Finite element parametric study on the performance of strip footings on a purely frictional soil using plaxis 2D

Iwinosa Osarugue Agbedo
aghedoiwinosu@gmail.com
Newcastle University, Newcastle upon Tyne, England

ABSTRACT

Traditionally the design of shallow foundations, has been conducted using conventional theories and empirical methods, based on foundation bearing capacity and settlement calculations including those provided by Terzaghi, Meyerhof or Hansen (Smith, I., (2015) and it has been considered that numerical analysis for such simple problems would not be cost or time effective. This research paper proposes that numerical analysis can also be used to provide a quick and cost effective tool for the Geotechnical Engineer to design a shallow foundation, that could be used to verify the design of a shallow foundation using conventional theories and empirical methods, and thus would lead to satisfying the requirement for a second method of verification as outlined in Eurocode 7 (EC7).

Keywords: Plaxis, Mohr Coulomb Model, Strip Footing, Bearing Capacity

1. INTRODUCTION

This research paper aims at conducting a finite element analysis parametric study to investigate the factors that influence the footing stiffness and the ultimate footing load of a rigid strip footing using the numerical analysis program PLAXIS. The rigid strip footing is resting on a layer of purely frictional soil that is described as an elastic perfectly plastic material obeying the Mohr Coulomb failure criterion, and the foundation is supposed sufficiently rigid to prescribe a uniform field of vertical displacement of 0.5m to the foundation base. The parametric study will be presented by load – displacement curves, that will lead to an assessment on the stiffness as well as the bearing capacity for a shallow foundation embedded in a purely frictional or cohesionless soil.

A two-dimensional plane strain model of the rigid strip footing on an elastic soil layer with H=4m(y) is presented in Figure 1. Due to symmetry of the foundation, only half of the foundation is simulated within the model. Its right boundary is placed 7m(x) away from the centre of the footing inorder not to influence its response. The stiff layer is not included in the model; instead, an appropriate boundary condition is applied at the bottom of the sand layer. The geomaterials were discretized using 15-node soil elements. A vertical force Fy to achieve a prescribed uniform vertical displacement of 0.5m acts upon the soil representing the settlement of the footing. The vertical force Fyis determined by the software during the calculation. For the smooth footing, the x-direction of the prescribed displacement is set to fixed, (no movement). The material properties are presented in Table 1. The Mohr-Coulomb model is used to model the behaviour of the soil in a Drained Condition.

2. ANALYSIS AND RESULTS

2.1 Investigate effects of proximity of boundaries of the model on footing stiffness and ultimate load

The effect of the proximity of the right-hand boundary was first investigated. X(m), the distance from the centre of the foundation to the right boundary of the model was simulated with x = 7m; x = 5m and x = 3m with y=4(m), the height of the model remaining constant. The load: displacement curves are shown in Figure 2. The effect of the proximity of the bottom boundary was investigated. Y(m) the distance from the base of the model, simulated to be an underlying stiff layer (i.e. bedrock) to the top of the soil profile (i.e. base of the foundation) was conducted with y = 4m, y =3m, y=2m with x=7m, the distance from the centre of the foundation to the right hand boundary remaining constant. Load: displacement curves are shown in Figure 3. During this simulation the groundwater elevation was kept at half of y max at the following elevations when y = 4m/head=2m, y =3m/head=1.5m and when y=2m/head=1m.

The results displayed in Figure 2 show that the proximity of the x boundary does influence the response of the model with applied load >20 kN/m. With an applied load <20 kN/m the effect is negligible. As the applied load increases >20 kN/m it is shown that the footing stiffness response, considered from the amount of displacement and gradient of the curve is greater when x is reduced, indicated by a curve with steeper gradient for x=3m followed by a curve with shallower gradient for x =5m and x=7m. At a force applied of 160 kN/m, the stiffness, measured in displacement ranged from 0.056m when x = 7m to 0.046m when x = 3m.
Beyond a loading of 160 kN/m to 180 kN/m, considered from the above curves to be the yield point at which soil failure mechanisms start to occur and approximation of maximum allowable safe bearing capacity corresponded to displacements of between 0.057m to 0.058m for each of x=7m, x=5m and x=3m. At the point of complete failure of the soil body, the ultimate load or ultimate bearing capacity varied from 204kN/m for x = 7m, to 197kN/m for x = 5m, and 201 kN/m for x =3m with total displacements of 0.096m, 0.079m and 0.081m respectively.

The results displayed in Figure 3 show that the proximity of the y boundary does have an immediate influence on the response of the model commencing from an initial applied load with the stiffness of the footing increasing with reduction in y(m), indicated by a curve with a steeper gradient for y=2m and reduction in the gradient for y=3m then y=4m.

At a force applied of 160kN/m to 165 kN/m, considered from the above curves approximately the yield point at which soil failure mechanisms start to occur, and approximation of maximum safe bearing capacity the stiffness measured in displacement ranged from 0.057m when y=4m to 0.035m when y = 2m.

The ultimate load or ultimate bearing capacity at the point of failure of the soil body varied from 204kN/m for y = 4m, to 210kN/m for y = 3m, and 174 kN/m for y =2m with corresponding total displacements of 0.096m, 0.089m and 0.039m respectively.

The effect of decreasing the size of the model simultaneously in each direction x and y was also investigated. The model was simulated with the x-y configurations of x = 7m/y =4m; x = 5m/y=3m and x = 3/y=2m, again groundwater elevation was kept half of y max.

The results showed that that the proximity of both the x and y boundary, when changed simultaneously does also have an immediate influence on the response of the model, commencing from an initial applied load. The stiffness response is similar for both x=5m/y=3m and x=3m/y=2m when compared to the curve produced for x=7m/y=3m and for x=7m/y=2m respectively. The curve produced for x=3m/y=2m terminates prematurely at an applied load of 153kN/m.

At a force applied of 118 kN/m to 160 kN/m, the yield point at which soil failure mechanisms start to occur or maximum safe bearing capacity, the stiffness measured in displacement ranged from 0.057m when x/y =7m/4m to 0.018m when x/y =3m/2m.

The ultimate load or ultimate bearing capacity at the point of complete failure of the soil body varied from 204kN/m for x/y = 7/4m, to 178kN/m for x/y = 5/3m, and 153 kN/m for x/y =3/2m with total displacements of 0.096m, 0.055m and 0.028m respectively.

The proximity of the x and y boundary has been shown to have an influence on both the footing stiffness and ultimate load and is summarised in Table 2. It was shown that the footing stiffness improved when x and y were reduced. With the effect of the location of the bottom boundary y, having a greater influence on footing stiffness than x, the distance to the right hand boundary.

The effect of the bottom and right hand boundary on the yield point at which soil failure mechanisms started to occur, an approximation of the safe bearing capacity showed that by decreasing x and y the safe bearing capacity and associated footing stiffness (measured in displacement) is improved. The effect of changing the bottom and right hand boundary on the ultimate load, or approximation of the ultimate bearing capacity is less clearly defined however, it is likely that x does not display a major influence on this, and again a reduction in y and indeed x/y may be greater contributing factors to reduce the ultimate load. This may be attributed to possible failure of the soil body early, due to confinement of the underlying stiff layer (i.e bedrock) and boundary condition in the x and y direction causing a limit in plasticity nature of the soil body.

It has been shown that the selection of x and y are key input parameters into the PLAXIS software, however, it is proposed that footing stiffness and the failure mechanism that govern the ultimate load is more significantly influenced by the soil type rather than the proximity of the model boundaries, and will be investigated in upcoming sections.

2.2 Investigate effects of mesh size on the footing stiffness and ultimate load
The effect of changing the element size with a very fine, fine, medium, coarse and very coarse mesh size was investigated using the control model configuration of x=7m/y=4m and soil parameters detailed in Table 1. Load displacement curves for the different mesh sizes are presented in Figure 4.

The results show that the mesh size has only a very slight effect on the stiffness of the footing. The gradient of the curves up to an applied force of 100 kN/m is similar and displacement at this applied force ranged from 0.032m for a very fine mesh to 0.028m for a very coarse mesh. With an increase in force >100 kN/m, it was observed that a smaller mesh size produced failure characteristic in the curve at a lower load than a coarse mesh. The commencement of failure (or safe bearing pressure) with the very fine mesh was at an applied force of 128 kN/m and for a very coarse mesh 204kN/m, corresponding to a displacement of between 0.044m and 0.078m respectively.

The ultimate load (or ultimate bearing capacity) at the point of complete failure of the soil body varied from 170kN/m for a fine mesh, to 229kN/m for a coarse mesh with total displacements of 0.073m and 0.121m respectively. The very coarse mesh did not produce a failure within the soil body but instead achieved the prescribed target displacement of 0.5m producing a peak ultimate load of 245 kN/m representing a total displacement of 0.127m and residual applied load near to 220kN/m. The results of the various mesh sizes are summarised in Table 3.

The results show that the effect of changing the mesh size on the ultimate load is very clear with a smaller mesh size producing a more conservative assessment of the commencement of soil failure and ultimate load but with a longer computing time. These results are consistent with other studies for example M.S.A Siddiquee et al (1999) who also found that a smaller mesh size produced a more conservative normalised footing pressure. The coarse mesh and very coarse mesh size overestimated the commencement of soil failure and ultimate load but took a shorter computing time. It can be observed in Table 3, that the model which is meshed with medium size can give an optimal combination of Accuracy and Efficiency.

The effect of the mesh size on the accuracy of the model is shown in Figure 5 where the total displacements calculated by a very fine and very coarse mesh for a strip footing are presented. The results demonstrate the importance of mesh size selection in the

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computation of accurate results and mesh size should be selected appropriately to the complexity of the model, the amount of time and resource allowed and also be selected by an experienced geotechnical professional.

2.3 Empirical calculation of bearing capacity coefficient

The angle of friction of the soil was varied inorder to discover the relationship between the numerical values of bearing capacity coefficient $N_Y$ and the angle of internal friction $\phi'$ with calculations from conventional theories, specifically Meyerhof and Brinch Hansen. This was based on the following computations performed for different values of $\phi$ ranging from 20° to 35° using the control model configuration of x=7m/y=4m and soil parameters detailed in Table 1.

$$q = \frac{1}{2} \gamma B N_Y - \text{Numerical}$$

$N_Y$ was calculated numerically with the values of $F_Y$ obtained from the Load-Displacement curve

Where:

$q =$ Ultimate footing pressure is $F_Y$  
$B =$ width of the foundation footing = 1m  
$\gamma =$ Unsaturated unit weight of soil = 17.0 KN/m$^3$

The $N_Y$ values calculated by the numerical methods where compared with those from the conventional theories of Meyerhof and Brinch Hansen and tabulated in Table 4:

$$N_Y = 1.8 \left( \frac{1+\sin\phi}{1-\sin\phi} e^{\pi \tan\phi} - 1 \right) \tan\phi - \text{Meyerhof}$$

$$N_Y = \left( \frac{1+\sin\phi}{1-\sin\phi} e^{\pi \tan\phi} - 1 \right) \tan1.4\phi - \text{Brinch Hansen}$$

The values for different values of $N_Y$ are provided in Table 4 (above). It can be seen that the values of $N_Y$ increase substantially with the increase in angle of friction $\phi$. The obtained values of $N_Y$ for different values of $\phi$ using the numerical analysis were compared with those of conventional theories of Meyerhof and Brinch Hansen. The results are illustrated in Figure 6 for $\phi = 20^\circ, 25^\circ, 30^\circ, 35^\circ$ and show that the values of $N_Y$ from the conventional theories (Meyerhof and Brinch Hansen) are consistently 2-5 bearing capacity coefficient values lower when compared to that obtained from the Numerical analysis. Interestingly, the calculation method adopted by Eurocode 7 ((BS EN 1997-1:2004+A1:2013) is Hansen which provides the closest approximation to the values derived by the numerical analysis. The numerical analysis provides the maximum comparative values of $N_Y$ in all the cases which may lead to an over-estimated values of $N_Y$ when compared to conventional theories.

2.4 Investigation of effect of Dilatancy angle

The behaviour of the soil layer would be expected to be influenced strongly by its friction angle and, to a lesser extent by its angle of dilatation, which is related to the friction angle. The parametric study was based on the use of angle of dilatation $\Psi'$ equal to 0°, half the friction angle of 15°, and equal to the friction angle of 30° ($\Psi' = 0^\circ, 15^\circ, 30^\circ$) using the control model configuration of x=7m/y=4m and soil parameters detailed in Table 1.

The results displayed in Figure 7 show that the ultimate load of the footing increased as the angle of dilation was increased from 200 kN/m for $\Psi' =0^\circ$, which increased to 254.50kN/m for $\Psi' = 15^\circ$ and 259.6KN/m for $\Psi' =30^\circ$ corresponding to a displacement of 0.045m, 0.070m and 0.075m respectively.

The effect of the change of the angle of dilation on the displacement pattern shows that $\Psi' = 0^\circ$, provided the lowest ultimate bearing load and the lowest displacement at commencement of failure of the soil body. When $\Psi' = 15^\circ$ the ultimate load increased from 200kN/m to 254kN/m followed by plateauing of the curve (more plastic strain) to the prescribed displacement of 0.5m. When $\Psi' =30^\circ$, the curve terminates prematurely at an applied load of 259.6kN/m. before failure.

Therefore it can be deduced that increasing the angle of dilation will increase the ultimate load producing more plastic strain behaviour and likely to produce, depending on soil type more heave around the footing as shown in Figure 8; which is likely to affect the horizontal extent of the model. These results are consistent with other studies including Zienkiewicz et al. (1975) who observed a similar response for dilation angles of 0° and 40° when $\phi =40^\circ$ was used , and Monahan & Dasgupta (1993) who reported such behavior for friction angles higher than 25°.

The results show that a choice of a non-zero angle of dilatancy will affect the required horizontal extent of the model due to the more plastic strain behaviour which causes more heave.
Table 1: Material properties of the soil model

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Name</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material Model</td>
<td>Model</td>
<td>Mohr-Coulomb</td>
<td></td>
</tr>
<tr>
<td>Type</td>
<td>Type</td>
<td>Drained</td>
<td></td>
</tr>
<tr>
<td>Soil unit weight above phreatic level</td>
<td>γ&lt;sub&gt;sat&lt;/sub&gt;</td>
<td>17.0</td>
<td>KN/m&lt;sup&gt;3&lt;/sup&gt;</td>
</tr>
<tr>
<td>Soil unit weight below phreatic level</td>
<td>γ&lt;sub&gt;sat&lt;/sub&gt;</td>
<td>20.0</td>
<td>KN/m&lt;sup&gt;3&lt;/sup&gt;</td>
</tr>
<tr>
<td>Young’s Modulus</td>
<td>E’</td>
<td>1.3 .10&lt;sup&gt;4&lt;/sup&gt;</td>
<td>KN/m&lt;sup&gt;3&lt;/sup&gt;</td>
</tr>
<tr>
<td>Poisson’s ratio</td>
<td>ν’</td>
<td>0.3</td>
<td></td>
</tr>
<tr>
<td>Cohesion</td>
<td>C&lt;sub&gt;ref&lt;/sub&gt;</td>
<td>0.0</td>
<td>KN/m&lt;sup&gt;3&lt;/sup&gt;</td>
</tr>
<tr>
<td>Friction Angle</td>
<td>φ’</td>
<td>30.0</td>
<td>λ</td>
</tr>
<tr>
<td>Dilatancy Angle</td>
<td>Ψ’</td>
<td>0.0</td>
<td>λ</td>
</tr>
</tbody>
</table>

Table 2: Effect of changing boundary dimensions x/y(m) on footing stiffness and ultimate load

<table>
<thead>
<tr>
<th>Dimensions</th>
<th>Load kN/m</th>
</tr>
</thead>
<tbody>
<tr>
<td>x (m)</td>
<td>y (m)</td>
</tr>
<tr>
<td>------------</td>
<td>-----------</td>
</tr>
<tr>
<td>7</td>
<td>4</td>
</tr>
<tr>
<td>5</td>
<td>4</td>
</tr>
<tr>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>7</td>
<td>3</td>
</tr>
<tr>
<td>7</td>
<td>2</td>
</tr>
<tr>
<td>5</td>
<td>3</td>
</tr>
<tr>
<td>3</td>
<td>2</td>
</tr>
</tbody>
</table>

Fig. 2: load: displacement curve x=7m; x=5m & x=3m with y constant at y = 4m

Fig. 3: load: displacement curve y=4m; y=3m; y=2m with width constant at x = 7m
Fig. 4: Load: displacement curve for mesh size of very fine to very coarse when x=7/y=4

Table 3: Effect of mesh size on footing stiffness and ultimate load

<table>
<thead>
<tr>
<th>Mesh size</th>
<th>Load kN/m</th>
<th>Commence Failure (displacement, m)</th>
<th>Failure (displacement, m)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Displacement, m at 100 kN/m (before failure)</td>
<td>SAFE BEARING CAPACITY</td>
<td>ULTIMATE BEARING CAPACITY</td>
</tr>
<tr>
<td>Very fine</td>
<td>0.032</td>
<td>128 (0.044)</td>
<td>170 (0.073)</td>
</tr>
<tr>
<td>Fine</td>
<td>0.031</td>
<td>139 (0.044)</td>
<td>197 (0.102)</td>
</tr>
<tr>
<td>Medium</td>
<td>0.030</td>
<td>160 (0.057)</td>
<td>204 (0.096)</td>
</tr>
<tr>
<td>Coarse</td>
<td>0.028</td>
<td>175 (0.065)</td>
<td>229 (0.121)</td>
</tr>
<tr>
<td>Very coarse</td>
<td>0.028</td>
<td>204 (0.078)</td>
<td>245* (0.127) &amp; 222* (0.500)</td>
</tr>
</tbody>
</table>

Fig. 5: Load: displacement curve for mesh size of very fine to very coarse when x=7/y=4

Fig. 6: Comparison of Numerical Analysis of $N_f$ with Meyerhof and Brinch Hansen Solution for $\theta = 20^\circ, 25^\circ, 30^\circ, 35^\circ$. 

Soil body starting to fail indicated by displacement with no increase in applied load between 128kN/m (very fine) and 204kN/m (very coarse) for each of the curves. The curve for very coarse mesh size continues in the x direction to achieve the displacement of 0.5m without complete failure of the soil body.
Table 4: Coefficient of Bearing Capacity Value ($N_v$)

<table>
<thead>
<tr>
<th>Angle of Friction (°)</th>
<th>Numerical Values</th>
<th>Meyerhof Values</th>
<th>Brinch Hansen Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>5.68</td>
<td>2.87</td>
<td>3.54</td>
</tr>
<tr>
<td>25</td>
<td>11.9</td>
<td>6.80</td>
<td>8.10</td>
</tr>
<tr>
<td>30</td>
<td>23.5</td>
<td>15.7</td>
<td>18.6</td>
</tr>
<tr>
<td>35</td>
<td>44.7</td>
<td>37.2</td>
<td>40.7</td>
</tr>
</tbody>
</table>

Fig. 7: load: displacement curve for change in dilation angle of 0° 15° and 30° when x=7m/y=4m

Fig. 8: Formation of heave shown with an angle of dilation of 15° and 30°

Fig. 9: Modelling of a UPVC pipe under a shallow foundation and simplified model of adjacent strip footings and services within PLAXIS 2D 2015.

3. CONCLUSION

Guidance for Engineers’ use of Finite Element Method (FEM) software with particular reference to shallow foundation design

The use of numerical analysis results with particular reference to the design of a shallow foundation may be treated sceptically by the Geotechnical Engineer (GE). This is because by and large, the use of numerical analysis (principally FEM analysis using computer software) has been restricted to larger and more complex projects, such as buildings outlined within Geotechnical Category 3, Eurocode 7 that have considerable time and resource committed by the client, and thus have the budget and requirement due to the complexity of the project for conducting numerical analysis. Furthermore the GE may not be familiar with the benefits of numerical modelling or may not understand the process by which the design parameters influence the numerical analysis.

Traditionally the design of shallow foundations, has been conducted using conventional theories and empirical methods, based on foundation bearing capacity and settlement calculations including those provided by Terzaghi, Meyerhof or Hansen (Smith, I., (2015) and it has been considered that numerical analysis for such simple problems would not be cost or time effective. Here it is proposed that numerical analysis can also be used to provide a quick and cost effective tool for the GE to design a shallow foundation, that could be used to verify the design of a shallow foundation using conventional theories and empirical methods, and thus would lead to satisfying the requirement for a second method of verification as outlined in Eurocode 7 (EC7). Based on our recent parametric study, to
achieve an effective numerical analysis of a shallow foundation it is proposed that the Geotechnical Engineer should follow the following basic guidance:-

1) Conduct appropriate level of geotechnical investigation. Obtain accurate information on the ground conditions and groundwater regime beneath the shallow foundation being constructed with the appropriate level of classification and soil behaviour tests including strength, compressibility and design sulphate class (BRE, 2015).

2) Selection of appropriate soil modelling software. For a basic strip footing it is recommended that a 2D approach such as PLAXIS 2D 2015 would be suitable however, if a complex ground model needs to be considered, for example due to the presence of underground services or adjacent structures consideration should be made to use of 3D software.

3) Selection of appropriate input parameters and material model. Largely based on information obtained from the ground investigation and laboratory testing, but could also include published information concerning the strata you are investigating (e.g. London Clay). This is critical to enable an accurate numerical model to be created.

4) Selection of appropriate soil model and undrained or drained behaviour. The correct soil model and the necessity to perform calculations on drained or undrained soils depending on soil characteristics should be chosen. For example Mohr coulomb model for linear plastic perfectly plastic soil behaviour or the Soft Soil model (based on Cam Clay Model) for modelling of soft normally consolidated clays. For stiffer soils the Hardening Soil model can be used. It is important to note the following generalisations as determined from our parametric study:-

   a) The effect of changing Ks, the initial ratio of horizontal to vertical stresses in the ground has the influence of increasing the stiffness and reducing the displacement.

   b) The effect of changing the dilatancy angle ϕ has the influence of increasing the volumetric strain and causing heave in the soil.

5) Selection of appropriate boundary conditions, ideally to closely represent those found in your ground model. It is suggested that the model extends in the y direction to at least the base of the known geology using borehole records obtained during the geotechnical investigation. It has been shown that the bottom boundary (y) is likely to have the most influence on the output parameters of the model so a minimum y depth of 4m is suggested. It is suggested the model should extend in the x direction a minimum 5m from the centre of the footing. It is important to highlight that the boundaries in both the x and y direction are set to normally fixed (roller support), fully fixed (i.e. hard strata) or free (e.g. ground surface) depending on the nature of the site.

6) Selection of appropriate mesh. It has been shown that mesh size has a significant influence on the accuracy of the model. Smaller mesh size will increase the accuracy of determining the footing stiffness and the ultimate load. It is recommended that the design of a shallow foundation, being a generally simpler model the software is able to accommodate a smaller mesh size and it is not recommended to use a mesh size greater than medium in such a simple simulation.

7) Consideration of partial factors when designing to EC7. It is possible within some software e.g. PLAXIS 2015 2D to account for the different design approaches prescribed in EC7 e.g. Design Approach 1 Combination 1 or Combination 2. This involves the factoring of actions or material properties and can be done in the software by selecting the required design approach. However, as found by Potts, D. M. & Zdravkovic, L. (2012), care should be taken when selecting partial factors for numerical analysis as it is often not clear if the software factors the actions and material properties before or during the analysis, which was shown to affect the results.

8) Consideration of the close proximity of underground services and adjacent structures. The possibility of underground services, such as gas pipes, electricity cables or water mains and sewers, in addition to adjacent structures such as other shallow foundations, pile foundations or retaining structures are a real possibility for the design of a shallow foundation on an actual site, given the complex nature of many construction projects often within a high density area. Numerical analysis however is able to build in such features within the model, to determine the effect of the adjacent structures and services on the foundation and calculations may be performed to determine the bending moment on such services. The use of FEM software to model underground services has been documented in a number of studies. R. Nirmala and R. Rajkumar (2016) performed simulations on a buried UPVC pipe and Liu, P. F., Zheng, J. Y., Shang, B. J. & Shi, P. (2010) performed calculations on natural gas buried steel pipeline. Figure 9 shows a simplified representation of an underground UPVC pipe modeled underneath a shallow foundation with calculation of the bending moment and representation of adjacent strip footing and sewer. Adjacent structures can therefore be modeled however for complex ground models it is suggested that a 3D analysis program is used.

9) Verification: It is essential that the results of the numerical analysis software are verified by an experienced geotechnical professional and user of the numerical software. Ideally where possible, the calculations should be checked using an empirical method as discussed above.

4. REFERENCES

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