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Seismic analysis of nailed vertical excavation using pseudo-dynamic approach

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Abstract: An attempt has been made to study the behavior of nailed vertical excavations in medium dense to dense cohesionless soil under seismic conditions using a pseudo-dynamic approach. The effect of several parameters such as angle of internal friction of soil (ϕ), horizontal (k_h) and vertical (k_v) earthquake acceleration coefficients, amplification factor (f_a), length of nails (L), angle of nail inclination (α) and vertical spacing of nails (S_v) on the stability of nailed vertical excavations has been explored. The limit equilibrium method along with a planar failure surface is used to derive the formulation involved with the pseudo-dynamic approach, considering axial pullout of the installed nails. A comparison of the pseudo-static and pseudo-dynamic approaches has been established in order to explore the effectiveness of the pseudo-dynamic approach over pseudo-static analysis, since most of the seismic stability studies on nailed vertical excavations are based on the latter. The results are expressed in terms of the global factor of safety (FOS). Seismic stability, i.e., the FOS of nailed vertical excavations is found to decrease with increase in the horizontal and vertical earthquake forces. The present values of FOS are compared with those available in the literature.

Keywords: earthquake; factor of safety; pseudo-dynamic approach; soil nailing; vertical excavation

1 Introduction

Due to rapid infrastructure development, more and more civil engineering structures such as railways and highways are being built in hilly regions where vertical excavation is common practice. Various ground improvement techniques such as soil nailing, application of geosynthetics, etc. are generally used to enhance the stability of these vertical excavations which are highly vulnerable to failure under static loads as well as seismic loading conditions.

Saran *et al*. (2005) and Meenal *et al*. (2009) used moment equilibrium method to evaluate the seismic stability of nailed vertical excavations in terms of a factor of safety using the pseudo-static approach. Mittal *et al*. (2005), Mittal and Biswas (2006) and Fan and Luo (2008) studied the effect of the angle of nail inclination on the stability of excavations using moment equilibrium and finite element methods under static loading conditions. It was observed that increasing the angle of nail inclination decreases the factor of safety of the vertical excavation. Jaya and Joy (2013), Saran *et al*. (2005), Mittal *et al*. (2005), and Sengupta and Giri (2011) have investigated the effect of nail length on the stability of the excavation under static as well as seismic conditions. With the pseudo-static approach, the effect of the angle of internal friction of soil, spacing between the nails, and earthquake acceleration coefficients has been explored by Saran *et al*. (2005), Babu and Singh (2008), Meenal *et al*. (2009), Sengupta and Giri (2011), and Jaya and Joy (2013); it was noticed that with the increase in the earthquake acceleration coefficients, the stability of the nailed excavation decreases. Mittal *et al*. (2005), Saran *et al*. (2005) and Meenal *et al*. (2009) considered circular and logarithmic spiral failure surfaces in their analyses for cohesive and cohesionless soil, respectively.

In the pseudo-static approach, the dynamic loading induced by earthquake is considered as time independent which is tantamount to assuming that the magnitude and the phase of the acceleration are uniform throughout the soil layer. To overcome this constraint, several researchers (Steedman and Zeng, 1990; Choudhury and Nimbalkar, 2006; Ghosh 2007, 2008; Sreevalsa and Ghosh 2009, 2011) have come out with pseudo-dynamic solutions where the effect of both shear and primary waves as well as the amplification of excitation can be considered along with the duration of earthquake and the period of lateral shaking, to predict the seismic earth pressure behind a retaining wall. It is worth mentioning here that the amplification of vibration generally takes place towards the ground surface and depends on soil properties such as stiffness, damping, and elastic and shear modulus (Steedman and Zeng 1990; Sreevalsa

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and Ghosh, 2009, 2011). A number of investigations (Choudhury *et al*. 2007; Eskandarinejad and Shafiee, 2011) have been carried out to determine the stability of geosynthetic reinforced wall and slope using the pseudo-dynamic approach. However, the study of seismic stability of nailed vertical excavations in soil using the pseudo-dynamic approach has not drawn much attention from researchers. Sabhahit *et al*. (1996) is the first to introduce the pseudo-dynamic approach in seismic analysis of nailed slopes. The response due to the horizontal component of the seismic force was considered in the procedure proposed by Steedman and Zeng (1990), and effort was made to determine the coefficient of reinforcement force using force equilibrium method. Later, Ghazavi *et al*. (2004) have employed the pseudo-dynamic approach to analyze the seismic stability of nailed excavations in terms of the tensile strength of nails. The horizontally applied earthquake force was considered using the pseudo-dynamic approach, whereas the vertical earthquake force was considered using the pseudo-static approach.

In the present investigation, seismic analysis of nailed vertical excavations has been performed using the pseudo-dynamic approach considering both horizontal and vertical seismic forces. The failure surface is assumed to be planar and the failure wedge is considered to be triangular in dry, medium dense to dense cohesionless soil. Both horizontal as well as inclined driven nails are considered. Stability of nailed vertical excavations is presented in terms of the global factor of safety (FOS). The analysis has been performed considering force equilibrium by balancing the different forces acting in the failure wedge. The effect of various parameters such as the angle of internal friction of soil (ϕ), horizontal (k_h) and vertical (k_v) earthquake acceleration coefficients, amplification factor (f_a), length of nails (L), angle of nail inclination (α) and vertical spacing of nails (S_v), on the stability of vertical excavations is explored.

2 Definition of the problem

A vertical excavation of height H is to be performed in a dry, medium dense to dense cohesionless soil deposit. Nails are installed for stabilizing the excavation along with the flexible concrete facing in order to protect the nails which are driven either horizontally or at some inclination α with the horizontal, into the soil with a constant length L throughout the excavation, as shown in Fig. 1. The objective is to determine the stability i.e. the factor of safety of the nailed excavation under seismic condition using the pseudo-dynamic approach. The horizontal and vertical earthquake forces in a pseudo-dynamic method can be represented by sinusoidal base shaking subjected to linearly varying horizontal and vertical accelerations having amplitudes of $\left(1+(f_a-1)\dfrac{(H-z)}{H}\right)k_h g$ and $\left(1+(f_a-1)\dfrac{(H-z)}{H}\right)k_v g$ respectively (Steedman and Zeng, 1990; Ghosh, 2009). The parameters, as shown in Fig. 1, are considered to be positive.

3 Assumptions

The following assumptions are made in the present study

- No tension head is considered at the nail and shotcrete (facing) joint, and property of the facing has not been taken into account.
- Shear resistance due to bending stiffness of the nail is not considered in the analysis as such contribution is reported to be fairly small (Sheahan and Ho, 2003).
- The stress along the axis of the nail is assumed to be K_a times the normal stress acting on the nail i.e. $\sigma_h = K_a\sigma_v$ (Saran *et al*., 2005).
- Length of the nails is considered to be uniform and the nails are employed in such a way that it would intersect the failure surface.

4 Analysis

4.1 Pseudo-dynamic approach

The formulation for the pseudo-dynamic approach, which considers a finite shear wave velocity, can be developed with constant shear modulus, G. The present analysis considers both shear wave velocity $V_s=\sqrt{\dfrac{G}{\rho}}$ and primary wave velocity $V_p=\sqrt{\dfrac{G(2-2\nu)}{\rho(1-2\nu)}}$, where ρ and ν are the density and Poisson's ratio of the soil medium, respectively, acting within the soil layer during an earthquake in the direction as shown in Fig. 1. The analysis includes a period of lateral shaking T, which can be expressed as $T=\dfrac{2\pi}{\omega}$.

Steedman and Zeng (1990) proposed that for sinusoidal base shaking subjected to linearly varying horizontal and vertical earthquake accelerations with amplitude of $\left(1+(f_a-1)\dfrac{(H-z)}{H}\right)k_h g$ and $\left(1+(f_a-1)\dfrac{(H-z)}{H}\right)k_v g$, respectively, the acceleration at any depth z below the ground surface and time t can be expressed as

$$a_h(z,\ t)=\left(1+(f_a-1)\frac{(H-z)}{H}\right)k_h g\sin\omega\left\{(t-\frac{H-z}{V_s})\right\} \tag{1}$$

$$a_v(z,\ t)=\left(1+(f_a-1)\frac{(H-z)}{H}\right)k_v g\sin\omega\left\{(t-\frac{H-z}{V_p})\right\} \tag{2}$$

The planar failure surface (BC) considered in the current analysis (Fig. 1) is inclined at an angle θ with the horizontal. Hence, the mass of the small shaded part of thickness dz (Fig. 1) in the triangular failure wedge ABC is given by

$$m(z)=\frac{\gamma(H-z)}{\mathrm{g}\tan\theta}\mathrm{d}z \tag{3}$$

The total weight of the failure wedge ABC, W, can be derived from Eq. (3) and is given by

$$W=\frac{\gamma H^2}{2\tan\theta} \tag{4}$$

The horizontal inertia force exerted on the small element due to the horizontal earthquake acceleration can be expressed as $m(z)a_\mathrm{h}(z, t)$. Therefore, the total horizontal inertia force $Q_\mathrm{h}(t)$ acting in the failure wedge ABC can be derived as

$$Q_\mathrm{h}(t)=\int_0^H\left[1+(f_\mathrm{a}-1)\frac{(H-z)}{H}\right]k_\mathrm{h}\mathrm{g}\sin\omega\left(t-\frac{H-z}{V_\mathrm{s}}\right)\frac{\gamma(H-z)}{\mathrm{g}\tan\theta}\mathrm{d}z \tag{5}$$

After integration, Eq. (5) becomes

$$Q_\mathrm{h}(t)=\frac{\lambda\gamma k_\mathrm{h}}{4\pi^2\tan\theta}\left[2\pi H\cos\omega\zeta+\lambda(\sin\omega\zeta-\sin\omega t)\right]+I_1(I_2+I_3) \tag{6a}$$

where,

$$I_1=\frac{\lambda\gamma k_\mathrm{h}}{4\pi^3 H\tan\theta}(f_\mathrm{a}-1) \tag{6b}$$

$$I_2=2\pi H\left[\pi H\cos 2\pi\left(\frac{t}{T}-\frac{H}{\lambda}\right)+\lambda\sin 2\pi\left(\frac{t}{T}-\frac{H}{\lambda}\right)\right] \tag{6c}$$

$$I_3=\lambda^2\left[\cos 2\pi\left(\frac{t}{T}\right)-\cos 2\pi\left(\frac{t}{T}-\frac{H}{\lambda}\right)\right] \tag{6d}$$

$\lambda = TV_\mathrm{s}$ = wavelength of vertically propagating shear wave

$\zeta = t - H/V_\mathrm{s}$

Similarly, the total vertical inertia force $Q_\mathrm{v}(t)$ acting in the failure wedge ABC can be deduced as

$$Q_\mathrm{v}(t)=\int_0^H\left[1+(f_\mathrm{a}-1)\frac{(H-z)}{H}\right]k_\mathrm{v}\mathrm{g}\sin\omega\left(t-\frac{H-z}{V_\mathrm{p}}\right)\frac{\gamma(H-z)}{\mathrm{g}\tan\theta}\mathrm{d}z \tag{7}$$

After integration, Eq. (7) becomes

$$Q_\mathrm{v}(t)=\frac{\eta\gamma k_\mathrm{v}}{4\pi^2\tan\theta}\left[2\pi H\cos\omega\chi+\eta(\sin\omega\chi-\sin\omega t)\right]+J_1(J_2+J_3) \tag{8a}$$

where,

$$J_1=\frac{\eta\gamma k_\mathrm{h}}{4\pi^3 H\tan\theta}(f_\mathrm{a}-1) \tag{8b}$$

$$J_2=2\pi H\left[\pi H\cos 2\pi\left(\frac{t}{T}-\frac{H}{\eta}\right)+\eta\sin 2\pi\left(\frac{t}{T}-\frac{H}{\eta}\right)\right] \tag{8c}$$

$$J_3=\eta^2\left[\cos 2\pi\left(\frac{t}{T}\right)-\cos 2\pi\left(\frac{t}{T}-\frac{H}{\eta}\right)\right] \tag{8d}$$

$\eta = TV_\mathrm{p}$ = wavelength of vertically propagating primary wave: $\chi = t - H/V_\mathrm{p}$.

In the limiting condition, the horizontal and vertical inertia forces due to earthquake become

$$\operatorname*{Lt}_{V_\mathrm{s}\to\infty} Q_\mathrm{h}(t)=\frac{\gamma H^2 k_\mathrm{h}}{2\tan\theta}=k_\mathrm{h}W \tag{9}$$

$$\operatorname*{Lt}_{V_\mathrm{p}\to\infty} Q_\mathrm{v}(t)=\frac{\gamma H^2 k_\mathrm{v}}{2\tan\theta}=k_\mathrm{v}W \tag{10}$$

Equations (9)−(10) are virtually the same as that considered in the pseudo–static approach.

For cohesionless soil, the equation proposed by

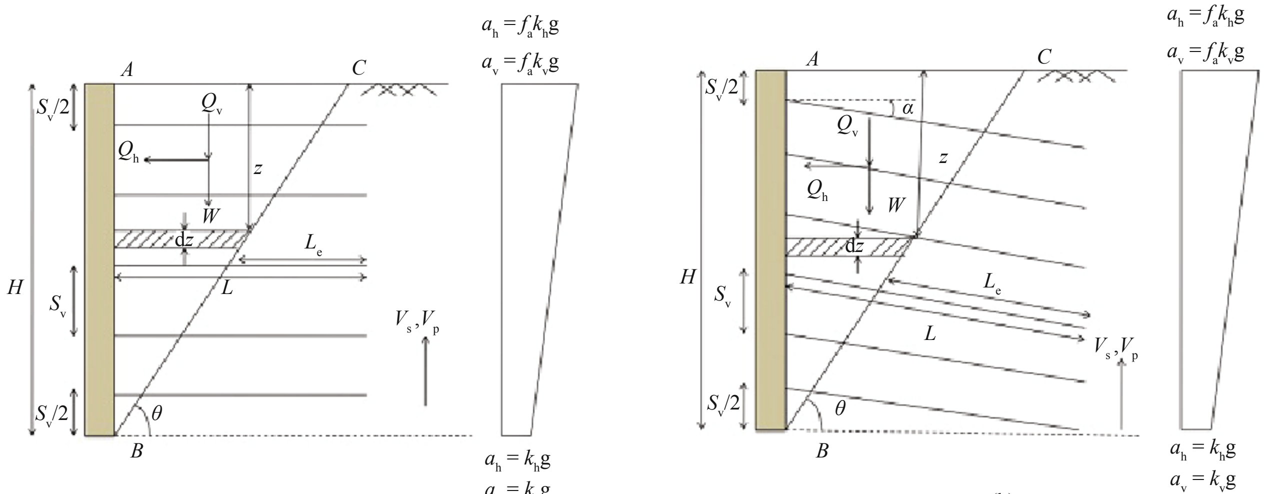

Fig. 1 Failure mechanism and associated forces for (a) horizontal (b) inclined nailed excavation

Richards *et al*. (1990) and later, modified by Ghosh (2009) to avoid the shear fluidization (i.e. the plastic flow of the material at a finite effective stress) for certain combinations of k_h and k_v can be expressed as follows:

$$\varphi \geq \arctan\left[\frac{f_a k_h}{1-f_a k_v}\right] \tag{11}$$

In the present study, the magnitudes of k_h and k_v are considered to satisfy the relationship given in Eq. (11).

4.2 Stability analysis with horizontal nails

Horizontal nails of length, L are placed normal to the facing as shown in Fig. 1(a). The horizontal and vertical seismic forces are computed using the pseudo-dynamic approach as discussed earlier. The tensile force acting in the nails is considered as the minimum of the pullout resistance and rupture due to yielding. The pullout resistance of the ith nail in cohesionless soil can be expressed using the relation proposed by Byrne *et al*. (1996) and Lazarte *et al*. (2003).

$$T_i = \frac{P L_{ei} \sigma_n^i \tan\delta}{S_h} \tag{12}$$

where, L_{ei} is the length of ith nail beyond the failure surface and can be given by the following relationship

$$L_{ei} = L - \frac{\left[H-(i-0.5)S_v\right]}{\tan\theta} \tag{13}$$

and σ_n^i is the normal stress at the mid-depth of the ith nail of length L_{ei} and can be expressed as $\sigma_n^i = \gamma(i-0.5)S_v$.

Whereas, the rupture force in the nail due to yielding can be determined as

$$T_{iy} = \frac{f_y A_s}{S_h} \tag{14}$$

It is worth noting that the design value of T_i may be adopted as the minimum of Eqs. (12) and (14). Therefore, the equivalent tensile force per unit horizontal spacing, T_{eq} acting along the nails can be expressed as

$$T_{eq} = \sum_{i=1}^{n} T_i \tag{15}$$

Applying force equilibrium along the horizontal ($\sum F_h = 0$) as well as the vertical ($\sum F_v = 0$) direction, the resistive (F_R) and driving (F_D) forces acting along the failure surface (BC) can be expressed as

$$F_R = \left[(Q_v + W)\cos\theta + T_{eq}\sin\theta - Q_h\sin\theta\right]\tan\varphi \tag{16}$$

$$F_D = (Q_v + W)\sin\theta + Q_h\cos\theta - T_{eq}\cos\theta \tag{17}$$

Subsequently, stability with horizontal nails can be expressed in terms of the global FOS, which can be obtained as

$$\text{FOS} = \frac{F_R}{F_D} = \frac{\left[(Q_v + W)\cos\theta + T_{eq}\sin\theta - Q_h\sin\theta\right]\tan\varphi}{(Q_v + W)\sin\theta + Q_h\cos\theta - T_{eq}\cos\theta} \tag{18}$$

4.3 Stability analysis with inclined nails

As shown in Fig. 1(b), inclined nails of length, L , are installed at an angle, α, with the horizontal. As the nails are inclined at an angle α, the equivalent tensile force, T_{eq} or the resultant tensile force in the nails also acts at an angle α with the horizontal and T_{eq} can be obtained from Eq.(15) by following similar procedure as adopted for the horizontal nail.

The length of the ith inclined nail beyond the failure surface can be determined as

$$L_{ei} = L - \left[H-(i-0.5)S_v\right]\frac{\cos\theta}{\sin(\alpha+\theta)} \tag{19}$$

The normal stress acting on the ith inclined nail beyond the failure surface can be expressed as (Saran *et al*., 2005)

$$\sigma_n^i = \frac{\sigma_v\cos^2\alpha - \sigma_h\sin^2\alpha}{\cos 2\alpha + \sin 2\alpha\tan\delta} \tag{20}$$

The pullout resistance of the ith inclined nail in cohesionless soil can be determined using Eqs. (12) and (14), where L_{ei} and σ_n^i can be obtained from Eqs. (19) and (20), respectively.

Applying force equilibrium along the horizontal ($\sum F_h = 0$) as well as the vertical ($\sum F_v = 0$) direction the expression for the global FOS can be obtained as

$$\text{FOS} = \frac{F_R}{F_D} = \frac{\left[(Q_v + W)\cos\theta + T_{eq}\sin(\theta+\alpha) - Q_h\sin\theta\right]\tan\varphi}{(Q_v + W)\sin\theta + Q_h\cos\theta - T_{eq}\cos(\theta+\alpha)} \tag{21}$$

5 Results and discussion

The analysis has been performed by developing a computer code in MATLAB. In order to find out the critical global factor of safety under the critical pseudo-dynamic earthquake forces, the optimization has been carried out with respect to t/T and θ varying from 0−1 and (45°+ϕ/2)-90° at an interval of 0.01 and 0.1, respectively. The failure surface has been varied as per the Rankine's criteria recommended by Sheahan and Ho (2003) and Lazarte *et al*. (2003). The results are presented for different ranges of parameters, which are presented in Table 1. The values of H/λ and H/η are chosen in such a way that V_p/V_s ratio becomes equal to 1.87, which is valid for most of the geological materials (Das, 1993). It is worth mentioning here that the minimum value of the angle of internal friction of soil is considered as 30° so as to allow the soil to exhibit enough strength to stand vertically till the first nail gets inserted into the soil (Lazarte *et al*., 2003).

Table 1 Ranges of different parameters

Parameters	Range
ϕ	30°−50°
L/H	0.6−0.9
S_v/H	0.1−0.2
f_a	1.0−2.0
k_h	0−0.2
k_v	$0.5k_h$−k_h
H/λ	0.3−0.6
H/η	0.16−0.32
α	0°−25°

5.1 Excavation with horizontal nails

The variation of global factor of safety with the horizontal seismic acceleration coefficient, k_h is presented in Figs. 2−3 for different values of ϕ and S_v/H ratio. The recommended value of minimum static and seismic global FOS for the nailed soil structure is also presented to indicate the limiting condition (Lazarte *et al.*, 2003). It can be observed that the FOS decreases with increasing k_h , and the $k_v = k_h$ condition provides the most critical situation with minimum stability. Predominant non-linearity can be observed in the variation of the FOS for higher values of ϕ with increasing k_v. Variation of the global FOS with L/H ratio is presented in Figs. 4−5 for different values of ϕ and S_v/H. In the present study, the value of L/H ratio is varied in the range of 0.6−0.9 as the minimum value recommended by the Federal Highway Administration (Lazarte *et al.*, 2003) happens to be 0.5. It can be observed that for a particular value of ϕ, the FOS increases almost linearly with increasing L/H ratio. This may be attributed to the fact that with the increase in the length of the nail, the pullout length of the nail beyond the failure surface increases, which offers higher pullout resistance due to the interaction between the nail and the surrounding soil and eventually the FOS increases. Figure 6 presents the variation of the FOS with the number of nails for different values of ϕ. The

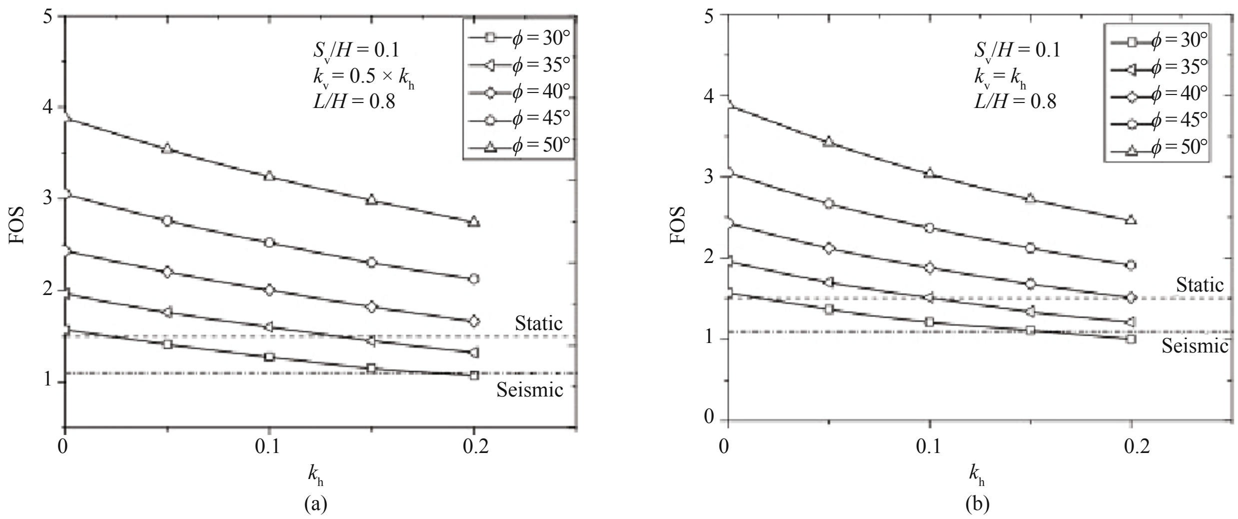

Fig. 2 Variation of FOS with k_h for $S_v/H = 0.1$, $L/H = 0.8$, $f_a = 1.0$, $H/\lambda = 0.3$ and $H/\eta = 0.16$ (a) $k_v = 0.5k_h$, (b) $k_v = k_h$

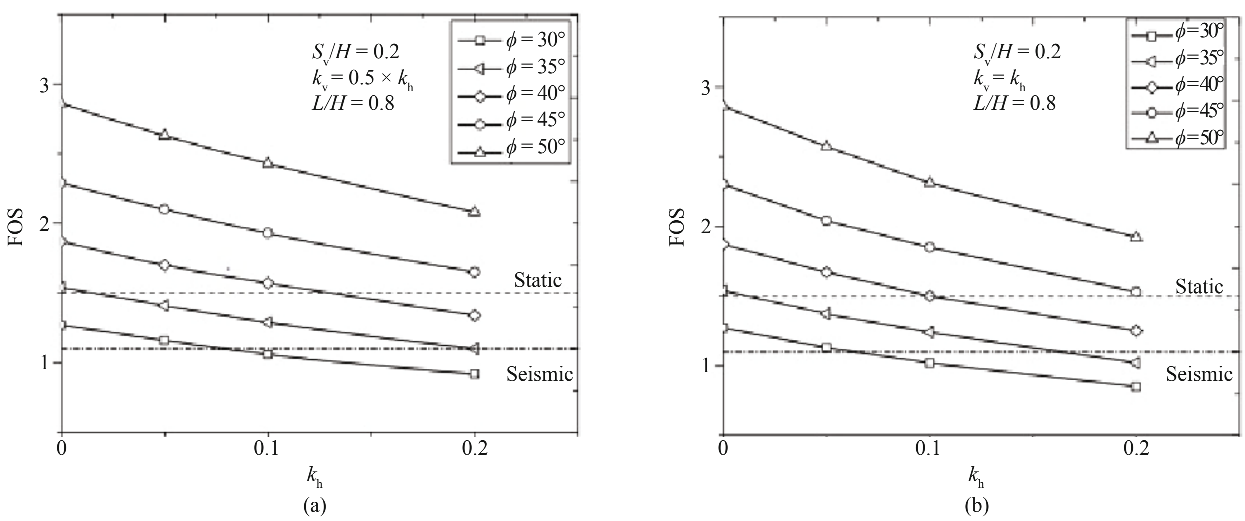

Fig. 3 Variation of FOS with k_h for $S_v/H = 0.2$, $L/H = 0.8$, $f_a = 1.0$, $H/\lambda = 0.3$ and $H/\eta = 0.16$ (a) $k_v = 0.5k_h$, (b) $k_v = k_h$

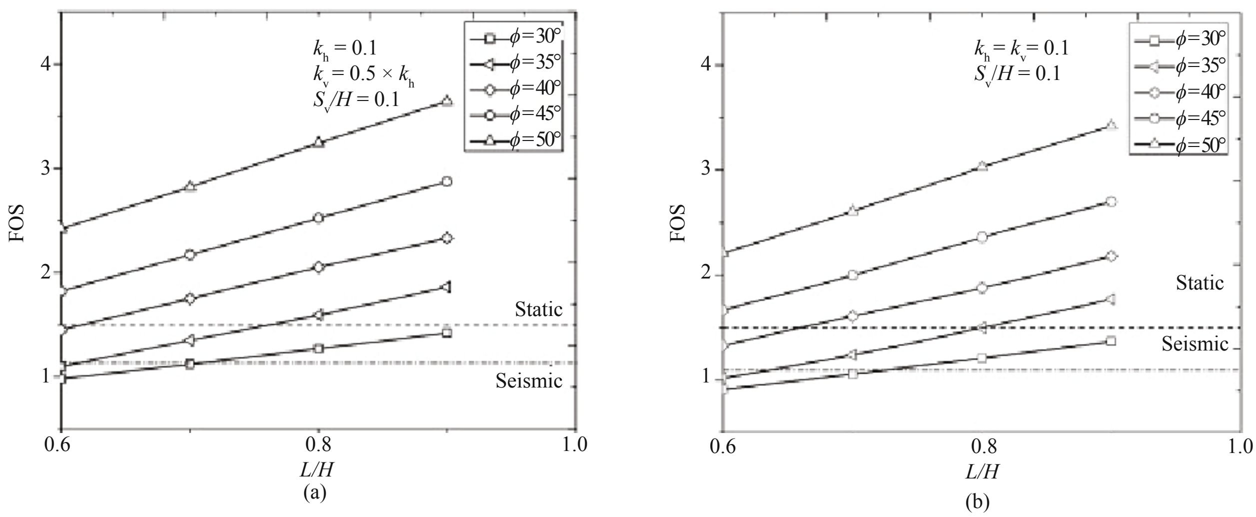

Fig. 4 Variation of FOS with *L/H* for S_v/H = 0.1, k_h = 0.1, f_a = 1.0, H/λ = 0.3 and H/η = 0.16 (a) $k_v = 0.5k_h$, (b) $k_v = k_h$

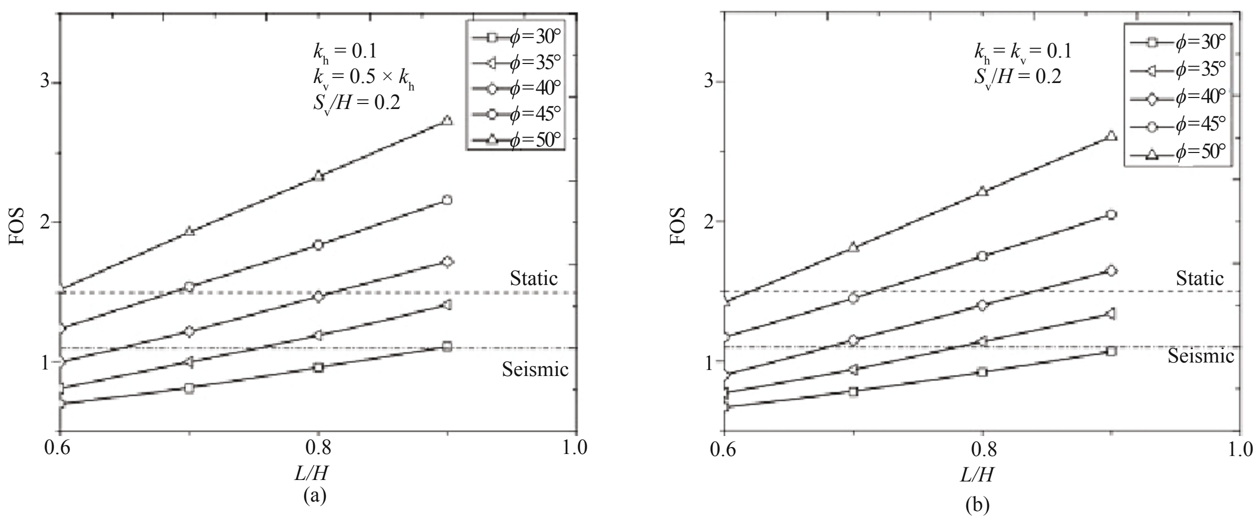

Fig. 5 Variation of FOS with *L/H* for S_v/H = 0.2, k_h = 0.1, f_a = 1.0, H/λ = 0.3 and H/η = 0.16 (a) $k_v = 0.5k_h$, (b) $k_v = k_h$

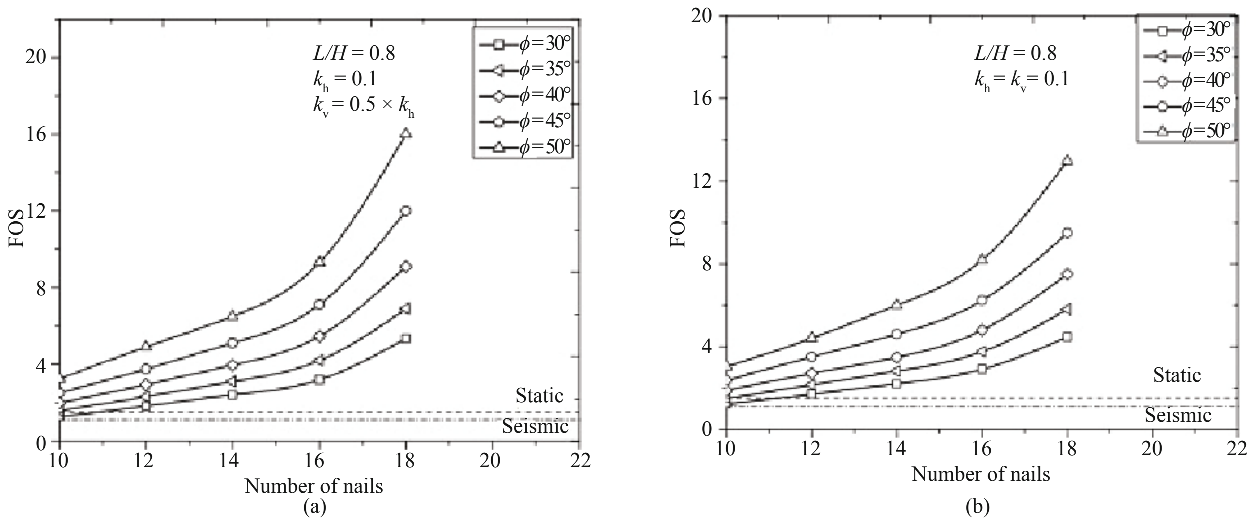

Fig. 6 Variation of FOS with number of nails for S_v/H = 0.1, *L/H* = 0.8, k_h = 0.1, f_a = 1.0, H/λ = 0.3 and H/η = 0.16 (a) $k_v = 0.5k_h$, (b) $k_v = k_h$

FOS is found to increase non-linearly with increasing number of nails of constant length placed horizontally and the non-linearity in the variation also increases with increase in the number of nails. It may be due to the fact that the increase in the number of nails ensures the group effect between adjacent nails and reduces the load carried by individual nails. Variation of the FOS with f_a for different values of H/λ and H/η is presented in Table 2 for $k_v = 0.5k_h$ and $k_v = k_h$ conditions. It can be observed that the FOS decreases with increasing amplification factor for a particular value of H/λ and H/η. It can be emphasized that with increase in f_a, the pseudo-dynamic horizontal and vertical earthquake forces (Q_h and Q_v) increase and hence, the FOS decreases. It can also be noted that the FOS increases with increase in the magnitude of H/λ and H/η. It is worth mentioning here that the present combination of H/λ and H/η is extracted from the study of Ghosh (2008). It can be pointed out that with increase in the magnitude of H/λ and H/η, the period of lateral shaking decreases i.e., the shear and primary waves travel at a slower speed, which results in increase in the FOS.

5.2 Excavation with inclined nails

Under seismic condition, variation of the global FOS with α is presented in Figs. 7−8 for different values of ϕ and S_v/H with $L/H = 0.8$. The angle of nail inclination is varied from 0° to 25° at an interval of 5°. It can be observed that magnitude of the FOS decreases with increase in the angle of nail inclination as well as the spacing (S_v) between consecutive nails. The decrease in the FOS may be attributed to the fact that the increase in the angle of nail inclination results in a reduction in the normal stress acting on the nails, which ultimately reduces the shear resistance offered by the nails. This is only valid for the vertical excavation as the optimum angle of nail inclination i.e., the value of α associated with the highest performance based on the global FOS, is always found to be 0° (Fan and Luo, 2008; Mittal *et al*., 2005; and Saran *et al*., 2005). Under seismic conditions, variation of the global FOS with L/H is presented in Fig. 9 for different magnitudes of ϕ at $S_v/H = 0.05$ and $\alpha = 10°$. It can be noticed that the FOS increases with increase in L/H ratio, which is found to be fairly similar to that observed for horizontal nails but differs in magnitude. Variation of the FOS with f_a for different values of H/λ and H/η is presented in Table 3 for $k_v = 0.5k_h$ and $k_v = k_h$ conditions. It can be seen from the results that the FOS decreases with increase in the amplification factor for a particular value of H/λ and H/η. It can also be noted that with increase in the magnitude of H/λ and H/η, the FOS increases for a particular value of f_a. The trend is found to be pretty similar to that observed for horizontal nails but differs in magnitude.

Table 2 Variation of FOS with f_a for horizontal nails with $L/H = 0.8$, $\phi = 35°$, $S_v/H = 0.1$ and $k_h = 0.2$

k_v	H/λ	H/η	FOS					
			f_a= 1.0	f_a= 1.2	f_a= 1.4	f_a= 1.6	f_a=1.8	f_a= 2.0
$0.5k_h$	0.3	0.16	1.32	1.25	1.18	1.12	1.09	0.98
	0.4	0.21	1.46	1.36	1.26	1.22	1.12	1.00
	0.5	0.27	1.55	1.44	1.34	1.26	1.18	1.12
	0.6	0.32	1.60	1.49	1.39	1.30	1.23	1.20
k_h	0.3	0.16	1.21	1.15	1.10	1.05	1.00	0.95
	0.4	0.21	1.37	1.27	1.22	1.16	1.10	1.06
	0.5	0.27	1.44	1.34	1.26	1.20	1.12	1.10
	0.6	0.32	1.49	1.40	1.31	1.24	1.17	1.12

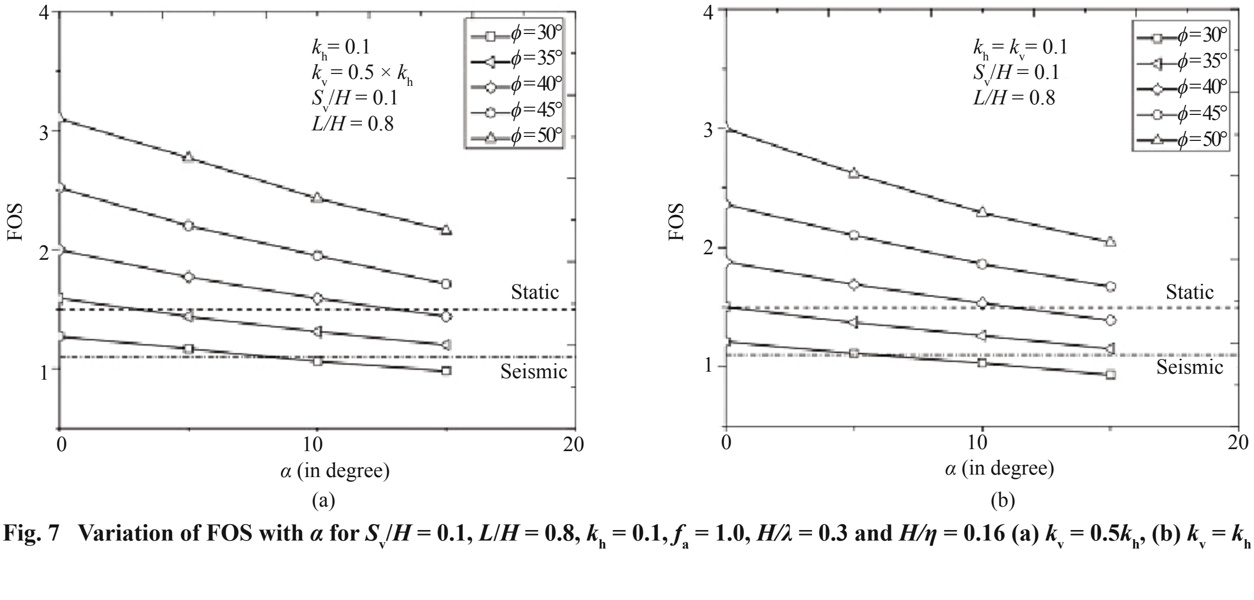

Fig. 7 Variation of FOS with α for $S_v/H = 0.1$, $L/H = 0.8$, $k_h = 0.1$, $f_a = 1.0$, $H/\lambda = 0.3$ and $H/\eta = 0.16$ (a) $k_v = 0.5k_h$, (b) $k_v = k_h$

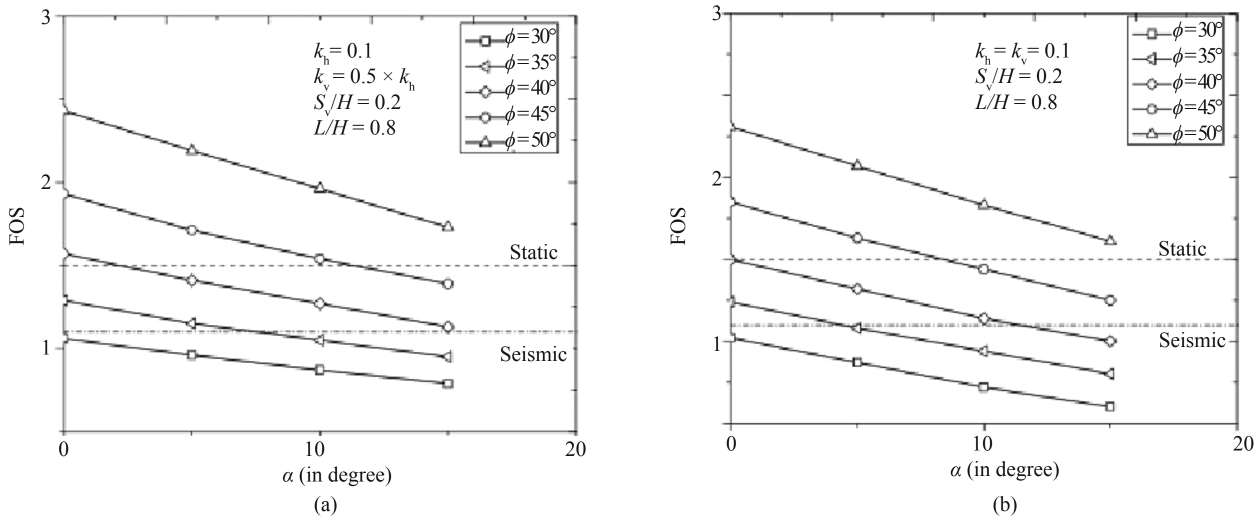

Fig. 8 Variation of FOS with α for S_v/H = 0.2, L/H = 0.8, k_h = 0.1, f_a = 1.0, H/λ = 0.3 and H/η = 0.16 (a) $k_v = 0.5k_h$, (b) $k_v = k_h$

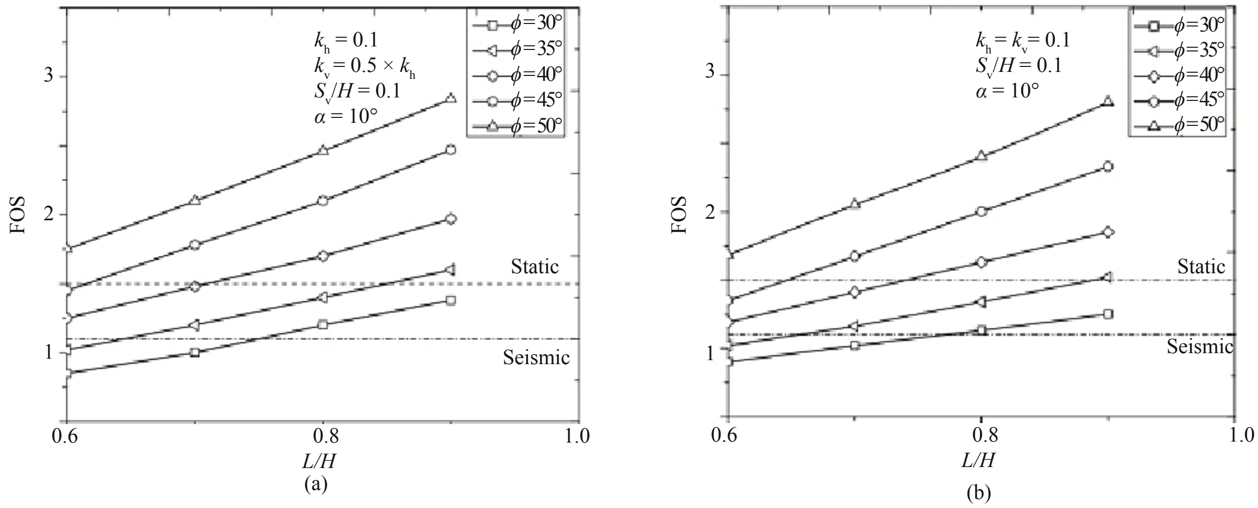

Fig. 9 Variation of FOS with L/H for S_v/H = 0.1, α = 10°, k_h = 0.1, f_a = 1.0, H/λ = 0.3 and H/η = 0.16 (a) $k_v = 0.5k_h$, (b) $k_v = k_h$

Table 3 Variation of FOS with f_a for inclined nails with L/H = 0.8, ϕ = 35°, S_v/H = 0.1, α = 15° and k_h = 0.2

k_v	H/λ	H/η	FOS					
			f_a = 1.0	f_a = 1.2	f_a = 1.4	f_a = 1.6	f_a =1.8	f_a = 2.0
$0.5k_h$	0.3	0.16	1.04	1.00	0.95	0.91	0.87	0.84
	0.4	0.21	1.12	1.06	1.00	0.96	0.91	0.87
	0.5	0.27	1.18	1.11	1.06	1.00	0.96	0.92
	0.6	0.32	1.20	1.14	1.09	1.04	1.00	0.95
k_h	0.3	0.16	0.98	0.94	0.90	0.87	0.83	0.80
	0.4	0.21	1.07	1.02	0.97	0.92	0.88	0.84
	0.5	0.27	1.12	1.07	1.01	0.97	0.93	0.89
	0.6	0.32	1.15	1.10	1.05	1.00	0.96	0.93

6 Comparison

The results obtained from the present investigation could not be directly compared with the results available in the literature due to lack of studies on pseudo-dynamic analysis of nailed vertical excavations in soil as well as lack of direct match in the parameters. However, efforts have been made to perform seismic analysis of nailed vertical excavation using pseudo-static approach along with planar failure surface in order to compare with the present results obtained with the pseudo-dynamic approach. In Fig. 10, present values of the FOS obtained from pseudo-dynamic and pseudo-static approaches are compared for both horizontal and inclined nails with $L/H = 0.8$, $S_v/H = 0.05$, $\phi = 30^o$, $H = 8$ m, $f_a = 1.0$, $H/\lambda = 0.3$, $H/\eta = 0.16$ and $k_v = 0.5k_h$. It can be observed that the pseudo-dynamic approach offers higher FOS as compared to that obtained from the pseudo-static analysis and the difference between pseudo-static and pseudo-dynamic approaches increases with increase in k_h value. Thus the comparison establishes the fact that the pseudo-static analysis of nailed excavations reveals conservative estimation of FOS and this is more so for higher seismic accelerations. Similar trends have also been observed by Reddy *et al*. (2009) where the seismic stability of a reinforced wall has been explored using the pseudo-dynamic approach with planar failure surface considering oblique displacement.

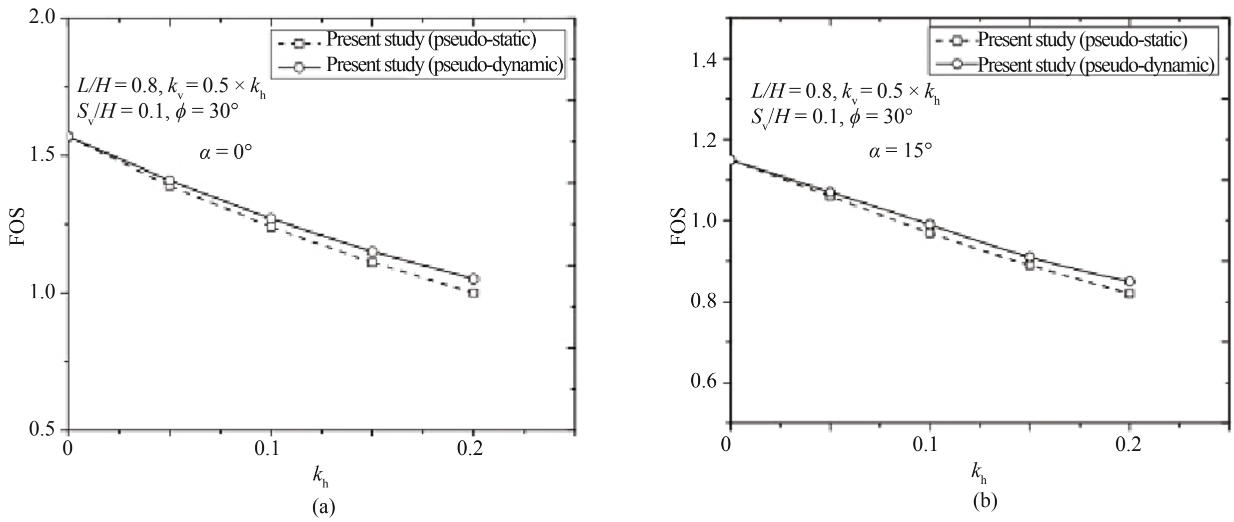

Fig. 10 Comparison of FOS obtained from pseudo-dynamic and pseudo-static approach with $L/H = 0.8$, $S_v/H = 0.1$, $\phi = 30°$, $H = 8$ m, $f_a = 1.0$, $H/\lambda = 0.3$, $H/\eta = 0.16$ and $k_v = 0.5k_h$ (a) $\alpha = 0$, b) $\alpha = 15°$

7 Conclusions

In the present study the pseudo-dynamic approach is used to determine the seismic stability of nailed vertical excavations in medium dense to dense sand assuming the failure surface to be planar. Compared to the pseudo-static approach, the pseudo-dynamic approach is found to be more reasonable as it considers seismic forces acting on nailed vertical excavations as coming from vertically propagating shear and primary waves. The magnitude of the global factor of safety for the excavation with both horizontal and inclined nails is found to decrease with increasing horizontal (vertical) earthquake acceleration. The FOS of nailed excavations decreases with increase in the soil amplification (f_a) and increases with increase in the magnitude of H/λ and H/η, which cannot be predicted by the conventional pseudo-static approach. The FOS of nailed vertical excavations is found to increase with increase in the length of the nails under both static and seismic conditions. The FOS is also seen to increase at a rate of 40% with increase in the angle of internal friction, ϕ by 5^o. Excavations with horizontal nails are found to offer higher FOS as compared to those with inclined nails under both static and seismic conditions and, precisely, the critical condition occurs at the $k_h = k_v$ condition. The value of the FOS for nailed excavations is found to be conservative for the pseudo-static approach as compared to the pseudo-dynamic approach for horizontal as well as inclined nails.

References

Babu GLS and Singh VP (2008), "Numerical Analysis of Performance of Soil Nail Walls in Seismic Conditions," *ISET Journal of Earthquake Technology*, **45**(1−2): 31−40.

Byrne RJ, Cotton D, Porterfield J, Wolschlag C and Ueblacker G (1996), "Manual for Design and Construction Monitoring of Soil Nail Wall," *Report No. SA-96-069R,* Federal Highway Administration, U.S. Department of Transportation, Washington, DC, USA.

Choudhury D and Nimbalkar S (2006), "Pseudo-dynamic Approach of Seismic Active Earth Pressure behind the Retaining Wall," *Geotechnical and Geological Engineering*, **24**(5): 1103–1113.

Choudhury D, Nimbalkar SS and Mandal JN (2007), "External Stability of Reinforced Soil Walls under Seismic Conditions," *Geosynthetics International*, **14**(4): 211–218.

Das BM (1993), *Principles of Soil Dynamics*, PWS-KENT Publishing Company, Boston, Massachusetts.

Eskandarinejad A and Shafiee AH (2011), "Pseudo-dynamic Analysis of Seismic Stability of Reinforced Slopes Considering Non-associated Flow Rule," *J. Cent. South Univ. Technol.*, **18**: 2091−2099.

Fan C C and Luo J H (2008), "Numerical Study on the Optimum Layout of Soil-nailed Slopes," *Computers and Geotechnics*, **35**(4): 585–599.

Ghazavi M,Karbor L and Hashemolhoseini H (2004), "A New Pseudo-dynamic Analysis of Soil Nailed Walls," *13th World Conference on Earthquake Engineering,* Paper No. 2960, Vancouver, B.C Canada.

Ghosh P (2007), "Seismic Passive Earth Pressure behind Non Vertical Retaining Wall Using Pseudo-dynamic Analysis," *Geotechnical and Geological Engineering*, **25**(6): 693−703.

Ghosh P (2008), "Upper Bound Solutions of Bearing Capacity of Strip Footing by Pseudo-dynamic Approach," *ActaGeotechnica*, **3**(2): 115−123.

Ghosh P (2009), "Seismic Vertical Uplift Capacity of Horizontal Strip Anchors Using Pseudo-dynamic Approach," *Computers and Geotechnics*, **36**(1−2): 342−351.

Jaya V and Joy A (2013), "An Investigation on the Dynamic Behaviour of Soil Nail Walls," *Journal of Civil Engineering and Science*, **2**(4): 241−249.

Lazarte CA, Elias V, Espinoza RD and Sabatini PJ (2003), "Geotechnical Engineering Circular No. 7 - Soil Nail Walls," *Report FHWA0-IF-03-017*, Federal Highway Administration, U.S. Department of Transportation, Washington, DC, USA.

Meenal G, Saran S and Mittal S (2009), "Pseudo-static Analysis of Soil Nailed Excavations," *Geotechnical and Geological Engineering*, **27**(4): 571−583.

Mittal S and Biswas AK (2006), "River Bank Erosion Control by Soil Nailing," *Geotechnical and Geological Engineering,* **24**(6): 1821−1833.

Mittal S, Gupta RP and Mittal N (2005), "Housing Construction on Inclined Cuts," *Asian Journal of Civil Engineering (Building and Housing),***6**(4): 331−346.

Reddy GVN, Choudhury D, Madhav MR and Reddy ES (2009), "Pseudo-dynamic Analysis of Reinforced Soil Wall Subjected to Oblique Displacement," *Geosynthetics International*, **16**(2): 61−70.

Richards R, Elms DG and Budhu M (1990), "Dynamic Fluidization of Soils," *Journal of Geotechnical Eng.*, ASCE, **116**(5): 740–759.

Sabhahit N, Madhav MR and Basudhar PK (1996), "Seismic Analysis of Nailed Soil Slopes−a Pseudo Dynamic Approach," *Earth Reinforcement*, Ochiai, Yasufuku and Omine (ed.), Balkema, Rotterdam.

Saran S, Mittal S and Meenal G (2005), "Pseudo Static Analysis of Nailed Vertical Excavations in Sands," *Indian Geotechnical Journal*, **35**(4): 401–417.

Sengupta A and Giri D (2011), "Dynamic Analysis of Soil Nailed Slope," *Ground Improvement*, **164**(4): 225−234.

Sheahan TC and Ho CL (2003), "Simplified Soil Wedge Method for Soil Nailed Wall Analysis," *Journal of Geotechnical and Geoenvironmental Engineering,* ASCE, **129**(2): 117−124.

Sreevalsa K and Ghosh P (2009),"Seismic Active Earth Pressure on Walls with Bilinear Backface Using Pseudo-dynamic Approach," *Computers and Geotechnics*, **36**(7): 1229−1236.

Sreevalsa K and Ghosh P (2011), "Seismic Earth Pressure behind Non Vertical Wall with Composite Failure Mechanism: Pseudo-dynamic Approach," *Geotechnical and Geological Engineering*, **29**(3): 363−373.

Steedman RS 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.

Notations

A_s	Surface area of nail (m^2)
F_D	Driving force along failure surface
F_R	Resistive force along failure surface
G	Shear modulus of soil (kN/m^2)
H	Height of vertical excavation (m)
K_a	Active earth pressure coefficient
L	Length of nail (m)
L_e	Length of nail beyond the failure surface BC (m)
P	Perimeter of the nail (m)
$Q_h(t)$	Horizontal inertia force due to seismic acceleration (kN/m)
$Q_v(t)$	Vertical inertia force due to seismic acceleration (kN/m)
S_v	Vertical spacing of nails (m)
S_h	Horizontal spacing of nails (m)
T	Period of lateral shaking (seconds)
T_{eq}	Equivalent tensile force along the nails (kN/m)
T_i	Pullout resistance of the ith nail (kN/m)
T_{iy}	Rupture force in the nail due to yielding (kN/m)
V_s	Shear wave velocity (m/s)
V_p	Primary wave velocity (m/s)
W	Weight of failure wedge ABC (kN/m)
$a_h(z, t)$	Horizontal seismic acceleration at any depth z and time t (m/s^2)
$a_v(z, t)$	Vertical seismic acceleration at any depth z and time t (m/s^2)
f_a	Amplification factor
f_y	Yield strength of nail (MPa)
g	Acceleration due to gravity (m/s^2)
k_h	Horizontal seismic acceleration coefficient

k_v	Vertical seismic acceleration coefficient
$m(z)$	Mass of small shaded part in the failure wedge ABC (kg/m)
n	Number of nails
t	Time (s)
z	Any depth below the ground surface (m)
α	Inclination of nail with horizontal (degree)
ϕ	Angle of internal friction of soil (degree)
γ	Unit weight of soil (kN/m^3)
η	Wavelength of primary wave (m)
λ	Wavelength of shear wave (m)
θ	Angle made by failure surface BC with horizontal (degree)
σ_n^i	Normal stress at the mid-depth of the *i*th nail (kN/m^2)
σ_h	Horizontal stress (kN/m^2)
σ_v	Vertical stress (kN/m^2)
ω	Angular/circular frequency (rad/s)