ABSTRACT

The traditional theories for determining bearing capacity assumes the strata to be homogeneous and infinite but multilayered soils are commonly encountered in practice. Soil in its natural form is a non-homogeneous mass and consists of more than one layer. The ultimate bearing capacity of foundation under non-homogeneous soil condition using experimental and numerical studies had been carried out by many researchers. IS: 6403-2002 gave the design chart only for surface strip footing resting on two layered cohesive soil system.

Zhu et al. (2010) studied bearing capacity of rectangular footing resting on layered clay with strong clay over weak clay using finite element analysis ABAQUS 3D. The bearing capacity is reduced due to presence of weak clay beneath strong clay and also is affected due to strength ratios and thickness ratios. Raman et al. (2012) carried the study for the settlement behaviour of model square footing on layered soil which shows that the placement of different layers of soil influences bearing capacity. Verma et al. (2013) performed plate load test to observe load settlement characteristics of model footing on layered granular soils and developed equation based on test results. Khanal (2013) back-calculated the plate load test using hardening soil model in PLAXIS 2D to study soil behaviour and constitutive models. Paul (2014) studied bearing capacity of shallow footing resting on two layered clay using PLAXIS 3D Foundation and compared the results with conventional theories. As per comparison the percentage variation was about 5 to 10%.

The present investigation is focused to study the ultimate bearing capacity of square footings resting on two layered cohesive soils using PLAXIS 2D. The depth of upper layer and properties of layers were varied to understand the behavior of strata. The undrained shear strength of soil was considered, satisfying the Mohr-Coulomb failure criterion. The soil domain was discretized with 15-noded plane strain triangular elements. The value of Young’s modulus of elasticity \(E\) was taken thousand times of undrained cohesion and the Poisson’s ratio was 0.3. The bearing capacity of square footing of width 2 m was analyzed using PLAXIS 2D. The parametric study includes effect of strength ratio of soil and thickness of top soil layer on bearing capacity.

It was observed that bearing capacity increases with increase in \(H1/b\) for \(c2/c1\) less than 1, as shown in Figure 1. Similarly for \(c2/c1\) greater than 1, the bearing capacity decreases with increase in \(H1/b\), only for the thickness ratio less than 1, thereafter the bearing capacity remains constant. The results were presented in the form of bearing capacity factor, shape factor and efficiency factor. The shape factors obtained were also compared with literature a result which shows good agreement with PLAXIS 2D results.
Keywords: Bearing capacity, FEM, Layered cohesive soil, Square Footing

Figure 1: Bearing Capacity Factor ($N_c^*$) for Square Footing Resting on Two Layered Clay

Reference

BEHAVIOUR OF SQUARE FOOTING RESTING ON TWO LAYERED CLAY DEPOSITS

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ABSTRACT: Soil in its natural form is a non-homogeneous mass and consists of more than one layer. The present study deals with the determination of bearing capacity of surface square footing resting on two layered cohesive soil system using PLAXIS 2D. The soil domain was discretized with 15-noded plane strain triangular elements. The parametric studies include effect of top layer thickness and strength ratio on bearing capacity of surface square footing. The results were presented in the form of bearing capacity factor, shape factor and efficiency factor. The shape factors obtained were also compared with literature a result which shows good agreement with PLAXIS 2D results.

INTRODUCTION
The determination of bearing capacity of footing resting on multilayered soil strata is complex problem as the properties of soil vary with depth and its extent. The ultimate bearing capacity of foundation under non-homogeneous soil condition using experimental and numerical studies had been carried out by many researchers. IS:6403-2002 gave the design chart only for surface strip footing resting on two layered cohesive soil system.

The bearing capacity of square footing resting on two layered clayey soil was determined using PLAXIS 2D. The strength ratio \( (c_2/c_1) \) and thickness ratio \( (H_1/b) \) was varied considerably to study its effect on bearing capacity. The obtained results of PLAXIS 2D were termed in the form of bearing capacity factor \( (N'_c) \), shape factor \( (S'_c) \) and efficiency factors \( (\eta) \). The shape factors were obtained from the PLAXIS 2D results which was compared with analytical results suggested by Zhu.

LITERATURE REVIEW
Zhu et al. (2010) studied bearing capacity of rectangular footing as a surface footing resting on two layered clay with strong clay over weak clay using finite element analysis ABAQUS 3D. The soil was discretized with eight noded quadrilateral elements and modeled as an isotropic elastic-perfectly plastic material satisfying Tresca failure criterion. It was also stated that values of \( E \) and \( \mu \) does not influence the ultimate bearing capacity. The bearing capacity is reduced due to presence of weak clay beneath strong clay and also is affected due to strength ratio \( (c_1/c_2) \) and thickness ratios \( (H_1/b) \). The shape factor is weakly dependent on the depth, whereas it varies distinctly with change in the strength ratio of the two layers.

Raman et al. (2012) carried the study for the settlement behaviour of model square footing on layered soil. The three cases that were studied are (a) Sand + Clay, (b) Sand + Clay + Sand and (c) Clay + Sand. It was concluded that using different layers of soil the settlement behavior and the bearing capacity of the soil can be increased.

Verma et al. (2013) performed plate load test to observe load settlement characteristics of model footing on layered granular soils and developed equation for predicting ultimate bearing capacity based on plate load test. The effective depth factor term was introduced which was defined as the multiplication factor which when multiplying with the width of test plates give the total thickness of soil affected by the applied load.

Khanal (2013) carried out back-calculation of the plate load test using hardening soil model in PLAXIS 2D. The soil profiles and parameters were
based on in-situ or laboratory tests. The square footing was modeled for axisymmetric condition as a circular footing with soil-foundation contact areas equivalent to those of the corresponding square footing 15 noded axi-symmetric elements. The results obtained from PLAXIS shows good agreement with the results of plate load test.

Paul (2014) studied bearing capacity of shallow footing resting on two layered clay using PLAXIS 3D Foundation. The results were compared with conventional methods of Terzaghi’s theory, Hansen’s method, Meyerhof’s method and IS Code method. The results obtained from PLAXIS 3D had been found to be in line of theoretical results with percentage variation lying within maximum of 5 to 10 %.

NUMERICAL ANALYSIS
Finite element based software (PLAXIS 2D) was used for analyzing the bearing capacity for two layered cohesive soil. The present investigation is focused to study the ultimate bearing capacity of square footings resting on two layered cohesive soils using PLAXIS 2D. The geometry of the finite element soil model adopted for the analysis was 15B x 10B. The soil domain was discretized with 15-noded plane strain triangular elements.

The square footing of width 2m was approximated as circular footing with soil-foundation contact areas equivalent to that of the square footing, i.e. with diameter 2.256 m. The square footing was modeled as axisymmetric model with half dimension due to symmetry. The depth of upper layer and properties of layers were varied to understand the behavior of strata. Fig. 1 shows the geometry model of surface square footing of width 2m resting on two layered clayey soil system.

The properties of soil and footing properties used in the analysis are shown in Table 1 and Table 2 respectively. The footing was elasto-plastic and isometric in behaviour. The various factors chosen for parametric study are revealed in Table 3.

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**Table 1: Soil Properties for the present study**

<table>
<thead>
<tr>
<th>Properties</th>
<th>Layer 1</th>
<th>Layer 2</th>
<th>Homogeneous Clay</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unsaturated unit weight</td>
<td>19</td>
<td>19</td>
<td>19</td>
</tr>
<tr>
<td>(kN/m³)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cohesion c</td>
<td>25</td>
<td>Varies</td>
<td>Average of the two layer</td>
</tr>
<tr>
<td>(kN/m²)</td>
<td></td>
<td>with (\frac{c_2}{c_1})</td>
<td></td>
</tr>
<tr>
<td>Poisson’s ratio (\mu)</td>
<td>0.3</td>
<td>0.3</td>
<td>0.3</td>
</tr>
<tr>
<td>Young’s modulus E</td>
<td>1000*c</td>
<td>1000*c</td>
<td>1000*c</td>
</tr>
<tr>
<td>(kN/m²)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Material model</td>
<td>Mohr</td>
<td>Mohr</td>
<td>Mohr</td>
</tr>
<tr>
<td>behavior</td>
<td>Coulomb</td>
<td>Coulomb</td>
<td>Coulomb</td>
</tr>
<tr>
<td>Type of material behavior</td>
<td>Un-drained</td>
<td>Un-drained</td>
<td>Un-drained</td>
</tr>
</tbody>
</table>

**Table 2: Footing Properties**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Width of footing m</td>
<td>2</td>
</tr>
<tr>
<td>Normal Stiffness (EA) kN/m</td>
<td>1.5x10⁷</td>
</tr>
<tr>
<td>Flexural Rigidity (EI) kN/m²/m</td>
<td>3.13x10⁸</td>
</tr>
<tr>
<td>Equivalent thickness (d) m</td>
<td>0.5</td>
</tr>
<tr>
<td>Poisson’s Ratio (\mu)</td>
<td>0.15</td>
</tr>
<tr>
<td>Weight kN/mm</td>
<td>12.5</td>
</tr>
</tbody>
</table>
### Table 3: Factor for Parametric Study

<table>
<thead>
<tr>
<th>Case</th>
<th>Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Effect of thickness of top layer on BC ((H_1/b))</td>
<td>0, 0.2, 0.4, 0.5, 0.6, 0.8, 0.9, 1, 2, 3</td>
</tr>
<tr>
<td>Effect of strength ratio ((c_2/c_1))</td>
<td>0.2 to 2.6</td>
</tr>
</tbody>
</table>

**RESULT AND DISCUSSIONS**

The surface square footing resting on two layered clay was analyzed using PLAXIS 2D for varying \(H_1/b\) and \(c_2/c_1\) ratios. The results were presented in the form of bearing capacity factor \((N_c^*)\), shape factor \((S_c^*)\) and efficiency factors \((\eta)\).

**Bearing Capacity Factor \((N_c^*)\):**

The bearing capacity factor was determined using,

\[
N_c^* = \frac{q_u}{c_1} \tag{1}
\]

where,

- \(q_u\) = Ultimate bearing capacity of square footing on two layered clay
- \(c_1\) = Undrained cohesion of top layer

For square footing, bearing capacity factors were calculated using eq. (1) for two layered soil with ratio of strength of soil \((c_2/c_1)\) and thickness of upper layer \((H_1)\) to half width of footing \((b)\). Fig. 2 shows the variation of bearing capacity factor for square footing resting. It was observed that when footing rests on strong clay over weak clay, the \(N_c^*\) increases with increase in strength ratio \((c_2/c_1)\) and depth ratio \((H_1/b)\), while for the case when weak clay rests over strong clay, \(N_c^*\) decreases with increase in depth ratio.

For weak clay overlaying on strong clay \((c_2/c_1 > 1)\), the bearing capacity factor, \(N_c^*\) is observed to be more than 6 while for strong clay overlaying on weak clay \((c_2/c_1 < 1)\), the bearing capacity factor, \(N_c^*\) is observed to be less than 6.

**Efficiency Factor \((\eta)\):**

The bearing capacity of homogeneous clay having soil properties average of the two layers was determined, which was used to obtain efficiency factor \((\eta)\). The efficiency factor was the ratio of \(q_u\) (Two Layered Clay) to \(q_0\) (Homogeneous clay)

\[
\eta = \frac{q_u}{q_0} \tag{2}
\]

The efficiency factors were presented separately for strong clay over weak clay \((c_2/c_1 < 1)\) and for weak clay over strong clay \((c_2/c_1 > 1)\) as shown in Fig. 3 and Fig. 4 respectively.

The efficiency factor less than 1 indicates that bearing capacity of square footing resting on layered clay has lower value as that obtained in case of footing resting on homogeneous clay (having average values properties of the two layers). Therefore, use of average values may mislead from the actual results.

When footing rests on layered clay in which strong clay overlying weak clay, efficiency factor increases with increase in \(H_1/b\). The higher efficiency factor is achieved for \(H_1/b > 1\) and \(\eta\) decreases with increase in \(c_2/c_1\) ratio. For \(H_1/b < 1\), \(\eta\) increases with increase in \(c_2/c_1\) ratio.

When footing rests on weak clay over strong clay, efficiency factor was decreased with increase in thickness ratio \((H_1/b)\). The higher efficiency factor is achieved for \(H_1/b < 0.2\) and \(\eta\).
increases with increase in \(c_2/c_1\) ratio. For \(H_1/b > 0.2\), \(\eta\) decreases with increase in \(c_2/c_1\) ratio. For \(H_1/b > 0.2\), \(\eta\) decreases with increase in \(c_2/c_1\) ratio.

The shape factor for square footing resting on two layered soil was determined using the concept that the bearing capacity factor obtained from present study \((N^*_c)_{sq}\) for square footing includes effect of shape if they are compared with the bearing capacity factor of strip footing \((N^*_c)_{st}\) resting on two layered soil. Hence,

\[
S^*_c = \frac{N^*_c}_{sq} \frac{N^*_c}_{st} \tag{3}
\]

The results obtained from PLAXIS 2D were presented in the form of shape factor \((S^*_c)\) as shown in Fig. 5 which shows that shape factors are weekly dependent on thickness ratio \((H_1/b)\) while strength ratio \((c_2/c_1)\) considerably affects its value.

The shape factor was found to be increased with increase in thickness of top layer till it equals one, thereafter it decreases. For higher \(c_2/c_1\) ratios shape factor has constant values. It was observed that for strong clay overlying weak clay \((c_2/c_1 < 1)\), shape factor was greater than 1.3 while in case of weak clay overlaying on strong clay \((c_2/c_1 > 1)\), shape factor was about 1.3.

The shape factors obtained from present study are compared with Zhu (2010) for strong clay resting over weak clay obtained using ABAQUS 3D. The present study shows good agreement with Zhu’s results as shown in Fig. 6.
The bearing capacity of square footing was obtained using equation given below,

\[ q_u = c_1 N_c S_c^* \]  

(4)

where,

- \( q_u \) = Ultimate bearing capacity of square footing on two layered soil
- \( c_1 \) = Un-drained cohesion of top soil layer
- \( N_c \) = Bearing capacity factor for strip footing resting on two layered cohesive soil as per IS: 6403, (1981)
- \( S_c^* \) = Shape factor for square footing resting on two layered clay obtained in present study

The ultimate bearing capacity for square footing on two layered soil obtained for different \( H_1/b \) and \( c_2/c_1 \) are shown in Table 4. The shape factor obtained in the present study were used to obtained bearing capacity as per IS bearing capacity factor for strip footing. It shows that the bearing capacity obtained using present shape factor shape factor (\( S_c^* \)) differ with PLAXIS 2D bearing capacity. The variation of about 15-37% was observed. The variation may be attributed to certain assumptions made in PLAXIS analysis.

<table>
<thead>
<tr>
<th>( H_1/b )</th>
<th>( c_2/c_1 )</th>
<th>PLAXIS 2D</th>
<th>IS CODE</th>
<th>% Variation</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.4</td>
<td>0.4</td>
<td>98.91</td>
<td>3.9</td>
<td>1.78</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>163.6</td>
<td>6.54</td>
<td>1.38</td>
</tr>
<tr>
<td></td>
<td>1.6</td>
<td>179.7</td>
<td>7.1</td>
<td>1.2</td>
</tr>
<tr>
<td>1</td>
<td>0.4</td>
<td>138</td>
<td>5.50</td>
<td>1.91</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>160</td>
<td>6.38</td>
<td>1.35</td>
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<tr>
<td></td>
<td>1.6</td>
<td>159</td>
<td>6.37</td>
<td>1.30</td>
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<tr>
<td>2</td>
<td>0.4</td>
<td>158.1</td>
<td>6.32</td>
<td>1.61</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>158.7</td>
<td>6.34</td>
<td>1.34</td>
</tr>
<tr>
<td></td>
<td>1.6</td>
<td>159.1</td>
<td>6.36</td>
<td>1.34</td>
</tr>
</tbody>
</table>

**CONCLUSIONS**

The formation of layered soil attributes to the variation in soil properties with thickness. The footing resting on layered soil behaves differently if it compared with footing resting on homogeneous soil. The bearing capacity of strip footing on two layered soil can be determined using IS: 6403, 1981. However, the bearing capacity of square footing resting on two layered soil cannot be determined. The present study gave the shape factors which can be used to determine the bearing capacity of square footing on two layered soil.

The present study also concluded that for square footing resting on two layered cohesive soil:

1. For strong clay over weak clay (\( c_2/c_1 < 1 \)), bearing capacity factor (\( N_c^* \)) increases with increase in depth ratio (\( H_1/b \)) ratio.
2. For weak clay over strong clay (\( c_2/c_1 > 1 \)), \( N_c^* \) decreases with increase in \( H_1/b \) ratio till it equals 1 thereafter it remains constant.
3. The shape factor is weakly dependent on thickness ratio (\( H_1/b \)) while it shows considerable variation with varying strength ratio (\( c_2/c_1 \)). Therefore it can be said that the soil properties affects shape factor and its values should not be based on shape of footing only.
4. The comparison of shape factor obtained using PLAXIS 2D and ABAQUS 3D shows good agreement.
5. Efficiency factor increases with increase in thickness ratio for case of strong clay overlying weak clay,
6. For case of weak clay overlying strong clay efficiency factor was found to be decreased with increase in \( H_1/b \) ratio.
7. The result obtained using modified equation of bearing capacity of square footing shows 15-37 % variation with PLAXIS 2D results.

**REFERENCES**


