Seismic Active Earth Pressure behind Retaining Wall

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Abstract: Knowledge of seismic active earth pressure behind rigid retaining wall is very important in the design of retaining wall in earthquake prone region. Commonly used Mononobe-Okabe method considers pseudo-static approach. This gives linear distribution of seismic earth pressure in an approximate way. A recently developed pseudo-dynamic method incorporates time dependent effect of applied earthquake load in a more realistic manner. This method gives a non-linear variation of seismic earth pressure along the depth of the wall. This research intends to compute the distribution of seismic active earth pressure on a cantilever retaining wall supporting cohesionless backfill. The variation in seismic earth pressure due to the effect of a wide range of parameters is included in this study. These parameters are wall friction angle, angle of internal friction of soil, shear wave and primary wave velocity of backfill soil, horizontal and vertical seismic accelerations. Expected results are to be in graphical non dimensional form which will compare the linear distribution given by the pseudo static method.

Key words: Seismic earth pressure, retaining wall, pseudo dynamic method

INTRODUCTION

The damage of retaining wall under seismic forces has been due to the increase in the pressure resulting from the movement of the structure during earthquake. Earthquake loading may result in a residual force on the wall, which may be as much as 30% greater than the static active force. Therefore, separate evaluation of dynamic earth pressure and stresses on the retaining structures should be done for retaining wall constructed in seismic area.

One common approach to the seismic design of retaining walls involves estimating the loads imposed on the wall during earthquake shaking and then ensuring that the wall can resist those loads. In the design of retaining wall, the earth pressure has to be computed properly. The most commonly used methods to determine the earth pressure of the retaining structures under seismic conditions are the force equilibrium based pseudo-static analysis, pseudo-dynamic analysis and the displacement based sliding block methods

FORCE BASED ANALYSIS

Pseudo-static analysis

The common form of pseudo-static analyses considers the effects of earthquake shaking by pseudo-static accelerations that produce inertial forces, F_h and F_v, which act through the centroid of the failure mass in the horizontal and vertical directions respectively [1]. The magnitude of the pseudo-static forces are

$$F_h = \frac{\propto_h W}{g} = K_h W$$

$$F_v = \frac{\propto_v W}{g} = K_v W$$

Where αh and αv are the horizontal and vertical pseudo-static accelerations

k_h, k_v = coefficient of horizontal and vertical pseudo-static accelerations

W = weight of the failure mass

Pseudo dynamic method of seismic active earth pressure

In the pseudo static method, the dynamic nature of earth quake loading is considered in a very approximate way without taking any effect of time. To overcome this drawback, the time and phase difference due to finite shear wave propagation behind a retaining wall was considered using a simple and more realistic way of pseudo dynamic method, proposed by Steedman and Zeng. In their analysis, they considered a vertical rigid retaining wall supporting a particular value of soil friction angle (φ) and a particular value of seismic horizontal acceleration ($k_h g$), where g is the acceleration due to gravity) only. But the effect of various parameters such as wall friction angle (δ), soil friction angle (φ), shear wave velocity (V_s), primary wave velocity (V_p), both the horizontal and vertical seismic accelerations ($k_h g$ and $k_v g$) on the seismic active earth pressure are not considered in the pseudo-dynamic method by Steedman and Zeng. A complete study to determine the seismic active earth pressure behind a rigid retaining wall by pseudo-dynamic approach has been carried out by Deepankar Choudhary and S.Nimbalkar in a more general way. The present study is based on the expressions generated by D. Choudhary and S. Nimbalkar for computing seismic active earth pressure.

In this analysis [2] the effect of various parameters on the seismic active earth pressure behind a rigid retaining wall by pseudo-dynamic method such as:

(i) wall friction angle (δ),
(ii) soil friction angle (ϕ),
(iii) shear wave velocity (V_s),
(iv) primary wave velocity (V_p),
(v) horizontal seismic acceleration $(k_h g)$,
(vi) vertical seismic acceleration $(k_v g)$.

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It is assumed that the shear modulus (G) is constant with depth of retaining wall throughout the backfill. Only the phase and not the magnitude of accelerations are varying along the depth of the wall. The method is explained as follows:

A fixed base vertical cantilever rigid retaining wall of height H, supporting a cohesionless backfill material with horizontal ground is considered in the analysis as shown in figures 1 & 2. The shear wave velocity, V_s and primary wave velocity, V_p are assumed to act within the soil media due to earthquake loading.

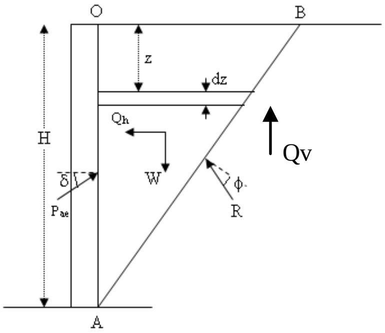


Fig.1 Model retaining wall for psuedo dynamic earth pressure

The shear wave velocity $V_s = \sqrt{\frac{G}{\rho}}$ …..(1)

where ρ is the density of backfill material and primary wave velocity

$$V_p = \sqrt{\left[G\left((2-2\nu)/\rho(1-2\nu)\right)\right]} \;\text{……………….. (2)}$$

where ν is the poisson's ratio of the backfill.

For most geological materials, $V_s/V_p = 1.87$

The period of lateral shaking, T = 2π/ω, where ω is the angular frequency is considered in the analysis.

Let the base of the wall is subjected to harmonic horizontal seismic acceleration, a_h (= k_hg) and harmonic vertical seismic acceleration a_v (= k_vg), the accelerations at any depth z and time t, below the top of the wall can be expressed as follows,

$$a_h\,(z,t) = a_h \sin\omega\left[\left(t-\frac{H-z}{V_s}\right)\right] \;\text{…….. (3)}$$

$$a_v\,(z,t) = a_v \sin\omega\left[\left(t-\frac{H-z}{V_p}\right)\right] \;\text{……… (4)}$$

The horizontal and vertical seismic accelerations acting on the soil wedge as described in equations (3) & (4) are not constants but dependent on effect of both, time and phase difference in shear and primary waves propagating vertically through the backfill

MATHEMATICAL MODEL

Seismic Active Earth Pressure

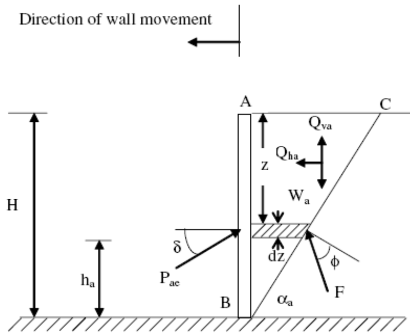


Fig.2 Error! Bookmark not defined. Model retaining wall for pseudo-dynamic active earth pressure

Fig. 2 shows the active state of earth pressure acting on the rigid retaining wall. A planar failure surface BC at an inclination of α_a with respect to horizontal is considered in the analysis. W_a is the weight of the failure wedge, Q_{ha} & Q_{va} are the horizontal and vertical seismic inertia force components, F is the soil reaction acting at an angle of ϕ (soil friction angle) to the normal to the inclined failure wedge, P_{ae} is the total active thrust acting at height h_a from the base of the wall at an inclination of δ (wall friction angle) to the normal to the wall.

The mass of a thin element of wedge at depth z is

$$m_a(z) = \frac{\gamma}{g}\frac{H-z}{\tan\alpha_a}dz$$

where, γ is the unit weight of the backfill.

The weight of the whole wedge is

$$W_a = \frac{1}{2}\frac{\gamma H^2}{\tan\alpha_a}$$

The total horizontal inertia force acting on the wall can be expressed as

$$Q_{ha}(t) = \int_0^H m_a(z)\cdot a_h(z,t)\,dz$$

$$= \frac{\lambda\gamma a_h}{4\pi^2 g\tan\alpha_a}[2\pi H\cos\omega\zeta + \lambda(\sin\omega\zeta - \sin\omega t)]$$

Again total vertical inertia force acting on the wall can be expressed as

$$Q_{va}(t) = \int_0^H m_a(z)\cdot a_v(z,t)\,dz$$

$$= \frac{\eta\gamma a_v}{4\pi^2 g\tan\alpha_a}[2\pi H\cos\omega\psi + \lambda(\sin\omega\psi - \sin\omega t)]$$

where λ = TV_s is the wavelength of the vertically propagating shear wave and

η = TV_p is the wavelength of the vertically propagating primary wave.

And ζ = t – H/V_s and ψ = t – H/V_p. As the horizontal acceleration is acting from left to right and vice-versa and the vertical acceleration is acting from top to bottom and vice-versa, only the critical directions of Q_{hs} (t) and Q_{vs} (t) are considered to result the maximum seismic active earth pressure.

The total (static + seismic) active thrust, P_{ae} can be obtained by resolving the forces on the wedge and considering the equilibrium of the forces and hence P_{ae} can be expressed as follows,

$$P_{ae} = \frac{W_a \sin(\alpha_a - \phi) + Q_{ha}\cos(\alpha_a - \phi) + Q_{va}\sin(\alpha_a - \phi)}{\cos(\delta + \phi - \alpha_a)} \quad \ldots\ldots..(5)$$

where W_a = Weight of the failure wedge in active case

α_a = Angle of inclination of the failure surface with the horizontal in active case

Q_{ha} = horizontal inertia force due to seismic accelerations in active case

Q_{va} = vertical inertia force due to seismic accelerations in active case

P_{ae} is maximized with respect to trial inclination angle of failure surface, α_a and then the seismic active earth pressure distribution, p_{ae} can be obtained by differentiating P_{ae} with respect to depth, z and can be expressed as follows,

$$p_{ae} = \frac{\gamma z}{\tan\alpha_a}\frac{\sin(\alpha_a - \phi)}{\cos(\delta + \phi - \alpha_a)} + \frac{k_h \gamma z}{\tan\alpha_a}\frac{\cos(\alpha_a - \phi)}{\cos(\delta + \phi - \alpha_a)}\sin\left[\omega\left(t - \frac{z}{V_s}\right)\right] + \frac{k_v \gamma z}{\tan\alpha_a}\frac{\sin(\alpha_a - \phi)}{\cos(\delta + \phi - \alpha_a)}\sin\left[\omega\left(t - \frac{z}{V_p}\right)\right] \quad \ldots\ldots(6)$$

Where $\omega = \frac{2\pi}{T}$ and

Wave length of shear wave, $\lambda = TV_s$

Wave length of primary wave, $\eta = TV_p$

For calculation and plotting graphs, the above equation is normalized with respect to height. The normalized active earth pressure distribution is given by [3]

$$\frac{p_{ae}}{\gamma H} = \frac{(z/H)}{\tan\alpha_a}\frac{\sin(\alpha_a - \phi)}{\cos(\delta + \phi - \alpha_a)} + \frac{k_h (z/H)}{\tan\alpha_a}\frac{\cos(\alpha_a - \phi)}{\cos(\delta + \phi - \alpha_a)}\sin\left[2\pi\left(\frac{t}{T} - \frac{z}{\lambda}\right)\right] + \frac{k_v (z/H)}{\tan\alpha_a}\frac{\sin(\alpha_a - \phi)}{\cos(\delta + \phi - \alpha_a)}\sin\left[2\pi\left(\frac{t}{T} - \frac{z}{\eta}\right)\right] \quad \ldots\ldots\ldots(7)$$

Assumptions:

The backfill material is homogeneous, cohesionless soil

The backfill surface is horizontal

The failure surface is planar

The failure surface is assumed to pass through the heel of the wall.

Different parameters

α = 20°, 30°, 40°, 50°

ϕ = 20°, 25°, 30° , 35°,40°, 45°,50°

δ = 0, 0.25ϕ, 0.5ϕ and ϕ

kh = 0.0g, 0.1g, 0.2g, 0.3g, 0.4g, and 0.5g

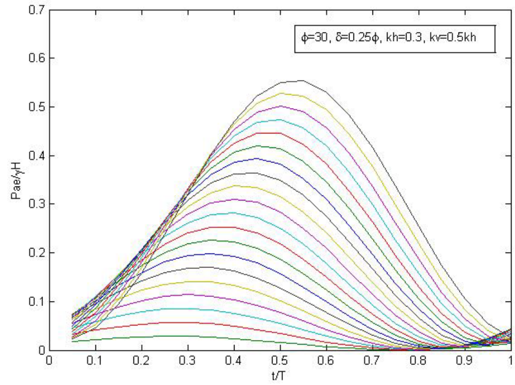
kv = 0.0kh,0.5kh and kh

β = 0

H/λ = 0.3 and H/η = 0.16

A program script was written in matlab for calculating the values of P_{ae} for different values of z/H and t/T. The program was run by changing the values of input parameters α, ϕ, δ, k_h & k_v and a database of results was generated.

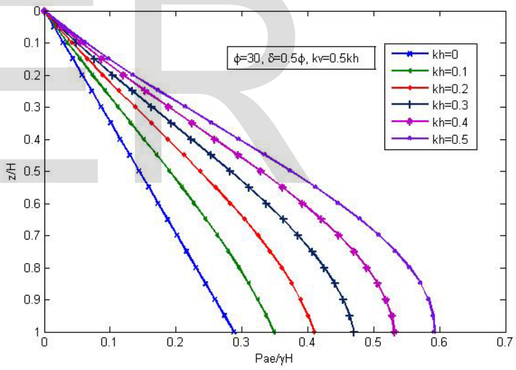
RESULTS AND DISCUSSIONS



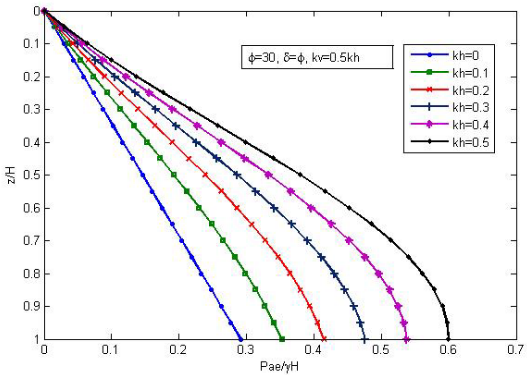
Graph 1 : Typical seismic active earth pressure distribution with respect to the normalized time period along the height of the wall.

The graph shows the effect of an earthquake with seismic horizontal acceleration 0.3g and vertical acceleration 0.15g acting on a retaining wall for a time period of T seconds. The maximum earth pressure will be felt at the base. This will be at a time period of 0.5 to 0.55T. The seismic active earth pressure increases from the top and reaches a peak at the base around half the time period. The earth pressure at any point from the top to the base of the retaining wall will reach a maximum between 0.25T and 0.50T

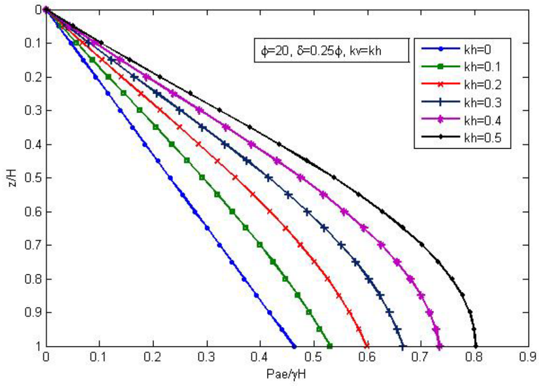
Effect of k_h on seismic active earth pressure, p_{ae}



Graph 2



Graph 3

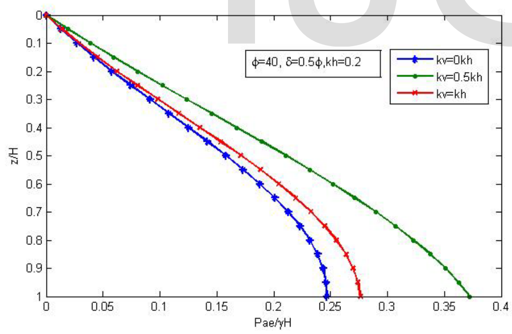


Graph 4

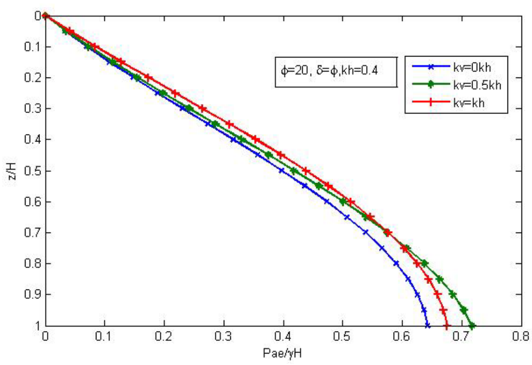
Effect of K_h on P_{ae}

Graphs 2, 3 and 4 show the variation of seismic active earth pressure distribution, p_{ae} when horizontal seismic coefficient, k_h is increased from 0 to 0.5g. As k_h increases p_{ae} also increases. The value of p_{ae} is maximum when k_h = 0.5g and $k_v = k_h$. This clearly shows the effect of horizontal acceleration in seismic active earth pressure. The seismic active earth pressure distribution, p_{ae} is linear when k_h =0, ie static condition. When k_h = 0.1 to0.5, variation of seismic active earth pressure is non-linear., Degree of of non-linearity of curve also increases for higher values of k_h. Near the top of the wall, the variation is almost linear. Non linearity increases towards the base of the retaining wall. The seismic active earth pressure becomes maximum towards the base of the wall.

Effect of k_v on P_{ae}



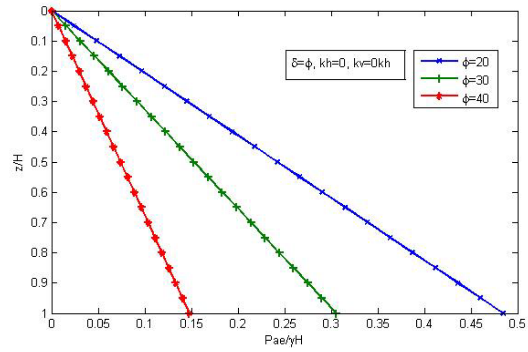
Graph 5



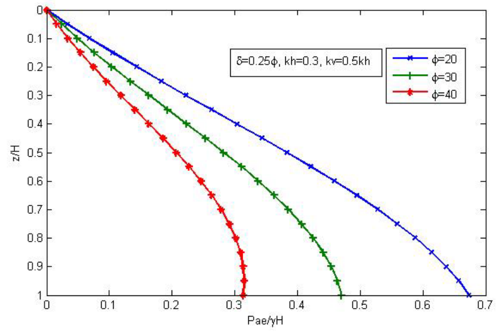
Graph 6

Graph 5 and 6 shows the effect of vertical seismic acceleration on p_{ae}. The value of p_{ae} increases with k_v for higher values of soil friction angle, ϕ. When ϕ reduces p_{ae} is more for k_v = 0.5kh than for $k_v = k_h$.

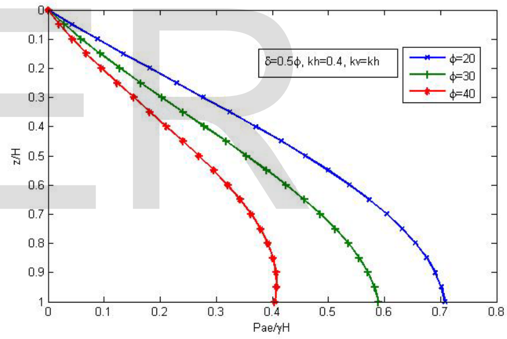
Effect of soil friction angle, ϕ



Graph 7



Graph 8

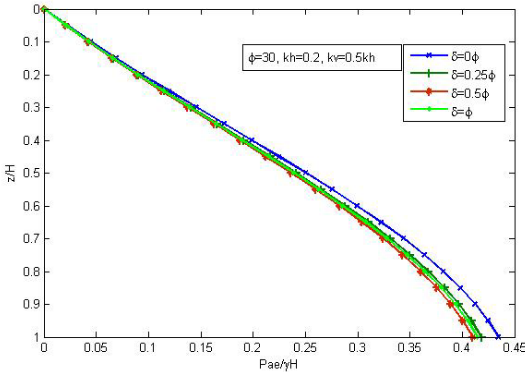


Graph 9

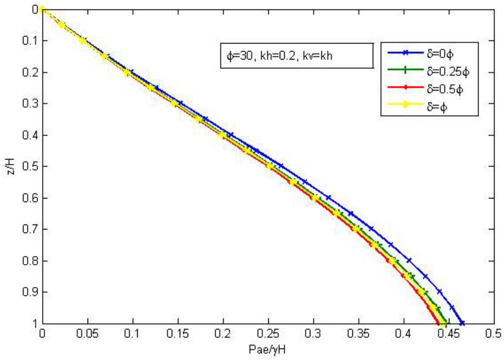
Graphs 7, 8 and 9 show the effect of soil friction angle, ϕ on seismic active earth pressure, p_{ae}. From the graphs, it can be seen that p_{ae} shows significant decrease with increase in value of soil friction angle. The value of p_{ae} in the three cases will be maximum when $\phi = 20^0$ and $k_v = 0.5\ k_h$

In graph 7, when k_h = 0 and k_v = 0, the seismic active earth pressure shows a linear variation. This is same as static condition. In graph 8, the difference in earth pressure at the base of the wall is more when $k_v = 0.5\ k_h$. This again confirms that for smaller values of ϕ, p_{ae} is more for k_v = 0.5kh than for $k_v = k_h$

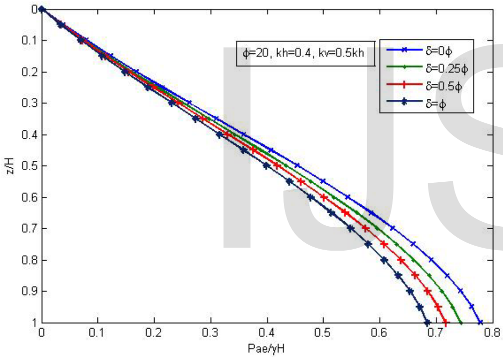
Effect of wall friction angle, δ



Graph 10



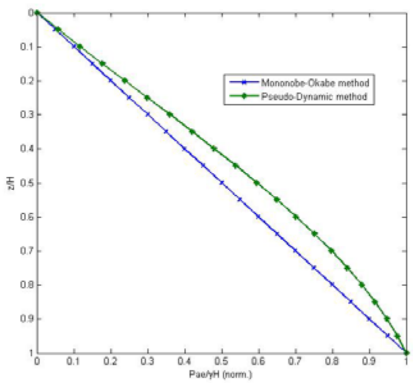
Graph 11



Graph 12

Graphs 10, 11 and 12 shows the normalized seismic active earth pressure distribution for different values of wall friction angle δ. For a particular value of ϕ, seismic active earth pressure decreases marginally as δ increases. The value of p_{ae} is almost equal when z/H is between 0.2 and 0.25

Comparison of Pseudo-Dynamic method and Pseudo-Static method



Graph 13

CONCLUSIONS

The pseudo-dynamic method of analysis by Choudhary and Nimbalkar, presented in this work highlights the effect of time and phase change in shear and primary wave propagating in the backfill behind the rigid retaining wall.

The following points are observed

1. The seismic active and passive earth pressure distribution behind the retaining wall by the pseudo-dynamic analysis is found to be non-linear. But the conventional Mononobe- Okabe method based on the pseudo-static method gives only linear earth pressure distribution irrespective of static and seismic condition.
2. The nonlinearity of active earth pressure distribution increases with increase in seismicity.
3. It is very clear that both horizontal and vertical seismic accelerations are significant for computing seismic earth pressures. Their significance increases as the earthquake intensity increases.
4. The seismic active earth pressure is highly sensitive to the friction angle of the soil,ϕ and comparatively less sensitive to the wall friction angle, δ.
5. The point of application of seismic earth pressure should be computed based on some logical analysis instead of selecting 1/3rd height from the base of the wall.

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