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Pseudo-dynamic Passive Earth Pressure Coefficients supporting c-Φ Backfill using Composite Failure Mechanism

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Abstract—**Knowledge of seismic passive earth pressures behind rigid retaining wall is very important. In this paper, the pseudo-dynamic approach, which considers the effect of primary and shear wave propagations, is adopted to calculate the seismic passive resistance of gravity retaining wall supporting c-Φ backfill. Considering the composite (combination of log-spiral and planar) failure mechanism, the effect of wall friction and soil friction angle, soil cohesion, shear wave and primary wave velocity, horizontal and vertical seismic coefficients are taken into account to evaluate the seismic passive resistance. Results as obtained from present analysis are compared with those given by other authors. It is shown that the pseudo-static methods considering planar rupture surface overestimates the passive earth pressure coefficients.**

Keywords— **Pseudo-dynamic, seismic, passive resistance, composite rupture surface, c-Φ backfill, gravity retaining wall.**

I. Introduction

Study of seismic passive resistance is essential for the safe design of retaining wall in the seismic zone. Many researchers have developed several methods to determine the seismic passive resistance of a rigid retaining wall due to earthquake loading. The pioneering works on earthquake induced lateral earth pressure under active and passive conditions acting on a retaining wall were reported by Okabe (1926) and Mononobe and Matsuo (1929). This pseudo-static approach which is the modification of Coulomb's (1776) approach, is known as Mononobe-Okabe approach and till date world-wide widely used to calculate the dynamic earth force (either active or passive) on the back of retaining wall.

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In pseudo-static approach, the dynamic loading induced by earthquake is considered as time-independent, which ultimately assumes that the magnitude and phase acceleration is uniform throughout the backfill. The phase difference due to finite shear wave propagation behind a retaining wall can be considered using a simple and more realistic pseudo-dynamic method, proposed by Steedman and Zeng (1990). Choudhury and Nimbalkar (2005) considered the case of passive earth pressure behind a retaining wall by a pseudo-dynamic method using planar rupture surface.

Terzaghi (1943) reported that planar rupture surfaces seriously overestimates the passive earth pressure for higher wall friction angles. Curved rupture surfaces results in more acceptable values of passive earth pressures. Duncan and Mokwa (2001) on the basis of experimental study concluded that the logarithmic spiral earth pressure theory provides more accurate estimates of passive resistance for higher value of angle of wall friction. For Φ backfill, using pseudo-static concept, Soubra (2000) and Kumar (2001) reported seismic passive earth pressure coefficients whereas, Basha and Babu (2008) reported seismic passive earth pressure coefficients using pseudo-dynamic concept. But, the case of pseudo-dynamic passive resistance supporting c-Φ backfill using composite failure mechanism is has not received any attention so far. Hence, in this paper, an attempt is made to evaluate the seismic passive resistance of rigid retaining wall supporting c-Φ backfill. Considering composite rupture surface, pseudo-dynamic method has been introduced for this particular study.

II. Method of analysis

A rigid, vertical, cantilever retaining wall of height H is placed with a dry c-Φ backfill the top surface of which is horizontal as shown in Fig.1. The objective is to determine the passive earth pressure coefficients considering the rupture surface as composite rupture surface in the presence of both horizontal and vertical seismic earthquake accelerations $k_h g$ and $k_v g$, where g is the acceleration due to gravity.

A. *Composite failure mechanism*

The pseudo-dynamic analysis, which considers a finite shear wave velocity, can be developed by assuming that the shear modulus G is constant with the depth through the backfill and the phase and not the magnitude of acceleration varies. In the present study, both shear wave velocity, $V_s = \left(\frac{G}{\rho}\right)^{\frac{1}{2}}$ and primary wave velocity, $V_p = \left(\frac{G(2-2\upsilon)}{\rho(1-2\upsilon)}\right)^{\frac{1}{2}}$ where ρ and ν are the density and Poisson's ratio of the backfill medium are assumed to act within the soil media due to earthquake loading. As the primary wave and shear wave approaches the ground surface, the vibrations are also amplified. The amplified motions within the backfill soils and retaining wall may have devastating effects on retaining wall. It is assumed that the horizontal and vertical seismic accelerations in soil vary linearly from the input seismic accelerations at the base to the higher value at the top of the wall. As suggested by Terzaghi (1943), the developing failure surface can be realistically represented by a logarithmic spiral and a straight line as shown in Fig.1. Logarithmic spiral portion of the failure surface (BE) is governed by height of the retaining wall and the location of the centre of the logarithmic spiral arc O. If r_1 (= OB) is the initial radius of the log spiral, then the final radius r_0 (= OE) is given by $r_0 = r_1 e^{\theta_1 \tan\phi}$ where θ_1 is the angle subtended by the log – spiral at the centre O.

B. *Computation of inertia forces*

Choudhury and Nimbalkar (2007) assumed that both the horizontal and vertical vibration start exactly at the same time and there is no phase shift between these two vibrations. So, for a sinusoidal base shaking subjected to both horizontal and vertical earthquake accelerations with amplitude $k_h g$ and $k_v g$, the acceleration at any depth z below the ground surface and time t can be expressed as

$$a_h(z,t) = k_h g \sin\omega\left(t - \frac{H-z}{V_s}\right) \quad (1)$$

$$a_v(z,t) = k_v g \sin\omega\left(t - \frac{H-z}{V_p}\right) \quad (2)$$

The principle of superposition is assumed to be valid.

So, horizontal inertia force acting on the part of logarithmic spiral wedge ABE is given by,

$$Q_{h\_ABE} = Q_{h\_ADE} + Q_{h\_BDE} \quad (3)$$

The total vertical inertia force acting on the part of logarithmic spiral wedge ABE is given by,

$$Q_{v\_ABE} = Q_{v\_ADE} + Q_{v\_BDE} \quad (4)$$

Where Q_{h_ADE}, Q_{v_ADE}, Q_{h_BDE}, Q_{v_BDE} are horizontal and vertical inertia forces acting on ADE and BDE respectively. These inertia forces can be calculated as follows:

From Fig.3

$$Q_{h\_ADE}(t) = \int_0^{AD} \frac{\gamma}{g} z \cot\theta_2 k_h g \sin\omega\left(t - \frac{H-z}{V_s}\right) dz \quad (5)$$

After integration, Eq. (5) is reduced to

$$\frac{Q_{h\_ADE}(t)}{0.5\gamma H^2} = 2k_h \cot\theta_2 \left[\begin{array}{l}\left(\frac{1}{2\pi}\frac{\lambda}{H}\right)^2 \{\sin 2\pi\xi_1 - \sin 2\pi\xi_2\} \\ + \left(\frac{1}{2\pi}\frac{\lambda}{H}\right)(hi)\cos 2\pi\xi_1\end{array}\right] \quad (6)$$

In Eqn (5) and (6), the terms AD, H, hi, ξ_1, ξ_2 are defined as follows:

$$AD = r_0 \sin\theta_2 \left[1 - e^{-\theta_1 \tan\phi} \frac{\cos(\theta_1 + \theta_2)}{\cos\theta_2}\right];$$

$$H = \left(\frac{\sin\theta_1}{\cos\theta_2}\right) r_1; \quad hi = \frac{AD}{H} \quad (7)$$

$$\xi_1 = \left[\frac{t}{T} - \frac{H}{\lambda}(1 - hi)\right]; \quad \xi_2 = \left[\frac{t}{T} - \frac{H}{\lambda}\right], \lambda = TV_s \quad (8)$$

The vertical inertia force acting on the wedge ADE can be written as follows:

$$Q_{v\_ADE}(t) = \int_0^{AD} \frac{\gamma}{g} z \cot\theta_2 k_v g \sin\omega\left(t - \frac{H-z}{V_p}\right) dz \quad (9)$$

Similar to the derived Eqn of horizontal inertia force, $Q_{h\_ADE}(t)$, the final Eqn for vertical inertia force, $Q_{v\_ADE}(t)$ can be obtained by replacing k_h by k_v and λ by $\eta = TV_p$ in Eqn 6.

The horizontal inertia force acting on BDE is given by,

$$Q_{h\_BDE}(t) = \int_0^{\theta_1} m(\theta) a_h(\theta, t) d\theta - Q_{h\_BJD} \quad (10)$$

Where m (θ) is mass of the elemental strip in the wedge BDE as shown in Fig.4 is

$$m(\theta) = \frac{\gamma}{g}\frac{1}{2}(r.rd\theta - xxd\theta) = \frac{\gamma}{2g}(r^2 - x^2)d\theta,$$

where

$$x = \frac{r_0 \sin\theta_2}{\sin(\theta_2 + \theta)} \tag{11}$$

a_h (θ, t) is the horizontal acceleration in the wedge BDE is given by

$$a_h(\theta,t) = k_h g \sin\omega \times \left(t - \frac{H - AD - (r - x)\sin(\theta_2 + \theta)}{V_s} \right) \tag{12}$$

Similar to the derived Eqn of horizontal inertia force, Q_{h_BDE} (t), the vertical inertia force Q_{v_BDE} (t) can be obtained by replacing k_h and V_s by k_v and V_p in Eqn 12 respectively. Both the integration for Q_{h_BDE} (t) and Q_{v_BDE} (t) are obtained in Mathematic (Wolfram Research, Inc. 2007) using Taylor series expansion for Trigonometric sine function into Taylor's series expansion.

The horizontal inertia force acting on the wedge AEF can be computed as follows:

$$Q_{h\_AEF}(t) = \int_0^{AD} z \cot\theta_2 a_h \sin\omega\left(t - \frac{H - z}{V_s} \right) dz \tag{13}$$

$$\frac{Q_{h\_AEF(t)}}{0.5\gamma H^2} = 4k_h \tan\theta_2 \times \left[\left(\frac{1}{2\pi}\frac{\lambda}{H} \right)^2 \{\sin 2\pi\xi_1 - \sin 2\pi\xi_2\} + \left(\frac{1}{2\pi}\frac{\lambda}{H} \right)(hi)\cos 2\pi\xi_1 \right] \tag{14}$$

The vertical inertia force acting on the wedge AEF can be obtained by replacing k_h and λ of Eqn 14 by k_v and η respectively.

C. Computation of weights

Weight of wedge ADE and AEF

$$W_{ADE} = \gamma \times \frac{1}{2}(AD)^2 \cot\theta_2 = \frac{W_{AEF}}{2} \tag{15}$$

Weight of wedge DBE

$$W_{DBE} = \frac{\gamma}{2}\int_0^{\theta_1} \left(r^2 - x^2\right) d\theta \tag{16}$$

where

$$x = \frac{r_0 \sin\theta_2}{\sin(\theta_2 + \theta)}$$

After simplification,

$$W_{DBE} = \frac{\gamma}{2}\left[r_1^2 \left\{ \frac{e^{2\theta_1 \tan\phi} - 1}{2\tan\phi} \right\} - r_0^2 \frac{\sin\theta_1 \sin\theta_2}{\sin(\theta_1 + \theta_2)} \right] \tag{17}$$

Computation of cohesive forces acting along the arc length

Horizontal component of the cohesive force acting along the arc BE

$$C_{h\_BE} = \int_0^{\theta_1} c r_1 e^{(\theta_1 - \theta)} \sin(\theta_1 + \theta_2 - \theta) d\theta \tag{18}$$

After simplification Eqn 18 becomes,

$$C_{h\_BE} = c r_1 \cos\phi \left\{ \cos(\phi + \theta_2) - e^{\theta_1 \tan\phi} \cos(\phi + \theta_1 + \theta_2) \right\} \tag{19}$$

Vertical component of the cohesive force acting along the arc BE

$$C_{v\_BE} = \int_0^{\theta_1} c r_1 e^{(\theta_1 - \theta)} \cos(\theta_1 + \theta_2 - \theta) d\theta \tag{20}$$

After simplification Eqn 20 becomes,

$$C_{v\_BE} = c r_1 \cos\phi \times \left\{ e^{\theta_1 \tan\phi} \sin(\phi + \theta_1 + \theta_2) - \sin(\phi + \theta_2) \right\} \tag{21}$$

E. Derivation of passive resistance

The passive earth pressure P_{pe} (t) can be obtained by resolving the forces in the horizontal and vertical directions on the two wedges ABE and AEF are explained below:

$$-Q_{h\_ABE} + R_H + N_3 \sin(\theta_2 + \phi) + C_{h\_BE} + C_{AE}\cos\theta_2 = P_{pe}(t)\cos\delta \tag{22}$$

$$R_V - P_{pe}(t)\sin\delta - C_{v\_BE} - c_a AD + C_{AE}\sin\theta_2 = N_3\cos(\theta_2 + \phi) + W_{ABE} - Q_{v\_ABE} \tag{23}$$

$$N_2 \sin(\theta_2 + \phi) - Q_{h\_AEF} = N_3 \sin(\theta_2 + \phi) \tag{24}$$

$$N_2\cos(\theta_2+\phi)+N_3\cos(\theta_2+\phi)$$
$$-2C_{AE}\sin\theta_2 = W_{AEF}-Q_{V\_AEF} \qquad (25)$$

In Eqns 22 and 23, R_H and R_V is given by

$$R_H = \int_0^{\theta_1} R\cos(\theta_1+\theta_2-\theta)d\theta =$$
$$R[\sin(\theta_1+\theta_2)-\sin\theta_2] \qquad (26)$$

$$R_V = \int_0^{\theta_1} R\sin(\theta_1+\theta_2-\theta)d\theta = \qquad (27)$$
$$R[\cos\theta_2-\cos(\theta_1+\theta_2)]$$

On simplification of Eqns. 22 to 25 considering c_a = c, the passive earth pressure is obtained as follows:

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$$P_{pe}(t)=\frac{\left\{\begin{array}{l}\left[0.5(W_{AEF}-Q_{V\_AEF})\tan(\theta_2+\phi)-0.5Q_{h\_AEF}\right]\left[\cot(\theta_2+\phi)\cot\left(\frac{\theta_1}{2}+\theta_2\right)+1\right]+\\(W_{ABE}-Q_{V\_ABE})\cot\left(\frac{\theta_1}{2}+\theta_2\right)-Q_{h\_ABE}\end{array}\right\}}{\left[\cos\delta-\sin\delta\cot\left(\frac{\theta_1}{2}+\theta_2\right)\right]}+$$
$$cH\frac{(hi)M+N-S+T}{\cos(\delta-\theta_2)-\cos(\delta-\theta_1-\theta_2)}$$

$$P_{pe}(t)=\frac{\gamma H^2}{2}k_{pw}(\theta_1,t)+cHk_{pc}(\theta_1) \qquad (28)$$

Or,
Where,

$$M=\frac{\left[\begin{array}{l}\cos\phi\cos\theta_2-\sin\theta_2\sin(\phi-\theta_2)\\-\cos\theta_1\cos(\phi+\theta_2)\end{array}\right]}{\cos(\phi+\theta_2)\sin\theta_2}$$

$$N=\left(1+e^{\theta_1\tan\phi}\right)\frac{\cos\theta_2}{\sin\theta_1}$$

$$S=\frac{\cos\theta_2\cos\phi}{\sin\theta_1}\left[e^{\theta_1\tan\phi}\cos(\phi+\theta_1)-\cos(\phi-\theta\ )\right]$$

$$T=\sin(\theta_1+\theta_2)-\sin\theta_2$$

On investigation of Eqn 28 and its related terms, it is seen that for a particular retaining wall – backfill system, all other terms except θ1, θ2, t/T, H/λ and H/η are constant. H/λ and H/η are considered 0.3 and 0.16 respectively to maintain the ratio Vp/Vs = 1.87 (Das'1998) and θ2 is considered 45-Φ/2 to fulfill the criteria of Terzaghi (1943). So, the optimization kpw (θ1, t) is done for the variation of θ1 from 0 to 90-θ2 and t/T from 0 to 1 to get kpw. kpc (θ1) is independent on t/T and therefore, optimized for the variation of θ1 from 0 to 90-θ2 to get kpc.

III. Results

The values of kpw are plotted in Fig.6, 7, 8 and 9 for different values of kh, Φ, δ/Φ with kv/kh = 0.5. The variation of kpc is shown in Fig.10 for different values of Φ and δ/Φ. From Fig. 6 to 10, it is clear that for higher values of Φ, the rate of increase of passive earth pressure coefficients is more when the δ/Φ ratio is greater than 0.5. This rate of increase will again become more when planar rupture surface is considered for analysis [Fig.12]. Therefore, Terzaghi (1943) recommended the curvilinear rupture surface for higher values of δ/Φ ratio. Fig. 11 shows that there is more or less uniform increase in the magnitude of kpw for higher values of kv/kh ratio.

Iv. Comparison

Table 1 shows the comparison of kpw values as obtained from present study with other available solutions. From this Table also, it is clear that Mononobe – Okabe theory over estimates the values of passive earth pressure coefficients especially for higher values of δ/Φ. The kpw values as calculated by Morrison and Ebeling, Chen and Lie and Soubra are also in little higher side. But the kpw values as calculated by Kumar, Subba Rao and Choudhury are almost same as obtained from present study.

v. Conclusion

Using pseudo-dynamic concept and considering combined logarithmic spiral curve and linear rupture surface, computation for seismic passive earth pressure on the back of a retaining wall supporting c-Φ backfill is done. From the analysis, it is seen that passive resistance due to cohesion is independent on seismic coefficients but increases with the increase in Φ and δ/Φ ratio. A comparison of the seismic passive earth pressure coefficients as obtained from present analysis with the earlier available analyses indicates that planar rupture surface overestimates the passive resistance. This overestimation will again become more for higher value of Φ. Results obtained from present analysis are plotted in non-dimensional graphical form and for intermediate portion a linear interpolation is suggested.

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TABLES AND FIGURES

Table 1: Comparison of k_{pw} values obtained from proposed method and available theories in Seismic case ($\Phi = 30°$)

δ/Φ	**k_h**	**k_v**	**Mononobe - Okabe**		**Morrison and Ebeling**		**Chen and Lie**		**Soubra**		**Kumar**		**Subba Rao and Choudhury**		**Present Study**
C1	C2	C3	C4	C4/C16	C6	C6/C16	C8	C8/C16	C10	C10/C16	C12	C12/C16	C14	C14/C16	C16
0.5	0	0	4.8	1.11	4.46	1.03	4.71	1.09	4.53	1.047			4.45	1.03	4.32
	0.1	0	4.4	1.06	4.24	1.03	4.37	1.06	4.20	1.019			4.24	1.028	4.12
	0.1	0.1	4.35	1.14	4.16	1.09							3.89	1.024	3.79
	0.2	0	3.99	1.06	3.87	1.03	4	1.06	3.9	1.036			3.86	1.025	3.76
	0.2	0.2	3.77	1.26	3.6	1.21							3.02	1.011	2.98
	0.3	0	3.54	1.04	3.46	1.01	3.59	1.05	3.47	1.016			3.45	1.010	3.41
1	0	0	8.74	1.51	6.15	1.07	7.1	1.23	5.94	1.031	5.78	1.003	5.78	1.003	5.76
	0.1	0	7.81	1.45	5.73	1.07	6.55	1.22	5.5	1.025	5.36	0.999	5.4	1.002	5.36
	0.2	0	6.86	1.38	5.28	1.07	5.95	1.20	5.02	1.013	4.9	0.989	5.1	1.028	4.95
	0.3	0	5.87	1.31	4.94	1.11	5.3	1.19	4.5	1.01	4.4	0.987	4.75	1.065	4.45

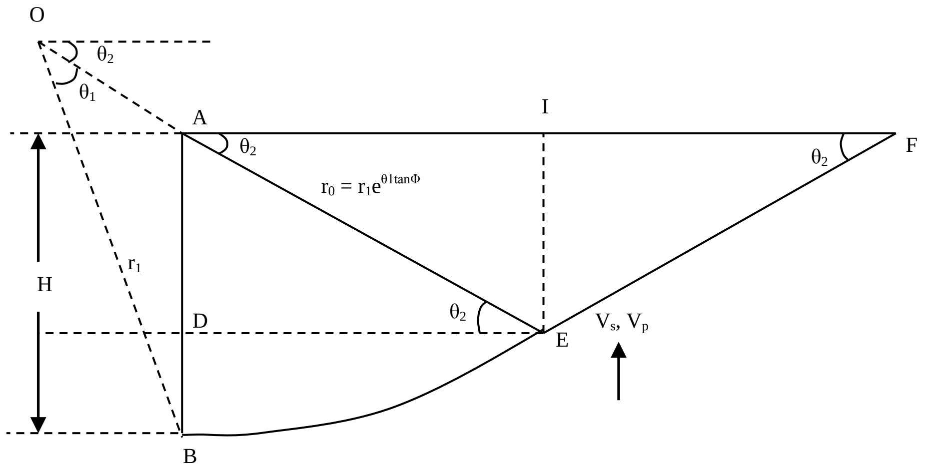

Fig.1. Composite Failure Mechanism of Soil Wedge System under Seismic Loading Condition

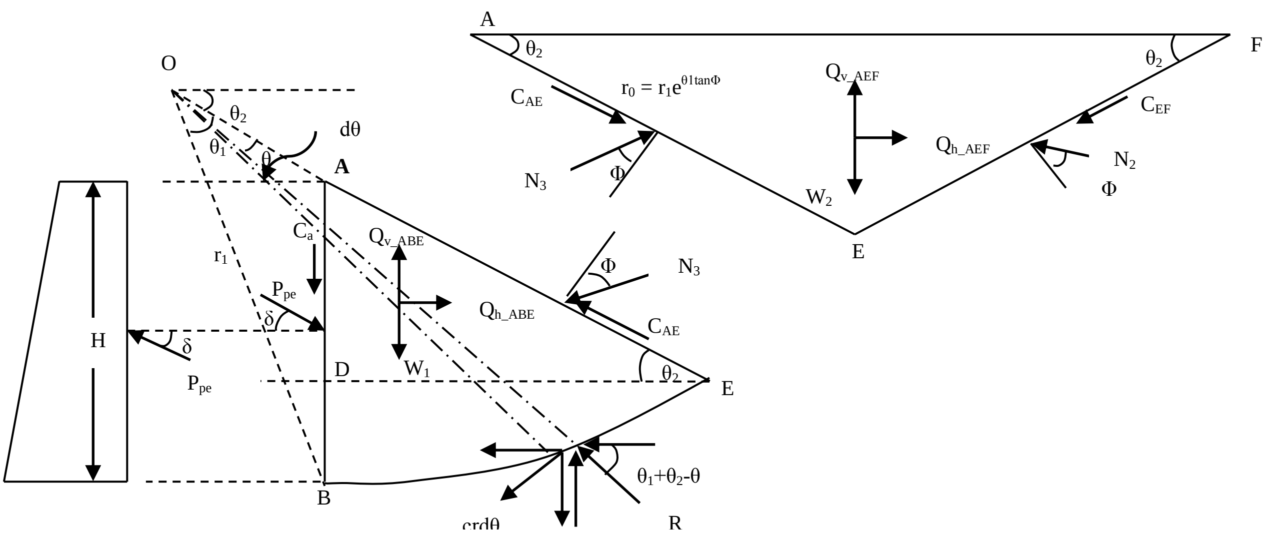

Fig.2. Pseudo-dynamic Forces Acting on Soil Wedges System supporting c-Φ Backfill during Passive State of Equilibrium Condition

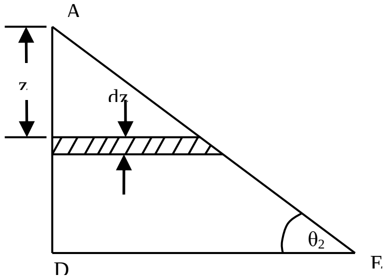

Fig.3. Details of wedge ADE

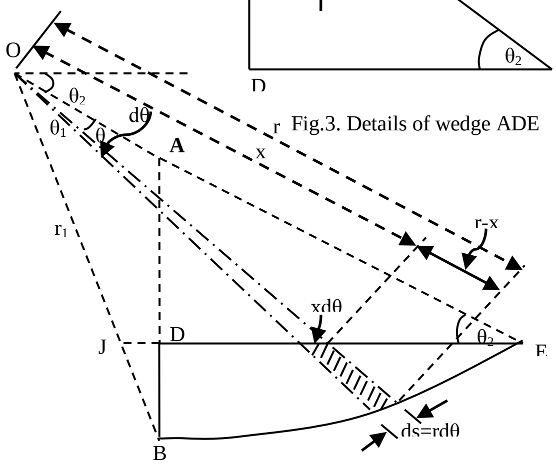

Fig.4. Details of wedge DBE

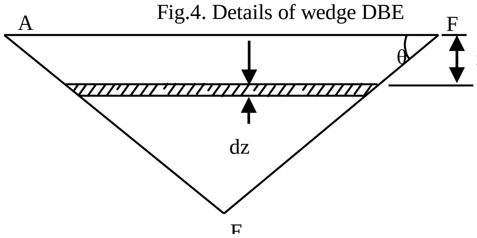

Fig.5. Details for wedge AEF

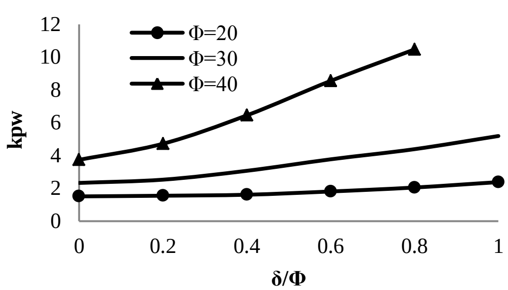

Fig.6. Variation of seismic passive earth pressure coefficients due to unit weight [k_h = 0.2, k_v/k_h=0.5]

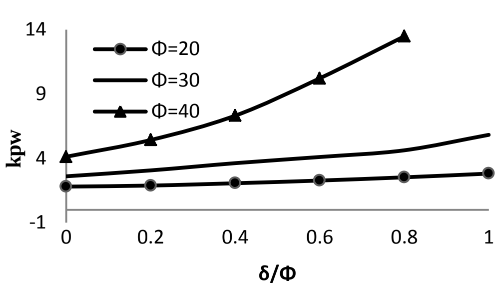

Fig.7. Variation of seismic passive earth pressure coefficients due to unit weight [k_h = 0.1, k_v/k_h=0.5]

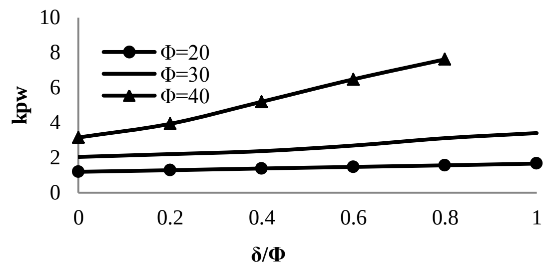

Fig.8. Variation of seismic passive earth pressure coefficients due to unit weight [k_h = 0.3, k_v/k_h=0.5]

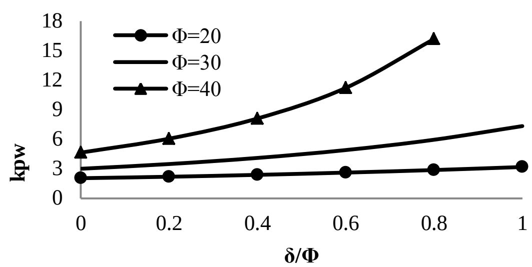

Fig.9. Variation of passive earth pressure coefficients due to weight for static condition

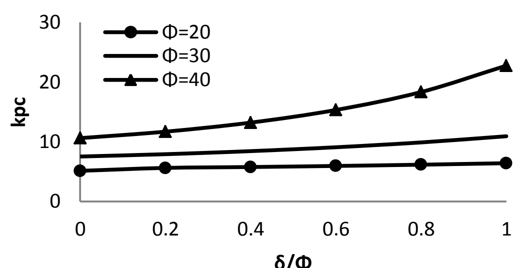

Fig.10. Variation of passive earth pressure coefficients due to cohesion

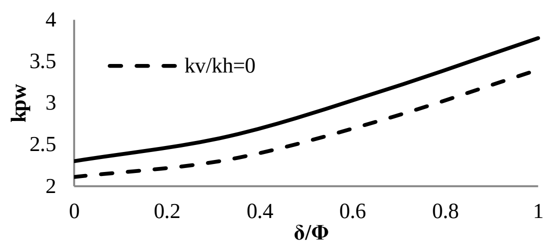

Fig.11. Variation of kpw for different values of k_v/k_h [Φ =30°]

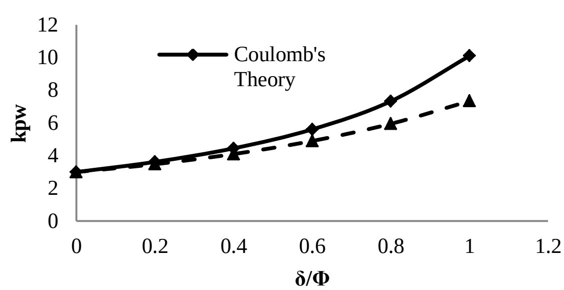

Fig.12. Comparison of k_{pw} under static loading condition with Coulomb's Theory