Bearing Capacity and Failure Mechanism of Shallow Footings on Unreinforced Slopes: A State-of-the-Art Review

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ABSTRACT

The analyses of load carrying capacity of shallow footings, located on semi-infinite horizontal surface, have been dealt at large by various researchers. With the growth in urbanization in the hilly regions, the recent years have recorded a boom in the infrastructure development on the hill-slopes. The presence of the slope face largely affects the load carrying capacity of the shallow footings for such infrastructures and presents a failure mechanism that is specifically different to that developed for footings located on horizontal grounds. Although there are certain literatures available, this problem has not received the required attention. This study presents a state-of-the-art review of the responses of shallow foundation placed on or near the face of sloping surface. The discussions have been categorized based on experimental, theoretical and numerical approaches. Finally, the critical appraisal of the state-of-the-art practice is provided and the scopes of further studies have been elucidated.

Keywords: Shallow footings on slope; Bearing capacity; Failure mechanism; Seismic response

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1. Introduction

The load carrying capacity of the footings is one of the most common topic of discussion in the area of geotechnical engineering. The assessment of ultimate bearing capacity of shallow footing placed on the horizontal surface depends on the associated geotechnical and geometrical characteristics of foundation system. In this regard, several researchers have provided classical approaches for the evaluation of ultimate bearing capacity (UBC) and the bearing capacity factors (BCF), along with the associated failure mechanisms (Terzaghi 1943; Meyerhof 1963; Hansen 1970; Vesic 1973; Michalowski 1997; Huang and Menq 1997). Experimental studies were also conducted by several researchers to assess the load-deformation behaviour of shallow surface or embedded footings resting on unreinforced or reinforced horizontal grounds (Samtani and Sonpal 1989; Yoo 2001; Li 2008). The assessment of load carrying capacity of a footing becomes further complicated when the either isolated or multiple footings rests on the crest or face of a sloping ground. Owing to growing urbanization of the hillslopes, practical cases of such foundations is gradually becoming prominent. The prevalent examples of such foundations pertain to the building, bridge abutment or transmission towers located on the hillslopes. The performance of such constructions on or near the slope depends on both bearing capacity of foundation and stability of slope. As compared to the footings resting on a horizontal ground, a shallow footing placed on or near the slope, and subjected to a variety of loading (axial, inclined, eccentric, coupled moments or their combinations), experiences a significant reduction in bearing capacity (Meyerhof 1957; Shields et al. 1977; Bauer et al. 1981). This is primarily attributed to the incomplete formation of the passive resistance zones towards the sloping ground, where there is not enough lateral restraint on the soil to resist its outward lateral movement (Acharyya and Dey, 2017).

Based on past researches, it is recognized that the load carrying capacity of a footing located on crest of slope is affected by several parameters, namely the loading direction and type of loading acting on the footing (Fedorovskii 2003), the setback distance and depth of embedment of the footing (Acharyya and Dey 2018c), the slope inclination (Acharyya and Dey 2017), the shear strength of the foundation soil (Acharyya et al. 2018) and hydrogeological conditions such as rainfall, degree of saturation and seepage within the slope (Talukdar et al. 2018). The loading characteristics play a vital role in the failure and deformation of the foundation on a slope. Inclined or oblique load acting on the footing and towards the slope face leads to an additional decrease in the load carrying capacity, as compared to the load acting away from the slope face. The closer a footing towards the slope face (i.e., having a lesser setback distance), the lesser is the lateral restraint against the soil movement and more is the chance of foundation failure. Beyond a threshold setback distance, the influence of the slope face will be completely diminished, and the footing will behave as if resting on horizontal ground. The saturation condition of the slope governs the shear strength of the foundation material. The presence of water table, seepage, percolation of water and the rate of precipitation and infiltration are the guiding parameters to ascertain the slope stability condition. Hilly areas around the world are expectant of frequent landslides and slope movements, which are mainly triggered either by torrential incessant rainfall (Cho and Lee 2001) or seismic actions (Kourkoulis et al. 2010). Moreover, due to increasing urbanization, the hilly regions is experiencing massive outgrowth in the number of habitations leading to widespread construction of residential and commercial buildings. Due to lack of proper ground, the construction is being carried out the slopes (Raj et al. 2018a), either using berm or terraces (where the foundations are laid in the crest or crown of the slope) or placed directly on the slope itself (where the foundations lie directly on the sloping face) (as shown in Fig. 1).

Many closely spaced low-rise residential buildings, schools, offices, barracks, hospitals or other not-so high-rise structures are being built with shallow foundations, many of them lacking proper geotechnical outlook or adequate geotechnical supervision. Foundations are laid unscrupulously without paying proper heed to the effect it would produce on the stability of the slope or on the adjacent structures. A common feature which can be seen in the hilly regions is that the foundation is placed at different levels with different depths of embedment. Such arrangements calls for improvised analyses and cannot be addressed by conventional bearing capacity theories. A thorough study in this aspect is vividly important with regard to safety of the upcoming projects in many of the hilly regions of the country or around the world. In this regard, this paper provides an exhaustive and critical review of the available techniques and researches conducted to address the problems associated with the foundations on slopes.

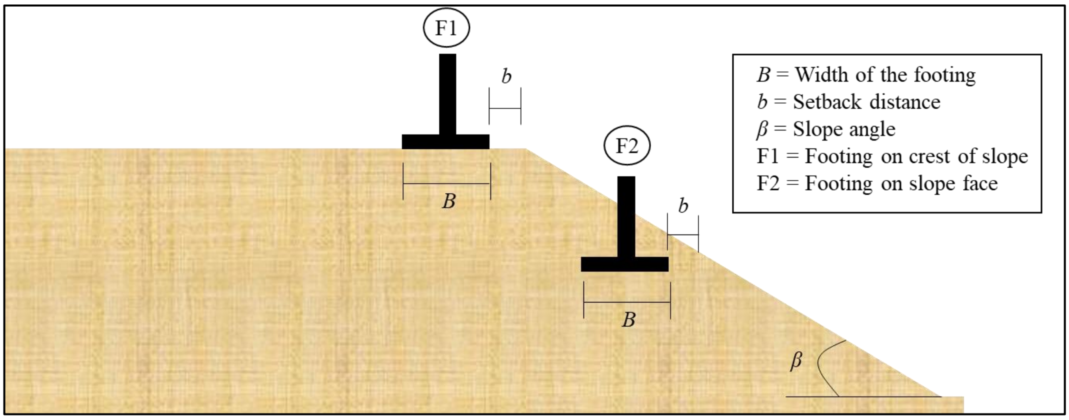

Fig. 1 Schematic diagram for footing located on crest of slope and resting on slope face

2. Shallow footings on horizontal ground

In order to understand the bearing capacity and failure mechanisms associated with the shallow footings on slopes, the classical concept of bearing capacity of shallow surface or embedded strip footings located on horizontal ground surface (Terzaghi 1943; Meyerhof 1951) is briefly recapitulated in this section. The classical theories were developed on the basis of several assumptions in which the footing was considered to be rigid, shallow and having a rough interface, while the foundation soil was considered to be elastic, homogeneous, semi-infinite, incompressible and isotropic (Terzaghi 1943; Murthy 2008). The soil was assumed to experience general shear failure under the action of centric and vertical loading applied on the footing. The failure zones underneath the footing (I – Active zone, II – Radial shear zone, III – Passive zone: as shown in Fig. 2) were also assumed to be symmetric (Terzaghi 1943). The ultimate load carrying capacity, estimated as the shearing resistance mobilized along the pre-defined failure surfaces, was determined by applying the principle of superposition to incorporate the static equilibrium of the active wedge immediately underneath the footing. Accordingly, three bearing capacity factors (N_c, N_q and N_γ) were proposed as a function of the internal angle of friction of foundation soil (φ).

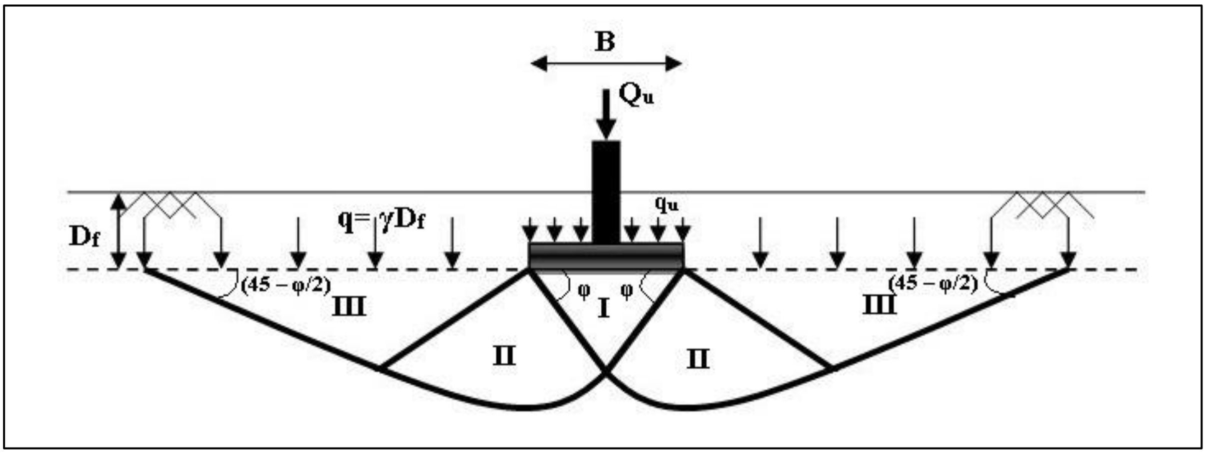

Fig. 2 Typical depiction of the conventional symmetric failure mechanism beneath a shallow strip footing subjected to a centric vertical load

Meyerhof (1951) modified the failure mechanism proposed Terzaghi (1943) by considering the slip surface of the passive zone, adjacent to the footing, to be extended up to the ground surface, and proposed a new set of expressions to determine the bearing capacity factors. Later, with the aid of laboratory and field experiments, for shallow footings on clays, Skempton (1951) proposed the magnitude of N_c as a function of the depth and shape of the foundation. Further, Hansen (1970) and Vesic (1973) provided the generalized expression for estimating the ultimate bearing capacity of shallow foundations by incorporating the shape factor (for strip, square, circular and rectangular footing), depth factor (surface or embedded footing) and inclination factor (vertical or inclined load). Later, several researchers had modified the generalized bearing capacity theory by introducing appropriate correction in the bearing capacity factors (Meyerhof 1978; Hanna 1982; Cerato and Lutenegger 2006).

In general, the classical expressions for bearing capacity mostly consider the footing to be subjected to centric vertical load. However, such loading rarely occurs in practice, and the actual loading condition is mostly accompanied by inclination, eccentricity and obliquity. Under such conditions, the failure mechanism beneath the footing becomes skewed, where the higher pressure develops towards the direction of the load. Several researchers had addressed this issue. With the aid of effective width method, Meyerhof (1953) pioneered the proposition of the bearing capacity beneath a continuous strip footing subjected to one-way eccentric loading. In the proposed method, it was assumed that under the action of the eccentric load, only a part of the footing takes part in the bearing resistance by developing uniform stress beneath the effective loaded area. Accordingly, depending on the location of the eccentric load, the actual width of the foundation was reduced. Later, based on the magnitude of the eccentricity, Purakayastha and Char (1977) proposed a reduction factor (R_k) to evaluate the bearing capacity of the eccentrically loaded continuous strip footing based with respect to the same obtained with centric load. Prakash and Saran (1971) introduced the assumption of asymmetric failure mechanism, wherein the active wedge beneath the footing was represented by a scalene triangle skewed towards the eccentric loading, while the radial shear is comparatively larger towards the eccentricity (as shown in Fig. 3). For rectangular and circular footings subjected to two-way eccentricity, Highter and Anders (1985) have provided design charts and expression to estimate the effective footing area resisting the applied load, and correspondingly evaluate the ultimate bearing capacity.

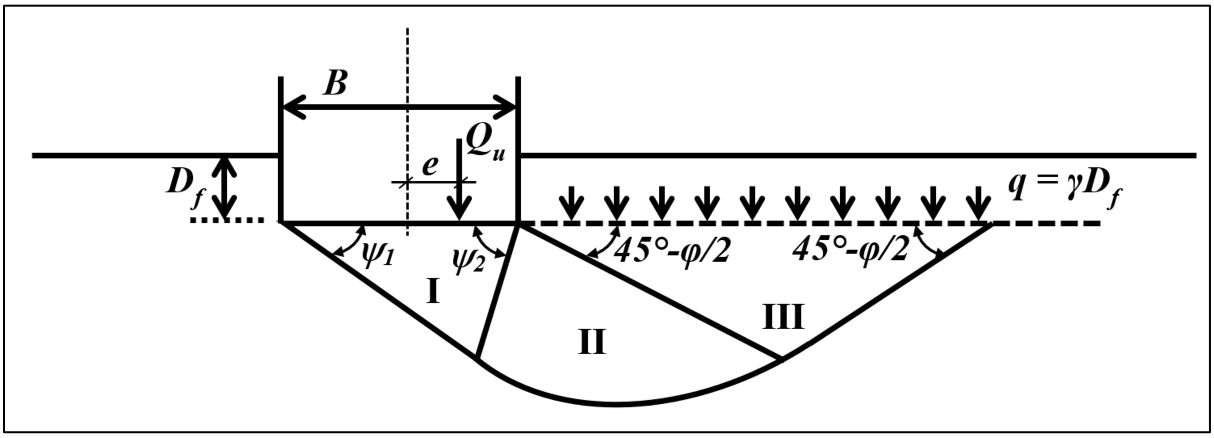

Fig. 3 Typical depiction of the asymmetric failure mechanism beneath a shallow strip footing subjected to an eccentric vertical load

Depending upon the type and direction of loading, the footing may be subjected to inclined or oblique (combined eccentric and inclined) loading. The literature reveals that theoretical analysis and experimental investigations were conducted on model strip and circular footings to estimate their ultimate bearing capacity when subjected to axially inclined loads (Hanna and Meyerhof 1981; Meyerhof and Koumoto 1987). The results obtained were used to modify the shape, depth and inclination factors, and use them in the generalized bearing capacity expression for shallow foundations. Based on kinematic approach and limit equilibrium analysis, Fedorovskii (2003) modified the Prandtl's classical solution to provide an estimate of the bearing capacity of strip footings on cohesive bed. Inclined and oblique loadings were considered, and the two-sided shear overflow was presented in detail. With the aid of experimental investigations on strip footing resting on sand and subjected to oblique loadings, the reduction factor proposed by Purakayastha and Char (1977) was further modified by incorporating the influence of load inclination angle and angle of internal friction (Patra et al. 2012a; 2012b; Atalar et al. 2013; Patra et al. 2016). Based on the data obtained from experimental and theoretical investigations, bearing capacity prediction expressions were presented based on artificial neural network (ANN) approach (Behera et al. 2013a; 2013b; Behera and Patra 2016). Neural-based sensitivity analysis revealed that the influence of eccentricity is notably higher than the angle of inclination of the applied load. Saran and Agarwal (1991) used the limit equilibrium and limit analysis methods to provide an estimate of the bearing capacity of eccentrically obliquely loaded strip footing on cohesive-frictional soil. It was assumed that failure takes place only in the same side of eccentricity on the footing.

Based on a finite element (FE) approach, researchers have estimated the collapse load of a rigid strip footing resting on granular soil and subjected to oblique loading (Loukidis et al. 2008; Krabbenhoft et al. 2013). Both associated and non-associated flow rules were considered to incorporate the effect of dilatancy in the analysis. Based on the results, the inclination factor, effective width, and the normalized vertical force-horizontal force-moment failure envelope was developed. The study was further extended by Haghighi et al. (2019) for strip footings subjected to combined loading and resting on sand over clay layers of varying thickness. Tang et al. (2014) applied lower-bound limit analysis theorem, in conjunction with finite element and second order cone programming (SOCP), to assess the influence of footing width on the failure mechanism of an eccentrically and obliquely loaded strip footing on sand. Normalized failure envelopes and load-interaction diagrams were presented by considering both constant and variable friction angle. In an exactly similar approach, Rao et al. (2015) highlighted the influence of oblique loading on the bearing capacity of two-layered clay. Ganesh et al. (2017)

collated the results of laboratory investigations from several studies and proposed an empirical non-dimensional reduction factor for determining the ultimate bearing capacity of embedded footings subjected to oblique loading. Figure 4 shows the typical failure mechanism observed beneath a footing resting on an unreinforced foundation bed and subjected to oblique loading.

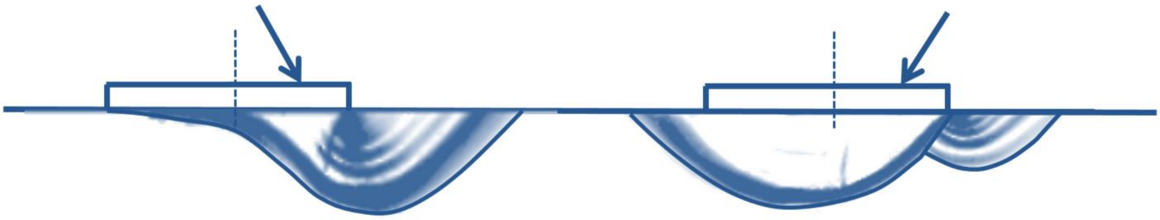

Fig. 4 Typical depiction of the asymmetric failure mechanism beneath a shallow strip footing resting on horizontal foundation bed and subjected to an oblique loading

Several researches were carried out to estimate the bearing capacity of special cases of shallow foundations, among which a few notable ones are presented here. Based on theoretical upper-bound analysis and experimental investigations on triangular shell strip footings, Hanna and Rahman (1990) introduced a modified set of shape and depth factors to be used in the generalized bearing capacity expression. Following the method of characteristics, Reddy et al. (1991) investigated the bearing capacity of strip and circular footings embedded in clay having a linear increment of cohesion with depth. With the aid of kinematic approach of limit analysis, Michalowski and Shi (1995) estimated the depth of collapse mechanism and the bearing capacity of surface strip footing resting on two-layered soils. For a specific case of footing resting on a granular soil overlying a clayey bed, a set of design charts was proposed to estimate the bearing capacity as a function of undrained cohesion of clay. Considering similar conditions of a strip footing resting on a sandy soil overlying a clay bed, Shiau et al. (2003) provided rigorous plasticity solutions using advanced upper and lower bound techniques to assess the bearing capacity. Considering the soils to follow an associated flow rule, finite element formulations were used to study the influence of footing roughness and clay inhomogeneity on the assessed bearing capacity. Through 2D and 3D finite element approach, researchers presented the influence of combined loading on strip and circular foundations resting on homogeneous and non-homogeneous clay (Gourvenec 2003; Zhang et al. 2011; Feng and Gourvenec 2015). Researchers have also incorporated different flow rules (associated and non-associated) and presented the influence of shear dilatancy on the bearing capacity and the failure mechanism of shallow strip, circular or ring footings resting on horizontal foundation bed (Vermeer and de Borst 1984; Bolton and Lau 1993; Erickson and Drescher 2002; Loukidis et al. 2008; Benmebarek et al. 2012; Acharyya and Dey 2018a, 2018b). Through numerical approach (Bransby and Randolph 1998) and model experiments (Prasad and Singh 2011), researches have illustrated the efficacy of adopting a skirting or box confinement beneath square or rectangular footings in resisting the effects of oblique loading and enhancement in bearing capacity. With the aid of numerical investigation and incorporating associated flow rule, Zhao et al. (2014) highlighted the influence of symmetric or asymmetric horizontal confinements, placed around the shallow strip footings, towards the enhancement of bearing capacity and the modification of the bearing capacity factor. In a similar manner, with the aid of upper-bound finite element method with rigid translatory moving elements (UBFEM-RTME), Yang et al. (2016) investigated the bearing capacity of a rough strip footing resting on granular soil, whose failure mechanism is constrained by a rigid basement located at a shallow depth below the footing. Researchers have also conducted advanced studies regarding the influence of ground water table and seepage on the bearing capacity of footings. Based on a kinematic approach of limit analysis, Ausilio and Conte (2005) incorporated the influence of groundwater on the bearing capacity of surface strip footing and provided modified bearing capacity factors to account for various depths of water table below the footing. With the aid of lower-bound finite element limit analysis, Kumar and Chakraborty (2013) investigated the influence of inclined groundwater flow (in both upward and downward directions) on the ultimate bearing capacity of strip footings resting on granular soils. Based on the results, depending on the hydraulic gradient of the flow, a correction factor (f_γ) was proposed to be multiplied to bearing capacity factor, N_γ, to account for the effect of groundwater seepage.

3. Shallow footings on unreinforced slopes

In contrary to the shallow foundations located on horizontal ground, the foundations located on slopes presents a more complex problem. For shallow footings located of the crest of the slope, the nearness of the footing to the slope face significantly governs the development of failure mechanism. In most cases, for a footing placed very near to the slope, the bearing capacity cannot be assessed independent of the stability analysis of the slope. The presence of the slope face leads to a freely deformable boundary, and the outward movement of the foundation soil along the slope face largely governs the bearing resistance of the foundation. Further, in contrary to the shallow footing on horizontal ground, the presence of slope boundary in vicinity to the footing results in a partial development of the passive zone, thus resulting in a reduced bearing capacity and an asymmetric failure mechanism in either side of the footing. As the distance between the footing the slope face (i.e. the setback distance) increases, the influence of the latter diminishes, and beyond an optimal setback distance, the slope face imposes no further influence and the footing behaves in similitude to that resting on a horizontal ground. The evolution of the failure mechanism becomes even more complicated when multiple footings interact with each other while resting on the slope crest or its face. Sequential and differential loading on the footings make the assessment intricate. The performance of footings placed near the slope is influenced by the angle of slope, setback distance, load distribution, embedment depth of the footing, and the strength and stiffness properties of foundation soil along with other factors namely, saturation status in the foundation soil, rainfall and earthquake loading. From early 1970s, geotechnical engineers are involved to decipher and understand the evolution of the failure mechanism and assessment of bearing capacity of shallow footings resting on slopes through experimental, analytical or numerical approaches. A critical treatise of the same are presented in the subsequent sections.

3.1 Development and understanding from experimental investigations

One of the earliest mention of the experiments indulging shallow footings on unreinforced slopes is by Shields et al. (1977). Laboratory investigations were carried out to estimate the bearing capacity of a vertically loaded strip footing resting on a sand-fill slope and having various embedment depths. The influence of relative density on the ultimate capacity was studied, and the experimental results were validated against one of the earlier theories related to foundations on slope proposed by Giroud (1971). Based on the experimentally determined ultimate capacity, the bearing capacity factor ($N_{\gamma q}$) was back-calculated, and the values were presented in the form of contours, pertaining to different footing locations along the cross-section of the slope. Bauer et al. (1981) extended the earlier research to incorporate rough-base rigid strip footings of two different widths (0.3m and 0.6m) and investigated the scale effect of footing on its ultimate bearing capacity. Footings placed at the slope face, with different embedment depths, were also included in the experimental investigation. Based on the results obtained using centric vertical and inclined loadings, a scale factor and an inclination factor was proposed to be incorporated in the modified bearing capacity expression for footings on slopes. For vertically-loaded footings located beyond a distance of $3B$ (B is the width of footing) from the slope face, the optimum scale factor obtained was 0.8, while the same was found to be 1.39 for footings subjected to inclined loading. In comparison to the vertical loading condition, it was seen that the bearing capacity factor reduced by 0.7 when the footing was subjected to inclined load. Gemperline (1988) carried out 215 centrifuge experiments, considering model footings placed on the crest of a cohesionless slope. In order to evaluate the ultimate bearing capacity, a modified bearing capacity factor ($N_{\gamma q}$) was proposed which was expressed as a function of angle of internal friction of soil (φ), width of footing (B), embedment ratio (D/B) and aspect ratio (B/L) of footing, slope angle (β), and setback ratio (b/B). Keskin and Laman (2013) had conducted laboratory investigations to evaluate the ultimate bearing capacity of strip footings located on the crest of dry sandy slope. The influence of various parameters (pertaining the soil, slope geometry and footing) on the bearing capacity was assessed. A finite element model was also developed to conduct a series of numerical analysis and it was found that the ultimate bearing increased with the increase in setback distance, relative density of sand and footing width, while it decreased with the increase in slope angle. An optimum setback distance, equal to four times the footing width, was also determined, beyond which the bearing capacity remained unchanged and equalled to that of a footing resting on the horizontal ground (Fig. 5). Similar experiments were conducted by Castelli and Lentini (2012) to investigate the bearing capacity of strip footings on sandy slope, and reconfirmed the finding that the failure mechanism of shallow footings on slopes are categorically affected by the nearness of the footing to the slope face. The results of the experiment were validated with the aid of limit equilibrium based numerical analysis.

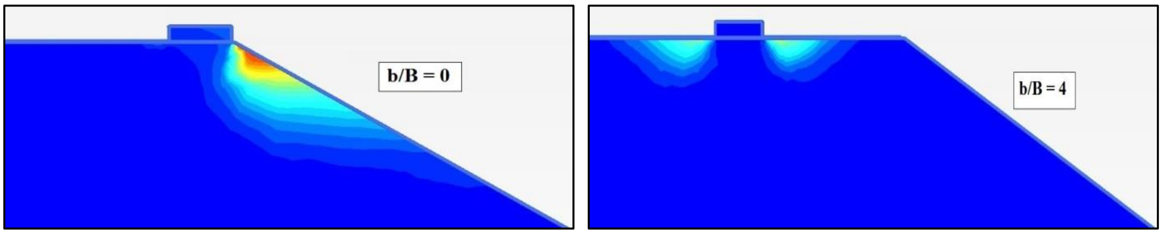

Fig. 5 Typical representation of the failure mechanisms beneath the footing resting on a slope having different setback distances

Cure et al. (2014) conducted model tests on strip footings located on the crest of a slope and subjected to eccentric loading towards the slope face. Similar to that for a footing on horizontal ground (Fig. 4), the failure mechanism was observed to be asymmetrical, with the primary failure surface forming towards the eccentricity, while the secondary failure surface developed in the other direction. Researchers have also resorted to experimental and numerical investigations to address the enhancement of bearing capacity with the aid of additional attachments (structural skirt, confining cylinders or micro-piles) to the base of a strip or circular footing resting on the crest of a sandy slope and subjected to vertical or oblique loads (Azzam and Farouk 2010; Elsaied 2014; Azzam and El-Wakil 2015). The results indicated that the failure mechanism was significantly altered (highlighting lesser outward movement of the slope) and the bearing capacity notably increased with the increase in the depth of the structural attachment. Abedi and Hataf (2014) conducted experiments with strip footings on grouted slopes and recommended that grouting beneath the footing, up to a depth of two times the footing width, is significantly effective in enhancing the bearing capacity. Rahman et al. (1995) conducted model tests with strip footings resting on cohesionless soil slopes in the presence of a shallow rigid boundary. Based on the results, modified bearing capacity factors were developed to incorporate the simultaneous effect of the shallowness of rigid boundary, setback distance and slope angle.

3.2 Theoretical and numerical investigation and developments

The earliest attempt to develop a theoretical formulation to assess the bearing capacity of shallow strip footings on a c-φ soil slope was pioneered by Meyerhof (1957). The conventional theory of bearing capacity of strip footing on horizontal ground was modified to include the influence of slope angle and slope stability on the bearing capacity of a surface or embedded strip footing resting on the face or crest of a slope. Based on a series of limit analysis, the modified bearing capacity factors (N_{cq}, $N_{\gamma q}$) were proposed as a function of embedment depth ratio (D_f/B), setback distance (b), slope angle (β), and shear strength parameters of the soil. The one-sided asymmetric failure zone was considered to comprise an elastic zone beneath the footing, a radial shear zone, and a mixed shear zone extending to the face of the slope (Fig. 6). A major limitation of the approach was to consider the estimation of bearing capacity factors independent of each other by considering the soil to either purely cohesionless or purely cohesive, and further superposing their effects to obtain the bearing capacity of the *c*-*φ* soil.

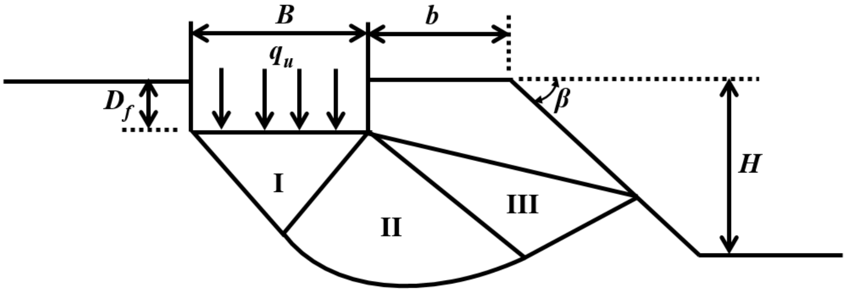

Fig. 6 Typical representation of the one-sided symmetric shear failure mechanism developed beneath a shallow footing resting on the crest of a *c*-*φ* soil slope

Similar to the earlier approach, Mizuno et al. (1960) considered a shallow strip footing resting on the crest of a cohesionless soil slope. In this case, the radial shear zone was disintegrated into a number of small wedges, and were successively analysed by force equilibrium approach to determine the overall failure mechanism. For specific cases, the results of bearing capacity and sliding mechanism of the theoretical analyses were validated with the experimental investigations. With the aid of limit equilibrium and limit analysis approaches, using the upper bound or lower bound theorems, the theoretical investigation by Meyerhof (1957) was further extended to address the specific cases of footings resting on the crest of a cohesionless slope with zero setback distance (Hansen 1970; Vesic 1975; Saran et al. 1989) or away from slope face (Kusakabe et al. 1981). In a similar approach, by considering two-sided asymmetric failure mechanism developing beneath the footing, Graham et al. (1988) adopted the method of stress characteristics to assess the bearing capacity of strip footing resting on edge of a cohesionless slope (Fig. 7). Shields et al. (1990) collated the results of the experimental investigations conducted by Shields et al. (1977) and Gemperline (1988) to provide a physical test based expression for bearing capacity of strip footings resting on the crest or face of cohesionless slopes. Narita and Yamaguchi (1990) evaluated the bearing capacity of shallow foundations on slopes by adopting a continuous logarithmic-spiral failure mechanism extending from the footing edge to the slope face. The results indicated that such an assumption of failure mechanism bears more correspondence to shallow footings on purely cohesive slopes, while for footings on cohesionless slopes, the bearing capacity gets overestimated. Based on the results of centrifuge tests, Arduino et al. (1994) included the complete load-deformation response of a footing resting on a slope for proper estimation of the allowable load bearing capacity of the footing.

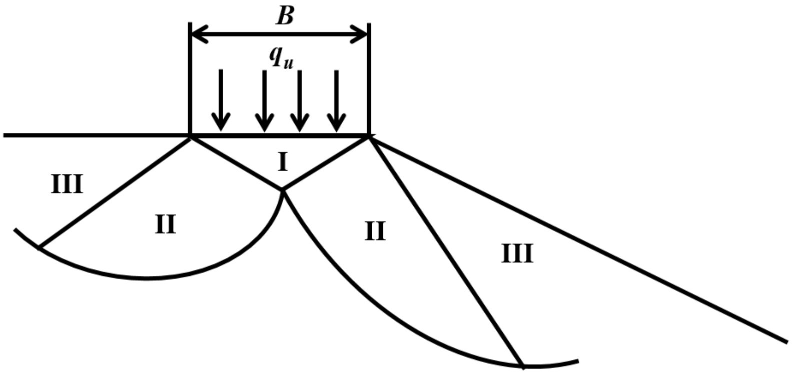

Fig. 7 Typical representation of the two-sided symmetric shear failure mechanism developed beneath a shallow footing resting on the edge of a soil slope

de Simone (1987) was the pioneer to propose the boundary integral equation method (BEM) to assess the bearing capacity of footing on clay slopes. However, owing to the complexity of the method, the researcher himself disregarded the method, and it has not been used over in the later years. In the following decades, based on finite element upper and lower bound approach, researchers have provided the solutions for ultimate undrained bearing capacity and load interaction mechanisms of a strip footing on the edge of a vertical or inclined slope comprising purely cohesive soil (Al-Jubair and Abbas 2007; Georgiadis 2010a; 2010b; 2010c; Nguyen and Merifield 2011; Shiau et al. 2011). Similar approach was also adopted for footings resting on cohesionless soils (Baazouzi et al. 2016; Zerguine et al. 2018). In such conditions, the failure can be governed by either foundation failure or the global slope failure. Based on the results, it was observed that the two modes of failure are influence by the critical undrained shear strength, which is further governed by Taylor’s stability number, height of the slope and width of the footing. Chakraborty and Kumar (2013) carried out a lower bound finite element analysis, accompanied by nonlinear optimization, to obtain the bearing capacity of a footing located on the bench of a sloping ground comprising c-φ soil. It was commented that the rough footings exhibit a larger extent of plastic zone as compared to that developed beneath a smooth footing. Zhu et al. (2016) adopted a strain based stability evaluation of locally loaded slopes. With the aid of the strains monitored in a model slope through distributed fiber optic strain sensing (DFOSS), a finite element based numerical model was developed. Several strain parameters were proposed for representing the state of strain in the slope, and an empirical correlation was established with the factor of safety. For spread footings resting on the crest of a cohesive-frictional soil slope, researchers (Leshchinsky 2015; Leshchinsky and Xie 2017) have adopted limit analysis (LA) using discontinuity layout optimization (DLO-LA), and accordingly proposed a modification on bearing capacity factors proposed by Meyerhof (1957). As an outcome of the conducted research, reduction coefficients and corresponding design charts were proposed. Due to altered collapse mechanism owing to higher frictional strength and deepened shear surfaces, the slope face was shown to have even more influence than that proposed by Meyerhof (1957). Based on the proposed DLO technique, Zhou et al. (2018)

investigated the bearing capacity of a strip footing located on the crest of a slope, and proposed six distinct failure mechanisms. Out of these, four modes pertained to bearing capacity failure (face failure, tow failure, base failure and Prandtl-type failure), while the remaining two conformed to slope stability failure (toe failure and overall slope failure). Acharyya et al. (2018) conducted finite element analysis to assess the bearing capacity of a surface and embedded strip footing resting on a cohesive-frictional slope. Various geotechnical and geometrical parameters were varied and an ANN prediction expression was provided for the estimation of bearing capacity. Sensitivity analysis highlighted that angle of internal friction of soil and the embedment depths are the most important parameters affecting the bearing capacity (Acharyya and Dey 2018c). Based on similar database prepared from finite element studies on strip footings on dry cohesionless slopes, Moayedi and Hayati (2018) used several non-linear machine learning and soft computing-based models to create prediction expressions for bearing capacity. The various models tried were the feedforward neural network (FFNN), radial basis neural network (RBNN), general regression neural network (GRNN), support vector machine (SVM), tree regression fitting model (TREE) and adaptive neuro-fuzzy inference system (ANFIS), out of which FFNN was observed to provide the best match with the finite element results.

Footings of tall transmission towers are often subjected to multitude of loading, especially combined vertical, horizontal and moment loading originating from the sway of tower due to the wind forces, occasional snapping of the high-tension wires or in case of seismic events. In this regard, it becomes imperative to address the response of such towers on slopes when subjected to combined loading. The influence of eccentric or oblique loading on the bearing capacity was also studied by the researchers. Jao et al. (2001; 2008) conducted plane-strain elasto-plastic finite element analysis to investigate the influence of vertical centric and eccentric loading on the bearing capacity of a strip footing on the crest of a slope. In comparison to the bearing capacity obtained with centric loading, the same was observed to have higher reduction when the eccentric loading on the footing was considered acting towards the slope rather than when the same is away from the slope. With a similar finite element approach, Georgiadis et al. (2008) investigated the influence of inclined loading, eccentric loading and combined loading on the bearing capacity of a strip footing on the crest of a cohesive slope, and provided separate load-interaction diagrams (horizontal-vertical, vertical-moment, and horizontal-vertical-moment, respectively) for each of the three cases.

Although the stability of saturated or unsaturated due to antecedent have been in the radar of several researchers over the years (Cho and Lee 2001; Huang and Jia 2009; Rahimi et al. 2011; Sasahara and Sakai 2014; Chatra et al. 2017; Tang et al. 2018), the stability of the shallow footings on slopes under the prevalent effect of rainfall did not attract any dedicated attention. Although not directly related to the stability and bearing capacity of foundations on slopes, the only article of recent times is by Talukdar and Dey (2018) which has reported the failure of building foundations due to slope movement triggered by rainfall infiltration and seepage. Immense mass movements of the soil, due to the rainfall infiltration induced reducing shear strength characteristics, led to the exposure of building foundations located on the hill-slopes and the subsequent reduction in bearing capacity which finally paved the way to the failure of superstructures. However, no estimation of the loss of bearing capacity was attempted in the reported study.

4. Seismic response of shallow footings on unreinforced slopes

Seismicity and its growing trend has and always will be subject matter of interest to geotechnical engineers as the footings resting on foundation soils are the primary means of seismic stress transfer to the supported superstructure. Vice versa, the supporting superstructures, especially those having large heights and otherwise supports rotatory or vibrating machines, also impart sufficient dynamic forces and moments to the footing and foundation soil. Thus, it becomes imperative to study the response of the foundation under seismic or dynamic loads. Shallow footings of structures located on hill-slopes are largely vulnerable to such seismic or dynamic motions, specifically due to two reasons: firstly, due to the topographic amplification of the seismic motion being transferred to the base of the foundation, and secondly, larger loss of resistance by the incomplete mobilization of passive resistance towards the slope face. Under such scenarios, it is highly important that the dynamic bearing capacity and dynamic response of foundations on slopes are critically assessed, and accordingly, the problem of determination of seismic bearing capacity of shallow foundations near slopes has attracted the attention of many researchers. The investigations and analyses mostly pertain to the cases where the foundation on slopes are subjected to pseudostatic or seismic loadings. A typical representation of the failure mechanism and forces considered for pseudo-static analysis of footings on slopes is represented in Fig. 8.

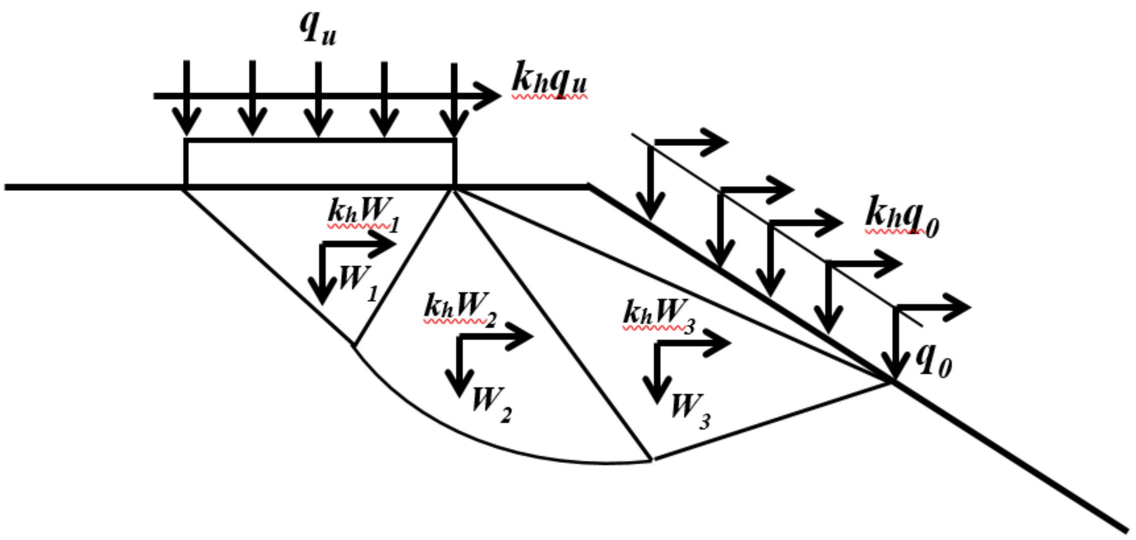

Fig. 8 Typical representation of considering horizontal pseudo-static forces while establishing the failure mechanism beneath a shallow footing on slope

Kumar and Kumar (2003) addressed the problem of seismic bearing capacity of rough strip footing embedded in a sloping ground. The influence of horizontal pseudo-static earthquake body forces was considered and the bearing capacity was assessed through a limit equilibrium method while simultaneously addressing the kinematic admissibility of the failure mechanism. It was assumed that the failure surface does not extend to the ground surface and remain embedded to the footing depth along the slope. The moment induced by the seismic loading was neglected in the analysis. Further, using method of stress characteristics and the kinematically admissible upper bound theorem, researchers have extended the earlier work by considering the developed failure mechanism to be extending to the slope face (Kumar and Rao 2003; Kumar and Ghosh 2006). An exactly similar approach was adopted by Askari and Farzaneh (2003) wherein the strip footing was considered resting on the crest of the slope and the failure mechanism reached the slope face. For a similar problem, Choudhury and Subba Rao (2006) determined the seismic bearing capacity factors for a strip footing embedded in a cohesive-frictional soil slope by considering both horizontal and vertical pseudo-static coefficients and establishing a novel technique to identify the critical focal point of the log-spiral failure mechanism. In all the above researches, it was observed that the increase in the pseudo-static horizontal coefficient led to drastic reduction in the bearing capacity and associated factors. Instead of using the commonly adopted upper bound theorem, Sarma (1999) applied the limit equilibrium technique to assess the seismic bearing capacity of a strip footing on slopes considering the failure mechanisms beneath the footing comprising rigid active and passive blocks along with the shear transition zone. Xiao-Li et al. (2007) incorporated the influence of shear dilation of cohesionless soil by coupling non-associated flow rules with the multi-wedge translational failure mechanism developed beneath a footing resting on a c-φ slope and subjected to horizontal pseudo-static forces. Energy dissipation method was adopted which was efficient enough in delineating the effects of dilatancy angle on the seismic bearing capacity factors. Huang and Kang (2008) combined the pseudo-static approach with Janbu's rigorous slice method to derive analytical expressions for factors governing the seismic bearing capacity of a rigid footing adjacent to a cohesionless slope. Castelli and Motta (2010) adopted a similar approach to be applied on a purely circular failure mechanism. Both inertial and kinematic effects of seismic loading were considered and a simple expression to evaluate the seismic bearing capacity of strip footing resting on cohesionless soil was framed. A similar type of problem was addressed by Ghazavi and Mahali (2014) wherein a Prandtl type failure mechanism was considered. The earlier work by Askari and Farzaneh (2003) was further extended for strip footings embedded in crest of a cohesionless (Yamamoto 2010) of cohesive slope (Georgiadis and Chrysouli 2011). Cinicioglu and Erkli (2018) addressed a similar problem of seismic bearing capacity of strip footings on clay slopes with the aid of finite element modelling. Qin and Chian (2011) extended the work by Askari and Farzaneh (2003) by addressing the problem of a strip footing resting on a two-stage layered soil slope where the sliding surface is considered to be representing the condition of base failure. Both horizontal and vertical pseudo-static coefficients were considered in this case, and the influence of the ratio of pseudo-static coefficients, soil strength ratios and setback distance of the footing on the bearing capacity were assessed. To assess the seismic bearing capacity of a strip footing embedded in the face of a cohesionless soil slope, Chakraborty and Kumar (2015) used the lower bound theorem coupled with nonlinear optimization to extend the work by Kumar and Kumar (2003), while a similar approach was adopted by Farzaneh and Mofidi (2013) for strip footing on cohesive slopes. Following the approach by Kumar and Kumar (2003), the research was extended for strip footings resting on homogeneous and isotropic rock slope (Saada et al.

2011; Ausilio and Zimmaro 2015), where the pseudo-static bearing capacity was assessed by considering a logarithmic-spiral failure mechanism. While Saada et al. (2011) used upper bound theorem to estimate the load bearing capacity, Ausilio and Zimmaro (2015) proposed a displacement based seismic design considering the influence of geometrical, seismic and rock strength parameters. In recent times, in order to address the practical problem of increasing urbanization in the hillslopes, with the aid of nonlinear finite element analysis, researchers have attempted to study the seismic response of closely spaced footings located on the crest or face of the slope in order to understand the interaction and interference between the footings during a dynamic event (Raj and Singh 2016; Raj et al. 2018b; 2018c). Some researchers have also investigated the dynamic response of foundation on slopes (Islam and Gnanendran 2013; Varzaghani and Ghanbari 2014); however, those researches are excluded from the scope of the present article.

5. Three-dimensional response of shallow footings on unreinforced slopes

As can be observed the literature review, most of the experimental or theoretical developments towards understanding the static or seismic response of shallow foundations on slopes were directed towards plane-strain two-dimensional problems. In most of the cases, strip footings were used to represent the shallow footing, and its failure mechanism and bearing capacity was assessed under different loading conditions. However, in practice, the use of plane-strain strip footings on the hill-slope urbanization is rather limited. In most of the cases, foundations of the buildings would conform to the isolated square, rectangular or circular footings, or, as necessitated, combined footings are also frequently used nowadays (NDMA 2013). In this regard, it becomes imperative to conduct three-dimensional analysis of shallow foundations on slopes, and assess their appropriate response towards static or dynamic loading. In contrary to the magnitude of research targeted to address the three-dimensional bearing capacity of shallow footings on horizontal ground, literature pertaining to three-dimensional analysis and response of shallow foundations on slopes are meagre, and only a handful of published material are available. A typical representation of the three-dimensional failure mechanism is represented in Fig. 9.

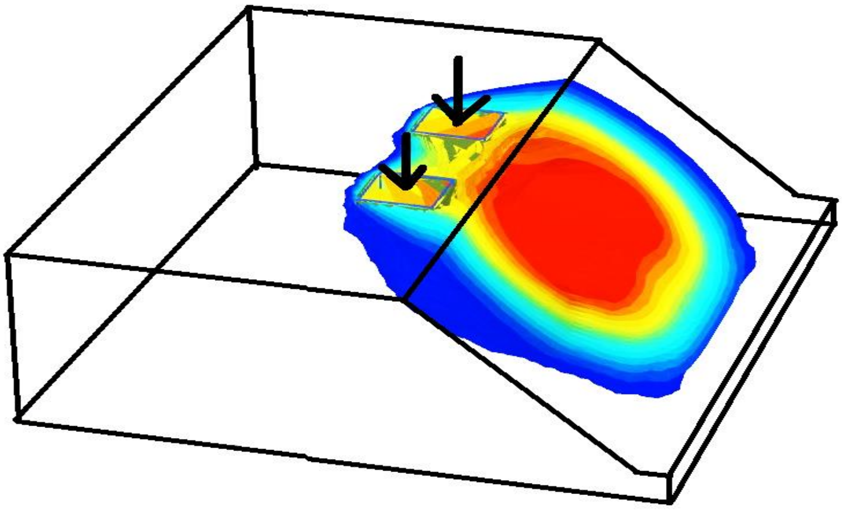

Fig. 9 Typical representation of three-dimensional failure mechanism beneath interacting shallow square footings on slopes as obtained from finite element analysis

One of the earliest theories in regard to the three-dimensional bearing capacity of shallow rectangular footing on cohesionless slopes was reported by de Buhan and Garnier (1998). The yield line theory was used to explain the true 3D failure mechanism of the footing. The overall outcome was obtained through optimal solution of the upper bound kinematic estimates of two independent failure mechanisms in orthogonal directions. The assumed failure mechanism corresponded to a punching failure mechanism derived from the Prandtl type shear failure mechanism. The analysis of rectangular footing was suitably modified to obtain bearing capacity estimates of square and circular footings resting at the edge of the slope. The results from the theoretical approach were compared against the limited number of centrifuge experiments (Bakir 1993), which showed an appreciable match, thereby highlighting the efficacy of the developed theory. Based on the theory, the reduction factor of the bearing capacity was provided as a function of the proximity of the footing to the slope face. For a similar problem, Arabshahi et al. (2010) used discrete element method (DEM) for addressing the 3D bearing capacity of rectangular footings on cohesive-frictional slopes. The failure mechanism beneath the footing was represented as discrete blocks connected with a set of normal and shear Winkler springs. The failure zone was defined by six independent angles which were adjudged by optimization to obtain the critical failure surface. Based on the approach, it was observed that the critical setback distance decreases with the decreasing soil friction angle. Majidi et al. (2011) extended the developed methodology to include the influence of different aspect ratios of the foundation on the bearing capacity factors. Castelli and Lentini (2012) conducted experimental investigations to assess the bearing capacity of square footing resting on the crest of a granular soil slope. Owing to the presence of the sloping face, a maximum reduction of bearing capacity of 50% was recorded against the results for a footing resting on horizontal cohesionless soil bed. The ratio of bearing capacity factor observed for footing near the slope surface to the same away from the slope was found to decrease with the increase in the ratio of footing width to setback distance. Based on the results, a simple relationship between the original and modified bearing capacity factors was proposed as a function of soil friction angle and footing width. With the aid of 3D finite element investigation, the bearing capacity of square footings resting on cohesionless slope was reported by Acharyya and Dey (2017). The effect of various parameters, namely the angle of internal friction of soil, setback distance, slope inclination, footing width and the depth of embedment of the footing, were investigated. Based on the observed failure mechanisms, the critical setback distance was found to be three times the footing width. The research was further extended by Acharyya et al. (2018) for a square footing resting on the crest of a cohesive-frictional soil slope. In this case, the critical setback distance was obtained to be four times the footing width. Based on an ANN approach, a bearing capacity prediction expression was provided. Sensitivity studies revealed that soil shear strength parameters and embedment depth are the most influential factors affecting the estimate of bearing capacity. Further, with the aid of finite element studies, very recently, Acharyya and Dey (2019) highlighted the suitability of the various typologies of shallow foundations that should be practiced in hillslopes. In an urbanized hill-slope, multiple types of footings are bound to coexist on the crest or the face of a slope, and it is important to understand the best footing practices such than an enhancement in the bearing capacity and a reduction in the outward deformation of slope is ascertained. In this regard, the study highlighted that interconnecting the isolated footings located near the slope face to those located away from the slope face provides a tieback mechanism, and is beneficial in reducing the bearing stresses as well as increasing the resistance to the outward deformation of slope face. Such interconnections are recommended to be provided perpendicular to the slope face for more sustainable design of shallow foundations on slopes.

6. Final remarks and future prospects

This article presents an elaborate review of the researches conducted in the context of bearing capacity and failure mechanisms of shallow footings located on slopes. The chosen topic is especially important in the context of hill-slopes which are experiencing rapid growth in urbanization and progressive development in modern times. Under this scenario, it becomes particularly important to pay a critical attention to the safety and stability of the already constructed or to be constructed structures on the hillslopes and the hillslope itself. In several cases, as noticed, the current practice of hill-slope urbanization in India, or in many other regions, is instinct-driven rather than engineering-driven. Under this scenario, it becomes important to revisit the knowledge base developed over years in regard to the stability assessment of footings on hillslopes, and further develop the same for the coming years to meet the growing demands. In this regard, this article lucidly presents the research conducted from early 1960s until date which has attempted to address the intricacies of the assessment of bearing capacity and failure mechanism of shallow footing located on hillslopes. It is revealed from the article that researchers have been instrumental towards both experimental investigation and theoretical/numerical analysis and have presented the various cases of bearing capacity of shallow footings on slopes through a plethora of methods. A major share of the research focused on the assessment of bearing capacity of surface/embedded strip footings resting on the crest of soil slopes (cohesionless, cohesive, or cohesive-frictional) and subjected to vertical centric loading. The influence of various geometrical and geotechnical parameters affecting the failure mechanism and bearing capacity are thoroughly investigated. Different types of failure mechanisms are taken into consideration, which has been solved by multitude of techniques ranging from simple limit equilibrium approaches to complex stress-deformation methodologies. Even advanced soft computing techniques are resorted to in several cases. Several expressions to assess the bearing capacity is also proposed by various researchers. In order to cater the influences of various types of loading (eccentric, inclined or oblique) which can be incumbent on the footing, several researchers have attempted and successfully presented the theoretical basis of analysing the bearing capacity and failure mechanism when the footings on slopes are subjected to complex loading scenarios. Assessment of the bearing capacity of special types of footings on slopes comprising structural attachments are also studied for their effectiveness in enhancing the bearing capacity. Seismic response of shallow footings on slopes has also received its fair share of attention. Several researchers are also involved with more complex researches related to foundations on reinforced slopes (Yoo 2001; Alamshahi and Hataf 2009; El-Sawaaf 2010; Altalhe et al. 2015;

Alam et al. 2018; Halder and Chakraborty 2018), however, the detailed treatise of the same is out-of-scope of the present article, as it is larger domain of research in itself.

In spite of the of the magnitude of variety of research already conducted in the domain of shallow footings on slopes, the changing and growing requirements calls for further research in those domains which has not yet received their fair share of attention.

- It is revealed from the available literature that the influence of rainfall in reducing the bearing capacity and triggering failures of foundations located on slopes still calls for further intricate research. Although the influence of rainfall, groundwater water fluctuation, infiltration and seepage is well studied towards understanding slope stability, however thorough study of the same in altering the bearing capacity and failure mechanism of shallow footings on slopes is still awaited.
- Most of the seismic studies conducted until date address the problem through pseudo-static approach. However, the slope material being amply responsible for altering the propagation and amplification characteristics of propagating seismic waves, due attention is required in the domains of topographic amplification and their influence on the time-dependent seismic bearing capacity of footings on slopes.
- A scrutiny of the available literature makes it amply clear that the Mohr-Coulomb shear strength parameters were mostly adhered to represent the hill-slope soils, and most of the analyses revolves around the stated constitutive model. The choice of a constitutive model is primarily governed by the type of prevalent soil and type of loading expected. Hill-slope soils around the world are of varied composition, and different hilly terrains can expect different loading conditions ranging from extremely short-term seismic loads to long-term creep loads, the magnitude of which can largely vary. This uncertainty and variation calls for the adoption of different constitutive models for soils

representing the hill-slopes, and accordingly assess the bearing capacity and failure mechanism of the supporting footing. Further, spatial variability and probabilistic analysis is also the need of the hour to deal with the uncertainties in soil parameters and loading characteristics and are desirable to be included in the bearing capacity theories for shallow footing on slopes.

- The majority of the research related to shallow footings on slopes comprise strip footings which represent two-dimensional plane-strain problems. Such footings might not be commonly adopted for the construction in hill-slopes, and in many cases rectangular, combined or raft footing are resorted to nowadays. The failure mechanisms of such three-dimensional footings are complex, and need more intricate analysis to comprehend. It can be noticed that until date, very few researches are attempted considering the three-dimensional analysis of shallow footings on slopes. In order to cater the realistic scenario of urbanization and construction on hillslopes, more attention is required on such three-dimensional analyses.
- Urbanization in hillslopes calls for multiple typologies of shallow footings to coexist on the crest or face of the hill slope. It is immensely important to study and understand their interaction and interference mechanism. In recent times, post 2015, few researches have been oriented towards this realistic issue. Few researchers have represented the bearing capacity and failure mechanism of coexisting multiple shallow footings in two-dimensional and three-dimensional domain, under static or seismic conditions. However, detailed and thorough research in this direction is the desirable necessity.

In a nutshell, a great deal of research in the above stated directions is further awaited to understand and develop a safe practice and planning of urbanization in hillslopes, so that the existing hill-slope does not get jeopardized or become susceptible to failure.

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