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Effect of Arching On Passive Earth Pressure for Rigid Retaining Wall in C-Φ Soil

Rupa S. Dalvi[1], Bharat R. Bombale[2]

[1,2]*Civil Engineering Department, College of Engineering Pune.*

Abstract: *Arching involves stress transfer from yielding part of a soil to unyielding part of soil. Many authors considered arching action for active earth pressure as well as passive earth pressure but many of them have considered arching effect for cohesion less soil. In this paper arching action is considered for passive earth pressure in C-φ backfill. The backfill is assumed to move downward in a form of circular arch due to arching. The value of θ_w (the angle of major principal plane) is calculated for soil-wall friction angle and soil friction angle. An expression for passive lateral stress ratio has been derived considering these angles. An illustrative example has been solved to show the effect on earth pressure distribution on retaining wall considering arching for different wall friction angles, soil friction angles and cohesion. The applicability of proposed formulation is compared with experimental test results.*

Keywords: *Arching, Passive earth pressure, C-φ soil, Wall friction, Retaining wall.*

Abbreviation used

σ_1 - Major Principal stress

σ_3 - Minor principal stress

σ_v - Vertical stress at wall

σ_{phw} - Horizontal stress at wall

$\bar{\sigma}_v$ - Average vertical stress

Φ - Angle of internal friction

Ψ - Angle between the tangent to arch at point D and vertical

δ - Soil-wall interface friction angle

θ_w - Angle of rotation of minor principal plane with vertical

τ_w - Shear stress at wall

γ - Unit weight of backfill soil

α - Angle made by failure plane with horizontal

K_p - Principal stress ratio

K_{pwn} - New passive lateral stress ratio

B_z - Distance between failure surface and wall at depth z

c - Cohesion of backfill soil

z - Depth below backfill surface

H - Height of wall

I. INTRODUCTION

Arching, as the word suggests, is a stress redistribution process by which stress is transferred around a region of the soil mass, which then becomes subject to lower stresses. Arching is one of the universal phenomena encountered in soil both in the field and laboratory. Since arching is solely maintained by shearing stresses in the soil, it is no less permanent than any other state of stress in the soil which depends on existence of shearing stresses.

If one part of the support of a mass of soil yields while remainder stays stationary, the relative movement of soil takes place. This relative movement of soil mass is opposed by shearing resistance developed within zone of contact. This reduces the stresses on yielding part and increases stresses on stationary part. This transfer of stresses is known as "Arching effect in Soil."

Many researchers have considered effect of arching on earth pressure. Many of them considered arching effect for active condition (Terzaghi 1943; Handy 1985; Paik and Salgado 2003; Jiang 2005; Ying et al. 2006; Goel and Patra 2008; Rao et al. 2016) as well as for passive condition (Dalvi and Pise 2012, Patra and Roy 2009) but most of them consider soil arching effect in cohesion less backfill. No study has been carried out on effect of arching on passive earth pressure in c-φ soil. The present study is devoted to effect of arching on passive earth pressure in C-Φ Soil.

1.1 Proposed method and assumptions

1. The soil is C-Φ soil, semi infinite, homogeneous, isotropic and the backfill is horizontal.

2. The problem is a plane strain problem i.e. two dimensional.

3. The soil mass is bounded between two parallel, unyielding rough vertical walls. The walls are assumed to rotate towards the soil mass creating passive case.

4. The soil mass moves down in a curved path which is considered as circular arch.

5. Failure surface makes an angle 45-(Φ/2) with horizontal.

6. Wall friction angle δ is less than soil friction angle φ.

8. The major and minor principal stresses have been considered to be constant along the length of the arch.

9. The ratio of horizontal to vertical pressure σ_{phw} to σ_v is constant and it is represented by $K_{pwn}=\sigma_{phw}/\sigma_v$

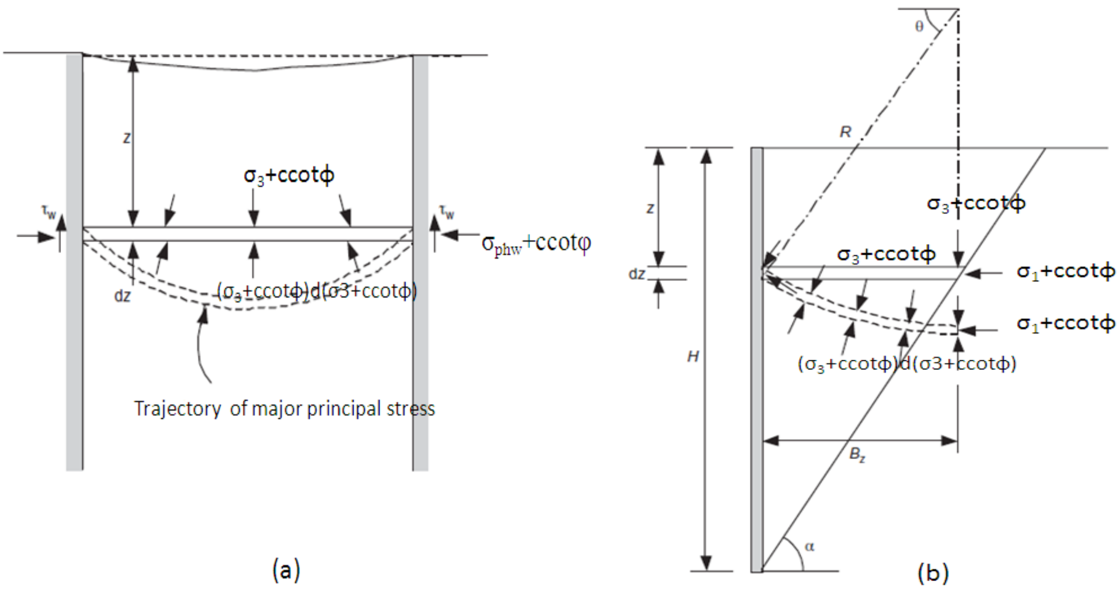

Figure.1. Trajectory of major principal stresses: (a) at ditch; (b) in backfill behind retaining wall

II. ANALYSIS

As shown in Fig.1(a) consider two parallel rough vertical walls $2B_z$ distance apart supports the backfill. Walls then allowed moving towards the backfill which creates the passive case. It is assumed that due to wall movement settlement of backfill is more enough to develop frictional resistance between wall and backfill. Due to this frictional resistance weight of retained soil is partially supported by wall friction which causes the major principal stress to tilt downward by amount θ initially which is horizontal at the wall and becomes horizontal at centre. This change in amount of rotation of major principal stress from θ° at wall to zero i.e. horizontal at centre causes major principal stress to follow the particular path which is known as trajectory of major principal stress. Some researchers assumed this as a catenary, parabolic etc. In present analysis it is assumed as an arc of a circle. Along this arc major and minor principal stresses remains constant. Due to cohesion all Stresses are increased by an amount of ccotΦ. (Fig.3)

Now, Similarly Fig.1(b) shows the retaining wall supporting backfill. Fig.1(b) shows failure surface is located at distance B_z from wall. Major principal stress (σ_1+ccotφ) acts tangential to circular arc and minor principal stress(σ_3+ccotφ) acts perpendicular to that at any point along trajectory.

Fig.2 shows the forces acting on triangular element at wall.

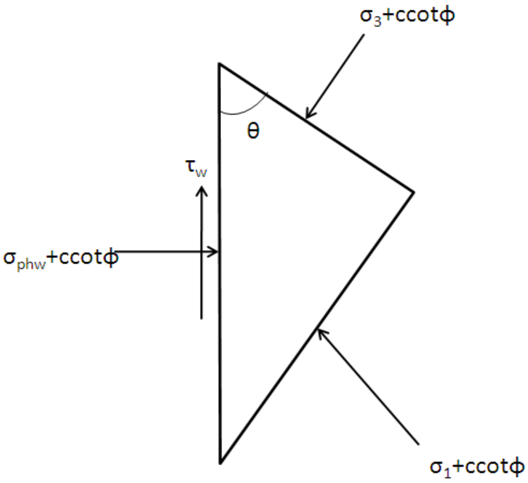

Figure 2. Triangular element at wall

From force equilibrium of triangular element as shown in Fig.2

$$\sigma_{phw}+c\cot\Phi=(\sigma_1+c\cot\Phi)\cos^2\theta+(\sigma_3+c\cot\Phi)\sin^2\theta \quad \text{- - - -(1)}$$

Dividing equation (1) by (σ_3+ccotΦ) and putting (σ_1+ccotΦ)/ (σ_3+ccotΦ) =K_p

Where K_p is the principal stress ratio

$$\sigma_{phw}=[(K_p\cos^2\theta+\sin^2\theta)\ (\sigma_3+c\cot\Phi)]-c\cot\Phi \quad \text{- - - -(2)}$$

Now from Mohr circle (Fig.3)

$$\sigma_1-\sigma_{phw}=\sigma_v-\sigma_3$$

There fore

$$\sigma_{phw}=\sigma_3+\sigma_1-\sigma_v \quad \text{- - - -(3)}$$

Equating equation (2) and (3) gives

$$\sigma_v=(\sigma_1+\sigma_3+c\cot\Phi)-[(K_p\cos^2\theta+\sin^2\theta)\ (\sigma_3+c\cot\Phi)] \quad \text{- - - -(4)}$$

2.1 Determination of θ (Rotation angle of minor principal plane with vertical)

Rotation angle can be calculated by using Mohr circle as shown in Fig.3 for any values of angle of internal friction(Φ) and soil wall friction angle(δ) but only condition is that δ<Φ.

Following Fig.3 shows the Mohr circle representation of state of stress of soil element at wall. In Fig.3 σ_1 and σ_3 are major and minor principal stresses , σ_v and σ_{phw} are the vertical and horizontal stresses at wall respectively. θ_w is the angle of rotation of major principal plane with horizontal. τ_w is the shear stress developed at wall. Φ is the angle of internal friction of backfill, δ is soil-wall interface angle, c is cohesion of backfill soil. To consider cohesion intercept of soil all stresses on soil element has been increased by an amount of **ccotΦ.**

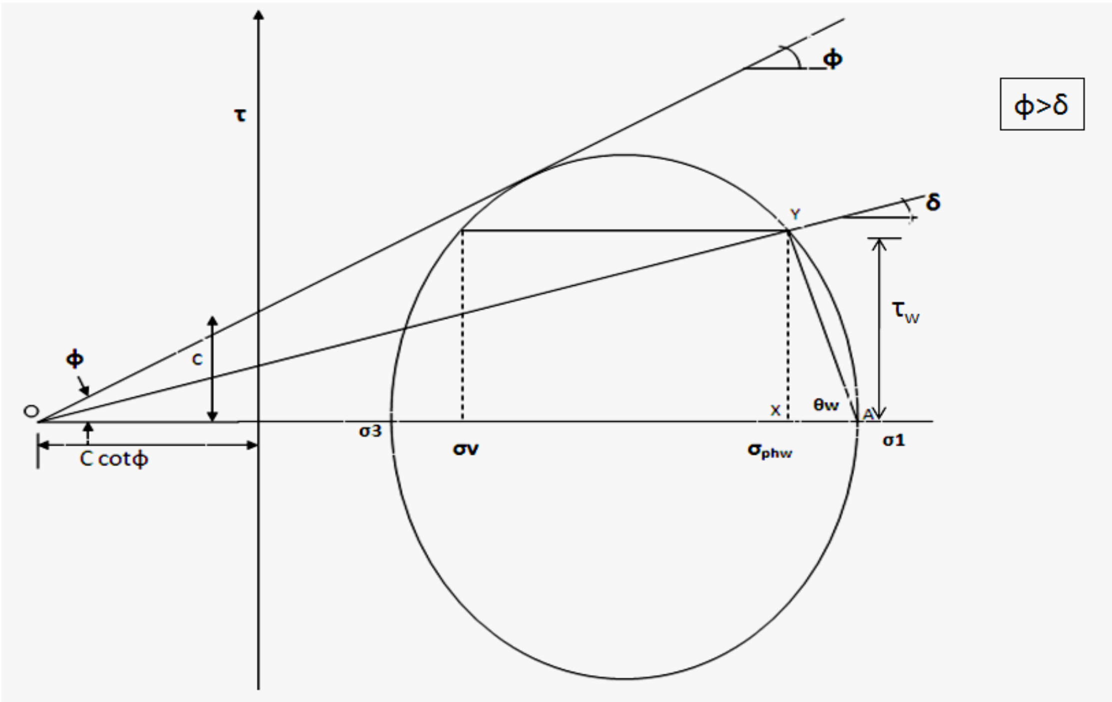

Figure 3. Mohr Circle at A (wall)

Now From ΔOXY (Fig.3)

$$\tau_w = (\sigma_{phw} + c\cot\phi)\tan\delta \qquad \text{----(5)}$$

From ΔAXY (Fig.3)

$$\tan\theta = \frac{\tau_w}{\sigma_1 - \sigma_{phw}} \qquad \text{Hence,} \quad \tau_w = (\sigma_1 - \sigma_{phw})\tan\theta \qquad \text{----(6)}$$

Equating equation (5) and (6)

$$(\sigma_{phw} + c\cot\phi)\tan\delta = (\sigma_1 - \sigma_{phw})\tan\theta$$

$$\tan\delta = \frac{[(\sigma_1 - \sigma_{phw})\tan\theta]}{(\sigma_{phw} + c\cot\phi)}$$

$$\tan\delta = \left[\frac{(\sigma_1 + c\cot\phi)}{(\sigma_{phw} + c\cot\phi)} - 1\right]\tan\theta$$

Divide by $(\sigma_3 + c\cot\Phi)$ to numerator and denominator of second term we get

$$\tan\delta = \left[\frac{K_p}{\left(K_p\cos^2\theta + \sin^2\right)} - 1\right]\tan\theta$$

$$\tan\delta = \left[\frac{K_p - \left(K_p\cos^2\theta + \sin^2\theta\right)}{\left(K_p\cos^2\theta + \sin^2\theta\right)}\right]\tan\theta$$

Rearranging the terms we get

$$\tan\delta = \left[\frac{\left(K_p - 1\right)\tan^3\theta}{\tan^2\theta + K_p}\right] \qquad \text{- - - -(7)}$$

By knowing values of K_p and δ , rotation angle of minor principal stress (θ) can be calculated.

2.2 Calculation of average vertical stress $\bar{\sigma}_v$ across differential element

Fig.4 shows the backfill behind the wall having shear strength parameters c (cohesion) and Φ (angle of internal friction). Due to wall movement towards backfill it is assumed that the backfill moves downward due that downward movement of backfill the upward shear stresses (τ_w) is generated at wall. Fig.4 also shows the circular trajectory of major principal stress (σ_1+ccotΦ). R is radius of principal stress trajectory. One arbitrary element is considered at D which is originally at point B before settlement of backfill. It's width is dA. Ψ is the angle between the tangent to arch at point D and vertical.

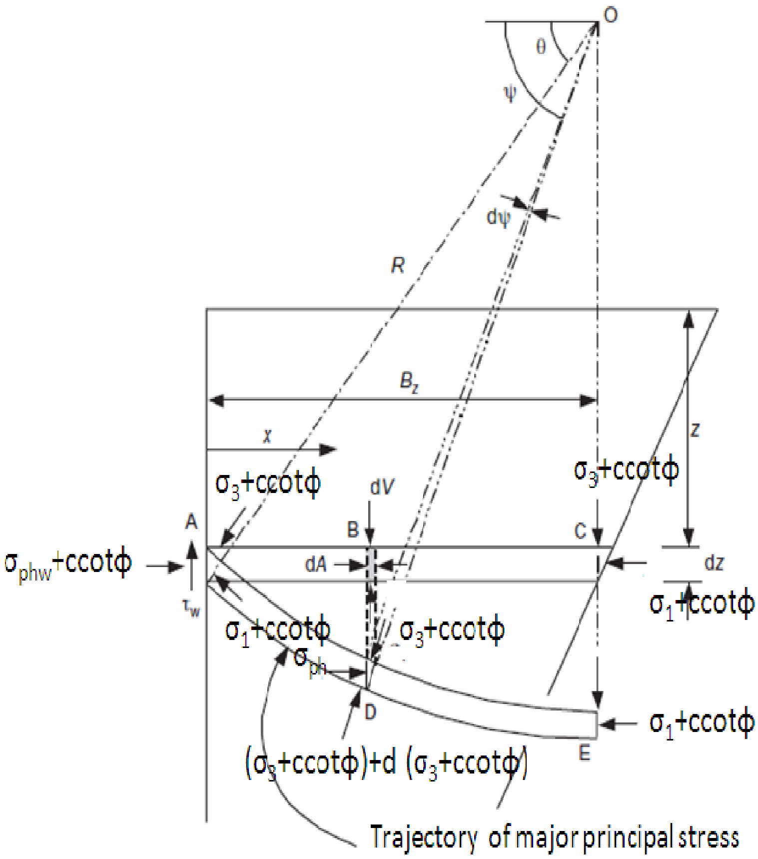

Figure 4. Stresses on differential flat element in backfill

Now, From Fig.4 vertical differential force dV at point B

$dV=\sigma_v\, dA=[(\sigma_1+ \sigma_3+ c\cot\Phi) -[(K_p\cos^2\Psi+\sin^2\Psi)\,(\sigma_3+c\cot\Phi)]\,(R\, d\Psi\, \sin\Psi)$

Where, dA=width of the shaded element at B &

σ_v =vertical force at differential element (Eq^n 4)

The average vertical stress $\bar{\sigma}_v$ across differential element

$\bar{\sigma}_v$ =Total vertical force/width of element

$$= \frac{V}{B_z} = \frac{\int_{\theta}^{\pi/2} dV}{B_z}$$

$$= \frac{\int_{\theta}^{\pi/2} \left[(\sigma_1+\sigma_3+c\cot\phi)-\left\{\left(K_p\cos^2\Psi+\sin^2\Psi\right)(\sigma_3+c\cot\phi)\right\}\right](Rd\Psi\sin\Psi)}{R\cos\theta}$$

Where B_z=Rcosθ (From fig.4)

$$\bar{\sigma}_v = \frac{\int_{\theta}^{\pi/2} \left[(\sigma_1+\sigma_3+c\cot\phi)-\left\{\left(K_p\cos^2\Psi+\sin^2\Psi\right)(\sigma_3+c\cot\phi)\right\}\right](d\Psi\sin\Psi)}{\cos\theta}$$

By integrating above equation we get,

$$\bar{\sigma}_v = (\sigma_1+\sigma_3+c\cot\phi)-\left[\frac{(\sigma_3+c\cot\phi)}{12\cos\theta}\left[3\cos\theta(1+3K_p)+\cos 3\theta(1-K_p)\right]\right] \text{ - - - - (8)}$$

Hence, New passive lateral stress ratio

K_{pwn} =Horizontal stress at wall/Average vertical stress

$K_{pwn} = \sigma_{phw} / \bar{\sigma}_v$ - - - - (9)

Putting values of σ_{phw} & $\bar{\sigma}_v$ From equation (2) and (8) respectively K_{pwn} can be calculated.

2.3 Passive earth pressure behind a wall

In Fig.5 differential flat element of thickness dz is considered at depth z from surface of backfill. B_z is the width of differential element at depth z. $\bar{\sigma}_v$ is the average vertical stress on differential element. C is the cohesive force acting on element at failure surface.

Fig.5 shows forces acting on the differential flat element. Since we assume failure surface makes an angle 45-(Φ/2) with horizontal the major and minor principal stresses at right side of the element must applied horizontal and vertical plane respectively. Therefore shear stresses at right side does not comes in to picture while taking summation of vertical forces but at same time there is non zero shear stress τ_w at wall.

$\tau_w = \bar{\sigma}_v K_{pwn} \tan\delta$

Fig.5 shows rectangular element behind the wall having thickness dz and it is located at depth z below the surface of backfill. It carries non zero shear stress τ_w at left edge and as explained earlier there is no shear stresses at right edge but there must be the cohesive force because backfill is assumed as c-Φ soil.

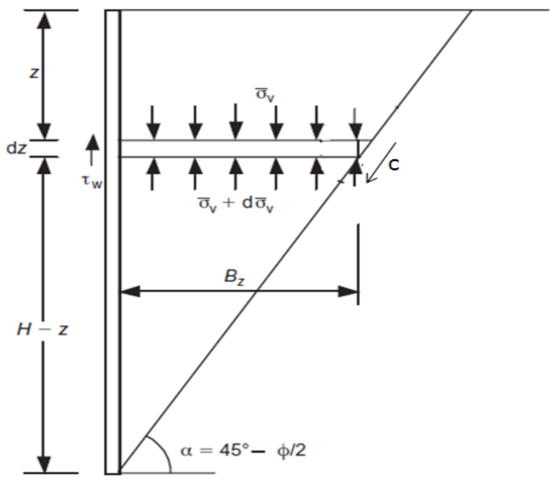

Figure 5. Free body diagram of differential flat element

Summation of all vertical forces acting on differential element as shown in Fig.5

$(d\bar{\sigma}_v + \bar{\sigma}_v - \bar{\sigma}_v)B_z + \tau_w\, dz = \gamma B_z\, dz + c\, dz$

Put value of $\tau_w = \bar{\sigma}_v K_{pwn} \tan\delta$ and $B_z = (H-z)/(\tan\alpha)$ (From Fig.5)

$(d\bar{\sigma}_v + \bar{\sigma}_v - \bar{\sigma}_v)(H-z)/(\tan\alpha) + \bar{\sigma}_v K_{pwn} \tan\delta\, dz = \gamma\,(H-z)/(\tan\alpha) dz + c\, dz$

Integrating above equation and rearranging the terms we get

$$\bar{\sigma}_v = \frac{[\gamma z(2H - z) + 2cz]}{2[(H - z) + K_{pwn} \tan\delta \tan\alpha . z]} + C$$

where C is integration constant. Which can be evaluated by applying boundary condition at z=0 ; $\bar{\sigma}_v$ =0 we get C=0

Therefore, average vertical stress at any depth z below backfill surface

$$\bar{\sigma}_v = \frac{[\gamma z(2H - z) + 2cz]}{2[(H - z) + K_{pwn} \tan\delta \tan\alpha . z]} \qquad \text{- - - - (10)}$$

The passive lateral stress at any depth acting on the wall can be calculated by multiplying equation (10) by K_{pwn}, which is given by equation (9)

$$\sigma_{ph} = \bar{\sigma}_v K_{pwn} = \frac{[\gamma z(2H - z) + 2cz]K_{pwn}}{2[(H - z) + K_{pwn} \tan\delta \tan\alpha . z]} \qquad \text{- - - - (11)}$$

III. RESULTS AND DISCUSSION

Parametric Study

By using above derived equations parametric study is done to study the effect of different backfill and interface parameters such as angle of internal friction of backfill (Φ), Soil-wall friction angle (δ), soil unit weight(γ) and cohesion on the passive earth pressure and its distribution along depth. While studying effect of any one above mentioned parameter other parameters are kept constant.

3.1 Angle of Internal Friction

The effect of angle of internal friction (φ) on the passive earth pressure and its distribution is studied. For this study the following data is assumed and kept constant : H=10m, $c=15kN/m^2$, δ=10°,$\gamma=20kN/m^3$ and φ is varied from

0°,10°,20°,30° & 40°. Fig.6 shows the passive earth pressure distribution with φ. From Fig.6 it is observed that passive earth pressure increases with increase in Φ but the shape of pressure distribution remains same.

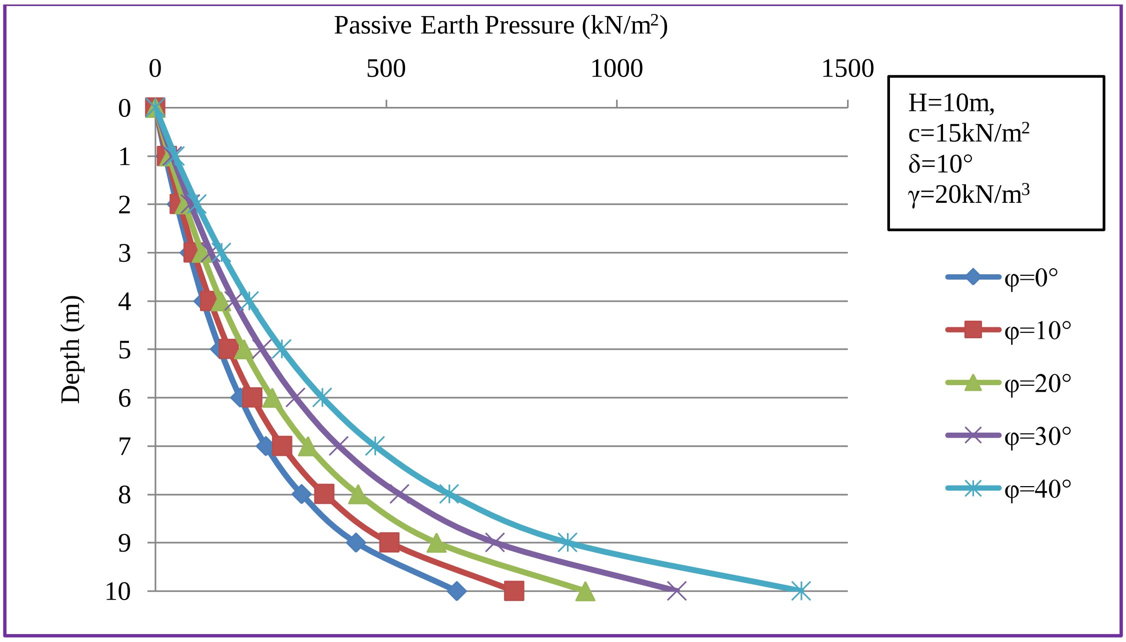

Figure 6. Change of passive earth pressure distribution with Φ

3.2 Soil-Wall Friction Angle

The effect soil-wall friction angle(δ) on the passive earth pressure and its distribution is studied. For this study the following data is assumed and kept constant: H=10m, c=15kN/m^2, Φ =35°, γ=20kN/m^3 and δ is varied from 10°, 20° & 30°. Fig.7 shows the passive earth pressure distribution with δ. From Fig.7 it is observed that passive earth pressure reduces with increase in δ and also the shape of pressure distribution becomes more linear with increase in δ.

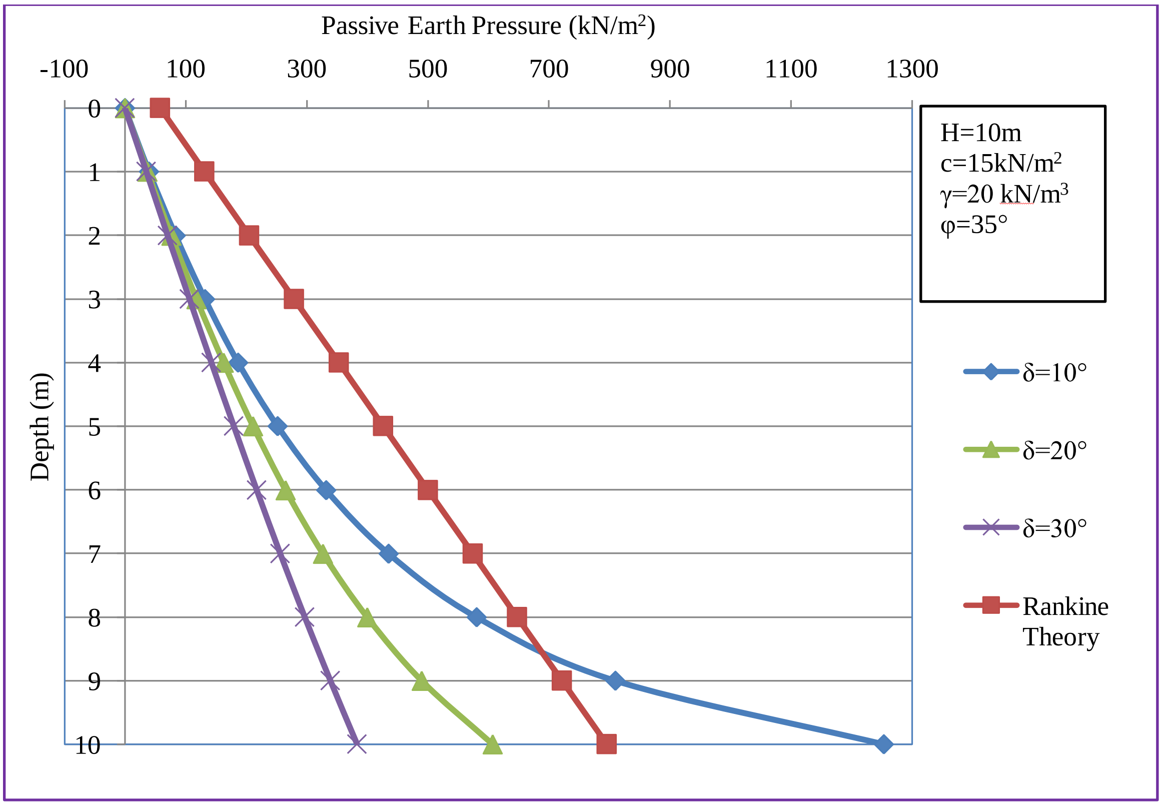

Figure 7. Change of passive earth pressure distribution with δ

3.3 Cohesion

The effect of cohesion on the passive earth pressure and its distribution is studied. For this study the following data is assumed and kept constant : H=10m, Φ=35°,δ=10°, γ=20kN/m^3 and c (cohesion) is varied from 5kN/m^2,10kN/m^2,15kN/m^2, to 20kN/m^2. Fig. 8 shows the Passive earth pressure distribution with cohesion. From Fig.8 it is observed that passive earth pressure slightly increases with increase in cohesion at every depth but the shape of pressure distribution remains same.

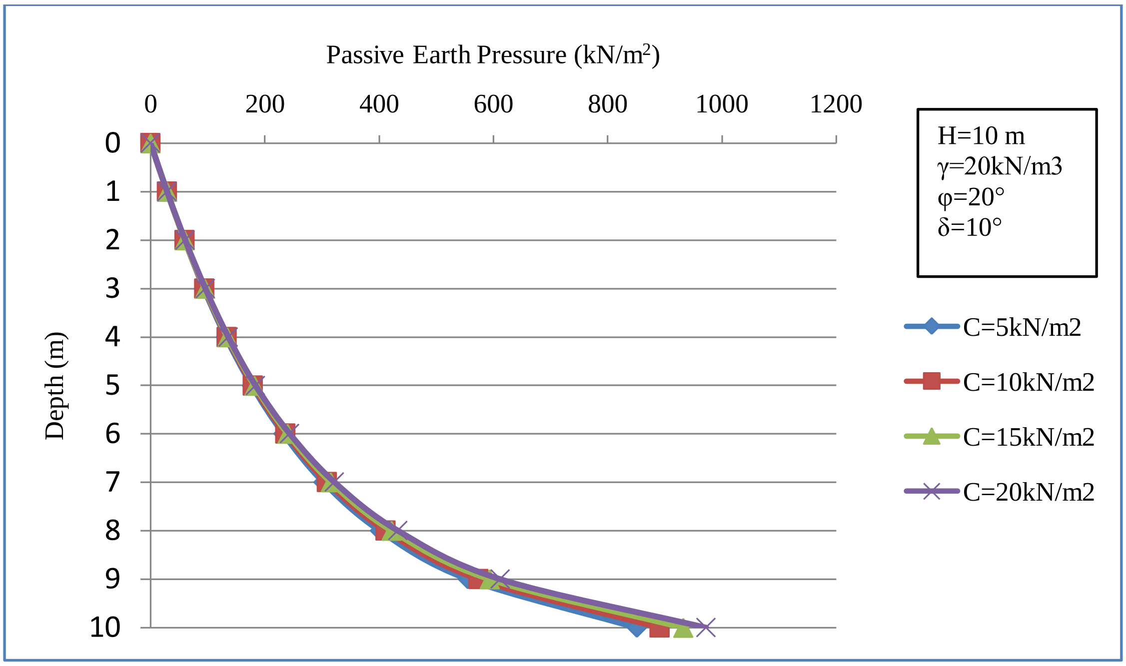

Figure 8. Change of passive earth pressure distribution with cohesion

3.4 Unit weight of soil

The effect unit weight of soil (γ) on the passive earth pressure and its distribution is studied. For this study the following data is assumed and kept constant: H=10m, c=15kN/m^2, δ=10°, Φ=35° and γ is varied from γ=12kN/m^3, γ=15kN/m^3, γ=18kN/m^3 to γ=21kN/m^3. Fig.9 shows the passive earth pressure distribution with γ. From Fig.9 it is observed that passive earth pressure increases with increase in γ but the shape of pressure distribution remains same.

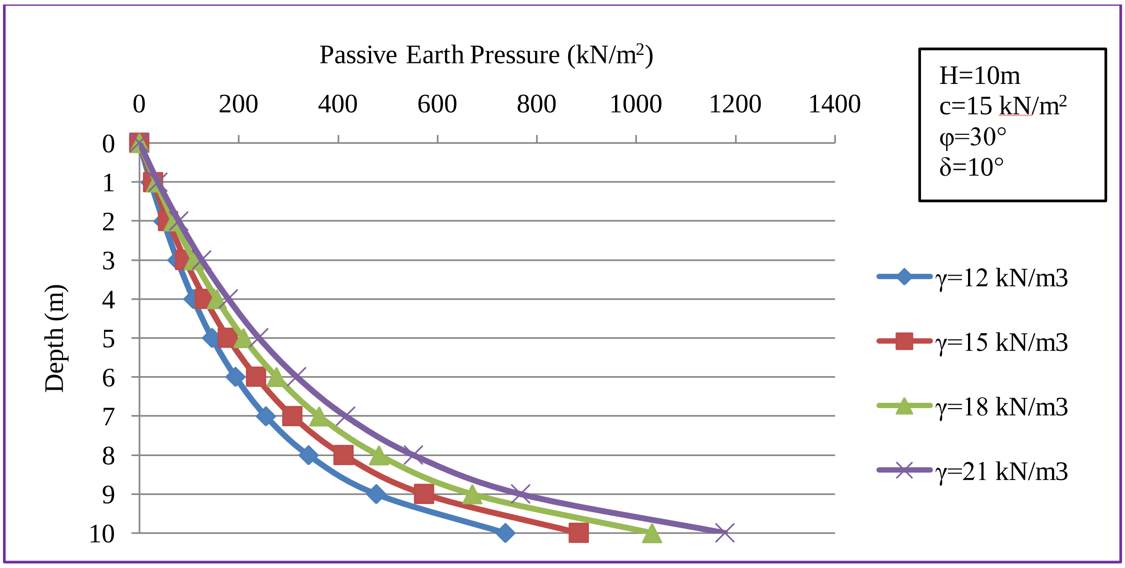

Figure 9. Change of passive earth pressure distribution with γ

IV. COMPARISON WITH EXPERIMENTAL RESULTS

In order to validate present analysis, the results of present study are results compared with the experimental results investigated by previous researchers. Comparison shows that the present analysis gives satisfactory results and found in a good agreement with experimental results.

4.1 Comparison with the results obtained by Wilson and Elgamal (2010)

Wilson and Elagmal (2010) have given the peak passive force with wall displacement. In order to compare total passive force first passive earth pressure distribution is obtained and then passive force is calculated by area of pressure distribution diagram (Fig.10) and results are shown in Table 1.

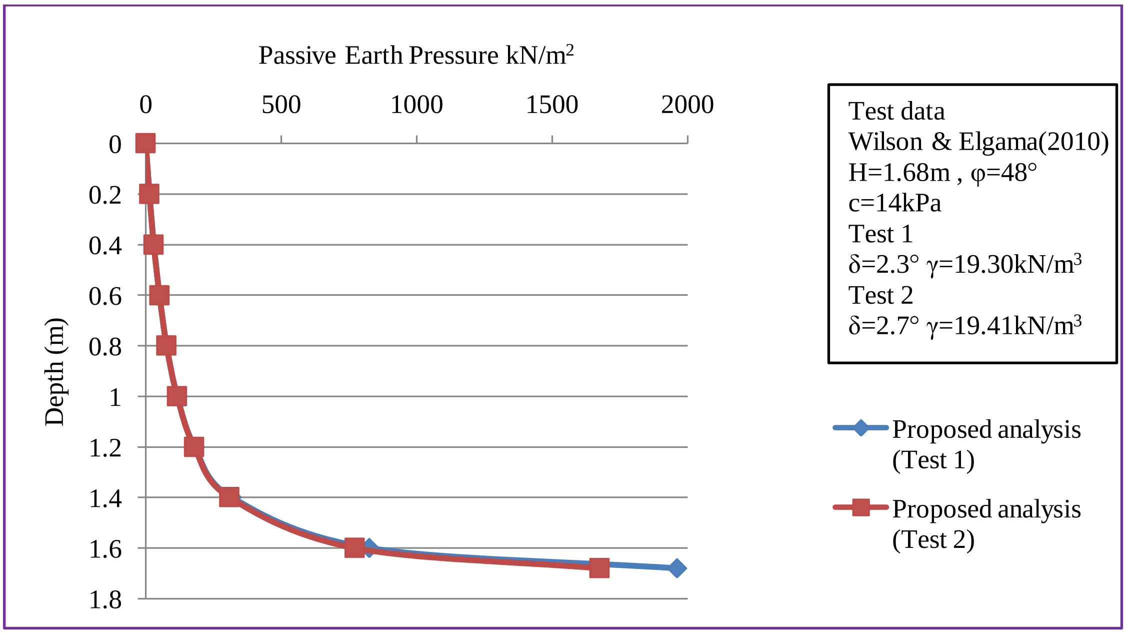

Figure 10. Passive earth pressure distribution

Table 1.Comparison of total passive force calculated using present study with experimental results(Wilson and Elgamal 2010), Coulomb, Rankine

Test No.	Passive force by proposed analysis (kN/m)	Measured passive force (Wilson & Elgamal) (kN/m)	Passive Force using Coulomb theory (kN/m)	Passive force using Rankine equation (kN/m)
Test 1	350.65	385	350	320
Test 2	328.21	326	355	320

4.2 Comparison with the results obtained by Fang et al. (1994)

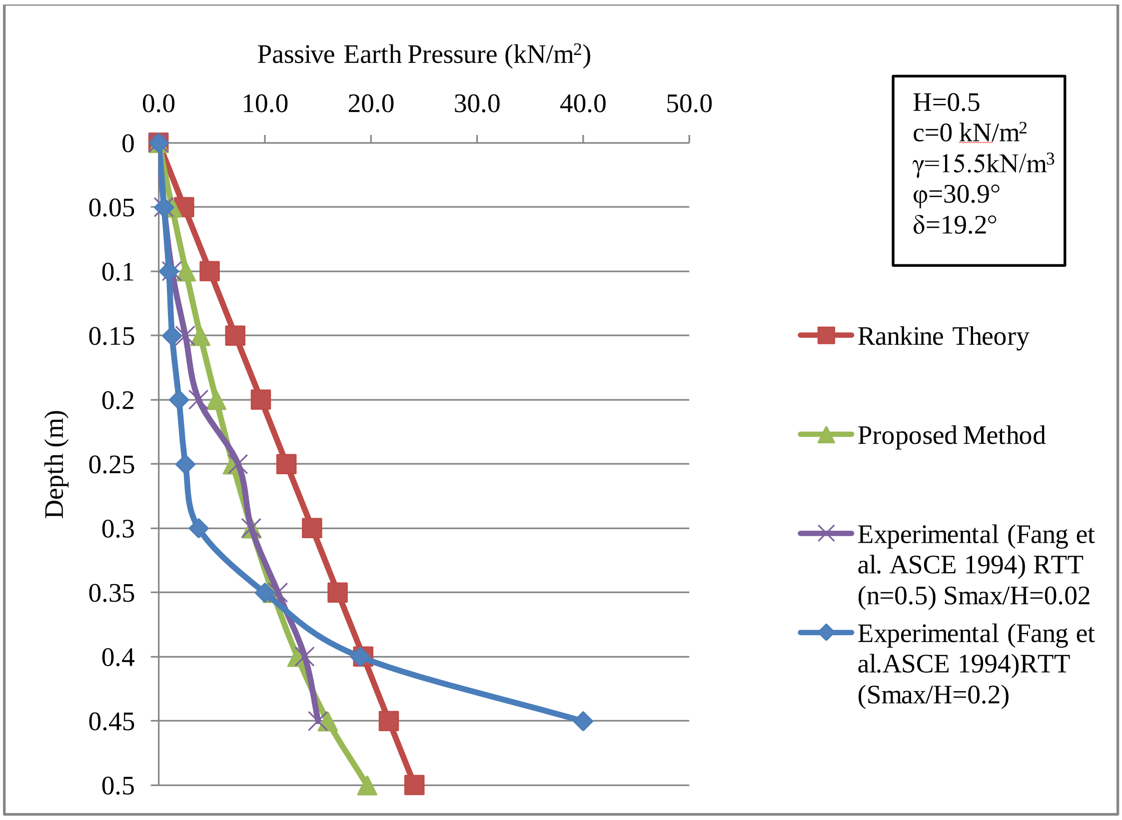

Figure 11. Passive earth pressure distribution

V. CONCLUSIONS

VI. 1. As δ (soil-wall friction angle) increases passive earth pressure decreases at every depth and pressure distribution becomes more linear.

VII. 2. Passive earth pressure increases with increase in φ (soil friction angle) at every depth but shape of distribution remains same.

VIII. 3. Passive earth pressure increases with increase in γ (unit weight of soil) but shape of pressure distribution remains unchanged.

IX. 4. Passive earth pressure increases with increase in c (cohesion of soil) but shape of pressure distribution remains unchanged.

X. 5. Total passive force calculated by proposed analysis found to be in good agreement with experimental result given by Wilson and Elgamal (2010).

XI. 6. Shape of passive earth pressure distribution matches with the experimental results of Fang et al. (1994) for RTT mode (S_{max}/H =0.02) and falls between experimental (S_{max}/H=0.2) and Rankine prediction.

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