Effect on a retaining wall design by change in parameters using different approaches-a comparative study

Pattanaik, Amitansu
Defence Terrain Research Laboratory (DTRL), DRDO
Mecalfe House, Delhi-110054
E-Mail: amitansu@yahoo.com
Tripathi, Abhay
PG Student, Department of Civil Engineering
Madan Mohan Malviya University of Technology Gorakhpur, India
E-mail:abhtript@gmail.com

Abstract

This study presents role of parameters for the calculation of lateral earth pressures on a retaining wall by adopting different approaches of analysis. The variation of internal friction angle, wall inclination, soil wall friction angle and horizontal and vertical seismic coefficient produces considerable effects in the lateral earth pressures which is graphically as well as in tabular form is presented here and a comparative study of lateral earth pressure coefficients is shown for different methods of analysis. Most common methods for static design of retaining walls are Rankine method and Coulomb method. The seismic methods of analysis are -Pseudo static method, Seed- Whitman method and Mononobe - Okabe method. Analysis of retaining wall includes obtaining the factor of safety for sliding and overturning. For the purpose of analysis a concrete retaining wall is considered with the certain dimensions and the results after calculations shows that Mononobe- Okabe method gives overestimated values and seed and Whitman method (1970) is the most prominent method for earthquake prone areas as the values of factor of safety for this method are lowest. It is also shown that soil parameter if considered affects mostly the passive earth pressure coefficient

Keywords: Lateral Earth Pressures, seismic coefficients, soil parameters

1. Introduction:

Seismic design of retaining walls is very important area of research to decrease the earthquake devastating effects. Retaining wall purpose is to protect movement of retained soil and water. For designing a retaining wall we must know the soil parameters like unit weight, angle of internal friction, angle of wall friction, and wall inclination.

After obtaining lateral earth pressures, retaining walls are analysed for stability, which includes bearing capacity failures, overturning, and sliding. Based on present available methods, force and displacement analysis are used for seismic lateral earth pressures computations but here we have only considered Force-based analysis. The stability of retaining wall is normally analysed by Pseudo-static method where earthquake forces and effects are expressed as horizontal and vertical accelerations. This paper shows the effects of soil parameters in the design of earth retaining wall and suitability of method of computation to calculate the lateral earth pressures under static and seismic conditions.

2. Literature review:

There has been lot of literature available for the different approaches adopted in the present times for stability of slopes depending upon the forces acting and displacement occurred during a seismic activity, which are as follows:

Coulomb Theory (1776) -Coulomb was first to compute the lateral earth pressures on retaining structure. By assuming that the force acting on a retaining wall resulted from the weight of a wedge of soil above a planar failure surface, Coulomb used force equilibrium to compute the magnitude of the soil thrust acting on the wall for both active and passive conditions

Rankine Theory (1857): Rankine created the simplest method for computing Lateral earth pressures. Taking assumptions for the stress and strength of the soil behind a retaining wall, Rankine render the lateral earth pressure problem and compute the static lateral earth pressures acting on retaining walls.

Mononobe- Okabe (1929, 1926): Mononobe and Okabe started the pseudo-static analysis of seismic earth pressures on retaining walls which is popularly known as Mononobe-Okabe method. The M-O method is extension of the coulomb theory to pseudo-static condition, in this analysis accelerations are applied to coulomb active and passive wedge.

Log Spiral Method (1948): Caquot and Kerisel gave the values of lateral earth pressure coefficient based on the logarithmic spiral method, Although the major principal stress axis may be nearly perpendicular to the backfill surface at some distance behind a rough wall ($\delta>0$), the presence of shear stresses on the wall-soil interface can shift its position near the back of the wall.. In other words, the failure surface must be curved. A logarithmic spiral function has been used to describe such curved failure surfaces for lateral pressures

Terzaghi (1943): showed that for the passive case, when wall friction angle, δ, exceeds one-third of soil friction angle, φ, the assumption of planar failure surface seriously overestimates the passive earth pressures and for active conditions values match the experimental values

Newmark (1965): The first analysis of permanent displacement induced by an earthquake has been carried out by Newmark, referring to the simple case of a rigid block sliding on a plane surface subjected to an acceleration time history.

Slip Line Method (1965): In this method, we assume that failure occurs at constant volumes of soil along slip lines that meet the Mohr-Coulomb failure criterion. This method has the advantage of providing a statistically admissible stress state that satisfy the following equations of the plane equilibrium involving the normal, σ, and shear, τ, stresses and using a system of rectangular coordinates x, y with x-axis oriented in the vertical direction:

Richard-Elms (1979): He proposed a method based on allowable permanent wall displacements for the seismic design of a retaining wall. This method of analysis estimates permanent displacements in a manner analogous to the Newmark sliding block procedure. Application of Richard-Elms method requires evaluation of the yield acceleration for the wall –Backfill system.

Whitman-Liao Method (1985): He investigated errors that result from the assumptions of the Richard-Elms procedure. The most significant of these are ignorance of dynamic response of the backfill, ignorance of kinematic factors, neglecting of tilting and vertical accelerations

Steedman- Zing Method (1990): To account for certain dynamic response characteristics in a relatively simple manner this method was introduced. Phase difference and amplification effects within the backfill are also considered here.

Zhang et al. (1998) : correlated the lateral earth pressure coefficient and the strain increment ratio and developed a new study for determining the lateral earth pressure between the active and passive states., Zhang et al. Gave extension of Mononobe-Okabe method to new earth pressure formulas for determining the dynamic lateral earth pressure.

Choudhury and Subba Rao (2002): They gave design charts for the estimation of seismic passive earth pressure coefficient for negative wall friction case..

Nimbalkar and Choudhary(2005): Planar rupture surface is considered in the analysis. Effects of a wide range of parameters like wall friction angle, soil friction angle, shear wave velocity, primary wave velocity and horizontal and vertical seismic accelerations on seismic active earth pressure have been studied.

Shukla et al. (2009): have described the derivation of an analytical expression for the total active force on the retaining wall for c-ϕ soil backfill considering both the horizontal and vertical seismic coefficients.

Puri and Prakash (2011): The method includes the effect of cohesion in the soil, adhesion between the retaining wall and backfill, the inclination of the backfill, horizontal and vertical seismic coefficients, surcharge on the backfill, and the inclination of the wall face and the backfill.

3. Essential steps of analysis:

(1) Sliding: The factor of safety for sliding can be expressed as the resisting force divided by the driving force.

$$F.S = (N \tan \delta + P_P)/P_H \qquad \text{(eqn- 1)}$$

N = Sum of the weight of the wall, footing and vertical component of the active earth pressure resultant force.

P_p = allowable passive resultant force divided by the reduction factor

P_H = Horizontal component of the active earth pressure resultant force

For static conditions the typical recommendation for minimum factor of safety for sliding are 1.5 to 2

Overturning: The factor of safety for overturning of the retaining wall can be calculated by taking moments about the toe of the footing and is:

F.S = Wa/(1/3PHH --Pve) (eqn-2)

a=lateral distance from the resultant weight W of the wall and footing to the toe of the footing.

P_H = horizontal component of the active earth pressure resultant force

P_v = active earth pressure resultant force (vertical component)

e = lateral distance from the location of PVto the toe of the wall.

For static conditions, typical recommendation for minimum factor of safety for overturning is 1.5 to 2

4. Parametric study based on different methods:

To design a retaining wall an engineer must know the basic soil parameter which includes unit weight, angle of internal friction, angle of wall friction, cohesion, wall inclination maximum acceleration and height of retaining wall. Knowing the properties of soil behind the wall helps the engineer to determine the Lateral pressure distribution that has to be considered in the design.

Rankine theory:

Rankine (1857) Rankine was able to render the lateral earth pressure problem determinate and directly compute the static pressures acting on retaining walls.

Active earth pressure:

$$(P_A) = \frac{1}{2}k_A\gamma_t H^2 \qquad \text{(eqn- 3)}$$

$$k_A = \tan^2(45^0 - \frac{1}{2}\phi) \qquad \text{(eqn- 4)}$$

Passive earth pressure:

$$(P_p) = \frac{1}{2}k_p\gamma_t D^2 \qquad \text{(eqn- 5)}$$

$$K_p = \tan^2(45^0 + \frac{1}{2}\phi) \qquad \text{(eqn- 6)}$$

$$K_A = \frac{\cos^2(\Phi-\beta)}{\cos^2\beta\cos(\delta-\beta)[1+\sqrt{\frac{\sin(\delta+\beta)\sin(\Phi-\varepsilon)}{\cos(\delta+\beta)\cos(\varepsilon-\beta)}}]^2} \qquad \text{(eqn-7)}$$

$$K_P = \frac{\cos^2(\Phi+\beta)}{\cos^2\beta\cos(\delta-\beta)\left[1+\sqrt{\frac{\sin(\delta+\beta)\sin(\Phi-\varepsilon)}{\cos(\delta-\beta)\cos(\varepsilon-\beta)}}\right]^2} \qquad \text{(eqn-8)}$$

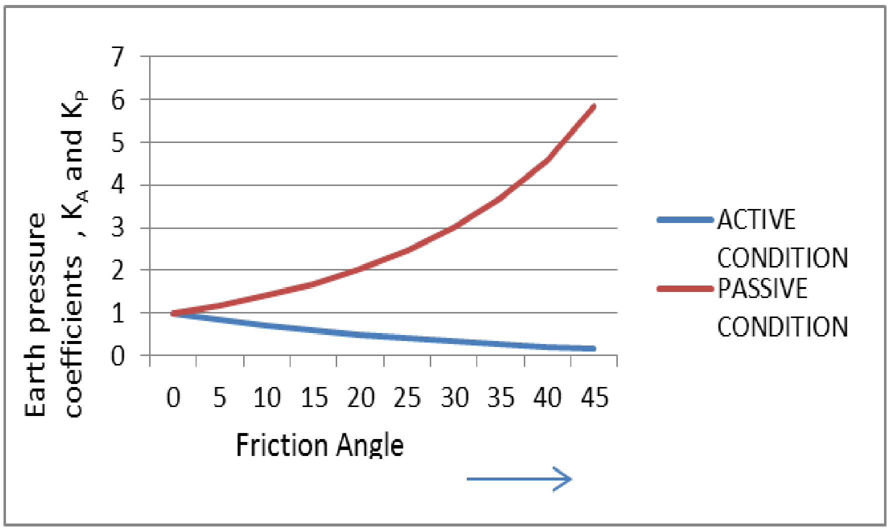

Figure 1 Variation of active pressure coefficient and passive pressure coefficient w.r.t Friction Angle.

We have observed that increase in friction angle increases the passive earth pressure coefficient (K_P) and decreases the active earth pressure coefficient (K_A)

This method do not take account of wall friction angle but Height of retaining wall, Passive and active earth pressure coefficient and weight of backfill are directly proportional to Active and passive earth pressure and hence increases for larger values of such parameters.

Coulomb method:

Coulomb used force equilibrium to determine the magnitude of the soil thrust acting on the wall for both minimum active and maximum passive conditions.. In contrast to the Rankine approach, Coulomb theory can be used to predict soil thrust on walls with irregular backfill slopes, concentrated loads on the backfill surface, and seepage forces.

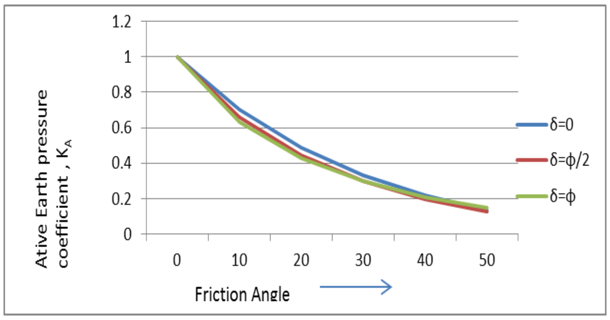

Figure 2 Variation of active pressure coefficient w.r.t friction Angle.

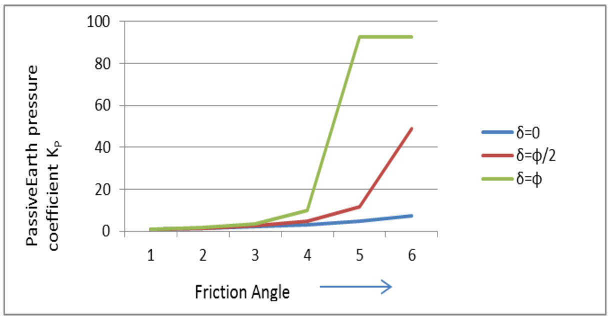

Figure 3 Variation of passive pressure coefficient w.r.t Friction Angle

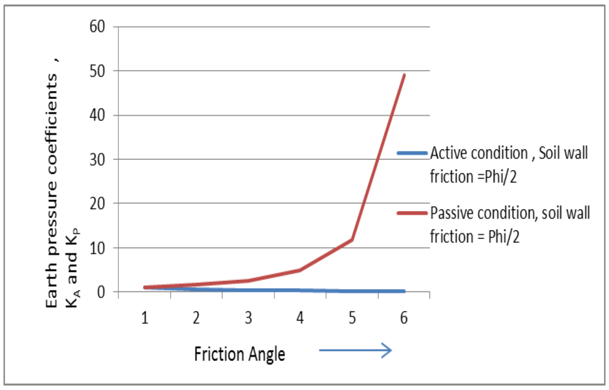

Figure 4 Variation of active and passive pressure coefficients w.r.t Friction Angle

By Coulomb method we have observed that increase in friction angle increases the passive earth pressure coefficient (K_P) and decreases the active earth pressure coefficient (K_A).This method take account of wall friction angle, inclination angle of the wall internal face respect to vertical inclination and angle of the backfill respect to horizontal. Increase in wall friction angle decreases the active pressures coefficients and increases the passive pressure coefficients.

Logarithmic spiral method:

If the inclination of the principal stress axes varies within the backfill, the inclination of the failure surface must also vary. In other words, the failure surface must be curved. A logarithmic spiral function has been used to describe such curved failure surfaces for active and passive earth pressure conditions. The effect of wall friction on the shape of the critical failure surface is more noticeable for passive earth pressure conditions. The passive failure surface also has curved and linear portions, but the curved portion is much more pronounced than for active conditions.

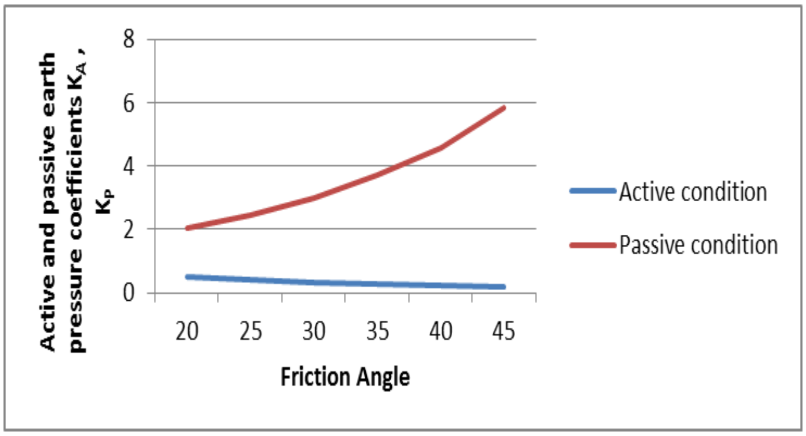

Figure 5 Variation of active and passive pressure coefficients w.r.t Friction Angle

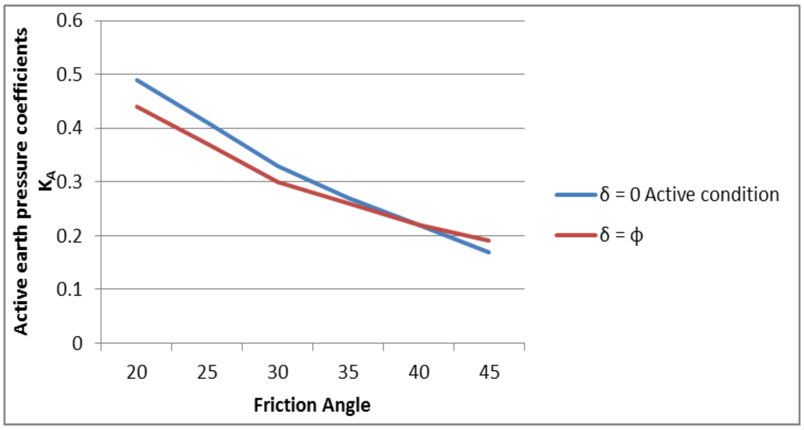

Figure 6 Variation of active pressure coefficient w.r.t Friction Angle

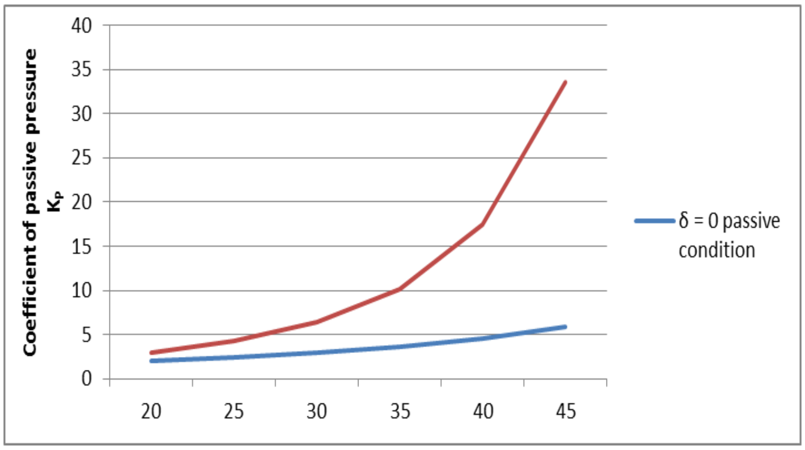

Figure 7 Variation of passive pressure coefficient w.r.t Friction Angle

The active earth pressure coefficients given by the log spiral approach are generally considered to be slightly more accurate than those given by Rankine or Coulomb theory, but the difference is so small that the more convenient Coulomb approach is usually used. The passive earth pressure coefficients given by the log spiral method are considerably more accurate than those given by Rankine or Coulomb theory; the Rankine and Coulomb coefficients tend to under predict and over predict the maximum passive earth pressure, respectively. Rankine theory greatly under predicts actual passive earth pressures and is rarely used for that purpose. Coulomb theory over predicts passive pressures (an unconservative error) by about 11% for $\delta=\varphi/2$ and 100% for $\delta=\varphi$. For that reason, Coulomb theory is rarely used to evaluate passive earth pressures when $\delta>\varphi/2$.

Mononobe-Okabe method:

The M-O method is a direct extension of the static Coulomb theory to pseudo static. In a M-O analysis, pseudo static accelerations are applied to a Coulomb active (or passive) wedge. The pseudo static soil thrust is then obtained from the force equilibrium of the wedge. In addition to those under static conditions, the forces acting on an active wedge in a dry cohesion less backfill wedge are constituted by horizontal and vertical pseudo static forces whose magnitudes are related to the mass of the wedge by the pseudo static accelerations $a_h = k_h g$ and $a_v = k_v g$. The total active thrust can be expressed in a form similar to that developed for static conditions, As a pseudo static extension of the Coulomb analysis, however, the M-O analysis is subject to all of the limitations of pseudo static analyses as well as the limitations of Coulomb theory. The determination of the appropriate pseudo static coefficient is difficult and the analysis is not appropriate for soils that experience significant loss of strength during earthquakes (e.g. liquefiable soils). Just as Coulomb theory does under static conditions, the M-O analysis will over predict the actual total passive thrust, particularly for $\delta > \varphi/2$. For these reasons the M-O method should be used and interpreted carefully.

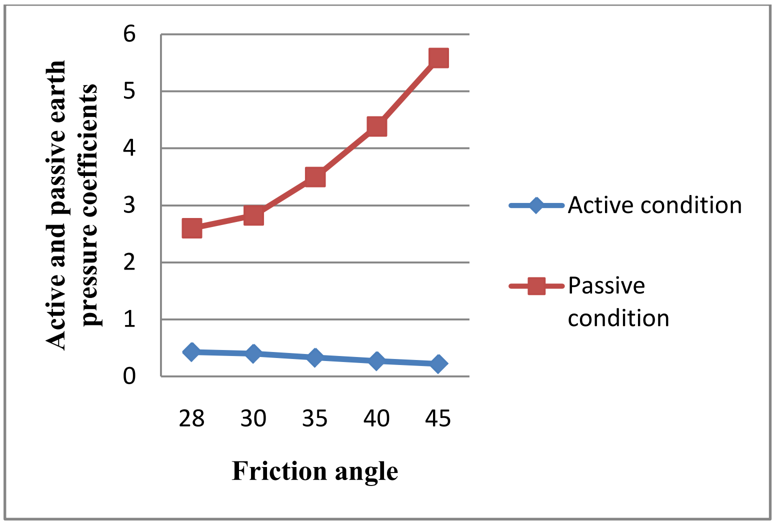

Figure 8 Variation of active and passive pressure coefficients w.r.t Friction Angle

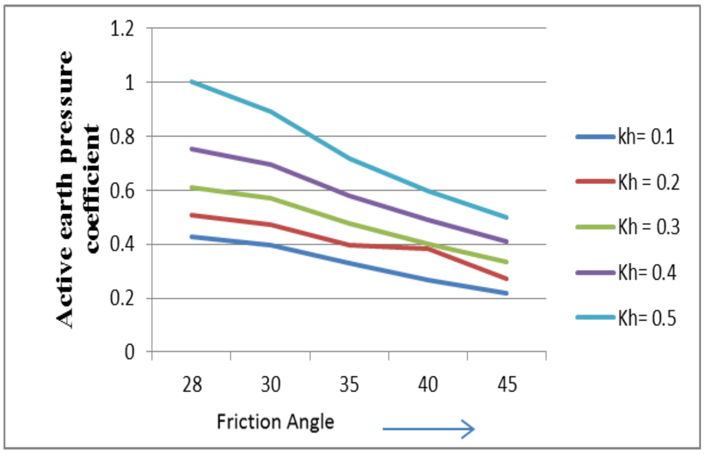

Figure 9 Variation of active pressure coefficient w.r.t Friction Angle

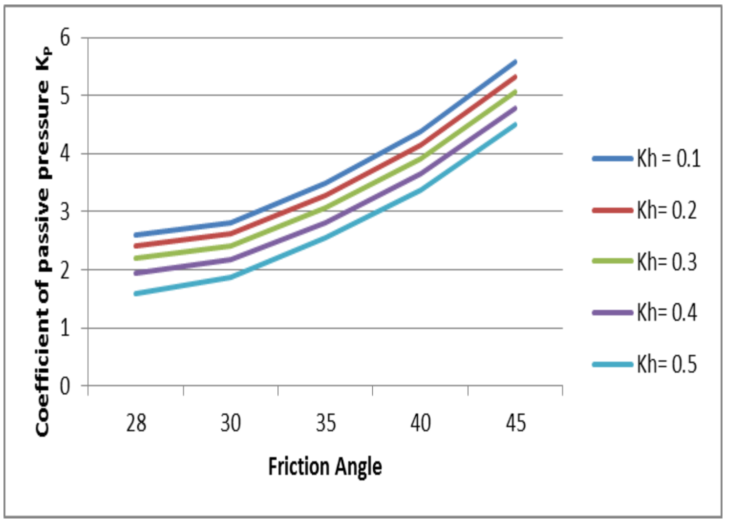

Figure 10 Variation of passive pressure coefficient w.r.t Friction Angle

The graphical representations of the seismic earth pressure coefficients and the critical failure surfaces in active and passive conditions evaluated with the M-O method for vertical walls retaining a horizontal backfill are plotted. The figures denote a slight influence of the soil-wall friction on the seismic active conditions while, as in the Coulomb method, strong differences exist in the passive case. Although conceptually quite simple, the M-O analysis provides a useful means of estimating earthquake-induced loads on retaining walls. A positive horizontal acceleration coefficient causes the total active thrust to exceed the static active thrust and the total passive thrust to be less than the static passive thrust. Since the stability of a particular wall is generally reduced by an increase inactive thrust and/or a decrease in passive thrust, the M-O method produces seismic loads that are more critical than the static loads that act prior an earthquake. For the passive case, the most critical sliding surface is much different from a planar surface as is assumed in the M-O analysis. The *KPEn* values are seriously overestimated by the M-O method. They are, in most cases, higher than those obtained by the limit analysis. This is especially the case when the wall is rough and the angle of wall repose is large.

Seed and Whitman method:

Seed and Whitman in 1970 derived an equation which can be used to find the lateral pseudo static force acting on the retaining wall:

$$P_E = \frac{3}{8}\frac{a_{max}}{g}H^2\gamma_t$$

According to Seed and Whitman the location of the Pseudo static can be assumed to be acting at a distance of 0.6*H* above the base of the wall and in this method earth pressure coefficients are calculated by adding additional factor of ΔK_A, ΔK_P for seismic considerations

$$K_{AE} = K_A + \Delta K_A = K_A + 0.75K_h \qquad \text{(eqn- 9)}$$

$$K_{PE} = K_P + \Delta K_P = K_P - 2.125K_h \qquad \text{(eqn- 10)}$$

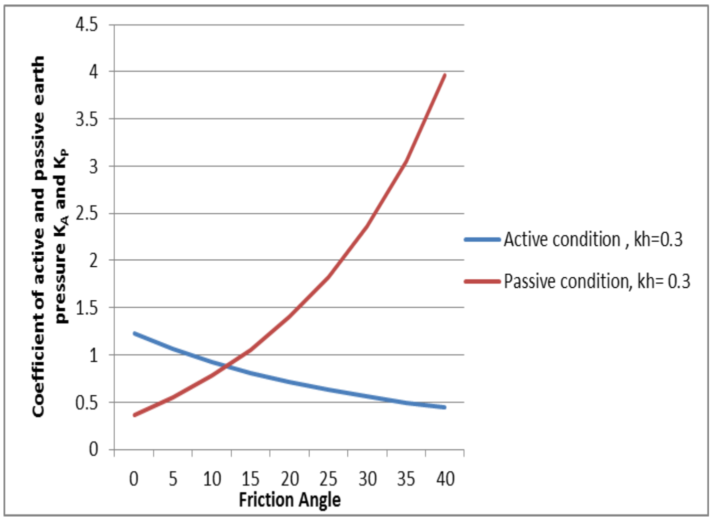

Figure 11 Variation of active and passive pressure coefficients w.r.t Friction Angle

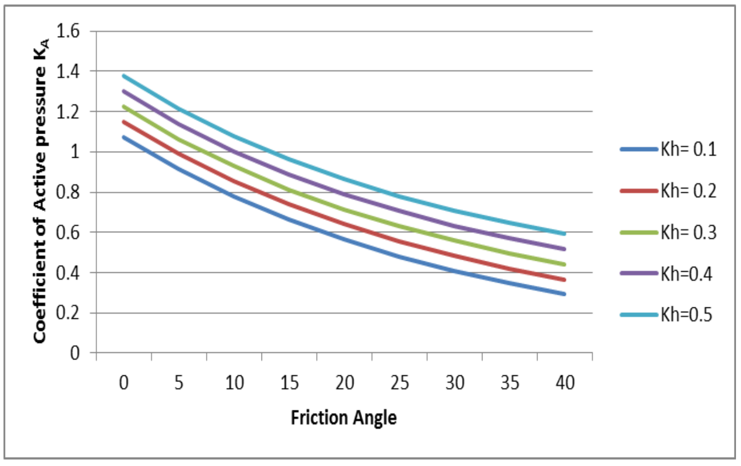

Figure 12 Variation of active pressure coefficient w.r.t Friction Angle

In this method we can see that at one point when friction angle is between 10^0 to 15^0 ,we get a common value for passive and active condition, which do not happen in any other method. This method gives low values for Active and Passive conditions as compared to overestimated values by M-O method. The role of seismic coefficient K_v is almost similar to M-O method.

5. Result and discussion:

Comparison of different force methods:

Comparison of different force methods for analysis of retaining wall based on the lateral earth pressures i.e. active earth pressure coefficients and passive earth pressure coefficients is presented in the figure 13 and 14

Table-1
Comparison of active earth pressure coefficients for different methods

Sl. NO.	Name of the Method	Angle of Internal Friction ϕ (Degree)									
		0		10		20		30		40	
		K_A	K_p	K_A	K_p	K_A	K_p	K_A	K_p	K_A	K_p
1	Rankine	1	1	0.704	1.42	0.4902	2.039	0.333	3	0.217	4.599
2	Coulomb	1	1	0.634	1.73	0.426	3.5	0.297	10.1	0.21	92.58
3	Log Spiral	1	1	0.69	1.61	0.44	3.01	0.3	6.42	0.22	17.5
4	Mononobe Okabe	1	1	0.767	1.48	0.519	3.1	0.372	9.02	0.274	83.25
5	Seed and Whitman	1.075	0.788	0.779	1.208	0.5652	1.826	0.408	2.787	0.292	4.386

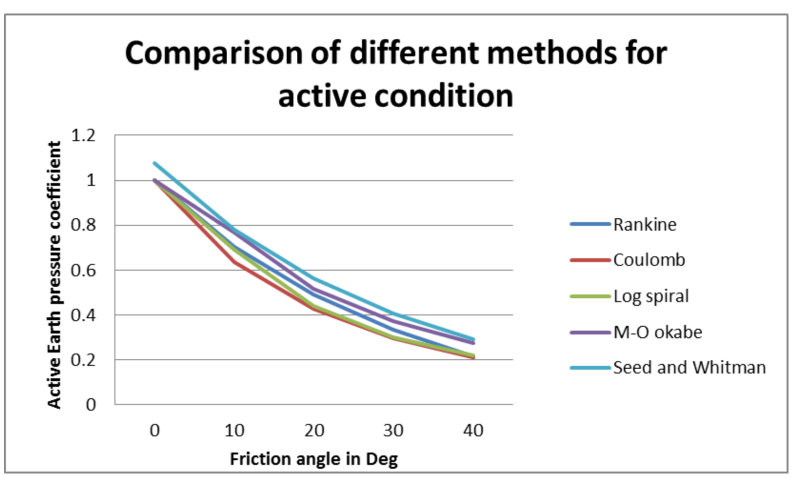

Figure 13 Variation of K_A w.r.t. friction angle by different methods.

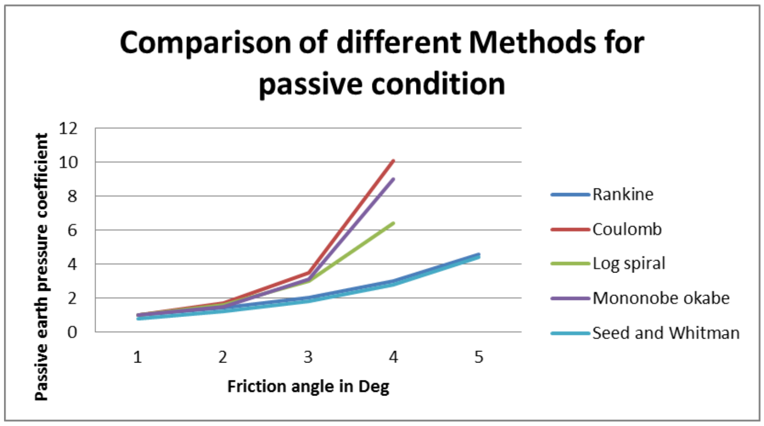

Figure 14 Variation of K_p w.r.t. friction angle by different methods.

Comparisons between the different static methods:

As can be noted from the graphical representations of the results obtained from the application of the different theories, the active earth pressures coefficients is not strongly affected by the soil wall riction angle δ, while, small variations of δ produce large differences on K_P values calculated with the various methods.

Figure 1 to Figure 7 the comparisons between the normal components to the wall of the active and passive earth pressure coefficients evaluated with the different methods for a horizontal backfill (ε=0) retained by smooth (δ=0) and rough (δ=φ) vertical walls are plotted. Note that the earth pressure coefficients was estimated till to a soil friction angle φ=40°. The passive earth pressure coefficients are more sensible to the soil wall friction. If the log spiral method can be interpreted as the most accurate determination close to the exact solution, the Coulomb method provides K_P values very similar to those expected while Rankine method gives conservative and easy-to-calculate passive coefficients.

Comparison between different seismic methods:

For the active case, the K_{AE} values obtained by Seed-Whitman method and M-O methods are practically identical. This is due to the fact that, when the wall is approximately vertical and the slope angle of the backfill is larger than zero, the most critical failure is practically planar.

For the passive case, the most critical sliding surface is much different from a planar surface as is assumed in the M-O analysis. The K_{PE} values are seriously overestimated by the M-O method. They are, in most cases, higher than those obtained by Seed-Whitman. This is especially the case when the wall is rough and the angle of wall repose is large. The condition φ = δ = 40° carries out very high K_{PE} values larger than 20, unreported in figures. For smooth walls, the potential sliding surface is practically planar and the different methods give almost identical results.

Problem considered:

We have considered a retaining wall shown in Fig. whose height is 4m and thickness of the reinforced concrete wall stem is 0.4 m, the reinforced concrete wall footing is 3 m wide by 0.5 m thick, the unit weight of concrete =23.5 kN/m^3. The wall backfill will consist of sand having ϕ =32° and γ_t=20 kN/m^3. We have also assumed that there is sand in front of the footing with the same soil properties. The friction angle between the bottom of the footing and the bearing soil is δ=38°. We will find factor of safety for sliding, and factor of safety for overturning for static conditions and earthquake conditions by different methods and a comparison between them is shown. We have assumed the wall to be present in the earthquake critical zone (IV) of north east where K_{hE} =0.36. Factor of safety was determined by considering static as well as seismic loading.

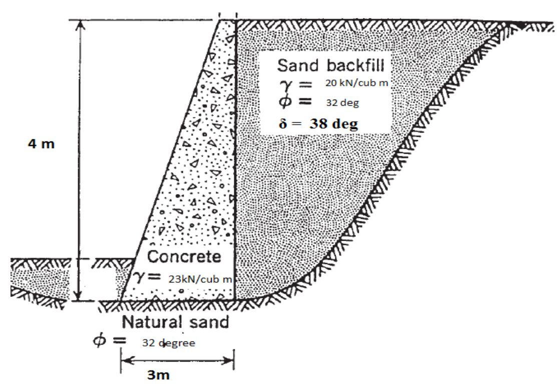

Figure15 Sketch of Typical Retaining Wall

Factor of safety for sliding and overturning:

The values of factor of safety for sliding and overturning from the static and seismic analysis using K_{hE} = 0.36 are summarized below.

Table 2
Factor of safety for sliding and overturning by different methods

Type of loading condition		P_E or P_{AE} kN/m	Location of P_E or P_{AE} above base of wall(m)	Factor of safety for sliding	Factor of safety for overturning
Rankine Method		P_E = 0	--	1.17	2.2
Coulomb Method		P_E = 0	--	1.775	2.3
Seismic Loading (K_{hE} = 0.36)	Pseudostatic	P_E = 31.91	2H/3 =2.66	0.81	1.14
	Seed and whitman	P_E = 43.2	0.6H = 2.4	0.7	1.0
	Mononobe --okabe	P_{AE} = 118.24	H/3 =1.33	1.06	1.31

For the analysis of sliding and overturning of the retaining wall, it is common to accept a lower factor of safety (1.1 to 2.2) under the combined static and earthquake loads. It is evident from Table 6.2 that Seed & Whitman method (1970) gives lower value of factor of safety as compared to other methods considered in this study. Thus, it is recommended method for the design of retaining walls in earthquake prone region.

6. Conclusion and future scope:

It has been observed by parametric study that active earth pressure coefficient are almost identical by different methods , the active earth pressures coefficients is not strongly affected by the soil wall friction angle δ, while, small variations of δ produce large differences on K_P values calculated with the various methods.

- In active and passive conditions, for a smooth wall, the computed K_A and K_P values are practically the same. For a rough wall, in the active conditions, the differences become relatively much larger. Rankine and Coulomb methods give the upper and lower threshold trends,
- The passive earth pressure coefficients are more sensible to the soil wall friction. Seed and Whitman method can be interpreted as the most accurate determination close to the exact solution; M-O method gives overestimated values.
- In the Table 2, it is evident that the factor of safety in sliding is equal to 0.7 and factor of safety in overturning is 1 based on the Seed and Whitman method is the lowest. It is also found that the factor of safety under seismic loading is more critical than in case of static a seismic loading. Thus, it is highly desirable to design the retaining walls in earthquake prone regions by Seed and Whitman method
- The Mononobe-Okabe equation does not account the effect of cohesion, because of that the lateral earth pressure coefficients calculated from dynamic analysis are less than those calculated using Mononobe-Okabe method. Further research is required in order to draw more general conclusions regarding the appropriateness of the Mononobe-Okabe method to evaluate the dynamic pressures induced on retaining walls.
- As the non-linear behavior is not considered in above methods , it is strongly recommended to use finite element but if only linear behavior is considered the Seed and Whitman method is the most suitable method

References:

1. Choudhury, D., Subba Rao, K. S., and Ghosh, S. (2002). "Passive earth pressure distribution under seismic condition" 15th Engineering Mechanics Conference of ASCE, Columbia University, New York,2002.
2. Choudhury, D., and Nimbalkar, S. (2005). "Seismic passive resistance by pseudo-dynamic method" J.Ge´otechnique 55, No. 9, 699–702
3. Kramer, S. L. (1996). Geotechnical Earthquake Engineering. Prentice-Hall, Englewood Cliffs, NJ, pp, 469-475
4. Mononobe, N., and Matsuo, H. (1929). "On the Determination of Earth Pressures During Earthquakes." Proceedings, World Engineering Congress
5. Nadim, F. (1982). "A Numerical Model for Evaluation of Seismic Behavior of Gravity Retaining Walls." Research Report R82-33. Department of Civil Engineering, Massachusetts Institute of Technology, Cambridge.

6. Okabe, S. (1926). “General Theory of Earth Pressures.” Journal of the Japan Society of Civil Engineering, vol. 12, no. 1. Society of Civil Engineering, vol. 12,
7. Seed, H. B., and Martin, G. R. (1966). “The Seismic Coefficient in Earth Dam Design.” Journal of the Soil Mechanics and Foundations Division, ASCE, vol. 92, no. SM3, pp. 25–58.
8. Seed, H. B., and Whitman, R. V. (1970). “Design of Earth Retaining Structures for Dynamic Loads.” Proceedings, ASCE Specialty Conference on Lateral Stresses in the Ground and Design of Earth Retaining Structures, ASCE, pp. 103–147.
9. Steedman, R.S., and Zeng, X., (1990) “The influence of phase on the calculation of pseudo-static earth pressure on a retaining wall” Geotechnique, 40 (1), 103-112.
10. Wood, J. H., (1973). “Earthquake-induced soil pressures on structures” Rep. EERL 73-05, Earthquake Engineering Research Laboratory, California Inst. of Technol., Pasadena, Calif.
11. Whitman, R. V. (1990). “Seismic Design Behavior of Gravity Retaining Walls.” Proceedings, ASCE Specialty Conference on Design and Performance of Earth Retaining Structures. Geotechnical Special Publication 25. ASCE, New York, pp. 817–842
12. Zeng, X., and. Steedman, R.S., (1993) “On the behaviour of quay walls in earthquakes” Geotechnique, 43 (1), pp- 417-413.
13. Das, B.M. (1992) , principal of soil Dynamics, McGraw Hill. pp- 432-455