Seismic bearing capacity factor of dry cohesionless soil under surficial strip footing

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ABSTRACT

The modified pseudo-dynamic method is used to calculate the seismic bearing capacity factor $N_{\gamma e}$ for dry cohesionless soil underlying a surficial strip footing. This new method is used to estimate the seismic accelerations and thus estimate the seismic force more accurately than the commonly used but approximate pseudo-static method. This study shows that $N_{\gamma e}$ is significantly affected by both the horizontal and vertical seismic accelerations, and soil friction angle, whereas the soil damping ratio and width of the footing have negligible effect. $N_{\gamma e}$ decreased by about 86% as compared to static case for k_h = 0.1 and if an additional k_v = 0.1 acts, the value of $N_{\gamma e}$ further reduced by about 13%. When the soil friction angle was decreased from 40^o to 25^o, $N_{\gamma e}$ was decreased by about 79%. Amplification factor was also found to strongly influence the value of $N_{\gamma e}$. If the seismic acceleration was in phase all along the depth up to the failure surface, drastic reduction in $N_{\gamma e}$ was observed as compared to the condition where it was out of phase. These outputs highlight the importance of using the modified pseudo-dynamic method compared to conventional pseudo-static method for estimation of $N_{\gamma e}$, which can be used for design of shallow strip footings under earthquake conditions.

Keywords: seismic bearing capacity; modified pseudo-dynamic method; strip footings; earthquake loading; shallow foundation; composite failure mechanism

1 INTRODUCTION

Designs of foundations to support the superstructures in seismically active areas are always challenging. Historically the pseudo-static method, developed by Okabe (1926) and Mononobe and Matsuo (1929) [see Kramer (1996)] has been used for estimation of inertia forces induced by earthquake loading as it is easy to use. Sarma and Iossifelis, (1990) and Budhu and Al Karni (1993) were some pioneers for determining the bearing capacity of soil in seismic conditions for shallow footings. Dormieux and Pecker (1995), Poulucci and Pecker (1997) Soubra (1997, 1999), Kumar and Rao (2002), Choudhury *et al.* (2004), Choudhury and Subba Rao (2005, 2006), Kumar and Ghosh (2006), Choudhury (2009), Kumar and Chakraborty (2013) and Cascone and Casablanca (2016) are some of the other prominent researchers who used pseudo-static method to estimate seismic bearing capacity.

However, pseudo-static method is very crude and approximate by considering the transient and complex seismic force by transforming it to a single equivalent static value. Hence, a simplified dynamic method was developed by Choudhury and Nimbalkar (2005, 2006), and Nimbalkar *et al.* (2006), known as the pseudo-dynamic method. This method accounts for both the horizontal and vertical seismic accelerations that vary with time, depth, amplification of seismic waves, and effects of the shear and primary wave velocities. Ghosh (2008) and Ghosh and Choudhury (2011) applied this method to estimate the seismic bearing capacity of shallow footing. But critical review of the pseudo-dynamic method by Choudhury and Katdare (2013), Choudhury *et al.* (2014), Bellezza (2014, 2015) and Pain *et al.* (2015, 2016a,b, 2017) showed that it violates the zero-stress at ground surface boundary condition and assumes linear amplification of seismic acceleration by incorporating an assumed amplification factor. These limitations were removed by the modified pseudo-dynamic method proposed by Bellezza (2014) and Pain *et al.* (2015, 2016a,b, 2017). The method considered standing seismic waves to be propagating through a visco-elastic soil represented by Kelvin-Voigt model. Seismic primary and shear wave velocities, frequency, damping, period of shaking and variation of seismic forces with time and depth are considered in this method, making it more realistic.

In the present study, this newly developed and more accurate method has been applied to understand the influence of various soil, foundation and seismic parameters on the value of the seismic bearing capacity factor ($N_{\gamma e}$) for surface strip footing in dry cohesionless soil by using limit equilibrium technique.

2 FAILURE MECHANISM AND METHODOLOGY

Considering one-directional nature of the major horizontal direction of earthquake at an instant, one-sided, non-symmetrical composite (log-spiral + planar) failure mechanism has been used in this study as shown in Fig. 1. The surface footing of width B (AC) is considered to rest on dry cohesionless soil. Block ACD shows the planar active wedge with angles as α_1 and α_2; block CED shows the log-spiral zone with initial radius r_0 (CD) and final radius r_f (CE) at an angle of θ with r_0. Focus of the log spiral is at the footing edge (point C) and block CFE shows the planar passive wedge with angles α_3 and α_4. The new modified pseudo-dynamic approach is applied and limit equilibrium equations are used to obtain the value of the seismic bearing capacity factor ($N_{\gamma e}$). Q_v and Q_h show the most critical directions of seismic inertia forces considered to be acting on all three zones. This value of $N_{\gamma e}$ is used for estimating the ultimate bearing capacity (q_u) of cohesionless soil under surficial strip footings for seismic conditions using the equation given by Terzaghi (1943) and modified for the present study (Eq. 1).

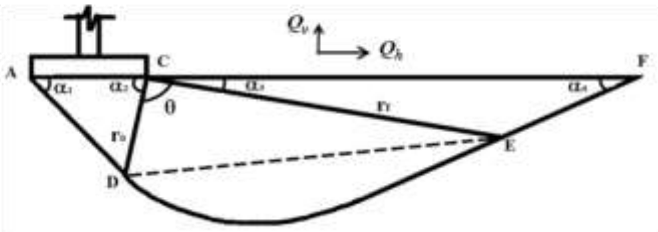

Fig. 1. One-sided failure mechanism showing composite failure surface under surface strip footing AC of width B

Using the equation of motion of seismic waves given by Yuan *et al.* (2006) and considering the soil to be a visco-elastic material, the modified pseudo-dynamic method gives the equations for horizontal and vertical accelerations in terms of soil damping ratio, seismic wave velocity, time period, horizontal and vertical acceleration coefficients, and depth to bedrock (Bellezza, 2015). These values of horizontal and vertical accelerations are used to determine the seismic forces acting on the surface strip footing and applying limit equilibrium equations in the horizontal direction and vertical direction, two values of $N_{\gamma e}$ are obtained. Iteration is carried out to determine the value of $N_{\gamma e}$ that gives the same value from both horizontal and vertical equilibrium equations and the least of these is the critical $N_{\gamma e}$. The variation in $N_{\gamma e}$ with changes in soil properties, foundation geometry and seismic parameters are obtained.

$$q_u = \frac{1}{2}\gamma B N_{\gamma e} \quad (1)$$

3 RESULTS AND DISCUSSIONS

Validation for this newly developed modified pseudo-dynamic method for estimating seismic bearing capacity factor has been reported by Nadgouda and Choudhury (2019). The $N_{\gamma e}$ values show a very good match to those given by Soubra (1999) and Vesic (1973) but were about 18% to 37% higher than those reported by Meyerhof (1963) due to differences in assumptions.

3.1 Variation with seismic acceleration coefficients

The seismic bearing capacity factor $N_{\gamma e}$ is significantly affected by changes in the seismic acceleration coefficient in horizontal direction (k_h) and vertical direction (k_v) as shown in Fig. 2. For a value of k_h = 0.1 and k_v = 0, the bearing capacity factor decreased by 86% for ϕ = 30° as compared to that of static case, whereas it decreased by 98% for k_h = 0.2 and k_v = 0. The values used for the study were: time period (T) = 0.33 sec, shear wave velocity (V_s) = 200 m/s, primary wave velocity (V_p) = 1.87 V_s depth to bedrock (H) = 3.5B, and damping ratio (ξ) = 10%. This shows the strong influence of the horizontal seismic acceleration coefficient on $N_{\gamma e}$. To quantify the influence of the vertical seismic acceleration coefficient on $N_{\gamma e}$, the values for k_h = 0.1 and k_v = 0 were compared to those for k_h = k_v = 0.1 and it was found that $N_{\gamma e}$ was lower by 12% to 13% for ϕ values ranging between 25° to 40°.

3.2 Variation with soil friction angle (ϕ)

Soil friction angle (ϕ) is another factor that strongly affects the value of $N_{\gamma e}$. As seen in Fig. 2, when the soil friction angle increases, $N_{\gamma e}$ also increases. Higher soil friction implies higher shear strength causing greater resisting forces, thus increasing the capacity.

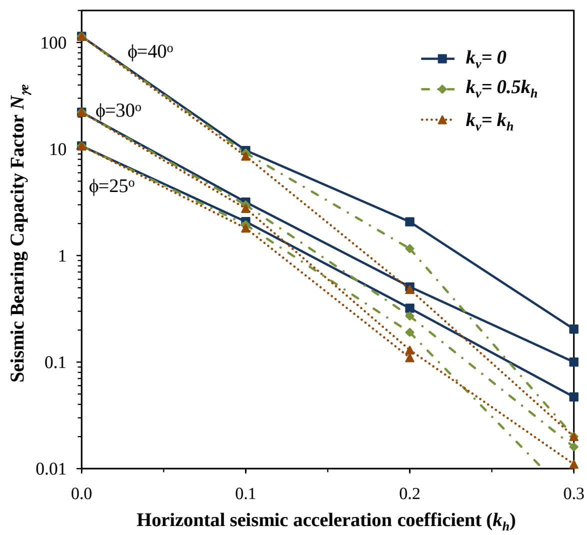

Fig. 2. Variation in $N_{\gamma e}$ with seismic acceleration coefficients (k_h and k_v) and soil friction angle (ϕ)

The figure also shows the effect of increasing k_v values in further lowering $N_{\gamma e}$. The parameters used were T = 0.33 sec, V_s = 200 m/s, ξ = 10%, and H = 3.5B.

3.3 Influence of footing width (*B*)

The value of $N_{\gamma e}$ depends on the depth of the failure surface below the ground level. Since this is a function of the footing width B, a parametric study was performed to quantify the influence of B on $N_{\gamma e}$. Table 1 shows the variation of footing width (B) with $N_{\gamma e}$ for values of ϕ varying from 20° to 40° for k_h = 0.05, k_v = 0.1, T = 0.33 sec, H = 3.5B, and ξ = 10%. It can be seen that the decrease in $N_{\gamma e}$ from width of 1 m to 2.5 m is only 5% for ϕ = 40°, and 9% for ϕ = 30°.

Table 1. Variation of $N_{\gamma e}$ with B for k_h = 0.1, k_v = 0.05, ξ = 10%, H = 3.5, T = 0.33 sec, V_s = 200 m/s.

ϕ = 20°		ϕ = 30°		ϕ = 40°	
B (m)	$N_{\gamma e}$	B (m)	$N_{\gamma e}$	B (m)	$N_{\gamma e}$
1.0	0.54	1.0	2.54	1.0	9.40
1.5	0.51	1.5	2.49	1.5	9.31
2.0	0.43	2.0	2.41	2.0	9.17
2.5	0.42	2.5	2.30	2.5	8.94

3.4 Influence of damping ratio (ξ)

The damping ratio indicates the rate of decay of the seismic wave so it is important to understand its influence on $N_{\gamma e}$. For k_h = 0.1, k_v = 0.05, T = 0.33 sec, H = 3.5B, and B = 2 m, the $N_{\gamma e}$ values were determined as shown in Table 2.

Table 2. Variation of $N_{\gamma e}$ with ξ for k_h = 0.1, k_v = 0.5k_h, T = 0.33 sec, V_s = 200 m/s, B = 2 m, H = 3.5B.

ϕ = 20°		ϕ = 30°		ϕ = 40°	
ξ(%)	$N_{\gamma e}$	ξ(%)	$N_{\gamma e}$	ξ(%)	$N_{\gamma e}$
5	0.42	5	2.41	5	9.15
10	0.43	10	2.41	10	9.17
15	0.43	15	2.42	15	9.19

When ξ increased from 5% to 15%, $N_{\gamma e}$ increased by 0.4% for ϕ = 40°, $N_{\gamma e}$ increased by 0.7% for ϕ = 30°, and $N_{\gamma e}$ increased by 1.7% for ϕ = 20° Thus, it can be seen that change in ξ from 5% to 15% has an insignificant influence on $N_{\gamma e}$ for all values of ϕ.

3.5 Variation with time period (*T*)

Variation in the time period (T), of the waves is expected to cause variation in the values of $N_{\gamma e}$. This was studied for typical periods of 0.2 sec to 0.5 sec and tabulated in Table 3. It can be seen that for T varying from 0.5 sec to 0.33 sec, there is nominal decrease in $N_{\gamma e}$. However, for T = 0.2 sec, there is drastic reduction in $N_{\gamma e}$ (60%) for ϕ = 20°, considerable reduction (25%) for 30°, and marginal reduction (10%) for 40°.

Table 3. Variation of $N_{\gamma e}$ with T for k_h = 0.1, k_v = 0.05, B = 2 m, V_s = 200 m/s, ξ = 10%, H = 3.5B.

ϕ = 20°		ϕ = 30°		ϕ = 40°	
T (sec)	$N_{\gamma e}$	T (sec)	$N_{\gamma e}$	T (sec)	$N_{\gamma e}$
0.2	0.17	0.2	1.82	0.2	8.24
0.33	0.43	0.33	2.41	0.33	9.17
0.4	0.45	0.4	2.47	0.4	9.27
0.5	0.52	0.5	2.51	0.5	9.35

The modified pseudo-dynamic method takes into account the non-linear variation in acceleration as the waves travel from bedrock to ground surface where the footing is located. Amplification factor (f_a) is defined as the horizontal seismic acceleration at ground surface to that at the bedrock. In the above case, 60% reduction in $N_{\gamma e}$ may be attributed to the high value of amplification factor as discussed below.

3.6 Influence of depth to bedrock (*H*), amplification factor (f_a) and phase

The depth to bedrock was varied from 3.5B to 9B to study its influence on the value of $N_{\gamma e}$. For k_h = 0.1, k_v = 0.5k_h, T = 0.33 sec, ξ = 10%, ϕ = 30° and B = 2 m, the $N_{\gamma e}$ values are shown in Table 4. This showed a somewhat random variation in $N_{\gamma e}$ values hence the amplification factor (f_a) was calculated as shown in Table 5.

Table 4. Variation of $N_{\gamma e}$ with H for k_h = 0.1, k_v = 0.5 k_h, B = 2 m, V_s = 200 m/s, ξ = 10%, *T = 0.33 sec and ϕ = 30°.*

H/B	H(m)	$N_{\gamma e}$
5.00	10.0	2.02
6.50	13.0	1.38
8.25	16.5	2.49
9.00	18.0	5.37

This highlights another important aspect of the modified pseudo-dynamic method that the horizontal seismic acceleration at the ground surface, when in phase with that at the bedrock level, gives 51% to 73% lower $N_{\gamma e}$ value than that when the accelerations are out of phase. This is because when the accelerations are out of phase, a part of the wedge experiences acceleration in one direction while other part in the opposite direction, thus decreasing the resultant acceleration and hence seismic force on the wedge.

Table 5. Variation of $N_{\gamma e}$ with *amplification factor* f_a for k_h = 0.1, k_v = 0.5 k_h, B = 2 m, V_s = 200 m/s, T = *0.33 sec and ϕ = 30°.*

	f_a	$N_{\gamma e}$
Out of phase	2.44	5.20
	1.60	4.15
	0.96	5.18
In phase	2.61	1.38
	1.66	2.02
	0.96	2.49

4 CONCLUSIONS

The present study highlights the importance of using the modified pseudo-dynamic method in place of the pseudo-dynamic method for obtaining more realistic values of seismic bearing capacity factor $N_{\gamma e}$. The study shows that $N_{\gamma e}$ decreased by 84% when k_h increased from 0.1 to 0.2 for $k_v = 0$ and it decreased by 95% when $k_v = k_h$ for ϕ=30°. For the case of amplification factor of 2.61, the out of phase accelerations caused about 73% reduction in $N_{\gamma e}$.

Thus, the study shows that seismic acceleration coefficient, its amplification factor and phase are the key parameters along with soil friction angle that significantly influence the value of the seismic bearing capacity of dry cohesionless soil under a surficial strip footing.

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