

Bearing Capacity of Strip Footings Resting on Sandy Sloping Ground: A Numerical Study



Atharv Anant Saurkar, Siddharth Pathak, and Mousumi Mukherjee

Abstract Construction of shallow footing near the sloping ground is a common practice in the hilly region. However, bearing capacity estimation of such footings requires special attention due to the interference of slope geometry with the failure zone of the footing. It has been observed that the bearing capacity of footing reduces substantially for such cases as compared to the plain ground due to the lesser passive resistance offered by the disturbed failure zone of the footing. In this regard, the conventional limit analysis-based bearing capacity theories are noticed to provide conservative results which lead to uneconomical design of the sub-structure. A finite element-based numerical study has been carried out in the present study to investigate the bearing capacity of strip footings resting on the sandy sloping ground. The influence of setback ratio and the effect of inclined loading on the load-carrying capacity of the footing has been investigated, and the results are discussed in details.

Keywords Bearing capacity · Sloping ground · Strip footing · Sand · Inclined loading

1 Introduction

Determination of bearing capacity is a vital aspect for design of foundation which depends on properties of soil (shear strength parameters and unit weight) and the geometry of foundation (depth, width, and shape of the footing). There exist several well-conceived theories along with number of experimental analyses (i.e., both field tests and in-situ tests) for the estimation of ultimate bearing capacity (q_u) of shallow foundation. Terzaghi [1] was the first to propose theoretical method for estimation of ultimate bearing capacity of strip footing resting over uniform horizontal ground surface. Further modifications to this theory were proposed in terms of bearing capacity factors taking into account the influence of shape, depth, and loading inclination [2–4].

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Around 15% of the total land area of India is covered by hilly region [5]. The rapid urbanization in these regions has resulted in residential and commercial constructions with shallow foundations located on or near the sloping surface. Bearing capacity estimation of such foundations requires special attention due to the interference of slope geometry with the failure zone of the footing. In this regard, there exist various theoretical and numerical studies addressing the bearing capacity estimation of footings resting on the sloping ground [3, 6–9]; whereas, limited literature is available focusing on the experimental investigations related to foundations on slopes [10–12]. It has been observed that the bearing capacity of footing reduces substantially for such cases as compared to the plain ground due to the lesser passive resistance offered by the disturbed failure zone of the footing. Most of these studies concentrate on the evaluation of bearing capacity of shallow footings resting on slopes of dry cohesionless soil along with influence of various governing parameters, e.g., width of footing (B), slope inclination angle (β), setback ratio, i.e., the ratio of the horizontal distance between the footing and the crest of slope (b) to the width of footing, depth of embedment, etc.

In very recent times, Acharya and Dey [6] carried out a 2D Finite Element (FE)-based numerical investigation to explore the bearing capacity of strip footing in the vicinity of slopes comprised of soil with both cohesion and friction values. It reports in-depth parametric study demonstrating influence of different geotechnical and geometrical properties on the bearing capacity of soil in case of sloping ground. However, the existing literatures only consider vertical loading and no study has been conducted taking into account the change in load inclination, which becomes important for designing foundations of transmission towers or any kind of structures subjected to wind load. In this regard, plane strain finite element (FE) simulations are conducted here to further explore the bearing capacity of surface strip footing resting on the crest of the slope and subjected to inclined loading. Further, influence of various setback distances have also been investigated in conjunction with the load inclination direction and magnitude.

2 Finite Element Modeling and Validation

The numerical analysis has been conducted employing RS2 module of RocScience software. As the present study is focused on the analysis of strip footing, the model geometry is developed in accordance with the plane strain condition. In general, model dimensions should be chosen in such a way that the model boundaries do not intersect with the significant stress contour of $0.1q$ beyond which the effect of applied stress (q) is considered negligible. In the present work, the model geometry conforms the same for the small scale model tests of Castelli and Lentini [11], which has been further used here for validation purpose (Fig. 1). In the numerical model, the restraint boundary condition are setup with horizontal fixity to the vertical edges (restrain X), complete fixity to the bottom edges (restrain X and Y) and no restraint

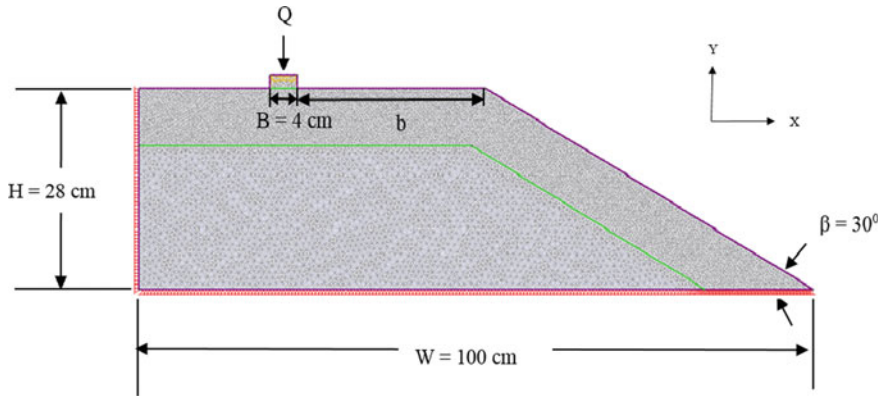


Fig. 1 Geometry of the finite element model

at the inclined slope face (free), thereby allowing for free deformation caused due to location and loading of the footing.

In the present study, elastic perfectly plastic associative Mohr–Coulomb model has been considered to mimic the soil behavior; whereas, the footing is assumed to be linear elastic. The adopted strength and stiffness properties for the soil domain and the footing are taken from the literature [11] and are shown in Table 1. No slip condition has been imposed for the interface between footing and the soil contact surface.

Initially, a graded mesh of 6 noded triangular elements has been used to discretize the model geometry. A finer mesh has been adopted for the zone surrounding the footing and extending up to a depth of $2B$, where most of the vertical deformation has been noticed to take place (Fig. 2a). A uniform coarse mesh size of 0.01 mm has been applied for rest of the domain. In order to determine the influence of mesh size (for the finer zone) on the estimated bearing capacity value, a mesh convergence study has been conducted and presented in Fig. 2b. An optimum mesh size of 0.005 mm has been selected for the finer mesh below which no influence of mesh size can be noticed.

The numerical model has been validated against the small scale model experiments of Castelli and Lentini [11] on ultimate bearing capacity estimation of strip footing resting on the crest of the soil slope. The small scale model tests were performed with

Table 1 Properties of the soil and footing

Properties	Soil	Footing
Dry unit weight (γ) (kN/m ³)	17	25
Angle of internal friction (ϕ)	38°	–
Cohesion (c)	0	–
Young’s modulus (E) (MPa)	50	22,000
Poisson’s ratio (μ)	0.3	0.15

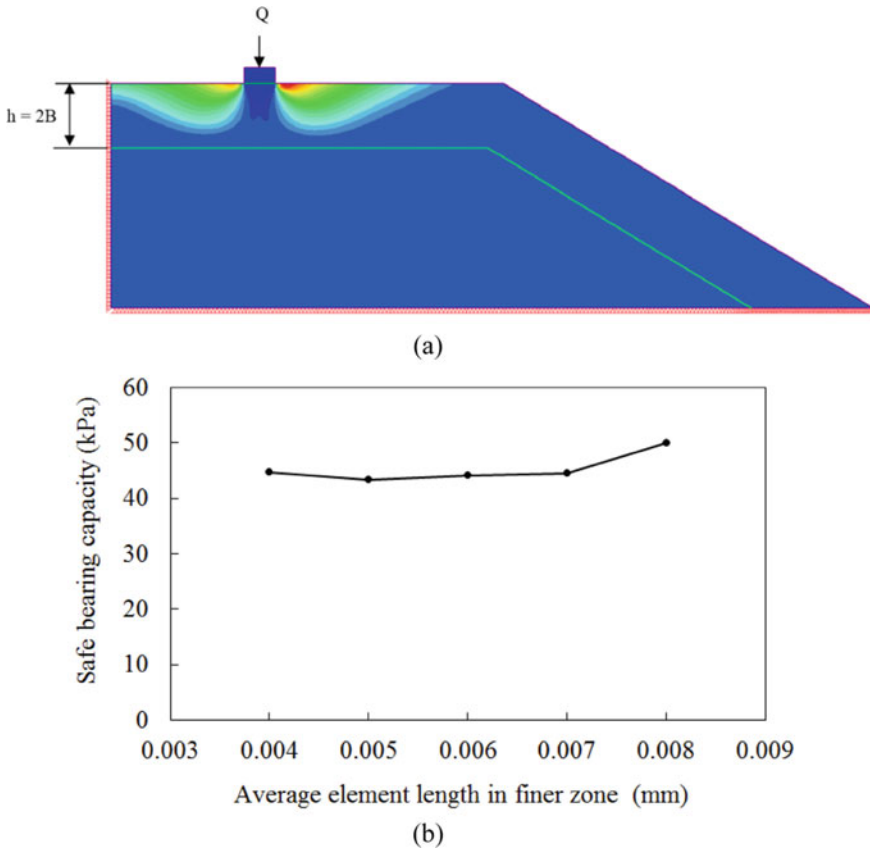


Fig. 2 **a** Vertical deformation contour for identification of zone of finer mesh and **b** convergence study for determining the optimum mesh size

a strip footing of 4 cm width placed on a compacted sand slope ($\beta = 30^\circ$), which was having dimensions as 100 cm long, 45 cm wide and 28 cm high. The model tests were performed on specimen of Playa Catania for which the referred properties are given in Table 1. The validation of the numerical model has been performed considering the optimal mesh size and for a case with setback distance, $b/B = 7$. The simulations have been performed applying a concentrated vertical load on the mid-point of the footing surface and the maximum settlement has been recorded along the width of footing. The predicted load-settlement curve has been presented in Fig. 3, which shows a good comparison with the experimental results of Castelli and Lentini [11]. The Plaxis 2D FEM simulation results of Acharya and Dey [13] has also been plotted here for reference.

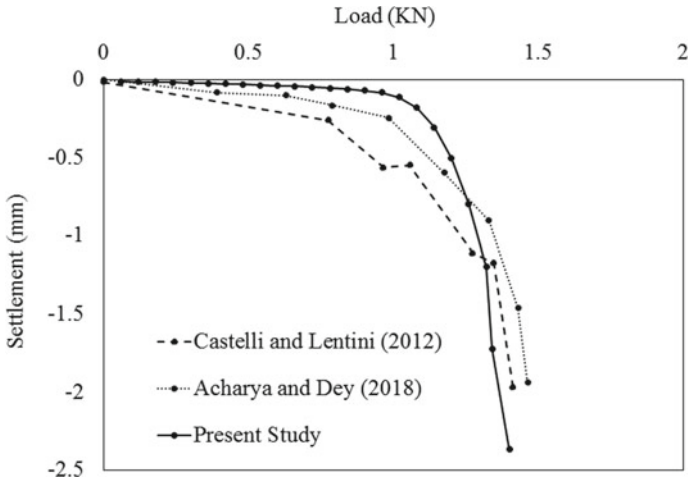


Fig. 3 Validation of numerical model against the experimental and numerical results of Castelli and Lentini [11] and Acharya and Dey [13], respectively

3 Results and Discussions

Finite element simulations have been performed for the case with vertical loading subjected to various setback ratios, $b/B = 7, 6, 4, 2, 0$. The load corresponding to the settlement value of 20% of B has been divided by the area of the footing for the estimation of safe bearing capacity (Q_{safe}). Figure 4 presents the variation in the predicted bearing capacity values with the considered setback distances. A

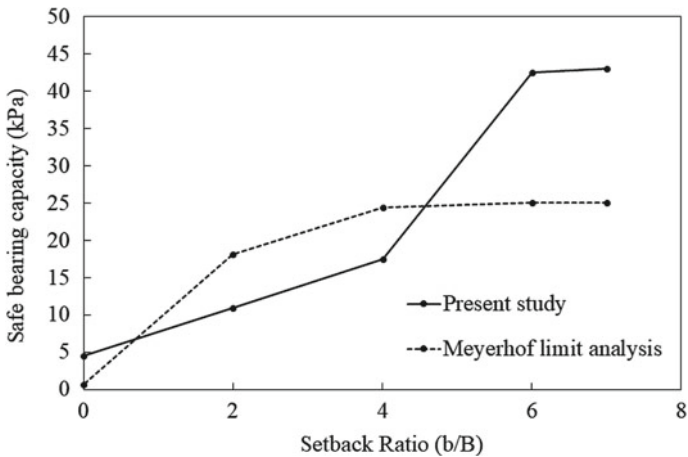


Fig. 4 Effect of setback ratio on bearing capacity for vertical loading

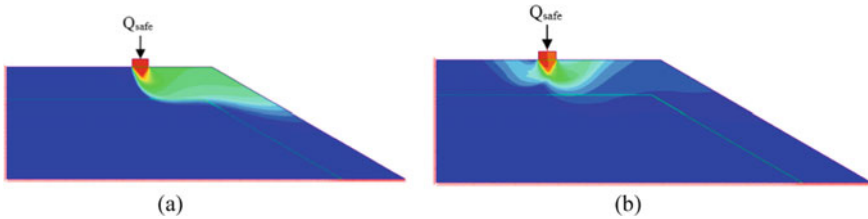


Fig. 5 Resultant deformation contour for footing loaded with vertical loading having **a** setback ratio = 2 and **b** setback ratio = 6

comparison has been added between predictions from present simulation and estimated bearing capacity from Meyerhof's [3] limit state analysis on sloping ground. For both the cases, an increase in the bearing capacity is evident with increase in the setback ratio due to less interference from the slope geometry. It can be also observed from Fig. 4 that Meyerhof's theory overestimates the bearing capacity for lower setback ratios and reports no effect on bearing capacity beyond a setback ratio of 4. Whereas, the numerical analysis reveals the variation in the bearing capacity till setback ratio of 6, beyond which no intervention of the slope geometry has been noticed on the emerging failure plane (Fig. 5b). On the contrary, Fig. 5a depicts a case with setback ratio of 2, where the failure plane extends till the slope face and the interference of the slope geometry results in the drastic reduction in the bearing capacity. Meyerhof's limit analysis assumed sudden wedge failure with predefined failure planes. On contrary, FEM assumes progressive failure with no assumption of predefined failure plane. This may be the reason behind higher bearing capacity values for numerical analysis as compared to that of Meyerhof limit analysis at higher b/B ratio.

A detailed numerical study has been further carried out to analyze the combined effect of load inclination and setback ratio on the bearing capacity of footings resting on slopes. In addition to the vertical load, four different loading inclinations ($\psi = -30, -15, 15, 30$) are considered along with earlier mentioned five setback ratios, $b/B = 7, 6, 4, 2, 0$. Fig. 5 illustrates the influence of these two parameters on the estimated bearing capacity magnitude. Unlike the vertical loading, the bearing capacity does not get affected by the inclined loading for a setback ratio beyond 4 (Fig. 6a). Beyond this critical setback ratio, the direction of load inclination has no influence on the bearing capacity of the footing (Fig. 6b). Whereas, below this critical setback value, the load inclined towards the slope incurs the least bearing capacity and this behavior remains independent of the inclination magnitude. In the present study, the most critical case has been encountered when the footing is situated at crest of the slope (i.e., setback ratio = 0) with load inclination of negative ψ angle (or towards the direction of slope); whereas, if the load inclination angle changes from negative to positive ψ angle (i.e., opposite to the sloping ground) then the capacity of the same footing increases approximately by 4 times. This reduction can be easily explained based on the higher interference by the slope face over the zone of deformation (Fig. 7). It is interesting to note that the maximum bearing capacity

Fig. 6 Influence of **a** setback ratio and **b** load inclination on the estimated bearing capacity

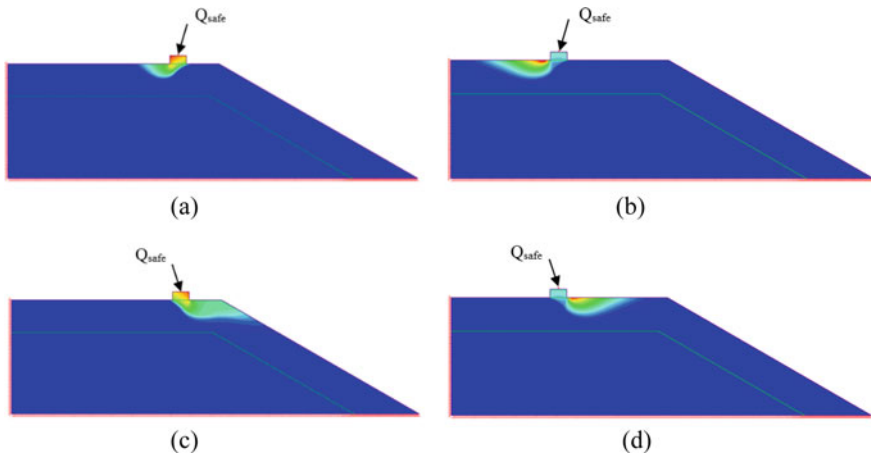
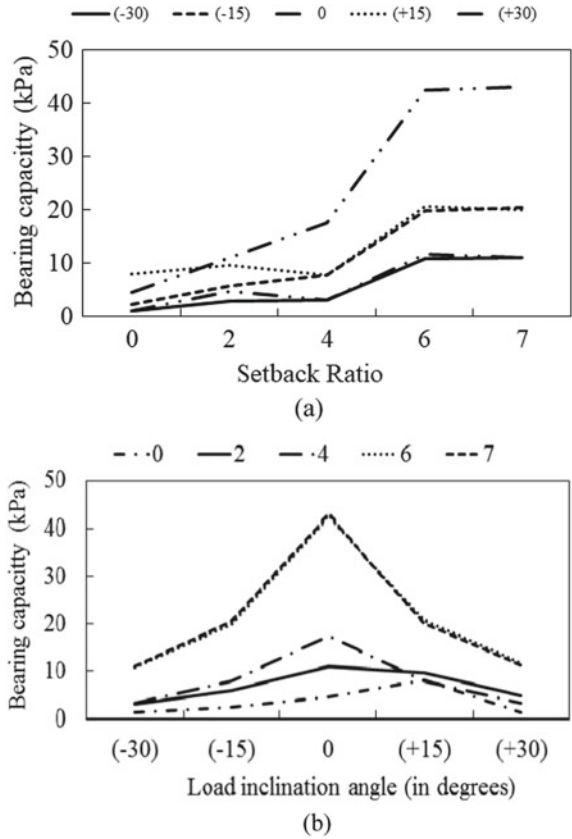


Fig. 7 Resultant deformation contour for footing with **a** setback ratio = 2 and $\psi = +15$, **b** setback ratio = 6 and $\psi = +15$, **c** setback ratio = 2 and $\psi = -15$ and **d** setback ratio = 6 and $\psi = -15$

is generally obtained under the vertical loading condition except for the case when $b/B = 0$. For this particular case, the maximum bearing capacity has been achieved for the inclined load with $\psi = 15$.

4 Conclusion

A finite element-based numerical study has been carried out in the present study to investigate the bearing capacity of strip footings resting on the sandy sloping ground. It has been observed that the bearing capacity of footing reduces substantially for such cases as compared to the plain ground due to the lesser passive resistance offered by the disturbed failure zone of the footing. In comparison to Meyerhof's predictions under vertical loading, a critical setback ratio of 6 has been noticed beyond which no influence of slope has been noticed on the predicted bearing capacity values. The influence of setback ratio and the effect of inclined loading on the load-carrying capacity of the footing have further been explored in details. Unlike the vertical loading, the bearing capacity does not get affected by the loading inclination for a setback ratio beyond 4. Below this critical ratio, the load inclined towards the slope incurs the least bearing capacity and this behavior remains independent of the load inclination magnitude. This reduction can be easily explained based on the higher interference by the slope face over the zone of deformation. The maximum bearing capacity is achieved when the footing has been placed on the crest and subjected to an inclined load with $\psi = 15$.

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