SEISMIC BEARING CAPACITY OF SHALLOW FOUNDATION WITH BASE INCLINATION

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ABSTRACT

The determination of seismic bearing capacity for strip footings with base inclination is the aim of this paper. For this purpose, a limit equilibrium based method is used. The seismic force is considered as pseudo-static forces acting on both footing and soil and determined. To obtain the ultimate bearing capacity, an imaginary retaining wall is assumed to pass the footing wedge and the lateral earth pressure exerted on the wall in active and passive conditions are determined. The bearing capacity factors are computed for various values of soil friction angle, seismic acceleration coefficients in horizontal and vertical directions, foundation inclination. The effects of various parameters on the seismic bearing capacity factors have been studied. The results obtained from the present method are compared with other available methods, confirming the reliability of the developed method.

INTRODUCTION

The determination of bearing capacity of shallow foundations basically is principle in geotechnical engineering. Limited studies have been carried out for estimating the seismic bearing capacity of strip footings with base inclination. Most of analyses were carried out for static situation.

Some researchers including Sarma and Iossifelis (1990), Budhu and Al-Karni (1993), Richards et al. (1993), Dormieux and Pecker (1995), Paolucci and Pecker (1997), Soubra (1997, 1999), Kumar and Rao (2002), Kumar (2003), and Choudhury and Subba Rao (2005) have studied the seismic bearing capacity of shallow footings for the horizontal ground. However, for sloping ground, data are very limited. Sawada et al. (1994), Sarma (1999) and Askari and Farzaneh (2003) have presented solutions for seismic bearing capacity of shallow foundations near sloping ground. Recently, Choundhury and Rao (2006) carried out the analysis for seismic bearing capacity factors of footings constructed on slopes.

The method used in the current paper was initially developed by Richards et al. (1993) for footings on homogeneous granular soil and extended to two layered granular soil by Ghazavi and Eghbali (2008), and Ghazavi and Salmani (2012) for frictional-cohesive soil. Salmani and Ghazavi (2013) have extended the imaginary retaining wall method for foundation base inclination.

This paper presents a simple method for determination of the seismic bearing capacity of strip footings with base inclination on granular soils. For this purpose, an imaginary retaining wall is assumed the vertical direction along the edge of the footing (Fig. 1). The lateral earth pressures exerted on the wall in active and passive conditions are determined. The conventional bearing capacity factors are extracted and then the bearing capacity equation is derived.

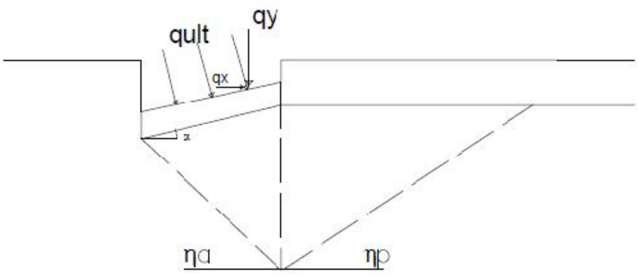

Figure 1. Failure mechanism and wedges assumed in present model

LIMIT EQUILIBRIUM ANALYSIS

A useful simplification for determination the ultimate bearing capacity of shallow strip footing is to imagine a retaining wall and with equal the active and passive forces, as shown in Fig. 2.

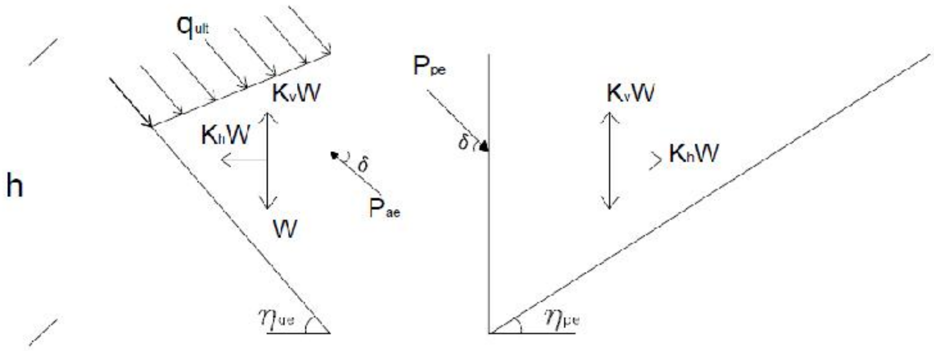

Figure 2. Failure surfaces and effective forces on slip wedge in limit equilibrium condition

Pseudo-static seismic forces are considered along with other static force. Also isotropic granular soil with equivalent surcharge is assumed in the analysis. The seismic acceleration coefficients are denoted as k_h and k_v in the horizontal and vertical directions, respectively.

Note that in Fig. 2:

η_{ae} = Angle of slip surface in the active zone.

η_{pe} = Angle of slip surface in the passive zone.

δ = friction angle along surface between active and passive zone.

P_a, P_p= active and passive force.

α: inclination angle of the foundation base.

The value of η_{ae} and η_{pe} may be given by:

$$\eta_{ae} = \phi - \psi + Atan\left|\frac{-tan(\phi-\psi+\alpha)+c1}{c2}\right| \tag{1}$$

$$c1 = \sqrt{tan(\phi-\psi+\alpha)\,[tan(\phi-\psi+\alpha)+cot(\phi-\psi)][1+tan(\delta+\psi)\,cot(\phi-\psi)]}$$

$$c2 = 1 + [tan\,(\delta+\psi)(tan(\phi-\psi+\alpha)+cot(\phi-\psi)]$$

$$\eta_{pe} = -\phi + Atan\left|\frac{-\tan(\phi+\beta)+c3}{c4}\right|$$

$$c3 = \sqrt{\tan(\phi-\psi)\,[\tan(\phi-\psi)+\cot(\phi-\psi)][1+\tan\,(\delta-\psi)\cot\,(\phi-\psi)} \quad (2)$$

$$c4 = 1 + [\tan\,(\delta+\psi)(\tan(\phi+\psi)+\cot(\phi-\psi)]$$

Ψ: seismic inertia angle caused by the earthquake.
The seismic inertia angle is given by:

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

In Eq. (3):

$$\mathrm{k_h} = \frac{\mathrm{a_h}}{\mathrm{g}} \quad (4)$$

$$\mathrm{k_v} = \frac{\mathrm{a_v}}{\mathrm{g}} \quad (5)$$

where a_h, a_v = seismic accelerations in horizontal and vertical directions, respectively.
g = acceleration of gravity
h = failure wedge

$$\mathrm{h} = \mathrm{B}cos\alpha\tan\eta_{ae} \quad (6)$$

As shown in Fig. 1, q_{ult} will be divided into two parts in x and y direction which can be calculated from the following relationship:

$$\mathrm{qy} = \mathrm{q_{ult}}\cos\alpha \quad (7)$$

$$\mathrm{qx} = \mathrm{q_{ult}}\sin\alpha \quad (8)$$

The active and passive earth forces according to the Mononobe-Okabe earth pressure theory are given by:

$$\sigma_{ae} = k_{ea}(\gamma h + q_{ult}) \quad (9)$$

$$\sigma_{pe} = k_{pe}(\gamma h + q) \quad (10)$$

where:
k_{ae} , k_{pe} = coefficient of active and passive pressure in seismic condition.
The coefficients of active and passive pressures are respectively given by:

$$k_{ae} = \frac{cos^2(\phi-\psi)}{cos\psi cos\delta[1+\sqrt{\frac{sin(\phi+\delta)\,sin(\phi-\alpha-\psi)}{cos(\delta+\psi)\,cos\,\alpha}}]^2} \quad (11)$$

$$k_{pe} = \frac{cos^2(\phi-\psi)}{cos\delta[1-\sqrt{\frac{sin(\phi+\delta)\,sin(\phi-\psi)}{cos(\delta+\Psi)}}]^2} \quad (12)$$

The total active thrust and passive force are determined using:

$$p_{pe} = k_{pe}(qh + 0.5\gamma h^2) \quad (13)$$

$$P_{ae} = \frac{1}{2}k_{ae}\gamma h^2 + k_{pe}\frac{q_{ult}cos\alpha}{\cos\,\alpha}h \quad (14)$$

The horizontal components of the total active and passive thrust are determined respectively using:

$$p_{aeh} = p_{ae}cos\delta + q_{ult}Bsin\alpha \quad (15)$$

$$p_{peh} = p_{pe}cos\delta \quad (16)$$

The ultimate bearing capacity may be obtained by combing Eqs. (16) and (17).

$$qult = \frac{1}{2}\gamma h^2 cos\delta \frac{(k_{pe}-k_{ae})}{k_{ae}cos\delta h+Bsin\alpha} + qcos\delta h \frac{k_{pe}}{k_{ae}cos\delta h+Bsin\alpha} \quad (17)$$

The bearing capacity factors may be obtained from Eq. (18) as:

$$N_{qe} = \frac{k_{pe}cos\delta tan\eta_{ae}cos\alpha}{k_{ae}cos\delta tan\eta_{ae}cos\alpha+sin\alpha} \quad (18)$$

$$N_{\gamma e} = \frac{(k_{pe}-k_{ae})cos\delta(tan\eta_{ae}cos\alpha)^2}{k_{ae}cos\delta tan\eta_{ae}cos\alpha+sin\alpha} \quad (19)$$

The shape of the failure surface is very simple, thus a relatively acceptable estimation of the bearing capacity depends on the value of δ. In this paper, we use $\delta = \frac{\varphi}{2}$ tentatively.

VERIFICATION

For validation of the developed method, data presented by Vesic (1970) and Hansen (1973) are selected for comparison with those obtained from the developed method. Figs. 6 and 7 show this comparison. To use this methods earthquake factors (e_c ،e_q ،e_γ) (Budhu and Al-Karni, 1993) and base inclination factors (b_c, b_q, b_γ) (Vesic, 1973) are used. As seen, in all figures, there is generally good agreement between two methods.

RESULTS

In this section, results of the above analyses are presented. Figs. 3 and 4 give the values of seismic bearing capacity factors for various k_h and k_v values with a particular D and α. As seen, seismic bearing capacity factors decrease with increasing the horizontal and vertical seismic acceleration coefficients, as expected.

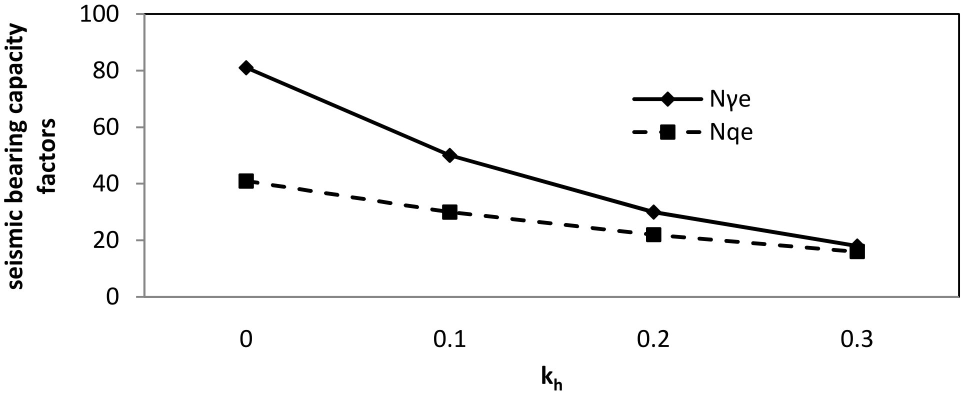

Figure 3. Variation of seismic bearing capacity factors with k_h
($\alpha=10^o$, $\varphi=40^o$, $k_v=0$)

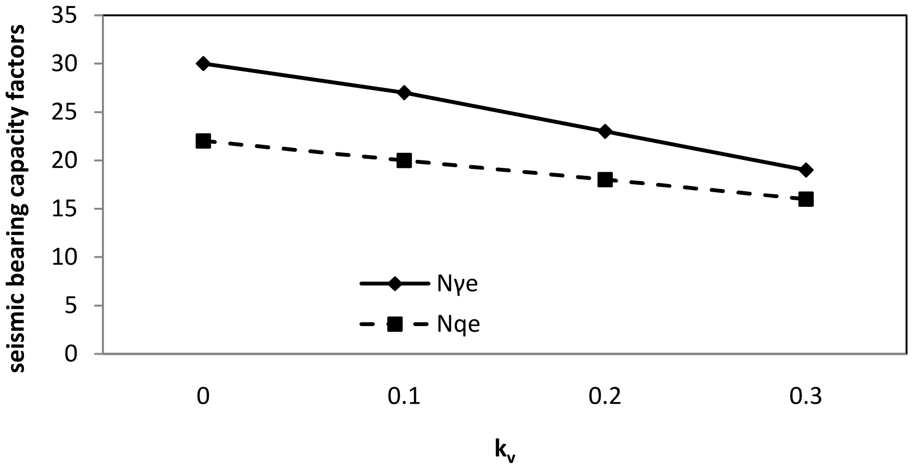

Figure 4. Variation of seismic bearing capacity factors with k_v
($\alpha=10^o$, $\varphi=40^o$, $k_h=0.2$)

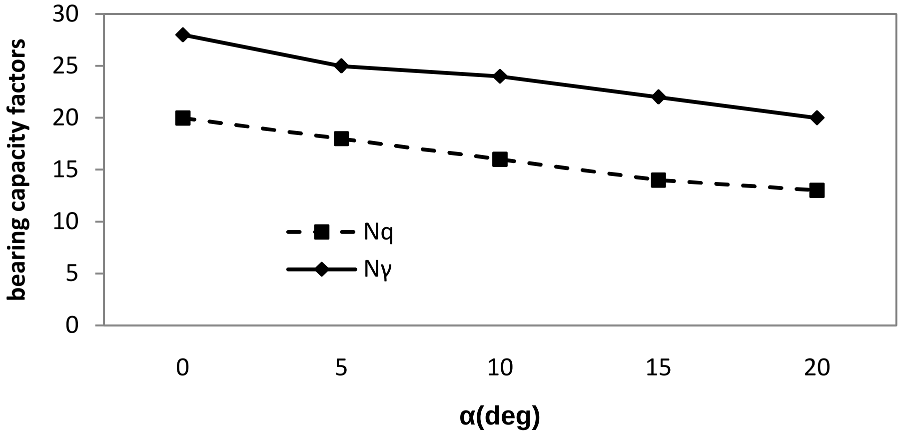

Figure 5. Variation of seismic bearing capacity factors with base inclination
($\varphi=35^o$, $k_h=0.1$, $k_v=0$)

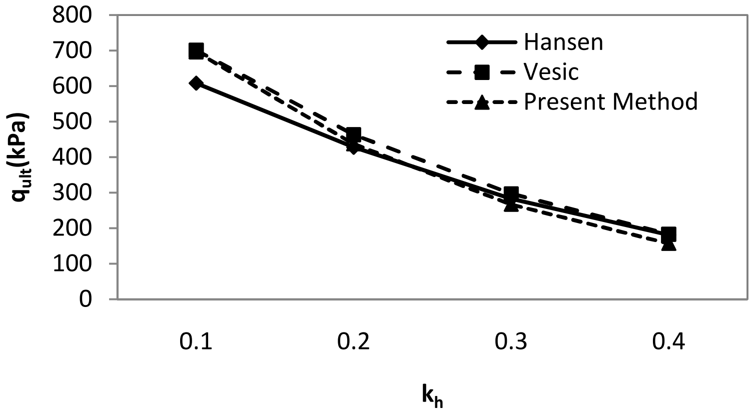

Figure 6. Variation of bearing capacity with k_h
($k_v=0$, $\gamma=016$ kN/m^3, D=0.5 m, B=2 m, $\varphi=35^o$, $\alpha=5^o$)

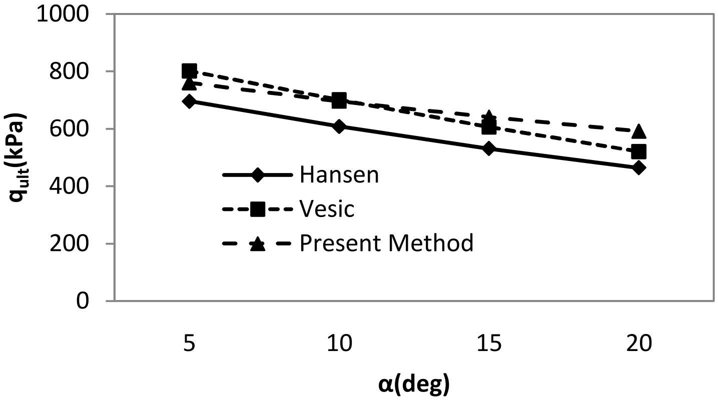

Figure 7. Variation of bearing capacity with α
(k_h=0.1, k_v=0, γ=016kN/m^3, D=0.5m, B=2 m, φ=35^o)

CONCLUSIONS

A pseudo-static approach for the seismic forces and with the assumption the lateral earth pressure theory determined from the well known Mononobe-Okabe method in conjunction with simple slip surface has been used to determine the total lateral active and passive thrusts exerted on a virtual retaining wall passing vertically through the edge of the footing. The seismic bearing capacity of strip footing with base inclination on granular soils was derived. The presented method predicts reasonable results compared with an available solution in the literature. The results show that with increasing the horizontal and vertical seismic acceleration components, the seismic bearing capacity factors decrease drastically, as expected.

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APPENDIX (DESIGN CHARTS)

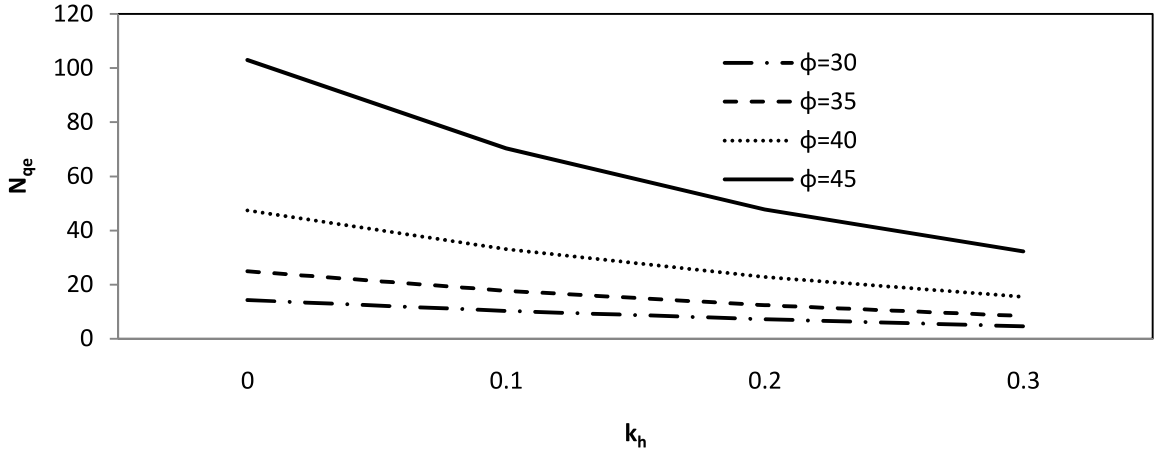

Figure 8. Design chart for determination N_{qe} for various k_h (k_v=0.1, α=5^o)

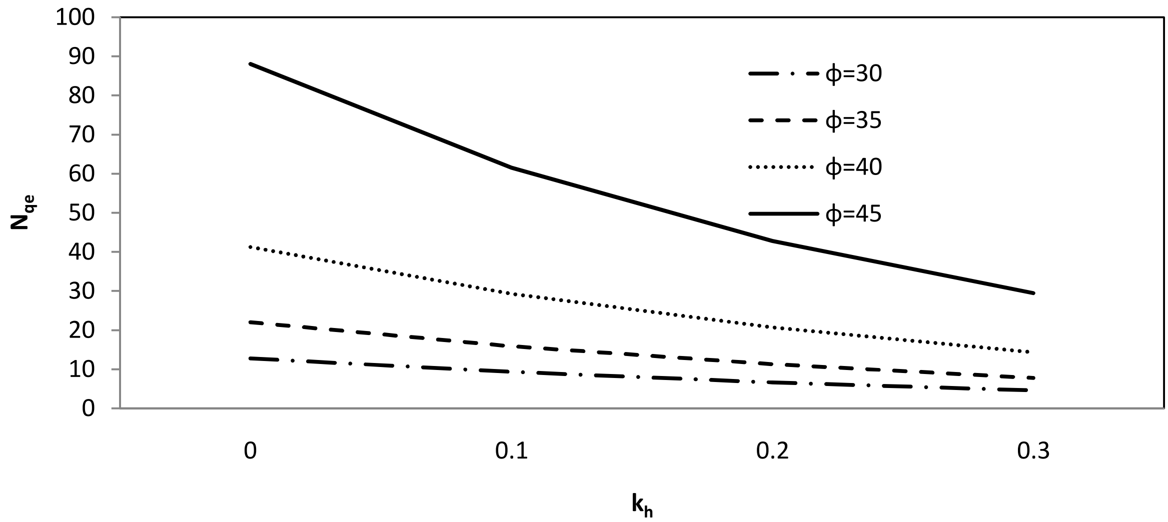

Figure 9. Design chart for determination N_{qe} for various k_h (k_v=0.1, α=10^o)

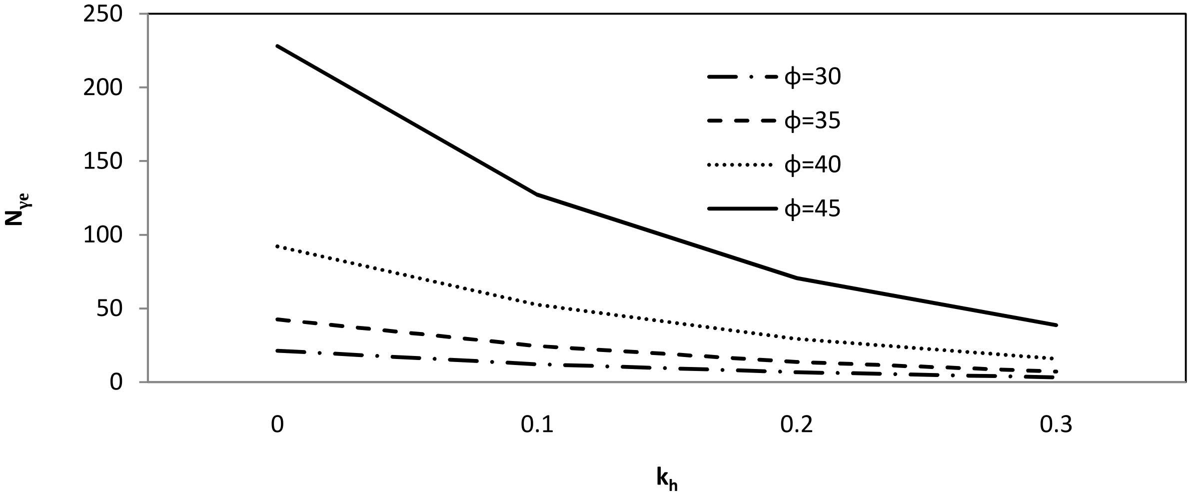

Figure 10. Design chart for determination $N_{\gamma e}$ for various k_h (k_v=0.1, α=5^o)

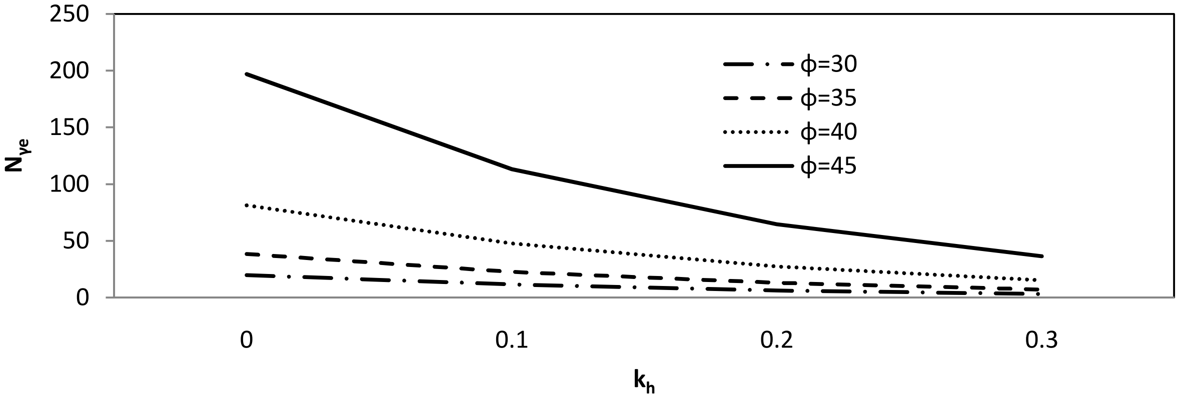

Figure 11. Design chart for determination $N_{\gamma e}$ for various k_h (k_v=0.1, α=10^o)