ASSESSMENT OF BEARING CAPACITY AND FAILURE MECHANISM OF
SINGLE AND INTERFERING STRIP FOOTINGS ON SLOPING GROUND

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ABSTRACT
Estimation of the bearing capacity of a shallow footing located at the crest of a slope is an
intricate problem. The problem becomes much more complicated when multiple numbers of
closely spaced footings interacts with each other while resting on the slope. In this regard, a
sequence of finite element analysis has been carried out using Plaxis 3D vAE.01 to investigate
the ultimate bearing capacity of isolated and interfering surface strip footings placed at the crest
of the c-φ soil slope. In the numerical analysis, the influence of different geo-parameters on
ultimate bearing capacity has been studied. From the failure mechanism, it has been seen that
the impact of slope and the influence interference disappeared above a critical setback ratio
($b/B$) of 6 and beyond a critical spacing ratio ($S/B$) of 3 for single and interfering strip footings
located at crest of slope respectively.

Key words: Interference of strip footings, c-φ slope, Finite element modelling, Failure
mechanism, Setback ratio, Spacing ratio
1. INTRODUCTION

Bearing capacity ($q_u$) of footing defines the maximum load that the foundation can carry without failure within allowable limits of settlement. The load carrying capacity of foundation depends on geotechnical and geometrical characteristics. Geotechnical characteristics comprise the shear strength and deformation parameters of soil. Geometrical characteristics include the size, depth and shape of the footing. In order to design an adequate foundation for superstructures, bearing capacity is the key for geotechnical engineers. In this matter, based on several assumptions, Terzaghi (1943) had given the first expressions to assess the bearing capacity of a strip footing resting over a semi-infinite horizontal ground surface. Meyerhof (1951) further extended the proposition by considering the by assuming that the developed failure surface in the passive zone extends up to the ground surface, thus providing a different set of bearing capacity factors ($N_c$, $N_q$ and $N_γ$). Later, based on theory, field and laboratory investigations, Skempton (1951) provided modified expressions for $N_c$ considering footings of different shapes, sizes and embedment depths within a saturated clay medium. Thereafter, based on the work of several researchers (Hansen 1970; Vesic 1973), a general bearing capacity expression had been formulated including all possible contributions of shape, size, embedment depth, load inclination, and compressibility of the founding medium.

The classical researches cited above primarily dealt with an individual footing. The development of the failure mechanism, and the corresponding bearing capacity, of an individual footing is altered in the presence of adjacent interfering footings. Stuart (1962) was the first to provide the concept of interference of shallow footings, based on which ‘efficiency factors’ were incorporated in the estimation of bearing capacity of interfering surface footings. Further, both experimental and numerical investigations have been conducted for evaluating the interference effect of shallow footings resting on horizontal ground. It has been observed that both settlement and bearing resistance of footings increases for closely spaced footings,
while the same decreases with increasing inter-footing spacing (Das and Larbi-Cherif 1983; Kumar and Ghosh 2007; Kumar and Kouzer 2007; Kumar and Bhoi 2008). It has been substantiated that the efficiency factors ($\xi_c$, $\xi_q$ and $\xi_\gamma$) decreases with the increasing spacing between the footings (Lee and Eun 2009; Mabrouki et al. 2010; Kumar and Bhattacharya 2010; Ghosh and Sharma 2010; Naderi and Hataf 2014; Javid, Fahimifar, and Imani 2015).

The effects of shear dilatancy on bearing capacity, bearing capacity factors and failure mechanism have been numerically investigated by several researchers (Vermeer and de-Borst 1984; Nova and Montrasio 1991; Drescher and Detournay 1993; Bolton and Lau 1993; Manoharan and Dasgupta 1995; Manzari and Nour 2000; Yin, Wang and Selvadurai 2001; Erickson and Drescher 2002; Shiau, Lyamin and Sloan 2003; Xiao-Li et al. 2007; Loukidis and Salgado 2009; Benmebareket et al. 2012; Acharyya and Dey 2018a).

In the hilly regions, as the construction permits, footings are mostly located on the crest of a slope (with some setback distance) or on the slope face itself, for e.g. footings of mobile and electric transmission towers, overhead water tanks, and bridge abutments. The bearing resistance of such footings is necessarily lower than the same placed on horizontal surface, attributed to the curtailed passive resistance zone developed towards the sloping face. For footings located on or near steeper slopes, the bearing resistance is substantially reduced. In order to address this problem, experimental investigations have been sought to assess the bearing capacity and bearing capacity factors of strip footing positioned on a sandy slope (Shields 1977; Bauer 1981). The formation of plastic zones underneath strip, square or circular footings placed on a sandy slope (Kumar and Ilamparuthi 2009; Castelli and Lentini 2012; Keskin and Laman 2013; Azzam and El-Wakil 2015; Shukla and Jakka 2016; Acharyya and Dey 2017) as well as on $c-\phi$ soil slope (Leshchinsky 2005; Acharyya, Dey and Kumar 2018b) has also been researched. In a similar line, researches have been conducted to investigate the overall performance of footing located at crest of slope, aided with single-sided micro pile or
skirt strip footing (Azzam and Farouk 2010; Elsaied 2014). Apart from laboratory and
numerical investigation, the performance of anchored inclined footings with aid of field
experiment, is also reported (Clark, McKeown and Crawford 1988). However, as earlier
classical researches, the above-cited cases deal with a single footing resting on a sloping terrain.

From the point of view of urbanized localities on hill-slopes, the mechanism of a single footing
does not necessarily address the presence of footings of various shapes, sizes and embedment
depths, in vicinity to each other. However, such situation is quite common in hilly regions due
to several constructions, whether residential or commercial structures, crammed into congested
locations on the crest or face of the hilly slopes. Survey conducted in the inhabited hilly terrains
of the North-Eastern (NE) areas of India reveal the dominant presence of shallow strip
foundations on unreinforced hill slopes or terraces of the same. With the passage of time,
growing inhabitation and changing trends of the building structures (from light-weight Assam-
type housing to multi-storied concrete structures) is gradually appending to the changing
deformation and instability of the slopes due to inadequate knowledge about the behaviour of
foundation placed near the sloping surface. It has been witnessed from the background check
that no work has been done regarding the interference effect of strip footings on hill slope.

From the above understanding, this investigation attempts to estimate the load carrying
capacity of isolated and interfering strip footings located at the crest of a sloping surface. In
this regard, FE simulations have been attempted with the aid of Plaxis 3D to comprehend the
load bearing behaviour of such single and interfering strip footings and their corresponding
failure patterns. The influence of dilatancy over bearing capacity and on the total displacement
has been assessed for isolated strip footing placed near sloping ground. Moreover, the impact
of various geo-parameters on the dimensionless ultimate bearing capacity \[ q_{un} = \frac{q_u}{\gamma D_{fs}} \] where,
\( q_u = \) Ultimate bearing capacity, \( \gamma = \) Unit weight of soil and \( D_{fs} = \) Depth of foundation soil\] has
also been investigated.
2. **FINITE ELEMENT MODEL OF STRIP FOOTINGS ON SLOPE**

The numerical modelling for the present study is achieved with Plaxis 3D vAE.01, a commercially available finite element tool, which incorporates 3-D ground water flow, stability and deformation analyses in geotechnical engineering. It is capable to deal with numerous intricate aspects of geotechnical structures. Plaxis 3D comprises constitutive models for advanced non-linear, anisotropic or time-dependent analyses of geo-materials, and incorporates non-hydrostatic and hydrostatic pore pressures in soil. Literatures reveal that Plaxis 3D has been successfully used in the numerical studies for the assessment of bearing capacity of footing located at crest of sandy slope (Kumar and Ilamparuthi 2009; Castelli and Lentini 2012; Acharyya and Dey 2017). In the present research, the same has been used in the numerical modelling of interfering strip footings resting on $c-\phi$ soil slope.

In the current research, the numerical model has been prepared for footings located near the sloping ground as revealed in Fig. 1. For the determination of optimum model dimensions, the “$0.1q$” stress contour ($q$ is the failure load) signifies the farthest important isobar has been considered, beyond which the impact of the applied stress is insignificant (as per Boussinesq’s elastic stress theory). The model size has been considered in such a way that the significant isobar does not touch the model boundaries.
“Standard fixity” has been applied on the numerical model. Figure 2 depicts that the bottom edge of the domain is rigid, therefore vertical and horizontal fixities have been employed, while only the horizontal fixity has been specified to vertical edges. In order to permit free deformation to slope face, no fixities have been provided on the same. In the current numerical study, the load carrying capacity of interfering strip footing has been assessed for their different locations within the domain.

In the finite element investigation, the domain of the geometry has been discretized into finite number of elements. In order to determine accurate displacements and stresses, 10 node tetrahedral elements was considered as it offers more nodes and Gauss points (Fig. 2). Plaxis 3D program generates automatic finite element meshes with aid of ‘robust triangulation technique’. Plaxis 3D provides a few basic meshing arrangements, which can be progressively refined with user defined coarseness factors. The adopted mesh should be adequately and optimally fine to attain precise and realistic numerical outcomes. The present investigation has been carried out with ‘fine meshing scheme’, aided with local refinements wherever large stress concentrations are expected to occur.
In the present study, elastic-perfectly plastic Mohr-Coulomb (M-C) model has been considered for soil behaviour. M-C model requires five material parameter inputs, specifically three strength parameters (cohesion $c$, angle of internal friction $\phi$, and dilatancy angle $\psi$) and two deformation parameters (Elastic modulus $E$ and Poisson’s ratio $\nu$). As per the plasticity theory, the influence of soil dilation is expressed in terms of dilative coefficient, $\eta = \psi / \phi$ which varies in the range of $0 \leq \eta \leq 1$. The case $\eta = 1$ corresponds to the material following an associated flow rule (Drescher and Detournay 1993; Xiao-Li et al. 2007; Acharyya and Dey 2018c). The soil properties considered in the present research is given in Table 1. It has been perceived from past research that the unit weight of soil ($\gamma$) has limited influence on $q_u$ (Acharyya and Dey 2017), and thus in the present numerical investigation, a constant magnitude of $\gamma = 16$ kN/m$^3$ has been used.

In the current study, the footing has been considered as rigid rough strip footing modelled for $M_{20}$ concrete and represented by linearly elastic (LE) model, the parameters of which are given in Table 2. An interface element has been given at the boundary of the concrete and soil elements, whose stiffness is obtained using Newton-Cotes algorithm (Nasr 2014). A strength reduction factor ($R_{inter}$) has to be chosen for the interface element in order to provide its deformation characteristics. In the present study, $R_{inter} = 1$ has been adopted to represent a rough strip with no-slip mechanism with respect to the adjacent soil elements.
Table 1 Geotechnical and geometrical parameters used in the analysis

<table>
<thead>
<tr>
<th>Input parameters</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>( c ) (kPa)</td>
<td>5-80</td>
</tr>
<tr>
<td>( \phi ) (°)</td>
<td>10-40</td>
</tr>
<tr>
<td>( \psi ) (°)</td>
<td>( \phi/4-\phi )</td>
</tr>
<tr>
<td>( B ) (m)</td>
<td>0.5-2</td>
</tr>
<tr>
<td>( b/B )</td>
<td>0-10</td>
</tr>
<tr>
<td>( \beta ) (°)</td>
<td>10-40</td>
</tr>
<tr>
<td>( S/B )</td>
<td>0-10</td>
</tr>
</tbody>
</table>

Table 2 Properties of concrete used for modelling the strip footing

<table>
<thead>
<tr>
<th>Unit weight ( (\gamma) ) (kN/m(^3))</th>
<th>Modulus of elasticity ( E ) (GPa)</th>
<th>Poisson's ratio ( (\nu) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>25</td>
<td>22</td>
<td>0.15</td>
</tr>
</tbody>
</table>

3. VALIDATION OF NUMERICAL WORK

Das and Larbi-Cherif (1983) had investigated the interference effect of strip footing through laboratory experimentations. Dry sand having relative density of \((D_r)\) of 54%, dry density of 15.88 kN/m\(^3\), and angle of internal friction \((\phi)\) of 38°, had been used to fill a test box of dimension 1.524 m x 0.305 m x 0.914 m. Steel footings, connected by frames, and each having dimension 50.8 mm x 304.8 mm, were placed over the crest of the sand slope. The centre-to-centre distance between the footings has been considered as the footing spacing \((S)\). For the purpose of validation, a 3-D numerical model has been developed in the present study which conforms to the exact dimensions used in the experimentation program. For a representative spacing of the interfering footings \((S/B = 1.5)\), a mesh convergence analysis has been done for selecting the optimum mesh size. Figure 3 describes the results of the convergence analysis in terms of non-dimensional average element size (NAES, ratio of average element length and the height of the domain), which shows that the outcomes are nearly similar beyond NAES \(\approx\)
0.03, and the same has been used for the estimation of the numerical results from the validation model. Fig. 4 shows that there is a significant match between the numerical results with those obtained from experimental investigations (Das and Larbi-Cherif 1983), thus rendering the developed numerical model to be validated.

Fig. 3 Typical convergence study for interfering strip footings resting on horizontal ground

Fig. 4 Validation of the finite element model
Numerical simulations have been conducted to model the experimental investigation done by Das and LarbiCherif (1983) for different spacing of the footings, ranging from $1B$ to $10B$, where $B$ is the width of an individual footing. The interference mechanism has been checked...
through slip mechanisms generated beneath the footing in terms of incremental displacement
as shown in Fig. 5. Figure 5portrays that the footings spaced within a distance of 6B can be
considered to have mutual influences on their stress and settlement characteristics and can be
termed as closely-spaced interfering footings. Beyond this spacing, the interaction effects of
the footings cease to exist, and hence, the footings can be considered as isolated footings.

4. RESULTS AND DISCUSSION

4.1 Numerical Results

4.1.1 Effect of dilatancy on bearing capacity for single footing on slope

An attempt has been made to understand the effect of flow rules on the ultimate bearing
capacity, displacement and failure mechanism of strip footings resting on crest of the slope. In
the present study, various dilation angles (ψ) have been considered namely ψ = φ/4, φ/2, 3/4φ
and φ. In the current investigation, different slope angles (β) and various setback distances (b)
were taken into account for the numerical investigation.

![Graph showing effect of dilatancy on bearing capacity for single footing on slope](image)

(a)
It has been perceived from the Fig. 6 that the $q_u$ increased with increasing the dilation angle ($\psi$). It has also been noticed from Fig. 6 that the $q_u$ increased with increasing setback distance ($b$) and decreasing slope angle ($\beta$).

Figure 7 depicts the total displacement ($U_{max}$) on the slope face for various dilation angles, slope angles and setback distances at failure. It has been observed from the Fig. 7 that the total displacement increased with increasing the dilation angle.
Fig. 7 Effect of flow rules on total displacement at slope face for various setback ratios and slope angles (a) $b/B = 0.5$, $\beta = 30^\circ$ (b) $b/B = 0.5$, $\beta = 40^\circ$ (c) $b/B = 2$, $\beta = 30^\circ$
Fig. 8 Incremental displacement pattern of strip footing resting on slope at its failure (a)

\( b/B = 0.5, \beta = 20^\circ, \psi = \phi/4 \) (b) \( b/B = 0.5, \beta = 20^\circ, \psi = \phi \) (c) \( b/B = 2, \beta = 30^\circ, \psi = \phi/4 \)

Figure 8 portrays the failure displacement pattern through displacement vectors for various slope angles, dilation angles and setback distances. It has been observed from the Fig. 8 that at
failure, the soil movement is always taken place to the slope direction for footing resting on slope crest regardless of slope angles, dilation angles and setback distances. This is primarily attributed to the incomplete development of the passive zone near the slope face where there is not enough lateral restraint on the soil to resist its outward lateral movement, thus resulting in substantial reduction in the bearing capacity and enhanced outward deformation of the foundation. Moreover, the further numerical analysis has been carried out by considering associated flow-rule ($\psi = \phi$).

4.1.2 Influence of setback distance for single footing on slope

The effect of setback ratio ($b/B$) on developed failure mechanism and ultimate bearing capacity has been studied for isolated strip footing placed near the $c-\phi$ soil-slope. Figure 9 depicts that $q_{un}$ increases with increasing setback ratio ($b/B$), and attains a constant magnitude above $b/B = 6$.

![Fig. 9 Typical setback ratio versus dimensionless ultimate bearing capacity behaviour](image-url)
Fig. 10 Representative development of plastic zones underneath the footing for different setback ratios ($b/B$)

For strip footings located at various setback distances from the slope face, Fig. 10 highlights the influence of sloping face in reducing the bearing capacity by intersecting the resisting passive zone formed toward the slope face. It can be witnessed that the developed passive zone
is largely one-directional and curtailed by the slope face when the footing is located at the crest
of the slope \((b/B = 0)\), which is attributed to the dominant free deformation of the soil due to
the loading of the footing until failure. This phenomenon results in a considerable decrease of
the confinement pressure, and hence, attenuation of the bearing capacity. As the setback ratio
increases, the dominant influence of the slope face on the development of the passive
mechanism gradually reduces, as shown in Fig. 10. It is observed that beyond a critical setback
ratio of 6, the footing behaviour corresponds to that of the same resting on horizontal ground.
For such cases, the developed displacement contours, representing the passive zone, remains
unaffected.

4.1.3 Influence of spacing, slope angle and setback distance of interfering footings on
slope

Figure 11 portrays the effect of spacing \((S)\) on bearing capacity of strip footings located near
the slope for various setback distances \((b)\) and slope angles \((\beta)\). It has been perceived that \(q_{un}\)
increases up to spacing 1.5\(B\) followed by a progressive reduction till 3\(B\), beyond which the
magnitude remains asymptotic for further spacing ratios. For \(S = 1B\) and 1.5\(B\), the footings
acting as a single footing of increased width \((2B)\). As the spacing increased to 1.5\(B\), the
interference of pressure bulbs beneath the two footings resulted in a larger zone of foundation
soil participating in the bearing resistance of the footing, resulting in an enhanced magnitude
of \(q_{un}\). With increase in spacing beyond 1.5\(B\), the interference effect gradually diminishes
resulting in reduction of the bearing capacity, and with further increase in spacing beyond 3\(B\),
the footings behaved as isolated strip footings of actual width \((B)\). It is also noticed that \(q_{un}\)
increased for higher setback distance ratio \((b/B)\), while the same decreased with increasing
slope inclination \((\beta)\).
(a)

(b)
Fig. 11 Impact of interference on ultimate bearing capacity for variation of setback distances and slope angles (a) $b/B = 0$ (b) $b/B = 1$ (c) $b/B = 2$ (d) $b/B = 3$ (e) $b/B = 4$ (f) $b/B = 5$

4.1.4 Influence of footing width on interfering footings on slope

Figure 12 depicts the influence of footings widths on the bearing capacity of interfering strip footings. It is observed that $q_{un}$ reduced with decreasing footing width, which is attributed to the fact that a wider footing involves a larger zone of foundation soil to participate in the
resisting mechanism, thereby increasing the bearing capacity. The effect of spacing of the interfering strip footings remains the same as highlighted in the previous section.

![Figure 12 Influence of interference for variation of footing widths](image)

**Fig. 12 Influence of interference for variation of footing widths**

### 4.1.5 Influence of soil types on interfering footings on slope

Figure 13 illustrates the effect of different types of foundation soil (as given in Table 1) on the bearing capacity of interfering strip footings.

![Figure 13 Impact of interference for variation of soil types](image)

**Fig. 13 Impact of interference for variation of soil types**
It is seen that the maximum value of $q_{un}$ has been obtained for soil having higher friction angle, while soil having lower angle of internal friction depicts the lowest $q_{un}$. This observation highlights that the trend of variation of $q_{un}$ with the soil types is primarily governed by the variation in $\phi$. Based on the results obtained with various types of soils as the slope material, it is observed that a spacing of $S = 3B$ can be considered as limiting spacing beyond which the interference effect completely disappears.

### 4.1.6 Interaction mechanism for footings resting on the crest of a slope

Figure 14 portrays the interaction mechanism of strip footings resting on the crest of a slope and separated by various spacing ratios ($S/B$). It can be seen that for a footing located at a spacing ratio of $S/B = 1$, the footings act as single footing having width $2B$. As $S/B$ increases, the influential effect of each footing on the generation of failure zones progressively reduces. In the present research, the formation of failure mechanism has been investigated up to spacing ratio ($S/B$) of 8. It can be observed from Fig. 14 that the overlap of the displacement contours totally disappears beyond $S/B = 3$ and that the footing located afar from the slope face exhibited a bearing phenomenon similar to an isolated strip footing placed on a horizontal semi-infinite medium.
Fig. 14 Typical displacement interaction mechanism for strip footings with various spacing ratios ($S/B$)
5. EFFICACY OF THE DEVELOPED NUMERICAL MODEL

From the past researches, it has been clear that there have been experiment works conducted for isolated strip footings located on horizontal or sloping grounds. There are few examples of experimental investigations involving isolated strip footing located on slope crest. However, there has been not a single experimental or theoretical investigation reported for multiple and interfering strip footings located on the crest of a slope. In this regard, to further calibrate and validate the developed numerical model to check its efficacy in predicting the bearing capacity of interfering strip footings on slope, typical experimental studies considering an isolated strip footing on slope crest have been considered. In this context, the experimental studies reported by Keskin and Laman (2013) and Mittal, Shah and Verma (2009) have been taken into account. It is worth mentioning that it has already been highlighted in Section 4.1.6 that the interfering effect of the footings completely disappear beyond a spacing ratio, $S/B = 3$. Hence, proper numerical models were developed in which the footing located away from the crest is kept at a spacing ratio $S/B > 8$, and the bearing capacity of the foundation is obtained. It is worth mentioning that the validation study of interference effect of strip footings resting on horizontal ground (Das and Larbi-Cherif 1983) has already been presented in Section 3.

Keskin and Laman (2013) had experimentally investigated the ultimate bearing capacity ($q_u$) of strip footing resting on crest of slope. In the experiment, different geotechnical and geometrical parameters had been varied to investigate the influence on $q_u$. For the validation, a strip footing of width ($B$) 70 mm, located on crest of sand-slope having angle of inclination ($\beta$) of 30°, have been considered. The angle of internal friction ($\phi$) and dry unit weight ($\gamma_d$) of the soil were 41.8° and 17 kN/m$^3$ respectively. Mittal, Shah and Verma (2009) had experimentally investigated the $q_u$ of a strip footing ($B = 75$ mm) located on crest of unreinforced and reinforced sandy slopes having angle of inclination 34°. The dry unit weight and angle of internal friction of the soil were 16.3 kN/m$^3$ and 36° respectively.
Fig. 15 Comparison of pressure-displacement patterns obtained from the numerical model and experimental studies (a) Keskin and Laman 2013 (b) Mittal, Shah and Verma 2009

For both the cases of validation, numerical models comprising a spacing ratio $S/B = 10$ has been considered so that the footing nearer the slope should behave like isolated strip footing on the crest of slope without having any interference of the far footing on its pressure-settlement pattern. Figure 15 depicts the load-settlement behaviour of the strip footings located...
on slope crest. It can be perceived that there is excellent agreement in pressure-settlement patterns, as well as the bearing capacity, obtained from present numerical investigation and those estimated from the experimental investigations. As the average difference between the measured and numerical values ranged less than 7\%, the developed numerical models can be considered well calibrated and efficient in predicting the bearing capacity of strip footings on slopes.

6. CONCLUSIONS

On the basis of the finite element numerical simulations, the following conclusions are drawn:

- The bearing capacity and displacement enhanced with increasing the dilatancy angle of soil. The change in magnitude of $q_{un}$ is marginal above the dilatancy angle of $\psi = 3/4 \phi$.
- Bearing capacity improves with increase in the setback distance. Beyond a setback ratio $(b/B)_{\text{critical}} = 6$, the footing exhibits similar behaviour to the one resting on horizontal semi-infinite ground.
- For footings resting on any type of soil, the maximum magnitude of $q_{un}$ was obtained at a spacing ratio $S/B = 1.5$. $q_{un}$ attained a constant asymptotic value beyond a spacing ratio $S/B = 3$, thus indicating the complete disappearance of the interference effect and exhibition of the behaviour of an isolated strip footing.
- $q_{un}$ increases with enhance in footing width, while it decreases with higher steepness of the slope.
REFERENCES


