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Study of Seismic Behaviour of Retaining Walls

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ABSTRACT: Determination of seismic active and passive earth pressure is necessary for the safe design of the retaining wall in earthquake susceptible regions. Pseudo-static and pseudo-dynamic methods do not consider the effect of Rayleigh waves. Rayleigh wave comprises of about 67% of total seismic energy. In this study a new Pseudo-dynamic method proposed by Deepankar Chaudhary Amey Deepak Katdare is used to compare the active and passive earth pressure with pseudo-static method. This latest pseudo-dynamic method considers primary waves, shear wave and also Rayleigh waves. This method satisfies the condition of zero stress condition on ground surface.

KEYWORDS: Pseudo dynamic, Rayleigh waves, Mononobe okabe method, Retaining wall, Zero ground stress.

I. INTRODUCTION

Coulomb (1776) gave mathematical solution for estimation of lateral static earth pressure on retaining wall. Coulomb used equilibrium of forces for determination magnitude of thrust on retaining wall to achieve maximum passive state and minimum active state condition. It is an indeterminate problem because a large number of rupture surfaces should be examined in order to determine the critical failure plane. In 1857 Rankine provided a simple method to estimate maximum passive and minimum active earth pressure. Rankine assumed shear failure in the backfill soil. Methodology provided by Coulomb and Rankine are the basis for static earth pressure estimation and also for the design of the retaining wall.

Breakthrough in estimation of the seismic forces on retaining wall was provided by Okabe ((1926) and Mononobe and Matsuo (1929). Method provided by Mononobe –Okabe is the extension of Coulomb wedge theory. This method was provided for the gravity retaining wall with cohesion less backfill soil. After Mononobe-Okabe various researchers Seed and Whitman (1970), Nazarian and Hadijan (1979), Prakash (1981) reviewed the problem. Mononobe –Okabe methodology was pseudo-static approach, it provides linear pressure distribution in a rough manner only. Steedman and Zeng (1990) overcame with drawbacks of Mononobe –Okabe method by providing a solution, in which he considered time and phase difference of shear waves propagating at the backfill of wall. Their theoretical result was compared with the centrifuge model test and outcome was similar. But Steedman and Zeng considered a particular value of seismic horizontal coefficient (k_h and k_v). In 2006 Chaudhury and Nimbalkar provided a better solution for the pseudo-dynamic problem. They provided a non linear solution to the problem, in the analysis primary, shear wave were considered along except the Rayleigh wave with the seismic coefficient. Chaudhury, Amey Deepak Katdare, A Pain (2014) provided solution for seismic active and passive earth pressure by considering the effect of Rayleigh waves too. Rayleigh wave comprises 67% of total seismic energy.

II. MONONOBE OKABE METHOD

First method for the determination of the combined static and dynamic earth pressure on retaining wall was proposed by Okabe (1926) and Mononobe and Matsuo(1929). Method is based on the plasticity theory and this method is extended version of Coulomb sliding wedge theory in which earthquake forces are represented by equivalent static force. The method was developed for the dry cohesion less soil.

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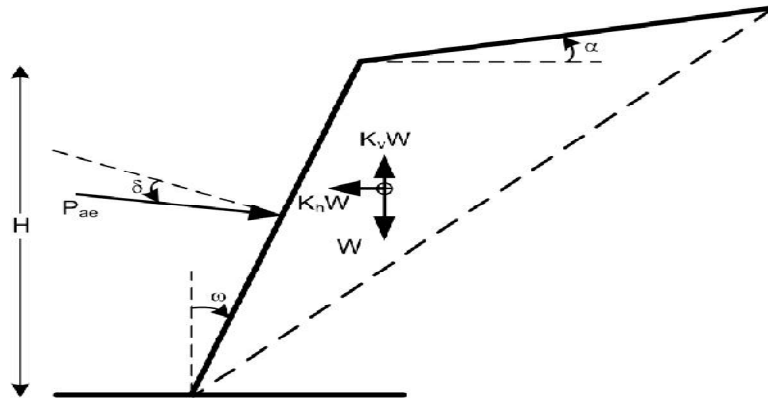


Fig forces acting on soil wedge

The active force on wedge is expressed as

$$P_{AE} = \frac{1}{2} \gamma H^2 (1 - k_v) K_{AE} \quad (1)$$

Where K_{AE} is active earth pressure coefficient with earthquake effect

$$K_{AE} = \frac{\cos^2(\phi - \theta - \beta)}{\cos\theta \cos^2\beta \cos(\delta + \beta + \theta) \left[1 + \sqrt{\frac{\sin(\phi + \delta) \sin(\phi - \theta - \beta)}{\cos(\delta + \beta + \theta) \cos(i - \beta)}} \right]^2} \quad (2)$$

$$\theta = \tan^{-1} \left(\frac{k_h}{1 - k_v} \right) \quad (3)$$

equation (i) is known as Mononobe-Okabe active earth pressure equation.

The passive force P_{PE} is derived as

$$P_{PE} = \frac{1}{2} \gamma H^2 (1 - k_v) K_{PE} \quad (4)$$

$$K_{PE} = \frac{\cos^2(\phi - \theta + \beta)}{\cos\theta \cos^2\beta \cos(\delta - \beta + \theta) \left[1 - \sqrt{\frac{\sin(\phi + \delta) \sin(\phi - \theta + \beta)}{\cos(\delta - \beta + \theta) \cos(i - \beta)}} \right]^2} \quad (5)$$

where

$$\theta = \tan^{-1} \left(\frac{k_h}{1 - k_v} \right)$$

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- P_{AE} =active force per unit length of wall
- P_{Pe} =passive force per unit length of wall
- γ =unit weight of soil
- H =height of retaining wall
- K_{AE} =active earth pressure coefficient
- ϕ =soil friction angle
- δ =angle of friction between wall and soil
- β =slope of back of the wall with respect to vertical
- i =slope of backfill with respect to horizontal

III. PSEUDO-DYNAMIC METHOD

A vertical rigid retaining wall is considered in the analysis. All types of seismic waves are considered in this method such as Rayleigh wave, shear wave, primary wave. The backfill behind the retaining wall is considered to be cohesion less material. During earthquake conditions the shear and primary wave velocities V_s and V_p are shown in the figure. These seismic wave velocities are the function of soil parameters like shear modulus of soil (G), density of soil (ρ), Poisson's ratio of soil (ν) and Rayleigh wave velocity is a function of K_R , where K_R is wave number for Rayleigh wave.

A thin element of thickness dz at distance of z from top having width dx is at a distance x from the wall as shown in the figure.

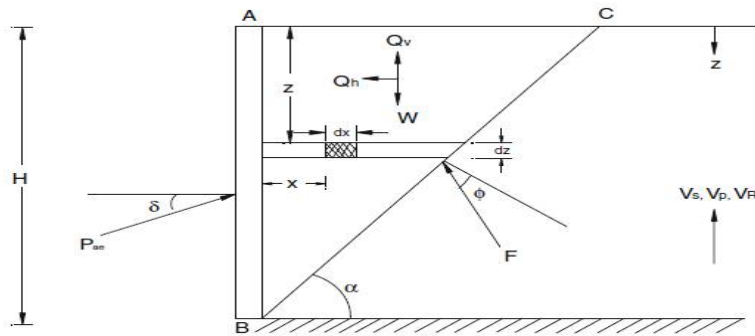


Fig vertical retaining wall considered for the active earth pressure calculations

The total (static and dynamic) active earth pressure is estimated by resolving forces on the wedge with the help of limit equilibrium approach and shown as,

$$P_{ae}(t) = \frac{W \sin(\alpha - \phi) \pm Q_h \cos(\alpha - \phi) \pm Q_v \sin(\alpha - \phi)}{\cos(\delta + \phi - \alpha)} \quad (6)$$

The seismic active earth pressure coefficient (K_{ae}) is defined as,

$$K_{ae} = \frac{2P_{ae}(t)}{\gamma H^2} \quad (13)$$

$$K_{ae} = \frac{1}{\tan \alpha} \frac{\sin(\alpha - \phi)}{\cos(\delta + \phi - \alpha)}$$

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$$\begin{aligned}
 & - \left\{ Q_h \left\{ \frac{\gamma k_h}{(-K_R)g \tan \alpha} \frac{\sin(\omega t + \frac{K_R H}{\tan \alpha}) - \cos \omega t}{\sin(\omega t - K_R x)} \left[\frac{2q e^{-qH}}{q^2} - \frac{2q K_R e^{-sH}}{(S^2 + K_R^2)(s)} \right] \frac{\cos(\alpha - \phi)}{\cos(\delta + \phi - \alpha)} \right\} + \right. \\
 & \left. \left\{ \frac{(2)k_v}{(-K_R)\tan \alpha} \frac{\cos(\omega t + \frac{K_R H}{\tan \alpha}) - \sin \omega t}{\cos(\omega t - K_R x)} \left[\frac{2q K_R^2 e^{-qH}}{(s^2 + K_R^2)q^2} - \frac{e^{-qH}}{q K_R} \right] \frac{\sin(\alpha - \phi)}{\cos(\delta + \phi - \alpha)} \right\} \right\} \quad (7)
 \end{aligned}$$

The seismic active earth pressure distribution is obtained by differentiating the total seismic active resistance acting on the retaining wall with respect to the depth of the wall.

$$\begin{aligned}
 p_{ae} = \frac{dp_{ae}(t)}{dz} &= \frac{\gamma z}{\tan \alpha} \frac{\sin(\alpha - \phi)}{\cos(\delta + \phi - \alpha)} \\
 & + \left\{ \frac{a_h \gamma z}{g(-K_R)\tan \alpha} \frac{\cos(\omega t + \frac{K_R z}{\tan \alpha}) - \cos \omega t}{\sin(\omega t - K_R x)} \left(e^{-qz} + \frac{2qs}{(s^2 + K_R^2)q^2} e^{-sz} \right) \frac{\cos(\alpha - \phi)}{\cos(\delta + \phi - \alpha)} \right\} - \\
 & \left\{ \frac{a_v \gamma z}{g(-K_R)\tan \alpha} \frac{\sin(\omega t + \frac{K_R H}{\tan \alpha}) - \cos \omega t}{\sin(\omega t - K_R x)} \left[\frac{2q K_R^2 e^{-qz}}{(s^2 + K_R^2)q^2} - \frac{e^{-qz}}{q K_R} \right] \frac{\sin(\alpha - \phi)}{\cos(\delta + \phi - \alpha)} \right\} \quad (8)
 \end{aligned}$$

PASSIVE RESISTANCE CASE

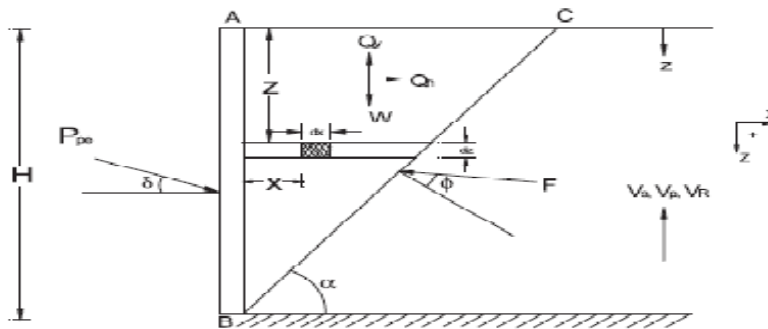


Fig vertical retaining wall considered for the active earth pressure calculations

Consider a fixed-base vertical cantilever wall AB of height H, supporting a horizontal cohesion less backfill as shown in Fig. An element of thickness dz at distance of z from top of retaining wall having width dx at distance x from the wall.

Total (static and dynamic) passive resistance derived by resolving forces on the wedge with the help of limit equilibrium approach

$$P_{pe}(t) = \frac{W \sin(\alpha + \phi) \pm Q_h \cos(\alpha + \phi) \pm Q_v \sin(\alpha + \phi)}{\cos(\alpha + \delta + \phi)} \quad (9)$$

The seismic passive earth pressure coefficient (K_{pe}) is given as

$$K_{pe} = \frac{2p_{pe}(t)}{\gamma H^2} \quad (10)$$

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$$\begin{aligned}
 K_{pe} &= \frac{1}{\tan \alpha} \frac{\sin(\alpha + \phi)}{\cos(\alpha + \delta + \phi)} \\
 &- \left\{ \frac{2a_h}{g\gamma H^2 (-K_R) \tan \alpha} \frac{\cos \left[\omega t - K_R \left(\frac{H}{\tan \alpha} \right) \right]}{\sin(\omega t - K_R(x)) \left[e^{-qz} + \frac{2qs}{[s^2 + K_R^2]q^2} e^{-sz} \right]} \left[\frac{2qe^{-qH}}{q^2} - \frac{2qK_R e^{-sH}}{[s^2 + K_R^2](s)} \right] \frac{\cos(\alpha + \phi)}{\cos(\alpha + \delta + \phi)} \right\} \\
 &+ \frac{2a_v}{g(-K_R)\gamma H^2 (K_R) \tan \alpha} \frac{\sin \left[\omega t - K_R \left(\frac{H}{\tan \alpha} \right) \right]}{\cos(\omega t - K_R(x))} \left[\frac{2q(K_R)e^{-sz}}{[s^2 + K_R^2](-s)} - \frac{e^{-qz}}{q} \right] \frac{\sin(\alpha + \phi)}{\left[\frac{2qK_R}{[s^2 + K_R^2]q^2} - \frac{qe^{-qz}}{K_R} \right] \cos(\alpha + \delta + \phi)} \quad (11)
 \end{aligned}$$

The distribution of the seismic passive earth pressure (p_{pe}) is given by

$$\begin{aligned}
 p_{pe}(t) &= \frac{dp_{pe}(t)}{dz} = \\
 &= \frac{\gamma z}{\tan \alpha} \frac{\sin(\alpha - \phi)}{\cos(\alpha + \delta + \phi)} \\
 &+ \left\{ \frac{a_h \gamma z}{g(-K_R) \tan \alpha} \frac{\cos[\omega t - K_R(x)]}{\sin(\omega t - K_R(x)) (e^{-qz} + Be^{-sz})(qz)} \frac{\cos(\alpha - \phi)}{\cos(\alpha + \delta + \phi)} \left[\frac{2qe^{-qH}}{q^2} \right. \right. \\
 &\quad \left. \left. - \frac{2qK_R e^{-sH}}{[s^2 + K_R^2](s)} \right] \right\} \\
 &- \frac{a_v \gamma z}{g(-K_R) \tan \alpha} \frac{\sin[\omega t - K_R(x)]}{\cos(\omega t - K_R(x))} \left[\frac{2q(K_R)e^{-sz}}{[s^2 + K_R^2](-s)} - \frac{e^{-qz}}{q} \right] \frac{\sin(\alpha - \phi)}{\left[\frac{2qK_R}{[s^2 + K_R^2]q^2} - \frac{qe^{-qz}}{K_R} \right] \cos(\alpha + \delta - \phi)} \quad (12)
 \end{aligned}$$

g = acceleration due to gravity;

H = height of retaining wall;

K_{pe} = seismic passive earth pressure coefficient;

K_R = wave number for Rayleigh wave;

k = seismic acceleration coefficient;

k_h, k_v = seismic acceleration coefficient in horizontal and vertical directions, respectively;

P_{pe} = dynamic passive resistance;

$$q = \sqrt{K_R^2 - \left(\frac{\omega^2}{V_p^2} \right)}$$

$$s = \sqrt{K_R^2 - \left(\frac{\omega^2}{V_s^2} \right)}$$

T = period of lateral shaking;

t = time;

V_p = primary wave velocity;

V_R = Rayleigh wave velocity;

V_s = shear wave velocity;

α = angle of inclination of failure surface to the horizontal;

γ = unit weight of soil;

δ = wall friction angle;

ϕ = soil friction angle; and

ω = angular frequency of base shaking.

Results and Discussions

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Shear wave velocity, $V_s = 80$ m/s, ratio of primary and shear wave velocity, $V_p/V_s = 1.87$ and ratio of Rayleigh and primary wave velocity, $V_R/V_p = \alpha K_{RS}$, where $\alpha = \sqrt{(1 - 2\nu)/(2 - 2\nu)}$ and

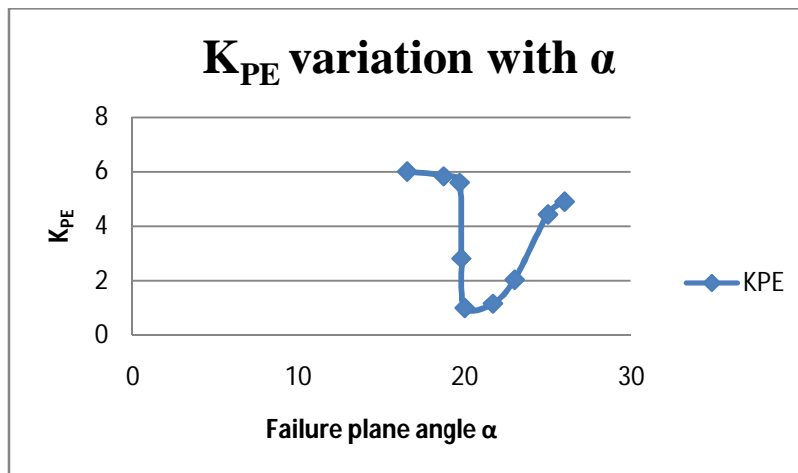
$$K_{RS}^6 - 8K_{RS}^4 + (24 - 16\alpha^2) K_{RS}^2 + 16(\alpha^2 - 1) = 0 \text{ with } K_{RS} = \frac{V_R}{V_s};$$

Unit weight of soil: $\gamma = 16$ KN/m³;

Height of wall: $H = 5$ m;

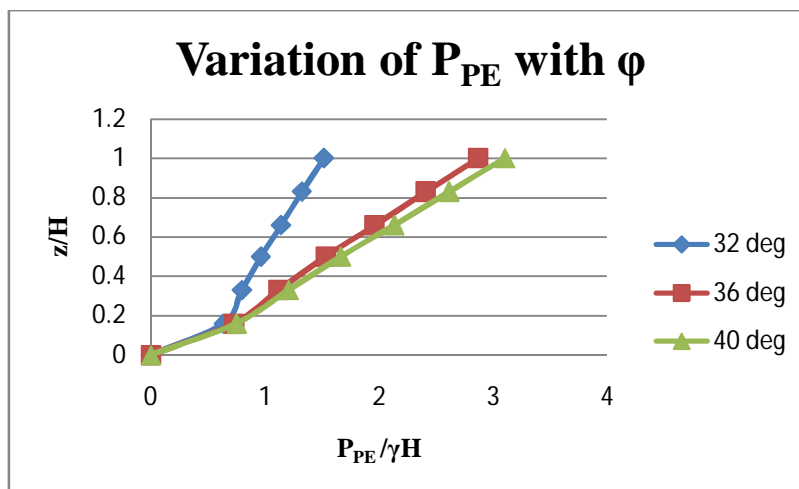
Poisson's ratio of soil: $\nu = 0.3$.

K_{pe} variation with the failure plane (α)



As the failure plane angle is increased the value for K_{pe} is decreasing and reaches to the minimum at 20° and then again it starts increasing, failure plane is taken as 20° .

Effect of soil friction angle on P_{pe}



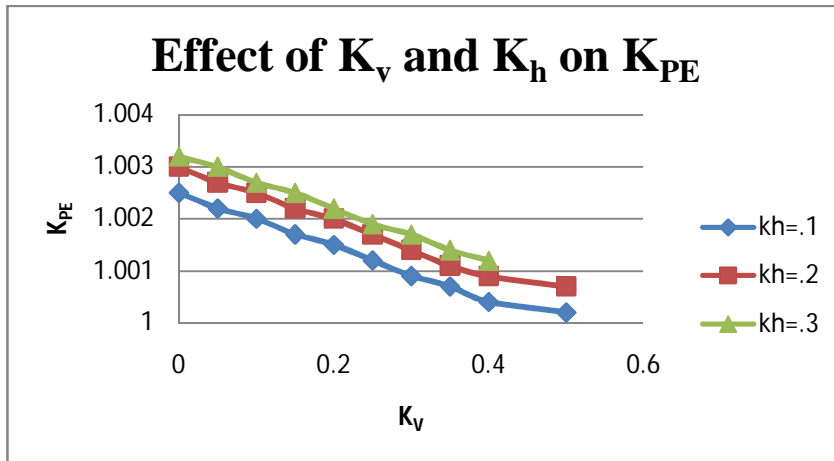
As the soil friction angle increases from 32° to 40° the passive earth pressure along the height of wall increase and it is found maximum for 40° soil friction angle. There is about 8.14% increase in passive pressure as soil friction angle increase from 36° to 40° at height ratio $z/H = 1$

Effect of K_h and K_v on the K_{pe}

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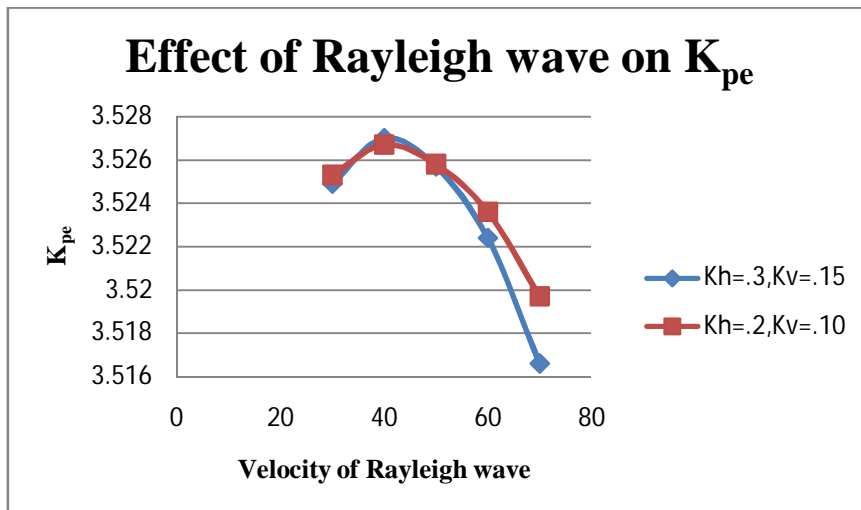
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As the value of seismic horizontal coefficient is increasing the K_{pe} value increases and as the seismic vertical coefficient value is increases K_{pe} is decreasing.

Effect of the Rayleigh wave velocity on K_{pe}



As the Rayleigh wave velocity is increases K_{pe} increases and reaches maximum for 40 m/s the value of K_{pe} is reduced.

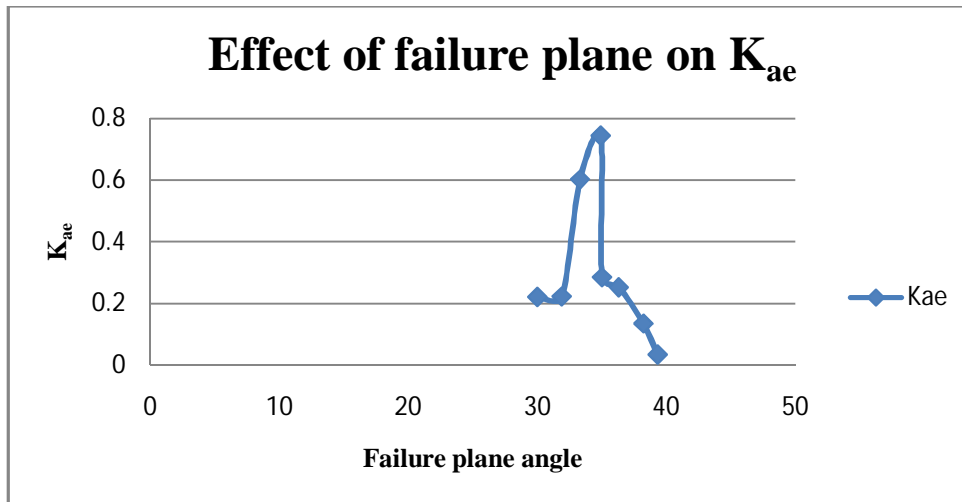
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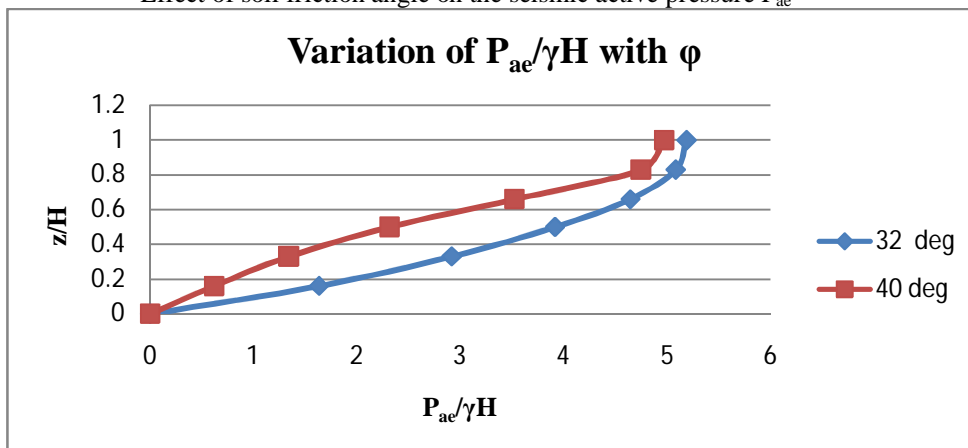
Effect of failure plane on K_{ae}

Soil friction angle (α) = 32°
 $t/T = 0.03$



As the failure plane angle increase the K_{ae} value also increases and reaches maximum for 34.9° . After that value of K_{ae} reduces.

Effect of soil friction angle on the seismic active pressure P_{ae}



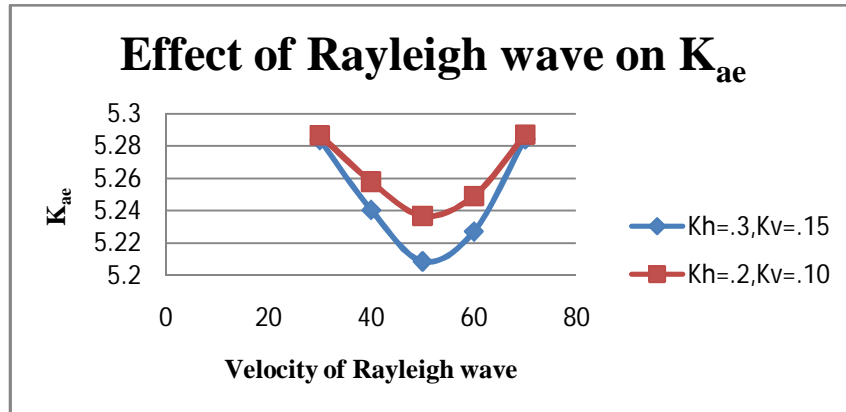
As the value of soil internal friction angle increase the seismic active pressure distribution value gets decreased. There is decrease of 4.20% in $P_{ae}/\gamma H$ value when soil friction angle increase from 32° to 40° at $z/H=1$.

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Effect of Rayleigh wave velocity on K_{ae}



As the Rayleigh wave velocity is increased value of K_{ae} is reduced and reaches minimum for 50m/s. After that as velocity increases the value of K_{ae} is increased.

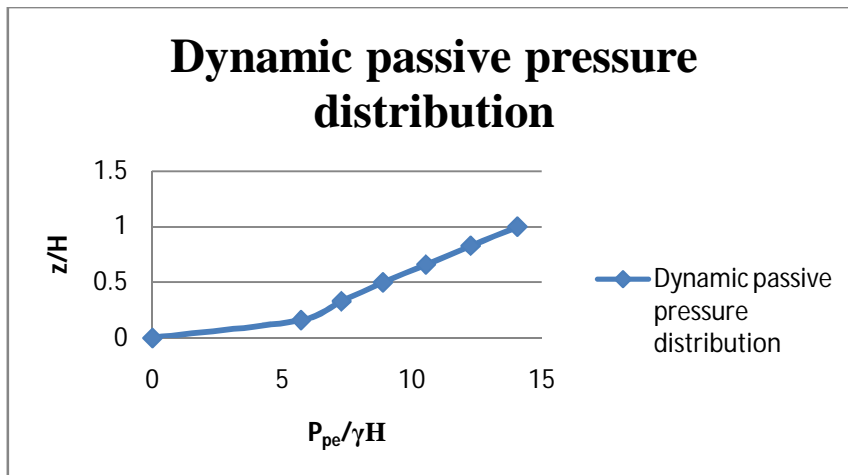
Comparison of Seismic passive pressure by Mononobe –Okabe and Deepankar Chaudhury (new method)

Soil friction angle = 32°

Wall friction angle = $\phi/2$

$K_h = 0.2, K_v = 0.5 K_h$

$t/T = 0.40$

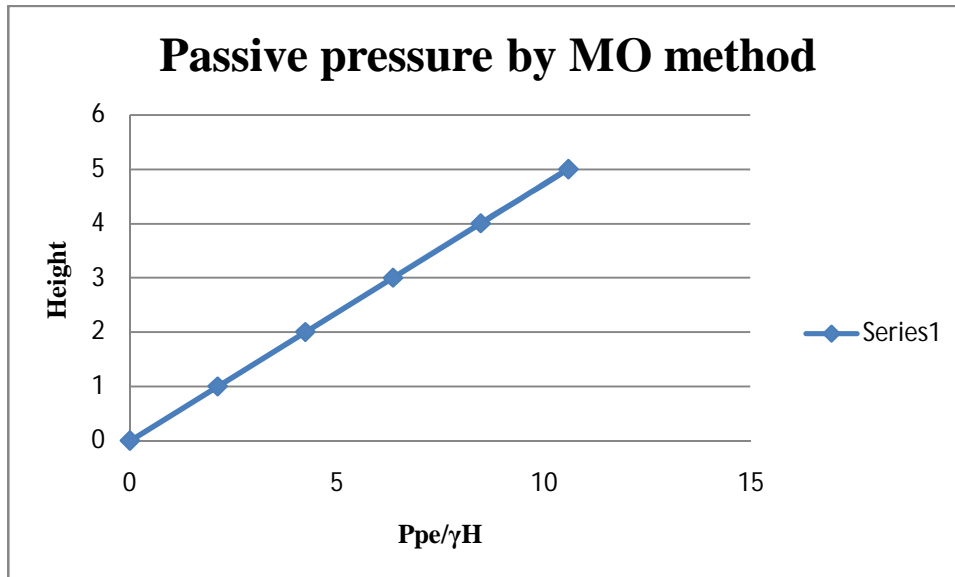


This figure shows the variation of the dynamic passive pressure distribution along the ratio of z/H . As the z/H value increases the passive pressure increases. It is maximum at $z/H=1$.

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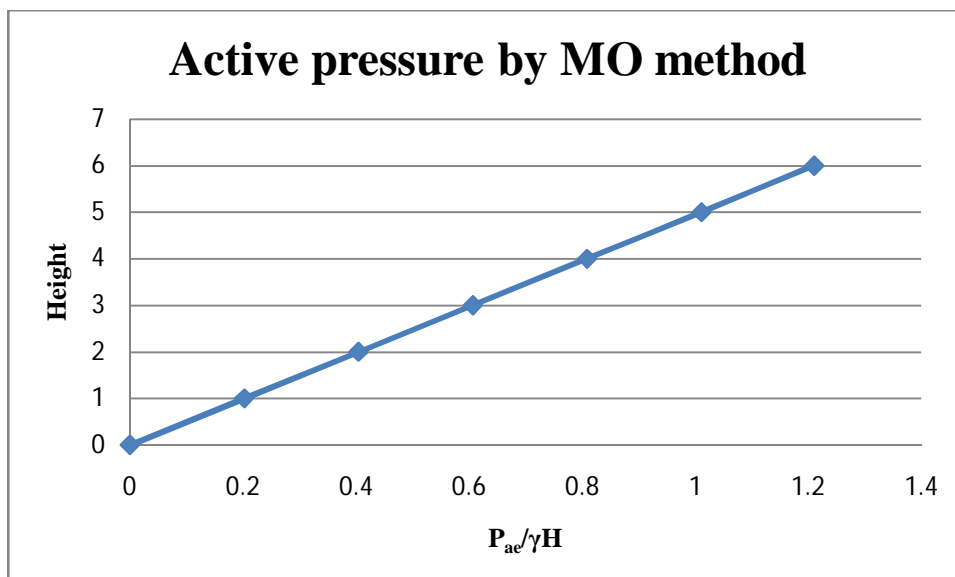


This figure shows the variation of passive earth pressure provided by Mononobe-Okabe method. There is linear variation along the height of the wall.

As the height of the retaining wall increases the seismic passive pressure also increases while comparing the seismic passive pressure by New method and Mononobe –Okabe method it is found that there is increase of pressure by 10.56%.

Comparison of seismic active pressure by MO and Deepankar Chaudhury (New method)

Soil friction angle = 32°
Wall friction angle = $\phi/2$
 $K_h = 0.2$, $K_v = 0.5 K_h$
 $t/T = 0.40$
 $K_{ae} = 0.449$

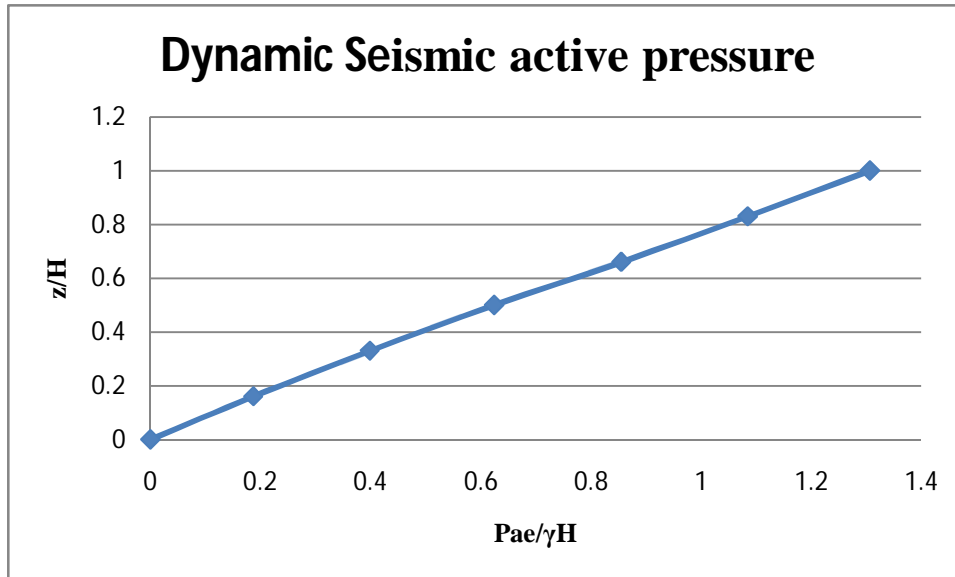


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This figure shows the variation of active earth pressure by Mononobe-Okabe method. Linear variation along the height of wall is found.

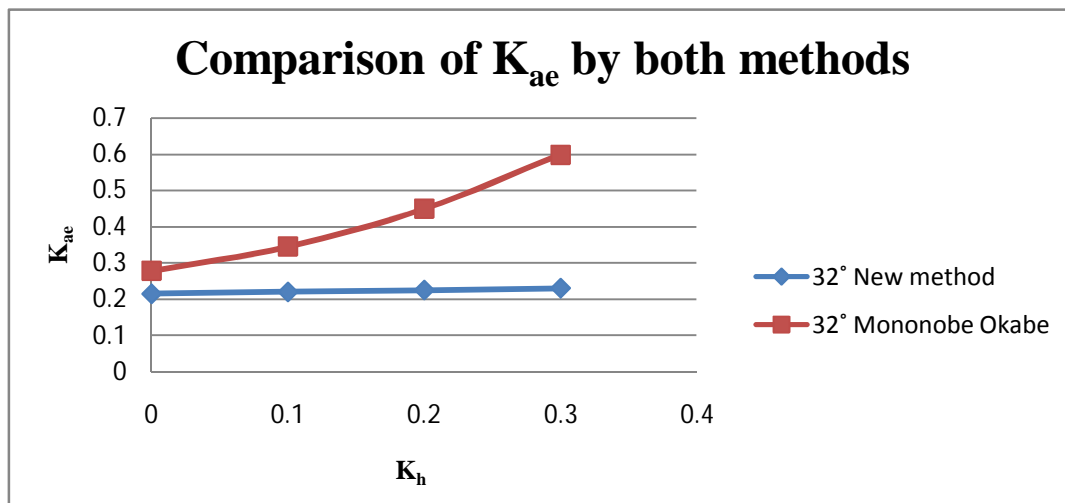


This figure shows the seismic active earth pressure by Deepankar Chowdhury latest method. Active earth pressure variation increases as z/H ratio increases. It is maximum for z/H=1.

As the height of the retaining wall increases the seismic active pressure increases. While comparing with the New method and MO method there is increase of 7.97% in the pressure.

COMPARISON OF K_{AE} BY BOTH METHODS:

Soil friction angle = 32°
Wall friction angle = $\phi/2$
 $K_h = 0, 0.1, 0.2, 0.3$



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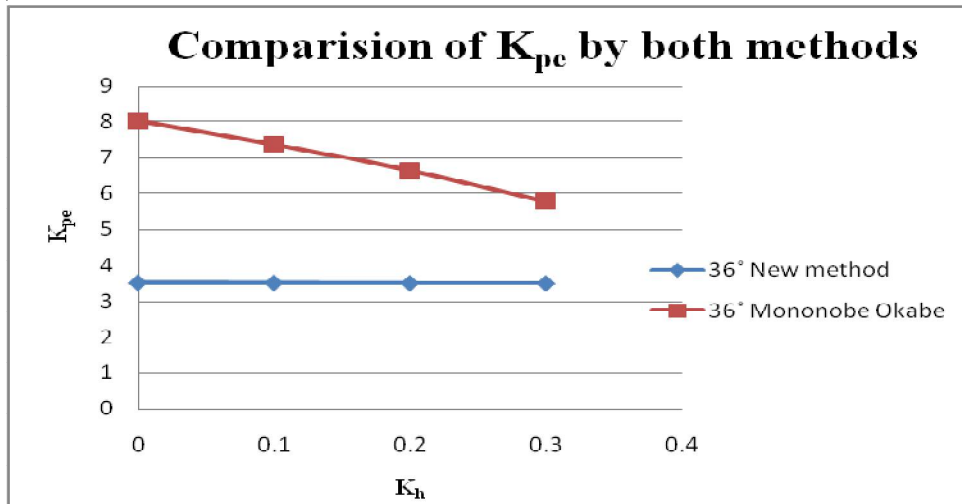
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As the value of k_h increases the value for K_{ae} also increases in both the methods. There is decrease of 61.18% in K_{ae} value in New method from MO method.

COMPARISON OF K_{pe} BY BOTH METHODS

Soil friction angle = 36°
Wall friction angle = $\phi/2$
 $K_h = 0, 0.1, 0.2, 0.3$



As the value of k_h increases, K_{pe} decreases in both the methods. There is decrease of 49.24 % in K_{pe} value in New method from MO method.

IV. CONCLUSIONS

Deepankar Chaudhury (new pseudo-dynamic) method includes all wave i.e primary waves shear waves and Rayleigh waves. For the pseudo-static analysis Mononobe –Okabe method is used... While comparing seismic active pressure by New method and Mononobe –Okabe method, it is found that there is an increase of 7.97%. In passive pressure comparison of New method with MO method there is increase of 10.56%. There is a decrease of 61.18% in K_{ae} value when compared by both the method. K_{pe} difference is of 49.24%. The difference in various values is due to the inclusion of the effect of Rayleigh wave. Therefore the effect of Rayleigh waves in the analysis of retaining wall is necessary.

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