P_{ac} \quad (20)$$

where

$$P_{a\gamma} = \frac{\gamma H_1^2}{2}(1 \pm \alpha_v) K_{a\gamma} \quad (21)$$

$$P_{aq} = (q + \gamma H_0) H_1 \frac{\cos\alpha}{\cos(\alpha - i)}(1 \pm \alpha_v) K_{a\gamma} \quad (22)$$

$$P_{ac} = c H_1 K_{ac} \quad (23)$$

Steps of Analysis for Dynamic Active Earth Pressure

Dynamic active earth pressure under seismic loading condition supporting c – ϕ backfill can be calculated using the following steps. All the forces along with their point of applications are shown in Figure 2.

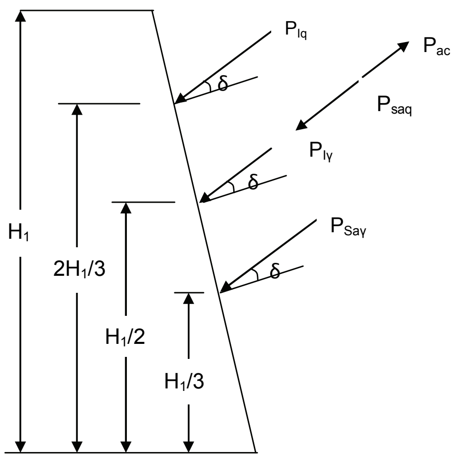

Fig. 2 Presentation of All the Forces Along with Their Point of Applications

1. Calculate the depth of tension crack (H_0) using the Eqn.1 and hence $H_1 = H – H_0$, where H is the total height of retaining wall.
2. Find out the seismic active earth pressure coefficient $K_{a\gamma}$ from the tables 2 to 8 and then calculate seismic active force due to unit weight, $P_{a\gamma}$ using Eqn 21.
3. Find out the static active earth pressure coefficient K_{as}, for $\alpha_h = \alpha_v = 0$ and then calculate the static active force due to unit weight, $P_{sa\gamma}$ using Eqn 21 and apply it at a height of $H_1/3$ above the base.
4. Find out the dynamic increment due to unit weight, $P_{I\gamma} = P_{a\gamma} - P_{sa\gamma}$ and apply it at a height of $H_1/2$ above the base.
5. Using the Eqn (22) and substituting the magnitude of $K_{a\gamma}$, find out the seismic active earth force due to surcharge and cracked zone.
6. Similarly, using the same value of K_{as} as found out in step (iii) in the Eqn (22), find out the static active force due to surcharge and cracked zone (P_{saq}) and apply it at a height of $H_1/2$ above the base.
7. Find out the dynamic increment due to surcharge and cracked zone, $P_{Iq} = P_{aq} - P_{saq}$ and apply it at a height of $2H_1/3$ above the base.
8. Find out the static active earth pressure coefficient due to cohesion (K_{ac}) from Table 1 and substituting this value of K_{ac} in Eqn (23) evaluate the static active earth pressure due to cohesion (P_{ac}) and apply it at a height of $H_1/2$ above the base.

Conclusions

The general conclusions of the present study are summarized as follows:

1. The present study provides an analytical expression for the total active force on the retaining wall supporting c – Φ backfill considering both horizontal and vertical seismic coefficients based on Coulomb's sliding wedge mechanism of total force equilibrium.
2. For a particular retaining wall backfill system, due to the increase of seismic acceleration and increase in backfill surface inclination i, the coefficients of seismic active earth pressure due to unit weight $K_{a\gamma}$ and corresponding critical wedge angle θ increases, which indicate higher value of active force and participation of more soil mass in vibration.
3. The coefficients of seismic active force, $K_{a\gamma}$ increases due to the increase of wall inclination but the critical wedge angle in that particular situation is going to be reduced. This may be due to the fact that positive inclination of the wall itself incorporates more participation of soil mass during active state of equilibrium. The active earth pressure coefficient due to cohesion (K_{ac}) is going to be reduced in that particular situation.
4. There is very little change both in seismic active earth pressure coefficients ($K_{a\gamma}$ and K_{ac}) and corresponding critical wedge angle due to the change in angle of wall friction but there is a considerable decrease in seismic active earth pressure coefficients ($K_{a\gamma}$ and K_{ac}) and critical wedge angle due to the increase in angle of internal friction of soil.

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Table 1 List of Active Earth Pressure Coefficients due to Cohesion K_{ac}

i	ϕ	δ = 0			δ = ϕ/3			δ = 2ϕ/3		
		α = -20	α = 0	α = 20	α = -20	α = 0	α = 20	α = -20	α = 0	α = 20
i = 0	0	4.36	2.83	2.04	4.36	2.83	2.04	4.36	2.83	2.04
	10	3.46	2.34	1.73	3.29	2.27	1.70	3.14	2.21	1.69
	20	2.74	1.92	1.43	2.55	1.84	1.41	2.40	1.79	1.41
	30	2.16	1.53	1.13	2.00	1.49	1.15	1.90	1.47	1.19
	40	1.65	1.18	0.83	1.56	1.18	0.89	1.53	1.22	0.99
	50	1.20	0.83	0.50	1.18	0.88	0.59	1.24	0.99	0.76
i =10	0	5.32	3.40	2.49	5.32	3.40	2.49	5.32	3.40	2.49
	10	4.07	2.76	2.09	3.83	2.66	2.05	3.62	2.56	2.02
	20	3.15	2.23	1.73	2.87	2.11	1.69	2.66	2.02	1.66
	30	2.44	1.78	1.38	2.21	1.68	1.37	2.05	1.63	1.39
	40	1.85	1.37	1.04	1.70	1.33	1.08	1.63	1.34	1.15
	50	1.35	0.98	0.70	1.29	1.00	0.78	1.30	1.09	0.93
i =20	0	6.61	4.10	3.00	6.61	4.10	3.01	6.61	4.10	3.01
	10	4.82	3.25	2.49	4.47	3.09	2.42	4.16	2.96	2.35
	20	3.62	2.58	2.04	3.22	2.40	1.96	2.92	2.26	1.90
	30	2.74	2.03	1.63	2.41	1.88	1.58	2.19	1.78	1.57
	40	2.05	1.55	1.25	1.83	1.47	1.25	1.70	1.44	1.30
	50	1.50	1.13	0.88	1.38	1.11	0.93	1.35	1.16	1.05

Table 2 List of Active Earth Pressure Coefficients due to Weight $K_{a\gamma}$ for α_h =0 α_v=0

i	ϕ	δ = 0			δ = ϕ/3			δ =2ϕ/3		
		α = -20	α = 0	α = 20	α = -20	α = 0	α = 20	α = -20	α = 0	α = 20
i = 0	1	1.01	0.97	1.04	1.00	0.96	1.03	1.00	0.96	1.03
	10	0.64	0.70	0.83	0.60	0.67	0.81	0.57	0.65	0.79
	20	0.38	0.49	0.65	0.34	0.46	0.62	0.32	0.44	0.61
	30	0.21	0.33	0.50	0.19	0.31	0.48	0.17	0.30	0.48
	40	0.11	0.22	0.38	0.09	0.20	0.37	0.09	0.20	0.38
	50	0.04	0.13	0.27	0.04	0.13	0.27	0.04	0.13	0.30
i =10	11	0.78	0.86	1.05	0.75	0.85	1.05	0.73	0.84	1.07
	20	0.44	0.57	0.77	0.40	0.54	0.75	0.38	0.52	0.75
	30	0.23	0.37	0.57	0.21	0.35	0.56	0.19	0.34	0.57
	40	0.11	0.24	0.42	0.10	0.22	0.42	0.10	0.22	0.44
	50	0.04	0.14	0.30	0.04	0.13	0.30	0.04	0.14	0.34
i =20	21	0.57	0.75	1.03	0.54	0.73	1.06	0.52	0.74	1.11
	30	0.27	0.44	0.69	0.25	0.42	0.69	0.23	0.41	0.71
	40	0.13	0.27	0.48	0.11	0.25	0.48	0.11	0.25	0.52
	50	0.05	0.15	0.34	0.04	0.15	0.34	0.04	0.15	0.39

Table 3 List of Active Earth Pressure Coefficients due to Weight $K_{a\gamma}$ for α_h =0.2 α_v=0

i	ϕ	δ = 0			δ = ϕ/3			δ =2ϕ/3		
		α = -20	α = 0	α = 20	α = -20	α = 0	α = 20	α = -20	α = 0	α = 20
i = 0	12	0.92	0.94	1.08	0.90	0.94	1.11	0.89	0.95	1.15
	20	0.59	0.67	0.83	0.55	0.65	0.83	0.53	0.65	0.85
	30	0.36	0.47	0.65	0.33	0.45	0.65	0.30	0.45	0.68
	40	0.21	0.33	0.50	0.19	0.32	0.51	0.18	0.33	0.57
	50	0.11	0.22	0.39	0.10	0.22	0.41	0.10	0.23	0.48
i =10	22	0.75	0.88	1.14	0.73	0.89	1.22	0.72	0.92	1.33
	30	0.42	0.57	0.80	0.40	0.56	0.83	0.38	0.57	0.90
	40	0.23	0.37	0.59	0.21	0.37	0.62	0.21	0.38	0.69
	50	0.12	0.24	0.44	0.11	0.24	0.47	0.11	0.26	0.57
i =20	32	0.56	0.78	1.15	0.55	0.80	1.27	0.55	0.86	1.50
	40	0.28	0.46	0.74	0.26	0.46	0.80	0.26	0.49	0.93
	50	0.13	0.28	0.51	0.12	0.28	0.56	0.12	0.31	0.70

Table 4 List of Active Earth Pressure Coefficients due to Weight $K_{a\gamma}$ for α_h =0.4 α_v=0

i	ϕ	δ = 0			δ = ϕ/3			δ =2ϕ/3		
		α = -20	α = 0	α = 20	α = -20	α = 0	α = 20	α = -20	α = 0	α = 20
i =0	22	1.00	1.08	1.33	1.00	1.13	1.49	1.02	1.22	1.73
	30	0.58	0.70	0.90	0.56	0.70	0.97	0.56	0.74	1.10
	40	0.35	0.49	0.69	0.34	0.49	0.75	0.34	0.53	0.91
	50	0.21	0.34	0.54	0.20	0.35	0.61	0.21	0.40	0.81
i =10	32	0.84	1.03	1.44	0.84	1.12	1.73	0.88	1.27	2.26
	40	0.43	0.60	0.89	0.42	0.63	1.01	0.43	0.70	1.29
	50	0.23	0.39	0.65	0.23	0.41	0.75	0.24	0.48	1.05
i=20	42	0.64	0.93	1.47	0.66	1.04	1.90	0.72	1.28	2.95
	50	0.29	0.49	0.84	0.28	0.53	1.02	0.30	0.64	1.53

Table 5 List of Active Earth Pressure Coefficients due to weight $K_{a\gamma}$ for α_h =0.2 α_v=0.1

i	ϕ	δ = 0			δ = ϕ/3			δ =2ϕ/3		
		α = -20	α = 0	α = 20	α = -20	α = 0	α = 20	α = -20	α = 0	α = 20
i = 0	11	1.02	1.03	1.18	1.00	1.03	1.20	0.98	1.04	1.24
	20	0.62	0.72	0.88	0.58	0.69	0.88	0.55	0.68	0.90
	30	0.37	0.5	0.69	0.34	0.48	0.69	0.33	0.48	0.72
	40	0.21	0.35	0.54	0.19	0.33	0.55	0.19	0.34	0.60
	50	0.11	0.23	0.41	0.10	0.23	0.43	0.10	0.24	0.51
i =10	21	0.83	0.96	1.24	0.80	0.97	1.32	0.79	1.00	1.43
	30	0.44	0.60	0.85	0.41	0.59	0.87	0.40	0.59	0.94
	40	0.24	0.40	0.63	0.22	0.38	0.65	0.21	0.40	0.73
	50	0.12	0.25	0.47	0.11	0.25	0.50	0.11	0.27	0.60
i =20	31	0.62	0.85	1.25	0.60	0.87	1.37	0.60	0.93	0.59
	40	0.28	0.48	0.78	0.26	0.47	0.83	0.26	0.50	0.96
	50	0.13	0.29	0.54	0.12	0.29	0.59	0.12	0.32	0.72

Table 6 List of Active Earth Pressure Coefficients due to weight $K_{a\gamma}$ for α_h =0.2 α_v=0.2

i	ϕ	δ = 0			δ = ϕ/3			δ =2ϕ/3		
		α = -20	α = 0	α = 20	α = -20	α = 0	α = 20	α = -20	α = 0	α = 20
i = 0	10	1.13	1.14	1.29	1.11	1.14	1.32	1.09	1.14	1.35
	20	0.65	0.76	0.94	0.61	0.73	0.94	0.58	0.72	0.96
	30	0.39	0.54	0.74	0.36	0.51	0.74	0.34	0.51	0.77
	40	0.22	0.37	0.57	0.20	0.35	0.58	0.20	0.36	0.63
	50	0.11	0.24	0.44	0.10	0.24	0.46	0.10	0.26	0.53
i =10	20	0.92	1.07	1.37	0.9	1.08	1.44	0.88	1.10	1.55
	30	0.46	0.63	0.90	0.43	0.62	0.92	0.41	0.62	0.98
	40	0.25	0.42	0.67	0.23	0.40	0.69	0.22	0.42	0.77
	50	0.12	0.27	0.50	0.11	0.26	0.52	0.11	0.28	0.62
i =20	30	0.70	0.94	1.37	0.67	0.97	1.51	0.67	1.03	1.74
	40	0.29	0.50	0.82	0.27	0.49	0.87	0.27	0.52	1.00
	50	0.13	0.3	0.57	0.12	0.30	0.62	0.13	0.33	0.75

Table 7 List of Active Earth Pressure Coefficients due to weight $K_{a\gamma}$ for α_h =0.4 α_v=0.2

i	ϕ	δ = 0			δ = ϕ/3			δ =2ϕ/3		
		α = -20	α = 0	α = 20	α = -20	α = 0	α = 20	α = -20	α = 0	α = 20
i = 0	20	1.03	1.10	1.33	1.00	1.12	1.42	1.0	1.16	1.55
	30	0.59	0.73	0.95	0.56	0.72	1.00	0.55	0.74	1.10
	40	0.36	0.51	0.74	0.33	0.51	0.79	0.33	0.54	0.92
	50	0.20	0.36	0.58	0.19	0.36	0.64	0.20	0.40	0.81
i =10	30	0.82	1.02	1.39	0.81	1.06	1.56	0.82	1.14	1.86
	40	0.42	0.61	0.92	0.40	0.62	1.01	0.40	0.68	1.22
	50	0.22	0.40	0.68	0.21	0.41	0.76	0.22	0.47	1.01
i =20	40	0.36	0.51	0.74	0.60	0.95	1.64	0.63	1.09	2.20
	50	0.20	0.36	0.58	0.26	0.51	0.98	0.27	0.59	1.36

Table 8 List of Active Earth Pressure Coefficients due to weight $K_{a\gamma}$ for α_h =0.4 α_v=0.4

i	ϕ	δ = 0			δ = ϕ/3			δ =2ϕ/3		
		α = -20	α = 0	α = 20	α = -20	α = 0	α = 20	α = -20	α = 0	α = 20
I = 0	16	1.41	1.47	1.74	1.4	1.51	1.86	1.41	1.56	2.02
	20	1.02	1.12	1.36	0.98	1.12	1.41	0.96	1.13	1.49
	30	0.61	0.78	1.03	0.57	0.76	1.06	0.56	0.77	1.15
	40	0.37	0.55	0.81	0.34	0.54	0.84	0.34	0.56	0.96
	50	0.20	0.37	0.63	0.19	0.37	0.67	0.2	0.41	0.83
I =10	26	1.01	1.22	1.64	0.98	1.26	1.80	1.20	1.60	2.51
	30	0.79	1.00	1.38	0.75	1.01	1.48	0.75	1.07	1.69
	40	0.42	0.64	0.97	0.40	0.64	1.05	0.40	0.68	1.23
	50	0.22	0.42	0.72	0.21	0.42	0.80	0.22	0.48	1.02
I =20	36	0.75	1.07	1.63	0.74	1.13	1.89	0.96	1.57	2.40
	40	0.55	0.84	1.32	0.53	0.87	1.50	0.54	0.97	1.88
	50	0.26	0.49	0.88	0.24	0.51	0.99	0.25	0.58	1.32