Seismic bearing capacity of shallow footing in layered soil

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Abstract. Ultimate bearing capacity of a footing resting on a stratified deposit reduces under a seismic excitation as soil stiffness degrades during a shaking. Ultimate bearing capacity depends on the shear strength parameters (Cohesion and angle of internal friction) of subsoil, along with shape and size of footings. An attempt has been made to study the bearing capacity of shallow circular and strip footings in a layered cohesionless soil under static and seismic conditions. The sub soil conditions resemble that of a site located at Rajarhat, Kolkata, West Bengal, India. The modeling has been done using finite element method. The analysis has been carried out for footing width (B) of 2.0 m and depth (D_f) to width ratio (D_f /B) of 0.5 and 1.0. For each D_f /B ratio the analysis has been repeated for three different ratios of layer thickness [Top layer (weaker): bottom layer (stronger)] which are 0.33, 1 and 3. For seismic condition, pseudo static analysis has been performed for horizontal seismic acceleration 0.1g to 0.3g. It has also been confirmed from the initial evaluation of liquefaction potential based on the SPT data for the site that the cohesionless soil layers considered here aren't prone to liquefaction. It has been observed that due to variation of layer thickness ratio from 0.33 to 3 the ultimate bearing capacity decreases up to 20.00% under static case, whereas for seismic case decrement of bearing capacity is about 18.00% under similar condition. It has also been found that with the increase in horizontal seismic acceleration from 0.1g to 0.3g the seismic bearing capacity factors N_q and N_γ reduces appreciably by 30 % and 60% respectively. Further attempt has been made to find the effect of shape of footing on seismic bearing capacity. The paper presents the importance of seismic effect, on layered soil and shape and size of footing in terms of ultimate bearing capacity.

Keywords: Ultimate bearing capacity, Layered soil, Finite Element method, PLAXIS 2D.

1 Introduction

Foundation of structure is designed to transfer and distribute the load of the superstructure to the underlying soil without overstressing it. The general bearing capacity theories proposed by Terzaghi (1943), Meyerhoff (1963), Hansen (1970) routinely used in foundation design. But in actual practice soil is non-homogeneous and anisotropic in nature. Richards et al. (1993) observed seismic settlements of foundations on partially saturated dense or compacted soils in terms of seismic bearing capacity reduction. He investigated that settlements were not associated with liquefaction or densification. Many researchers worked on the problem and have studied the seismic bearing capacity of strip footing (Sarma and Iossifelis, 1990; Chaudhury and Subba Rao, 2005; Lotfizadeh and Kamalian, 2016; Mosallanezhad and Moayedi, 2017). Saadda (2011) investigated seismic bearing capacity of the kinematic approach of limit analysis theory. The analysis focuses on evaluating the reduction in bearing capacity induced by seismic loading. Due to seismic loading, foundations may experience a reduction in bearing capacity and increase in settlement. Although several studies have been carried out to study the seismic bearing capacity but the study of seismic bearing capacity on layered soil is limited. And this paper attempts to include the effect of layer thickness ratio in ultimate bearing capacity under static and seismic conditions.The paper uses pseudo-static approach to determine bearing capacity of the foundations subjected to seismic loads in non-liquefying soils, considering also the depth effects for an embedded footing. In dynamic response, dynamic nature of the load and other factors are not being considered. In the present paper, bearing capacity of strip footings has been estimated on sandy soil which satisfies Mohr-Coulomb strength criterion. The analyses are based on pseudo-static method. The commercially available code, PLAXIS 2D, is used for the finite element analyses. The analysis has been carried out for footing width (B) of 2.0 m and depth (D_f) to width ratio (D_f/B) of 0.5 and 1.0 considering three different ratios of layer thickness [Top layer (weaker): bottom layer (stronger)] which are 0.33, 1 and 3. In this present study, the effects of the Depth to width ratio (D_f/B), layer thickness ratio and seismic acceleration on bearing capacity has been investigated.

2 Mathematical background

The ultimate load that the foundation soil can sustain is expressed by the linear combination of the three bearing capacity factors Nc, Nq and Nγ. The bearing capacity evaluation is based on the assumption that a failure surface can develop beneath the foundation, by the limit equilibrium method or by the limit analysis. The ultimate bearing capacities for strip foundations in granular soil for static condition are expressed in eq.1 and for seismic condition eq. 2.

$$qu = qNq + \frac{1}{2}\gamma BN\gamma \quad (1)$$

Earthquake conditions:

$$Qu = qNq_{\mathrm{E}} + 1\ 2\gamma BN\gamma_{\mathrm{E}} \quad (2)$$

Where,

Nq, $N\gamma$, NqE , $N\gamma$E =bearing capacity factors

NqE , $N\gamma$E $=f(\phi,\tan\theta)$

The settlement of a strip foundation due to an earthquake (Richards et al., 1993) presented in eq.3,

$$\text{SE}q\text{=(m)}= \frac{0.174v^2}{A\,g}\,\frac{k_h}{A}^{-4} \quad (3)$$

Where, V =peak velocity for the design earthquake (m/sec)

A =acceleration coefficient for the design earthquake

g = acceleration due to gravity (m/sec2)

3 Present study

The present study has been formulated to determine the ultimate bearing capacity for strip footing of width(B) =2.0 m depth (D_f) to width ratio (D_f /B) of 0.5 and 1.0. For each D_f /B ratio the analysis has been repeated for three different ratios of layer thickness [Top layer (weaker): bottom layer (stronger)] which are 0.33, 1 and 3. For seismic condition, pseudo static analysis has been performed for horizontal seismic acceleration 0.1g to 0.3g. The soil profile of RAJARHAT, West Bengal site has been shown in Table -1.

Table 1. Soil profile at RAJARHAT site, West Bengal

Stratum No.	Description	Properties
I	Medium brownish grey sandy clayey silt (0.00 – 5.50m)	Submerged density = 8.00 kN/m^3 Cohesion = 5 kPa Friction angle = 30 degree Specific gravity = 2.65
II	Loose brownish grey sandy silt with mica (5.50m – 18.00m)	Submerged density= 8.50 kN/m^3 Friction angle = 33 degree Specific gravity = 2.60
III	Dense brownish grey silty fine sand with mica (18.00 – 49.00m)	Submerged density = 9.20 kN/m^3 Friction angle = 34 degree Specific gravity = 2.65, Corrected N = 44

4 Methodology and modelling PLAXIS-2D

An attempt has been made to carryout numerical analysis of the present study by finite element method using PLAXIS 2D software. Two-dimensional plane strain condition has been considered for all the analyses. Material nonlinearity has been considered to model the soil using Mohr –Coulomb failure theory and elastic-perfectly plastic behavior of soil. In the finite element analysis, the entire domain has been discretized by 15 nodded triangular elements. Soil nonlinearity was considered. Soil was idealized as elastic-perfectly plastic material satisfying Mohr-Coulomb criterion. Shear failure criterion has been used only, no settlement criterion has been considered. Fig. 1 also shows the model discretization, loading and boundary conditions adopted in this study. Each node of the element has two degrees of freedom, displacement u in the horizontal direction (x) and displacement v in the vertical direction (y).

The generalized displacement vector (u) at a point within an element is related to the nodal displacement vector (q) by shape function matrix [N]

$$As\{u\}=\begin{Bmatrix}u\\v\end{Bmatrix}=[N]\{q\} \qquad (4)$$

where {u}=displacement vector at the point within an element,

$$\{q\}T=\{u1v1u2v2.................u15v15\} \qquad (5)$$

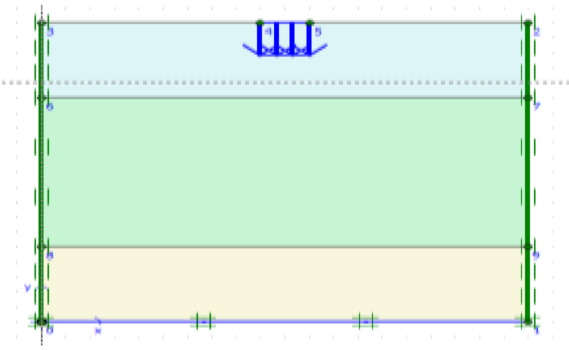

Fig. 1. Boundary and geometry condition of the footing (Seismic boundary condition)

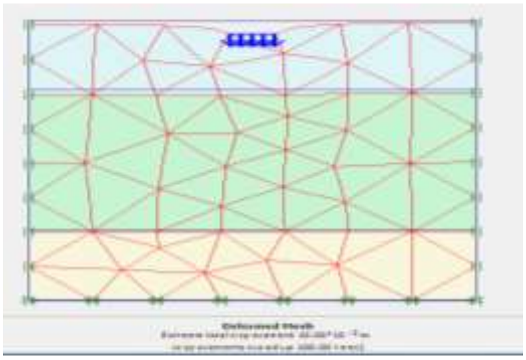

Fig. 2. Deformed mesh of 2m wide strip footing (D_f/B =0.5) static condition

A pseudo- static approach is adopted to account for the earthquake effects for the seismic bearing capacity evaluations. The loading of rigid strip footing has been modeled by applying stresses at the surface nodes below the footing base. The loading process has been continued incrementally until the nodal out of balance forces was solved. Figure 2 and Figure 3 represents that deformed mesh for D_f/B ratio=0.5 with and without seismic condition.

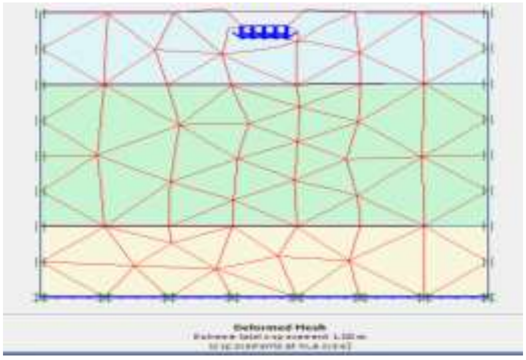

Fig. 3. Deformed mesh of 2m wide strip footing (*Df/B* =0.5) for seismic condition for 0.3g

5 Results and discussions

5.1 Load Settlement Criteria

Typical pressure -settlement graph for static and seismic condition for a fixed D_f/B ratio with varying layer thickness ratios of 0.33, 1 and 3.0, has been shown in Figure 4 and Figure 5. The results have been presented for both static and seismic condition for D_f/B ratio=1 for layer thickness ratio=0.33,1and 3.0 = 0, 1 and 3.0.

It has been shown that for a fixed D_f/B ratio, bearing capacity decreases due to increase of thickness ratio. Hence the results show that the layering effect of foundation has a good effect on the bearing capacity.

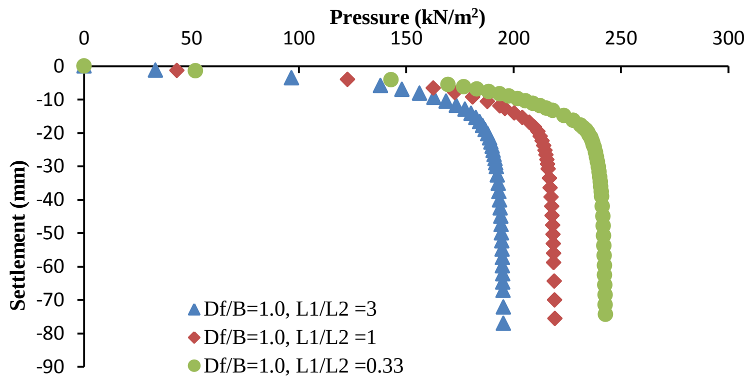

Fig. 4. Pressure vs settlement graph for D_f/B ratio=1 for layer thickness ratio=0.33,1and 3.0 (static case)

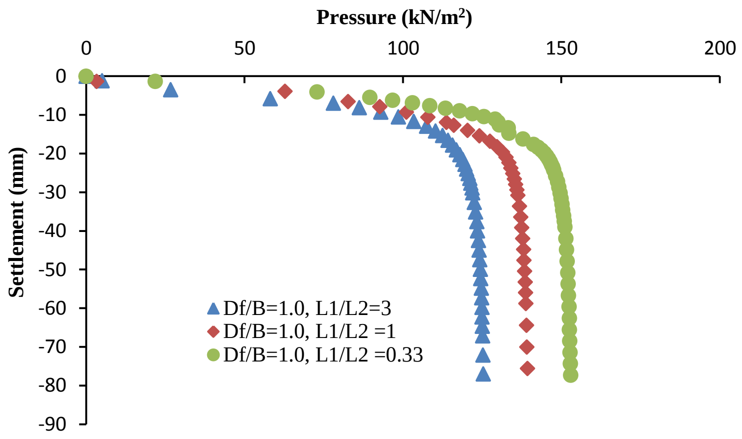

Fig. 5. Pressure vs settlement graph for D_f/B ratio=1 for layer thickness ratio=0.33,1 and 3.0 (seismic case at 0.1g acceleration)

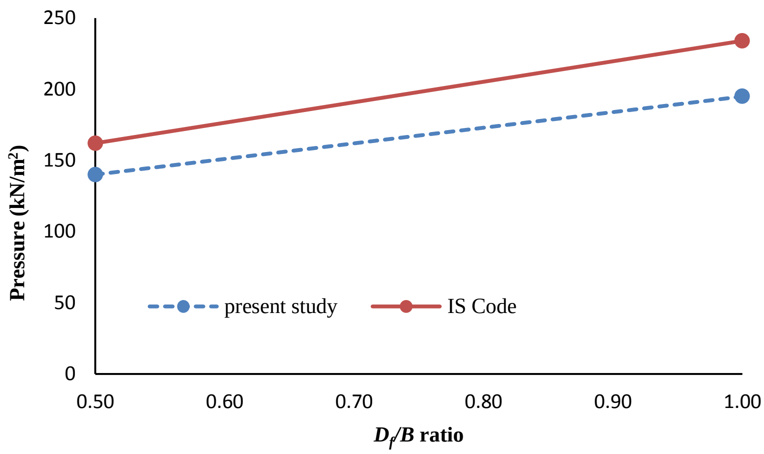

Fig. 6. Pressure vs settlement graph for D_f/B ratio=1 for layer thickness ratio at static case

Comparison of seismic bearing capacity factors obtained by the present numerical study with IS: 6403 for static case and Richard et al. (1993) obtained for layered soil of (φ_{top} = 30° and φ_{bottom} = 33°) is shown in Figure 7 and Figure 8. It has been evident that results are matches well.

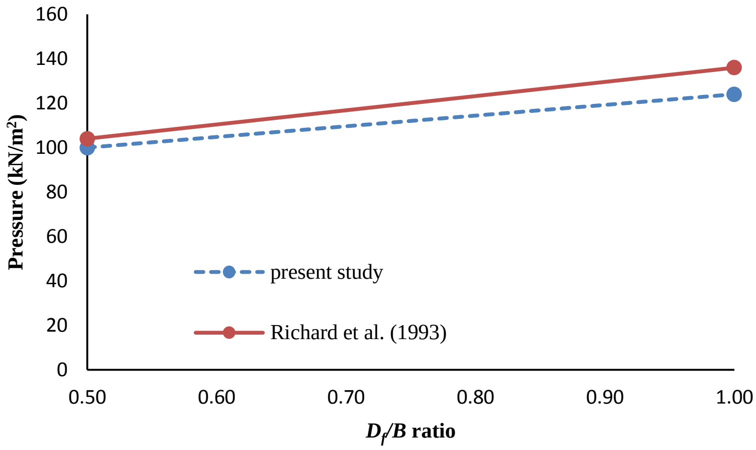

Fig. 7. Pressure vs settlement graph for D_f/B ratio=1 for layer thickness ratio=1 (seismic case at 0.1g acceleration)

5.2 Effect of Thickness Ratio and D_f/B Ratio

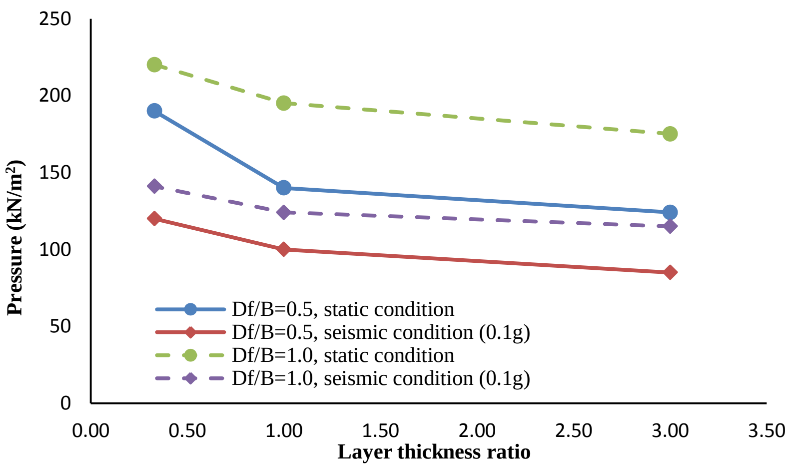

Fig. 8. Load vs settlement graph for D_f/B ratio=**1** for layer thickness ratio=0.33,1 and 3.0 (seismic case at 0.1g acceleration)

A typical graph for D_f/B ratio= 0.5 and 1, with varying layer thickness ratios of 0.33, 1 and 3.0, at static and seismic condition has been shown in Figure 8. It has been shown that when D_f/B ratio increases bearing capacity also increases on an average by 15.00% for static condition and 20% for seismic condition. Hence the results show that the foundation depth has a remarkable effect on the seismic bearing capacity. It has been observed that due to variation of layer thickness ratio from 0.33 to 1 the ultimate bearing capacity decreases up to 11.00% under static case, whereas for seismic case decrement of bearing capacity is about 12.00% for a D_f/B ratio of 1. A decrease in ultimate bearing capacity of 26% and 16% are observed under static and seismic cases, respectively for a D_f/B ratio of 0.5. It has been observed that due to variation of layer thickness ratio from 0.33 to 3 the ultimate bearing capacity decreases up to 20.00% under static case, whereas for seismic case decrement of bearing capacity is about 18.00% for a D_f/B ratio of 1. A decrease in ultimate bearing capacity of 34% and 29% are observed under static and seismic cases, respectively for a D_f/B ratio of 0.5. Further it has been observed that, reduction of bearing capacity due to seismic effect is on an average 35.00%.

5.3 Determination of Bearing Capacity Factors N_{Υ} and N_q

An attempt has been made to generate bearing capacity factors, Nγ and Nq numerically, using PLAXIS 2D, to enable a broad comparison with those found in the literature. In determining Nγ, a unit soil weight (γ) of 18 kN/m^3 was used, cohesion c was set to null and no surcharge load was applied to enable an independent assessment of the contribution of the soil wedge beneath the footing to the bearing capacity of the soil. Secondly, Nq was found by setting soil unit weight and cohesion to null and applying a surcharge load. The seismic bearing capacity of saturated sands is redefined with new seismic bearing capacity factors, Nq and Nγ. Figure 9 and Figure 10 represents variation of Nq and Nγ with D_f/B ratio. It has been shown that in case of seismic condition Nq and Nγ value less than static case. It has been also observed that Nq value increases linearly with D_f/B ratio.

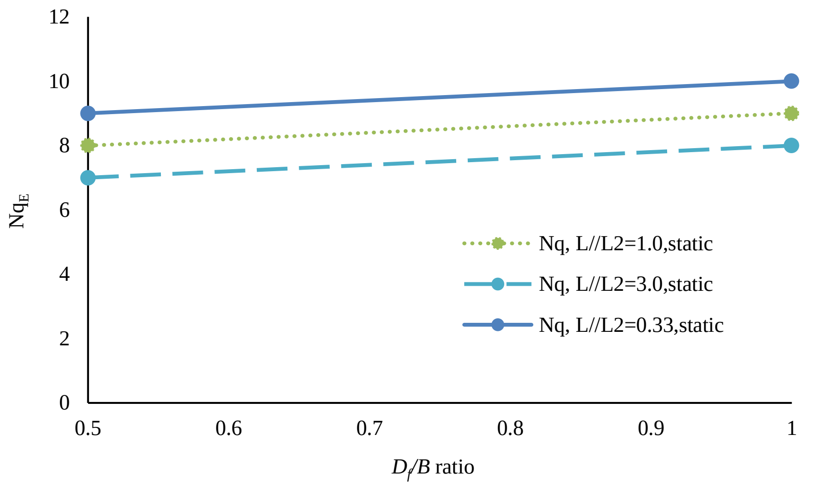

Fig. 9. variation of Nq_E with D_f/B ratio with varying layer thickness at static condition

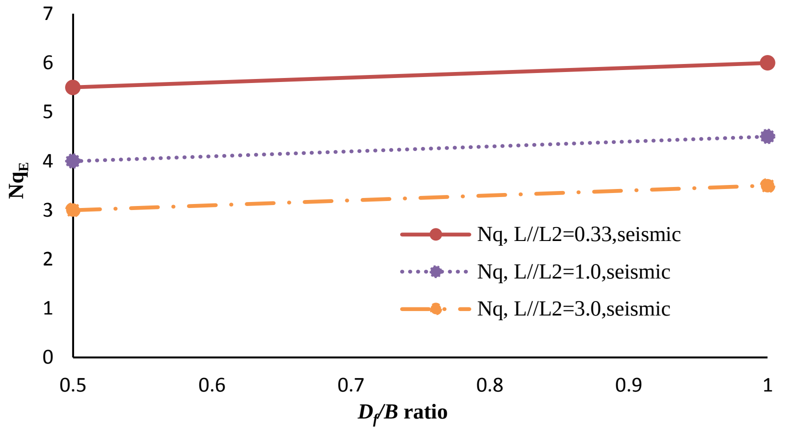

Fig. 10. variation of Nq_E with D_f/B ratio with varying layer thickness at seismic condition

It has been observed from figure 9 and figure 10 that the equivalent bearing capacity factor Nq_E, for two-layered cohesionless soil system (strong soil overlaid by a weak soil deposit i.e. Top layer (weaker): bottom layer (stronger) ≥ 1) decreases with increase in the thickness of the top layer. Nq_E is also found to increase with increase in relative frictional strength between two layers. The curves are more or less linear which eases in using interpolated values of Nq_E for any thickness of the top layer (h) during investigation of bearing capacity of strip footing. It has been observed that, with variation of D_f/B ratio, the increase of equivalent bearing capacity factor NqE is approximately 11.00% for static case and 10.00% for seismic condition. It has been further observed that for the decrease of layer thickness ratio equivalent bearing capacity factor N_{qE}, increases on an average by 25.00%.

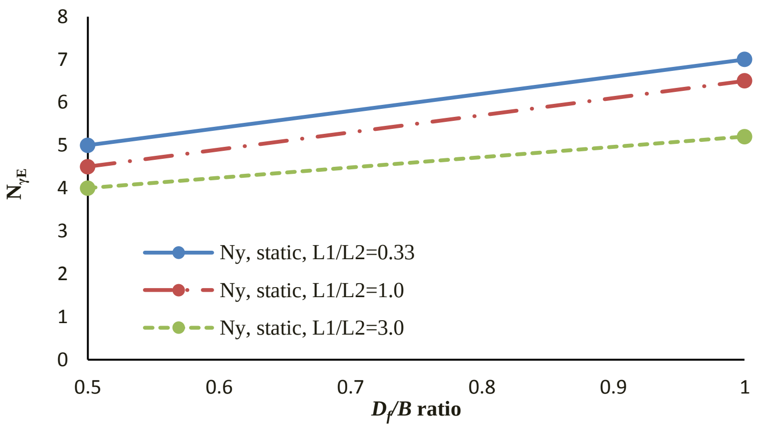

Fig. 11. variation of $N\gamma_E$ with D_f/B ratio with varying layer thickness at static condition

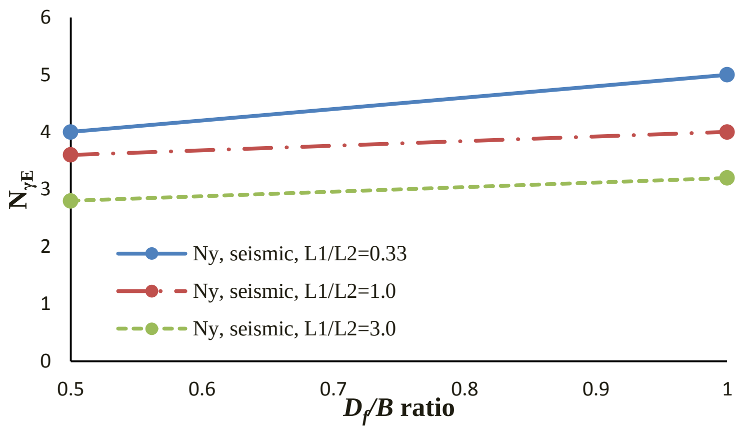

Fig. 12. variation of $N\gamma_E$ with D_f/B ratio with varying layer thickness at seismic condition

It has been observed from figure 11 and figure 12 that the equivalent bearing capacity factor $N\gamma_E$, for two-layered cohesionless soil system (strong soil overlaid by a weak soil deposit i.e. Top layer (weaker): bottom layer (stronger) ≥ 1) decreases with increase in the thickness of the top layer. $N\gamma_E$ is also found to increase with increase in relative frictional strength between two layers. The curves are more or less linear which eases in using interpolated values of Nq_E for any thickness of the top layer during investigation of bearing capacity of strip footing. It has been observed that, with variation of D_f/B ratio, the increase of equivalent bearing capacity factor $N\gamma_E$ is approximately 40.00% for static case and 25.00% for seismic condition. It has been further observed that for the decrease of layer thickness ratio equivalent bearing capacity factor $N\gamma_E$, increases on an average by 30.00%.

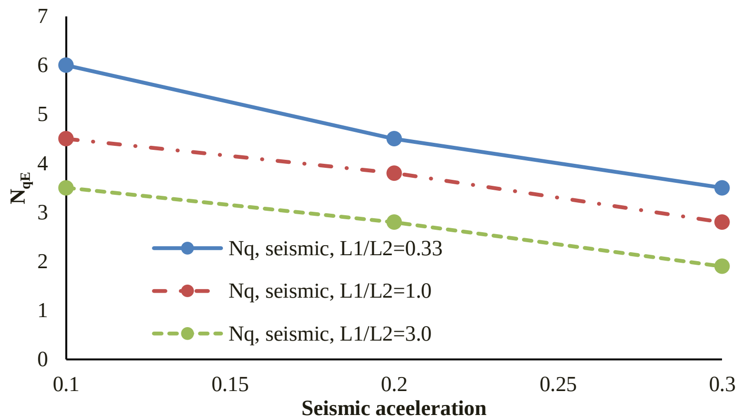

Fig. 13. variation of Nq_E for D_f/B ratio=1, with varying layer thickness at seismic acceleration (0.1g to 0.3g)

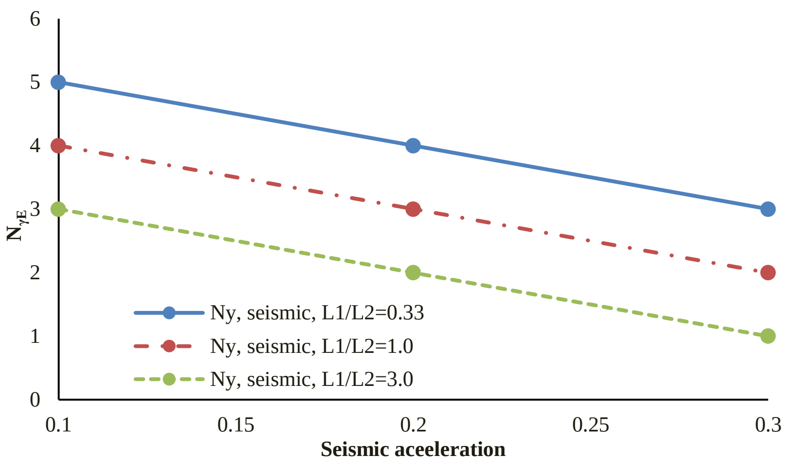

Fig. 14. Variation of $N\gamma_E$ for D_f/B ratio=1, with varying layer thickness at seismic acceleration (0.1g to 0.3g)

Figure 13 and Figure 14 represents the variation seismic bearing capacity factors, NqE and NγE with seismic acceleration = 0.1g to 0.3g, at *Df/B* ratio=1. It has been observed that, seismic bearing capacity factors, NqE and NγE decreases with increase of seismic acceleration from 0.1g to 0.3g. Numerical analysis shows that, by considering pseudo-static seismic forces, design solutions can be found for the computing of seismic bearing capacity factors for shallow foundations. It has been found that for the increase of seismic acceleration = 0.1g to 0.3g, decrease of equivalent bearing capacity factor NγE is approximately 60.00% for and 30.00% for NqE . The reduction of seismic bearing capacity is due to the fact of the soil inertia (kinematic effect).

6 Conclusions

From the current investigations the following conclusions may be drawn:

i) The analysis shows that, by considering pseudo-static seismic forces, design solutions can be obtained for the computing of seismic bearing capacity factors for shallow foundations. It has been observed that with the increase in D_f/B ratio bearing capacity also increases on an average by 15.00% for static condition and 20% for seismic condition.

ii) It has also been observed that due to variation of layer thickness ratio from 0.33 to 3 the ultimate bearing capacity decreases up to 20.00% under static case, whereas for seismic case decrement of bearing capacity is about 18.00% under similar condition. It has also been found that with the increase in horizontal seismic acceleration from 0.1g to 0.3g the seismic bearing capacity factors Nq and Nγ reduces appreciably nearly by 30 % and 60% respectively.

iii) With the variation of Df/B ratio, the increase of equivalent bearing capacity factor NqE is approximately 11.00% for static case and 10.00% for seismic condition. It has been further observed that for the decrease of layer thickness ratio equivalent bearing capacity factor NqE, increases on an average by 25.00%.

iv) The analysis further shows that with variation of D_f/B ratio, the increase of equivalent bearing capacity factor NγE is approximately 40.00% for static case and 25.00% for seismic condition. It has been further observed that for the decrease of layer thickness ratio equivalent bearing capacity factor NγE, increases on an average by 30.00%.

v) It can further be observed that for the increase of seismic acceleration = 0.1g to 0.3g, decrease of equivalent bearing capacity factor NγE is approximately 60.00% for and 30.00% for NqE . The reduction of seismic bearing capacity is due to the fact of the soil inertia (kinematic effect).

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