EVALUATION OF SEISMIC ACTIVE EARTH PRESSURE USING HORIZONTAL SLICE METHOD AND LOG-SPIRAL FAILURE SURFACE

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ABSTRACT

Evaluation of active earth pressure in seismic condition is one of the important problems of geotechnical earthquake engineering. In this study the static and seismic active earth pressure exerted by a homogeneous backfill behind a rigid retaining wall is evaluated using Horizontal Slice Method (HSM). Both cohesionless and cohesive soils are considered using c-ϕ soil in the formulation. The failure surface is assumed to be a logarithmic spiral which represents a more realistic failure surface compared to the commonly used planar surface. The seismic inertia force is considered by using pseudo-static horizontal acceleration coefficient, leading to simple formulation of an otherwise complex phenomenon.

Important parameters in the seismic earth pressure problem *viz.*, depth of tension crack, surcharge over the backfill, seismic horizontal acceleration, batter angle of the wall, and, the shear strength parameters of the backfill are included in the study.

Earth pressure is expressed in terms of dimensionless factors termed as Earth Pressure Factors (EPF) which makes it possible to express both static and seismic earth pressure by simple equation resembling the familiar bearing capacity equation.

The efficacy of HSM is first verified using a planar wedge failure for which results are known from previous studies. The method is then extended for logarithmic spiral failure surface. The critical failure surfaces are identified by using different initial radii of the spiral in order to optimize the EPFs producing maximum active earth-pressure. The advantage of HSM is exploited to find the variation of seismic earth pressure along the height of the retaining wall.

The results are presented in the form of user friendly non-dimensional design charts.

Seismic Earth-Pressure, Horizontal Slice Method, Pseudostatic

1. INTRODUCTION

Evaluation of seismic active earth pressure behind retaining walls is one of the important problems of geotechnical earthquake engineering. The various methods used for the purpose are pseudostatic, pseudodynamic and dynamic analysis. Pseudostatic methods are usually preferred due to simplicity. Among the limit equilibrium methods used for pseudostatic analysis of seismic earth pressure, the most well known is the Mononobe-Okabe (MO) method. Although extensively used, recent studies (Gazetas, *et. al.*, 2004; Psarropoulos, *et.al.*, 2005) have indicated that the method overestimates the earth pressure, especially in the upper half of the backfill. In addition, the variation of pressure along the backfill height is not available. Another simple and user friendly method proposed by Prakash and Saran (Prakash and Saran, 1966; Saran and Prakash, 1968), here referred to as PSM, expresses the active earth pressure in terms of non-dimensional factors termed here as Earth Pressure Factors (EPFs) similar to Terzaghi's bearing capacity factors. They have considered c-ϕ soil, effect of wall friction, pseudostatic inertia force and have separated the contributions of surcharge, cohesion and frictional resistance of soil to the active earth pressure. This leads to simple formulation of total earth pressure. However, variation of earth pressure along the backfill height is not available. In the recent past a new limit equilibrium method, known as Horizontal Slice Method (HSM), based on subdivision of the failure wedge into horizontal slices is proposed (Shahgholi *et. al.*, 2001; Nouri *et. al.*, 2006). The method is based on equilibrium of forces and moments acting on the horizontal slices. The method is suitable for analysis of homogeneous and non-homogeneous backfills/slopes and for reinforced backfills.

In this study, first the HSM is used to find EPFs using a triangular failure wedge and results are compared to those obtained by using full triangular wedge as per PSM. After verification of efficacy of HSM, it is extended for finding EPFs by assuming log-spiral failure surfaces. In both the cases the EPFs are optimised by considering different trial failure surfaces in order to produce maximum active earth pressure. Results are presented in the form of user friendly design curves.

2. VERIFICATION OF HSM USING PLANAR FAILURE WEDGE

2.1 Earth Pressure using Whole Wedge (PSM)

Fig. 2.1 shows a failure wedge formed by a planar failure surface in the $c-\varphi$ backfill behind the retaining wall having batter angle α, carrying a surcharge q. Weight of the wedge is W, angle of wall friction is δ, soil-wall adhesion is c_a, and the depth of tension cracks is H_c. This depth can be expressed in terms of crack depth factor $f_c = H_c / H$. The active earth pressure on the wall is P and makes an angle δ with the normal to the wall-backfill interface. The horizontal inertia force in seismic condition is replaced by a pseudostatic force k_hW where k_h is the horizontal coefficient of acceleration.

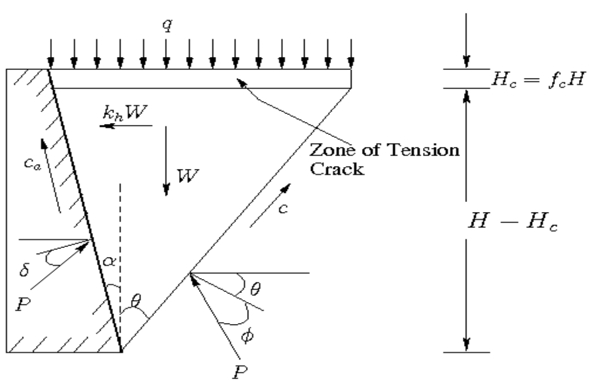

Fig. 2.1 Planar Failure Wedge and Forces Acting on the Wedge

By resolving the forces in vertical and horizontal directions and simplifying, the earth pressure can be expressed as (Prakash and Saran, 1966; Saran and Prakash, 1968):

$$P = \gamma H^2 N_{a\gamma} + qHN_{aq} - cHN_{ac} \tag{2.1}$$

where, $N_{a\gamma}, N_{aq}, N_{ac}$ are the Earth Pressure Factor (EPF)s and are given by

$$N_{a\gamma} = \frac{\left[(f_c + 0.5)(\tan\alpha + \tan\theta) + 0.5 f_c^2 \tan\alpha\right]\left[\cos(\theta+\varphi) + k_h \sin(\theta+\varphi)\right]}{\sin(\beta+\delta)} \tag{2.2a}$$

$$N_{aq} = \frac{\left[(f_c + 1)\tan\alpha + \tan\theta\right]\left[\cos(\theta+\varphi) + k_h \sin(\theta+\varphi)\right]}{\sin(\beta+\delta)} \tag{2.2b}$$

$$N_{ac} = \frac{\cos\beta\sec\alpha + \cos\varphi\sec\theta}{\sin(\beta+\delta)} \tag{2.2c}$$

$$\beta = \varphi + \theta + \alpha \tag{2.2d}$$

For a particular wall-backfill system, Eqn. 2.1 shows that in order to maximize P the EPFs $N_{a\gamma}$ and N_{aq} are to be maximized and N_{ac} is to be minimized, by considering different values of inclination of failure plane, θ. The earth pressure in static condition can be obtained by putting $k_h = 0$ in Eqn. 2.2a-b. N_{ac} is independent of k_h as cohesion is not affected by inertia force.

2.2 Earth Pressure using Horizontal Slice Method

Fig. 2.2 shows the same failure wedge explained in Sec. 2.1 but sliced horizontally. The ***i***-th slice has an area A_i, thickness t_i, top width b_i weight W_i, and, earth pressure P_i.

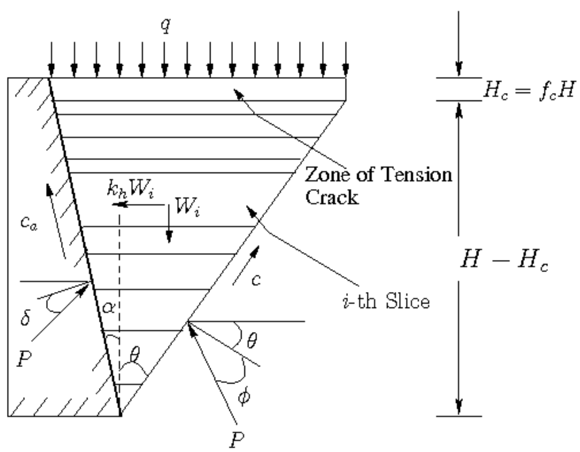

Fig. 2.2 Horizontal Slices in Planar Failure Wedge and Forces Acting on the Wedge

Considering equilibrium of the ***i***-th slice the earth pressure acting on it can be expressed as

$$P_i \sin(\beta+\delta) = \gamma A_i\left[\cos(\theta+\varphi) + k_h\sin(\theta+\varphi)\right]$$
$$+ qb_1\left[\cos(\theta+\varphi) + k_h\sin(\theta+\varphi)\right] - ct_i\left[(\tan\theta - \tan\alpha)\sin(\theta+\varphi) + 2\cos(\theta+\varphi)\right] \tag{2.3}$$

where b_1 is the width of topmost slice. Summing up such forces for all the slices and based on geometry of slices, the total earth pressure can be expressed again as given by Eqn. 2.1. The expressions for $N_{a\gamma}$ and N_{aq} are found to be same as those given by Eqn. 2.2a and 2.2b. EPF for cohesion in this case is given by

$$N_{ac} = \frac{\{[\tan\theta - (f_c + 1)\tan\alpha]\sin(\theta + \varphi)\} + 2\cos(\theta + \varphi)}{\sin(\beta + \delta)} \qquad (2.4)$$

EPFs using PSM and HSM are calculated for different inclinations of failure plane and are shown in Fig. 2.3. This shows that EPFs calculated by both the methods are identical.

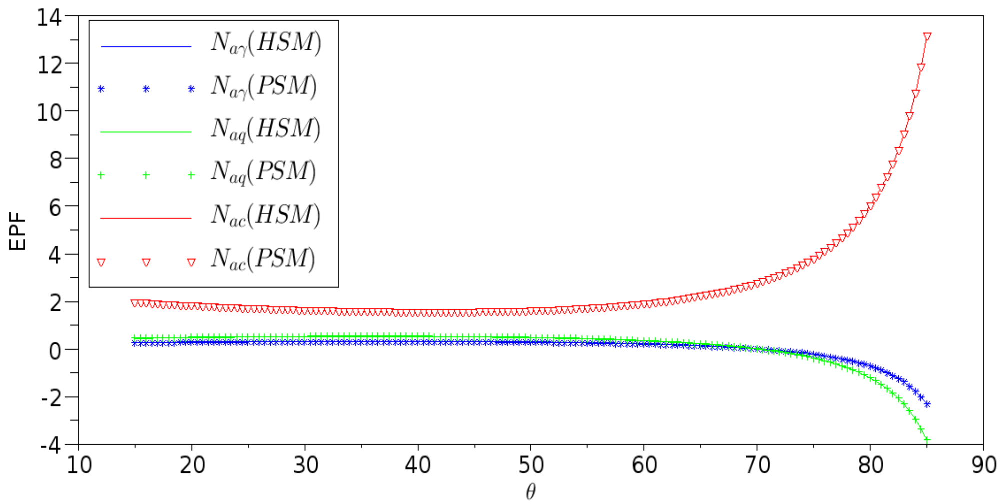

Fig. 2.3 EPFs using HSM and PSM $(\varphi = 20^0, \alpha = 10^0, k_h = 0, f_c = 0)$

In order to maximize earth pressure, the EPFs are calculated for each value of φ by varying the inclination of failure plane and optimal values of EPFs calculated by both HSM and PSM are selected. Fig. 2.4 shows such values of $N_{a\gamma}$ for different values of k_h for a practical range of φ, while Fig. 2.5 shows values of N_{ac} for all values of k_h .

Fig. 2.3 through Fig. 2.5 clearly shows that the EPFs calculated by using HSM are identical to those obtained by using PSM. This further shows that HSM can reliably be used for calculation of seismic active earth-pressure.

3. EPFS USING HORIZONTAL SLICE METHOD AND LOG-SPIRAL FAILURE SURFACE

Fig. 3.1 shows a failure wedge formed by a log-spiral failure surface in a $c-\varphi$ soil. The various quantities associated with the backfill and the wall are kept same as described in Sec. 2.1. The equation of log-spiral is taken as

$$R_\theta = R_1 \exp(\tan\varphi(\theta - \varphi)) \qquad (3.1)$$

where R_θ is the radius vector making angle θ with the horizontal at the origin. R_1 is the initial radius of the spiral at the surface of the backfill. The origin is taken at point (X_0, Y_0) from the top of the wall at the toe side. The spiral is normal to the backfill surface and passes through the toe of the wall.

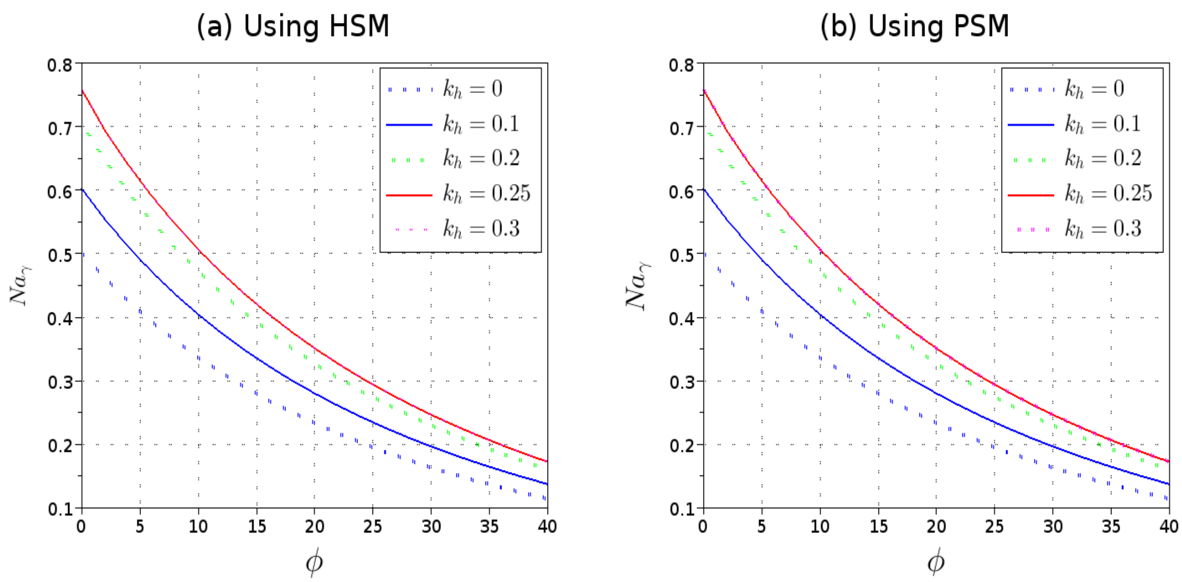

Fig. 2.4 Values of $N_{a\gamma}$ for different values of φ $\left(\alpha = 4^0, f_c = 0\right)$

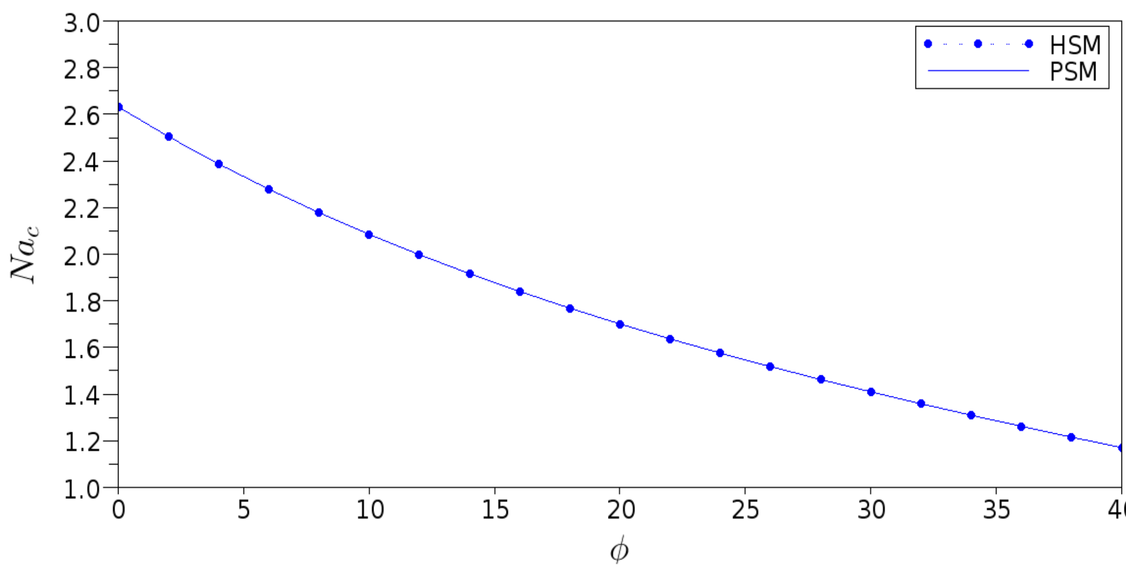

Fig. 2.5 Values of N_{ac} for different values of φ $\left(\alpha = 4^0, f_c = 0\right)$

Referring to Fig. 3.1, the ***i***-th horizontal slice has a thickness t_i, and the radii vectors at its top and bottom are R_i and R_{i+1} respectively, making respective angles θ_i and θ_{i+1} with horizontal at the origin. The various forces acting on the ***i***-th slice are shown in Fig. 3.2.

By resolving the forces acting on the ***i***-th slice, the earth pressure acting on it can be expressed as

$$P_i = \gamma A_i \frac{\left[\cos\left(\theta_{ave} + \varphi\right) + k_h \sin\left(\theta_{ave} + \varphi\right)\right]}{\sin\left(\beta + \delta\right)} + qb_1 \frac{\left[\cos\left(\theta_{ave} + \varphi\right) + k_h \sin\left(\theta_{ave} + \varphi\right)\right]}{\sin\left(\beta + \delta\right)}$$
$$- cL \frac{\sin\left(\theta_i^* + \theta_{ave} + \varphi\right)}{\sin\left(\beta + \delta\right)} + c_a t_i \frac{\left[\tan\alpha \sin\left(\theta_{ave} + \varphi\right) - \cos\left(\theta_{ave} + \varphi\right)\right]}{\sin\left(\beta + \delta\right)} \qquad (3.2)$$

where,

$$\theta_{ave} = 0.5\left(\theta_i + \theta_{i+1}\right) \qquad (3.3a)$$
$$\beta = \alpha + \theta_{ave} + \varphi \qquad (3.3b)$$

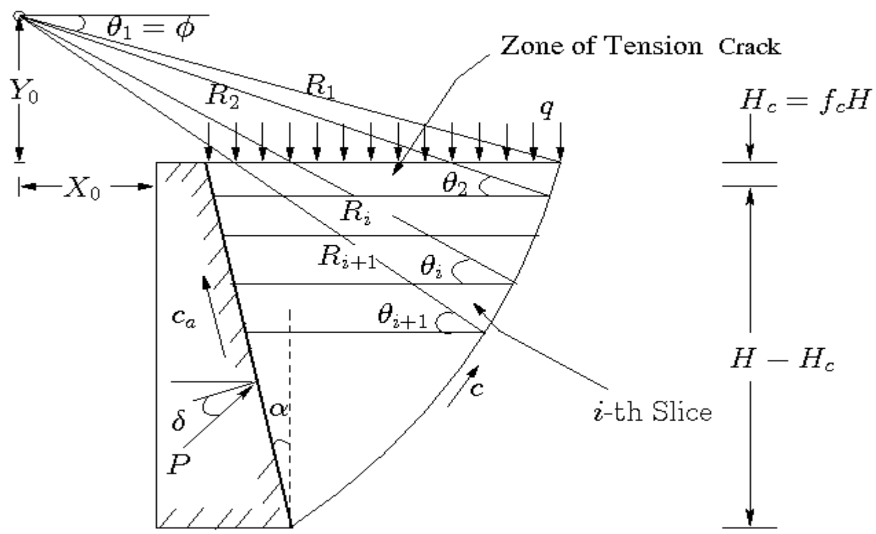

Fig. 3.1 Horizontally Sliced Failure Wedge formed by Log-Spiral Failure Surface

Using c_a = cohesion c, Eqn. 3.2 can be expressed as

$$P_i = \gamma A_i N_{a\gamma i} + qb_1 N_{aqi} - cL_i N_{aci} \qquad (3.4)$$

where

$$N_{a\gamma i} = \frac{\left[\cos\left(\theta_{ave} + \varphi\right) + k_h \sin\left(\theta_{ave} + \varphi\right)\right]}{\sin\left(\beta + \delta\right)} \qquad (3.5a)$$

$$N_{aqi} = \frac{\left[\cos\left(\theta_{ave} + \varphi\right) + k_h \sin\left(\theta_{ave} + \varphi\right)\right]}{\sin\left(\beta + \delta\right)} \qquad (3.5b)$$

$$N_{aci} = \frac{\sin\left(\theta_i^* + \theta_{ave} + \varphi\right)}{\sin\left(\beta + \delta\right)} - \frac{t_i}{L_i} . \frac{\left[\cos\left(\theta_{ave} + \varphi\right) - \tan\alpha \sin\left(\theta_{ave} + \varphi\right)\right]}{\sin\left(\beta + \delta\right)} \qquad (3.5c)$$

By summing up contribution of each slice to earth pressure and using properties of the log-spiral, the the total earth pressure and EPFs for total earth pressure can be expressed as

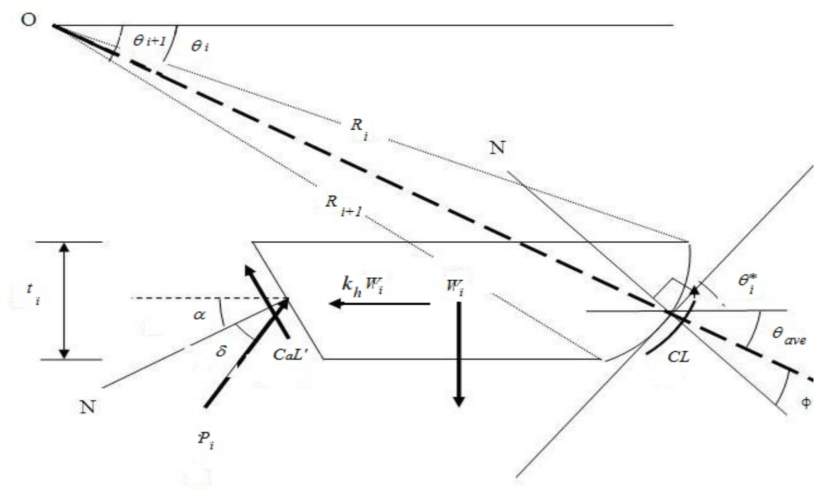

Fig. 3.2 Forces acting on *i*-th Slice

$$P = \gamma H^2 N_{a\gamma} + qHN_{aq} - cHN_{ac} \tag{3.6}$$

$$N_{a\gamma} = \frac{A}{H^2} \sum N_{a\gamma i} \tag{3.7a}$$

$$N_{aq} = \frac{b_1}{H} \sum N_{aqi} \tag{3.7b}$$

$$N_{ac} = \frac{(R_{toe} - R_1)}{H \sin\varphi} \sum N_{aqi} \tag{3.7c}$$

Here, A = area of whole failure wedge and R_{toe} is the radius of spiral at the toe of the wall. It is important to note that in order to maximize the total earth pressure, it is necessary to consider a number of failure surfaces assuming different values of initial radius R_1. The value of R_{toe} and corresponding angle of spiral θ_{toe} are to be obtained by trial and error.

In case of tension crack of depth $H_c = f_c H$, the angle made by the radius vector at the bottom level of tension cracks, θ_{cr}, can be obtained as

$$\theta_{cr} = \frac{1}{\tan\varphi} \left[\ln\left(\frac{f_c H}{R_1} + \sin\varphi \right) + \varphi \tan\varphi - \ln(\sin\theta_{cr}) \right] \tag{3.8}$$

By solving Eqn. 3.8, the corresponding radius vector R_{cr} and the length of arc in the tension crack zone L_{cr}, whose contribution to N_{ac} should be neglected in such cases, is obtained as

$$L_{cr} = \frac{(R_{cr} - R_1)}{\sin\varphi} \tag{3.9}$$

4. RESULTS AND DISCUSSION

Fig. 4.1 through 4.3 shows the values of EPFs corresponding to those failure surfaces that produce maximum total earth pressures.

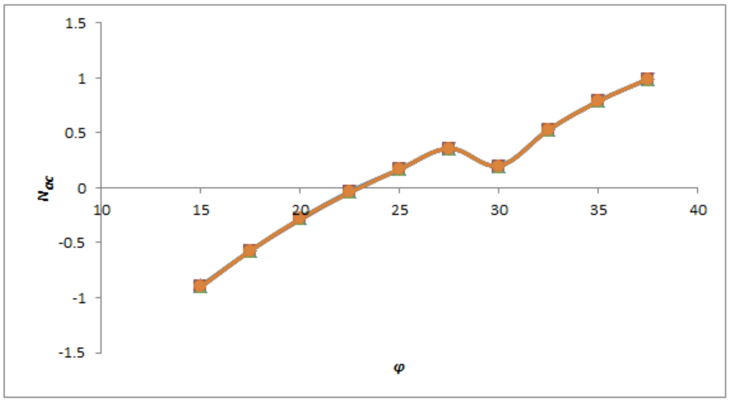

Fig. 4.1 Values of N_{ac} for different values of φ $\left(\alpha = 8^0, f_c = 0.10\right)$

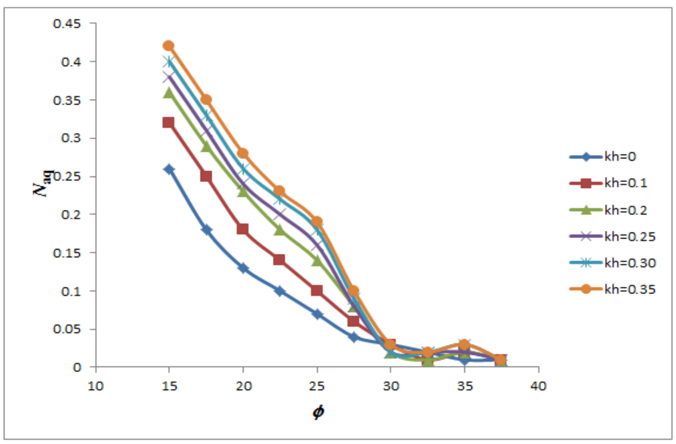

Fig. 4.2 Values of N_{aq} for different values of φ $\left(\alpha = 4^0, f_c = 0.10\right)$

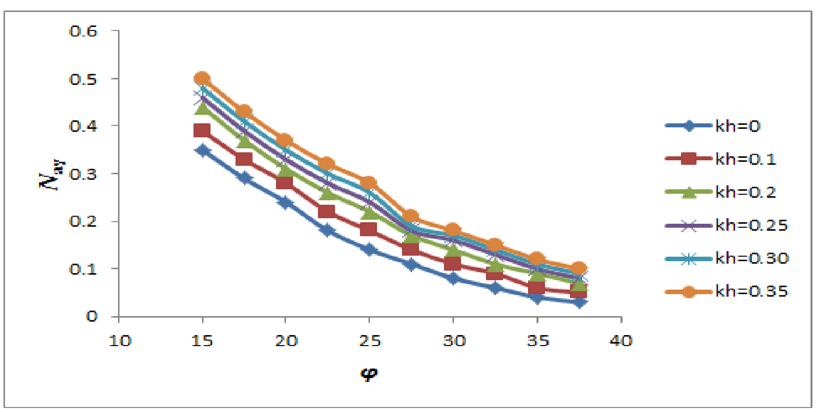

Fig. 4.3 Values of $N_{a\gamma}$ for different values of φ $\left(\alpha = 8^0, f_c = 0.10\right)$

Figs. 4.2 and 4.3 shows that active earth pressure increases with increase in horizontal acceleration coefficient k_h . This increase for surcharge component *i.e.* N_{aq} however decreases with increase in φ value of soil.

Use of HSM is advantageous to find the variation of earth pressure along the height of wall which is not available in other pseudostatic methods like MO and PSM. Pressures at the middle of horizontal slices are computed by using Eqn. 3.4 and are normalised with the maximum pressure intensity under static condition. Such variations of normalised pressure with wall height are shown in Figs. 4.4 to 4.6, for a 10 m high wall with batter angle $\alpha = 4^0$. These Figures show that the variation of pressure along wall height is more or less parabolic. Presence of surcharge adds a component of earth pressure that remains more or less constant with height, while presence of cohesion leads to negative earth pressure at the top portion of the wall. In all cases, seismic earth pressure is higher than the static pressure.

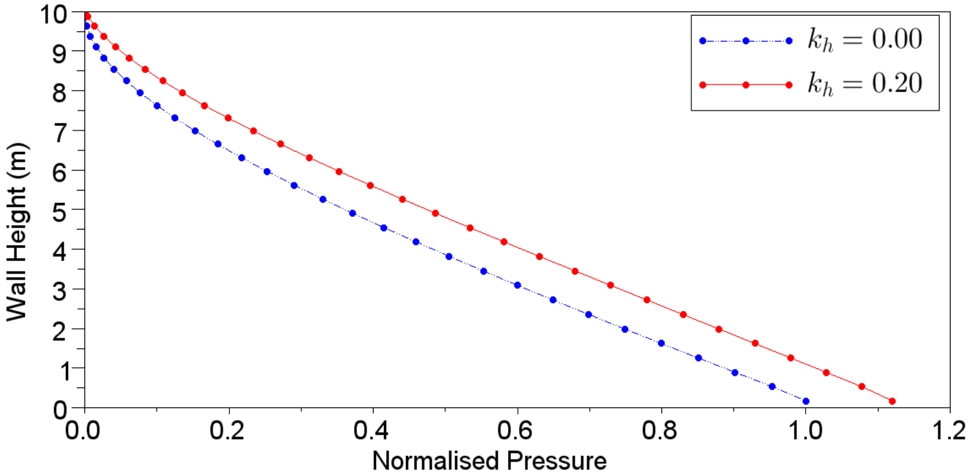

Fig. 4.4 Variation of Earth Pressure along Wall Height $\left(\varphi = 15^0 \alpha = 4^0, q = 0, c = 0, \ f_c = 0\right)$

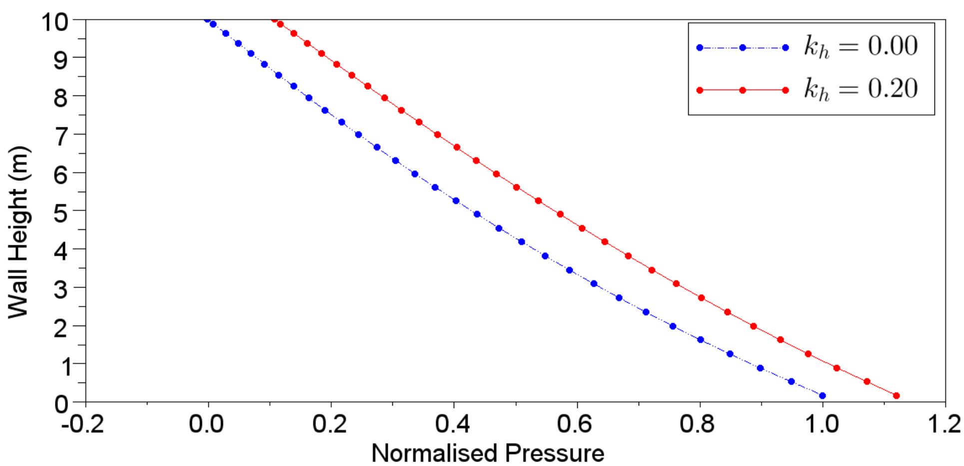

Fig. 4.5 Variation of Earth Pressure along Wall Height $\left(\varphi = 15^0 \alpha = 4^0, q = 10, c = 0, \ f_c = 0\right)$

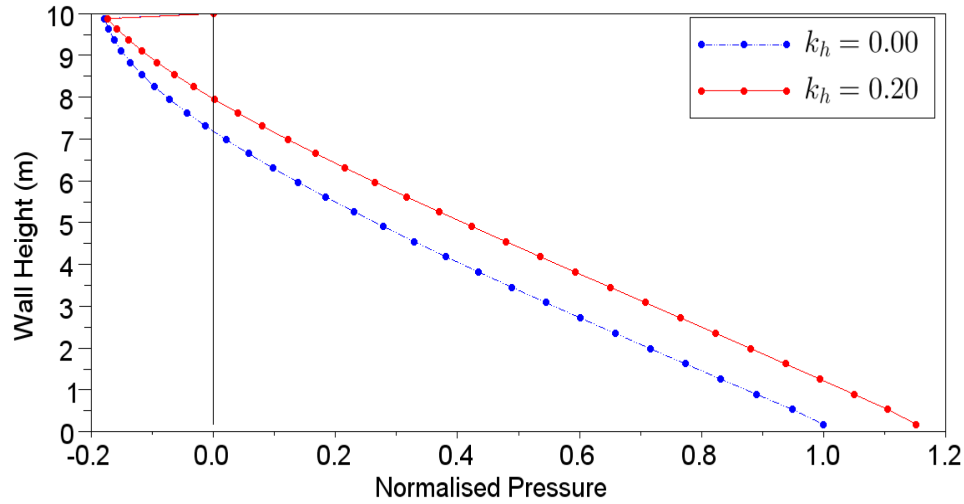

Fig. 4.6 Variation of Earth Pressure along Wall Height $\left(\varphi = 15^0 \alpha = 4^0, q = 0, c = 30, f_c = 0\right)$

5. SUMMARY AND CONCLUSION

In this study the Horizontal Slice Method is used to analyse earth pressure exerted by $c-\varphi$ soil under seismic condition using pseudostatic approach. Use of realistic Log-Spiral failure surface is made in the analysis. The total earth pressure is expressed in terms of non-dimensional Earth Pressure Factors (EPFs) separating the contributions of frictional resistance, surcharge and cohesion. Use of HSM gives, in addition to total earth pressure, the variation of earth pressure along the wall height. The results of this study is useful in analysis of seismic active earth pressure behind retaining walls.

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