



Influence of Load Inclination on Bearing Capacity of Footing Resting on Slope

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Abstract. In the hilly and mountainous region, shallow foundations are commonly constructed near or on the face of sloping ground. Conventional bearing capacity theories, established mainly for the plain ground, are not applicable for estimation of bearing capacity for these foundations and a reduction in the estimated bearing capacity is expected due to lesser passive resistance offered by the disturbed failure zone of the footing influenced by the slope face. Such reduction in the bearing capacity depends on the slope geometry, soil strength parameters, position of the footing and inclination of the applied load. In this regard, limit-analysis based bearing capacity theories often provide conservative results leading to uneconomical design of the sub-structure and a numerical framework can further be employed for this purpose. A detailed finite element investigation has been carried out in the present study to explore the influence of slope angle, setback ratio, i.e. location of the footing from the slope crest and load inclination angle on the bearing capacity of a strip footing resting on sloping ground. In addition, the stability of the slopes under consideration is also assessed for the cases when the footing is positioned on the slope crest which has the maximum possibility of slope failure.

Keywords: Bearing capacity · Strip footing · Inclined loading · Sloping ground · Finite element analysis

1 Introduction

Bearing capacity of soil is an important factor in design of foundations as it decides the magnitude of the load that supporting soil can carry without resulting shear failure and excessive settlement. Terzaghi (1943) first proposed an expression for bearing capacity estimation of shallow strip footing resting on the plain ground and subjected to vertical loading. Later, Meyerhof (1957) extended the bearing capacity formulation and gave a generalized equation for bearing capacity of shallow foundations considering the inclination of load, shape and embedment depth of the footing supported on the plain ground. For the same soil, Meyerhof's equation estimates the higher values of bearing capacity as compared to Terzaghi due to consideration of shear strength of the soil above the base of the footing.

India is a country which has 15% of its area covered with the mountainous ranges (Joshi et al. 2011) and these hilly regions are getting used for the construction purposes due to rapid urbanization. In such places, the footings are constructed near the vicinity of sloping ground and estimation of bearing capacity requires to incorporate the influence of ground slope. Meyerhof (1963) categorized such cases into two different types, i.e. footing on top of the slope and footing on the face of the slope, and presented limit analysis based bearing capacity equations for both the cases. Shields et al. (1977) and Bauer et al. (1981) carried out the small-scale laboratory experiments with strip footings resting on the slopes and have developed bearing capacity equations based on experimental observation. In recent times, a more comprehensive similar model experiments have been performed by Castelli and Lentini (2012) to address the effect of sloping ground on the bearing capacity. Acharyya and Dey (2017, 2018) have performed a finite element based numerical analysis for investigating the bearing capacity of strip and square footings located at top of the slope and subjected to vertical loading.

The available literature shows that the bearing capacity reduces drastically in case of sloping ground due to lesser passive resistance offered by the failure zone of the footing which gets disturbed by the slope face. Such reduction in the bearing capacity depends on the slope geometry, soil strength parameters, width and position of the footing, and inclination of the applied load. A 2D plain strain finite element investigation has been carried out in the present study with emphasis on the influence of slope angle (β), setback ratio, i.e. location of the footing from the slope crest (b) and load inclination angle (ψ) on the bearing capacity of a surface strip footing resting on dry cohesionless sloping ground. Further, the slopes are also assessed, employing limit equilibrium-based slope stability analysis, for the cases when the footing is positioned on the slope crest with the maximum possibility of slope failure.

2 Finite Element Modeling and Validation

The 2D plain strain finite element analysis has been carried out employing RS2 v. 9.0 module of Rocscience software package. The simulation has been validated against the small-scale model of Castelli and Lentini (2012) and the model geometry has been presented in Fig. 1. The model boundaries confirm that the applied stress (q) contour of $0.1q$ does not touch the boundary of the model. The bottom horizontal boundary is assigned with pinned (restrained in both horizontal and vertical direction) boundary condition; whereas, the vertical boundary is assigned with rollers which allows free movement of soil particles only in the vertical direction and no displacement is allowed in horizontal direction.

The surface strip footing has a width (B) of 4 cm and the interface between soil and footing element has been modeled considering no slip condition. In present study, the soil has been assumed to follow an elastic perfectly plastic behavior conforming Mohr-Coulomb model; whereas, M20 grade concrete, having a linear elastic behavior, has been considered as the material for footing. The properties of soil and concrete are listed in Table 1.

In order to reduce the computational time, the region within the depth of $2B$ below the base of the footing is discretized with a finer mesh of average element length of 0.005 m and rest of the model is discretized with relatively coarse mesh of uniform mesh size of 0.01 m. The details of the convergence study can be found in Saurkar et al. (2019). For the validation of the numerical model, simulation has been performed by applying a concentrated vertical load at the center of the footing, which is placed at the setback ratio equal to 7. The maximum vertical displacement along the base of the footing has been considered for obtaining the load settlement curve, which is presented in Fig. 2. The load settlement curve compares well against the experimental and numerical results reported by Casteli and Lentini (2012) and Acharya and Dey (2018), respectively.

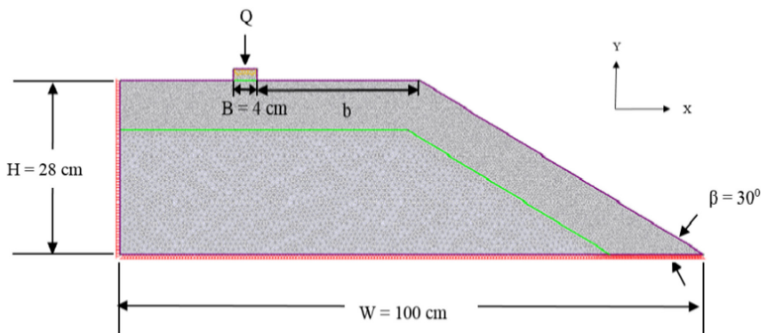


Fig. 1. Geometry of the finite element model

Table 1. Properties of the soil and footing

Properties	Soil	Footing
Dry unit weight (γ)	17 kN/m ³	25 kN/m ³
Angle of internal friction (ϕ)	38°	–
Cohesion (c)	0	–
Young's modulus (E)	50 MPa	22000 MPa
Poisson's ratio (μ)	0.3	0.15

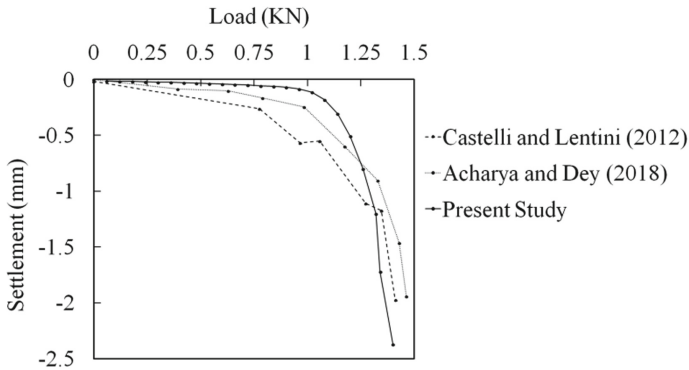


Fig. 2. Validation of numerical model against the Castelli and Lentini (2012) experimental and Acharya and Dey (2018) numerical results.

3 Results and Discussions

Finite element simulations have been performed for three different slope angles $\beta = 35^\circ, 30^\circ$ with setback ratios, $b/B = 7, 6, 4, 2, 0$. Due to the model boundary constraint, for $\beta = 25^\circ$ it is possible to carry out finite element simulation only with $b/B = 4, 2, 0$. At each location, footing is analyzed with load inclination angle, $\psi = -30^\circ, -15^\circ, 0^\circ, +15^\circ, +30^\circ$, where negative ψ angle denotes that the load has been applied away from the direction of slope. The load settlement curve has been simulated till 20% of B value. A double tangent method is then applied to mark the ultimate load, which has been divided by the area of the footing for estimation of the ultimate bearing capacity. Figure 3(a), (b) and (c) present the ultimate bearing capacities for different slope angles and setback ratios, when the footing is subjected to vertical loading, inclined load at $+30^\circ$ and -30° , respectively. In addition, the variation of ultimate bearing capacities with load inclination and setback ratio has been illustrated in Fig. 3(d), (e) and (f) for three different slope angles.

Figure 3(a) depicts the change in the predicted bearing capacity values under vertical loading for the considered setback distances. For all three slope angles, an increase in the bearing capacity can be noticed with increase in the setback ratio due to less interference from the slope geometry (Fig. 4). Bearing capacity estimations from Meyerhof’s (1957) limit analysis on a sloping ground with $\beta = 30^\circ$ has also been added for comparison with the present simulation. It is evident that Meyerhof’s limit analysis results are conservative for all setback ratios and it reports no effect on bearing capacity beyond a setback ratio of 4. Whereas, the numerical simulation for the case with ground slope $\beta = 30^\circ$ reveals that the variation in the bearing capacity exists till setback ratio of 6, beyond which no intervention of the slope geometry has been observed over the emerged failure envelop. However, for the steeper slope angle, i.e. $\beta = 35^\circ$, such influence extends even at $b/B = 6$, which can be noticed from the total displacement contours plotted in Fig. 4. In case of $\beta = 25^\circ$, a maximum setback ratio of $b/B = 4$ has been reported as beyond this setback ratio the vertical face on the left side of the model domain starts interfering with the failure plane.

In case of inclined loading, an asymmetric failure envelop will form with a bigger zone of deformation in the direction of load inclination (Fig. 5). For load inclined towards the slope face, e.g. $\psi = +30^\circ$, the asymmetric failure envelop experiences more interference from the slope face compared to the loads inclined away from the slope face and hence, results into reduction in the bearing capacity magnitude. As depicted in Fig. 3(d), such reduction is higher with increase in the magnitude of the load inclination angle and decrease in the setback ratio. This enhanced effect can easily be explained based on the higher interference by the slope face over the zone of deformation, which is further depicted by the total displacement contours in Fig. 5 for $\psi = -30^\circ, -15^\circ, +15^\circ, +30^\circ$ at two different setback ratios. Similar to the vertical loading condition, the predicted bearing capacity under inclined load also remains nearly constant beyond a setback ratio of 6 (Fig. 3b, c, d, e).

On the contrary, for load inclined away from the slope face (e.g. $\psi = -30^\circ$), the asymmetric failure plane develops in the opposite direction of the slope and it nearly remains unaffected by the sloping ground. As a result, not very significant effect of setback ratio and slope angle can be noticed on the bearing capacity magnitudes for such cases (Fig. 3c). Whereas, a general trend of decreasing bearing capacity has been noted with increase in the slope angle when the footing is either subjected to a loading inclined towards slope or loaded vertically (Fig. 3a, b).

The bearing capacity predictions on sloping ground are usually carried out with assumption of full mobilization of shear strength within the failure envelop. However, the slope itself can become unstable long before the mobilization of such failure envelop. In the present study, the stability of the slopes are further assessed, employing limit equilibrium based slope stability analysis, for the cases having maximum possibility of the slope failure, i.e. when the footing is positioned on the slope crest ($b/B = 0$). The factor of safety (FOS) has been calculated using Slide module of the Rocscience software and employing Generalized Limit Equilibrium (GLE) approach proposed by Morgenstern and Price (1965), which satisfies both force and moment equilibrium of each slices along with the consideration of all inter-slice forces. The virgin slopes are assessed to be initially stable with a FOS of 1.17, 1.35 and 1.72 for sloping angles $\beta = 35^\circ, 30^\circ, 25^\circ$, respectively. Figure 6 illustrates the variation of FOS with load inclination angle for three different slope angles. For most of the depicted cases in Fig. 6, the FOS has been noticed to be less than 1 indicating potential failure of the slopes. In case of vertical loading, the FOS has been noticed to be least for $\beta = 25^\circ$ and maximum for $\beta = 35^\circ$ due to differences in their respective computed ultimate loads, which is highest for $\beta = 25^\circ$ and least for $\beta = 35^\circ$ (Fig. 3). Whereas, stability of the slopes under inclined loading depends on the combined influence of direction of the applied load and magnitude of the computed bearing capacity under consideration. The analysis clearly indicates that the slopes will fail much before the mobilization of the estimated bearing capacity magnitudes. Hence, the bearing capacity for such cases should be analyzed in conjunction with the stability analysis of the slopes under consideration.

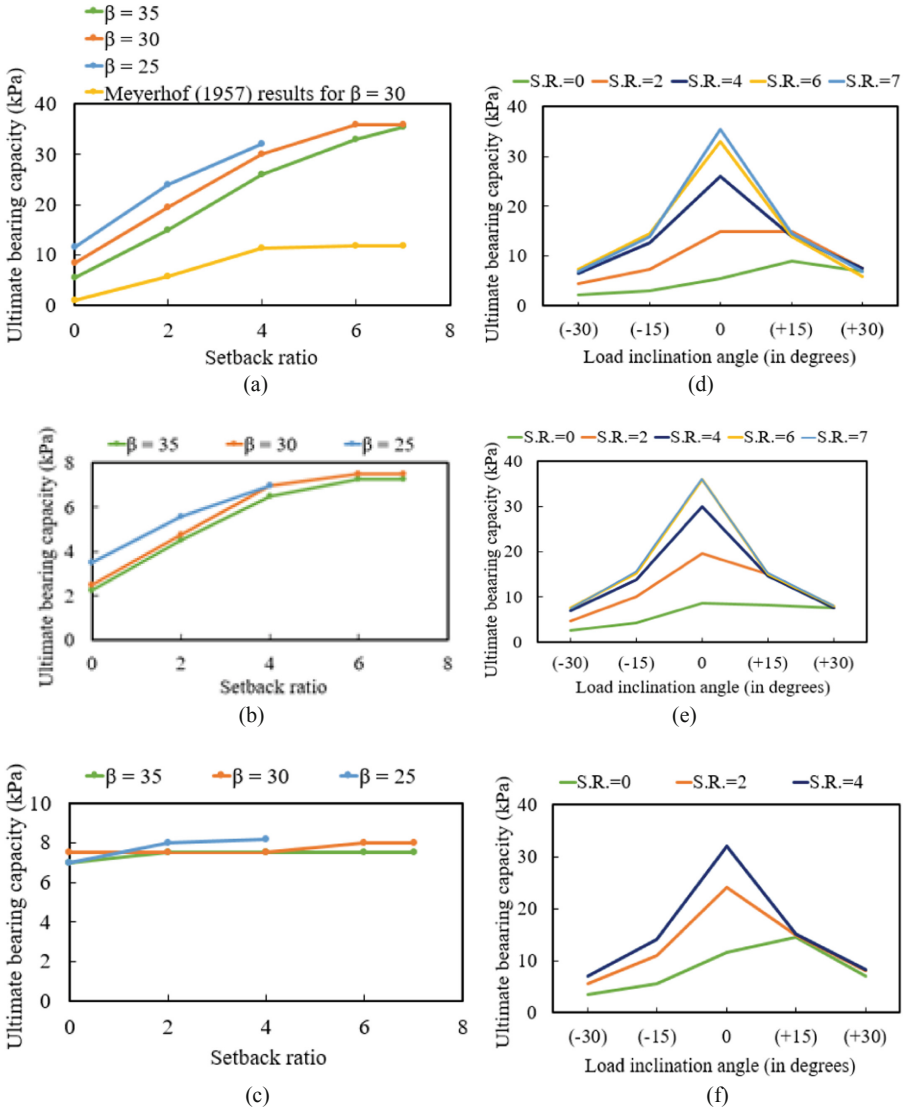


Fig. 3. (a, b, c) Effect of setback ratio on bearing capacity for footing subjected to vertical loading, inclined load at $+30^\circ$ and -30° , respectively; (d, e, f) Influence of load inclination on the estimated bearing capacity on sloping ground with $\beta = 35^\circ, 30^\circ, 25^\circ$, respectively.

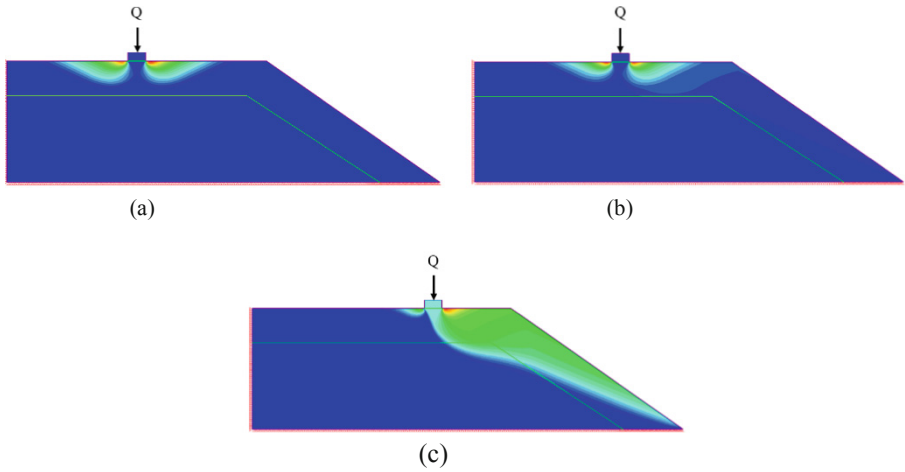


Fig. 4. Total displacement contour for sloping ground with $\beta = 35^\circ$ when footing is subjected to vertical load and positioned at (a) $b/B = 7$, (b) $b/B = 6$ and (c) $b/B = 4$.

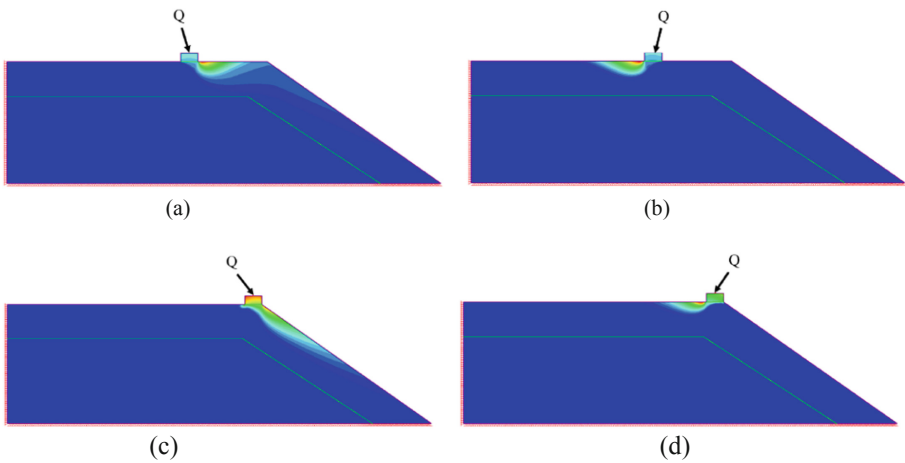


Fig. 5. Total displacement contours for sloping ground with $\beta = 35^\circ$ and footing with (a) $b/B = 4$ & $\psi = +15^\circ$ (b) $b/B = 4$ & $\psi = -15^\circ$ (c) $b/B = 0$ & $\psi = +30^\circ$ (d) $b/B = 0$ & $\psi = -30^\circ$.

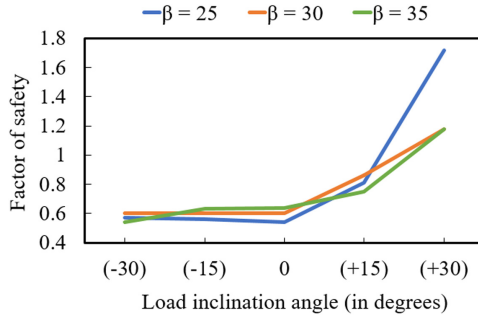


Fig. 6. Effect of load inclination angle on slope stability when footing is positioned at slope crest i.e. $b/B = 0$.

4 Conclusion

A 2D finite element based numerical study has been presented for investigating the bearing capacity of surface strip footings resting on dry cohesionless sloping ground with due importance to the factors, like slope angle, setback ratio and load inclination angle. 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. There exists a critical setback ratio of 6, beyond which the slope geometry noticed to have nearly no influence on the bearing capacity magnitude. 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. On the contrary, the bearing capacity nearly remains unaffected by the setback ratio and slope angle when the footing is subjected to load inclined away from the slope face. A general trend of decreasing bearing capacity has been noted with increase in the slope angle when the footing is either subjected to a loading inclined towards slope or loaded vertically. The stability of the slopes is further assessed, employing limit equilibrium-based slope stability analysis, for the cases having maximum possibility of the slope failure, i.e. when the footing is positioned on the slope crest. The analysis clearly indicates that the slopes may fail much before the mobilization of the estimated bearing capacity magnitudes. Hence, the bearing capacity for such cases should be analyzed in conjunction with the stability analysis of the slopes under consideration.

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