EFFECT OF WATER TABLE FLUCTUATIONS ON BEARING CAPACITY OF FOOTINGS IN UNSATURATED SOILS

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ABSTRACT: Footings are often subjected to water table fluctuations in engineering practice due to varying climatic changes throughout a year. A common engineering practice to incorporate the effect of water table is to use the water table correction factor in the ultimate bearing capacity formula. The varying water table causes a variation in the ultimate bearing capacity of the footing throughout a year. Hence, the bearing capacity of soils may be under predicted or may be overestimated from the bearing capacity formulations. In the present study, the effect of fluctuating water table has been analyzed on a circular footing using a coupled finite element analysis program in ABAQUS. The variation in the ultimate bearing capacity is evaluated for a sandy soil. From literature, soil water characteristic curve (SWCC) for the selected soil, dimensions and domain size for the footing were selected. The SWCC containing specific points were added to sorption curve in ABAQUS to simulate the ultimate bearing capacity. The results from the numerical simulations showed that the partially saturated zone above the water table has significant effects on the ultimate bearing capacity of soils.

Keywords: footing, unsaturated, SWCC, numerical

1 INTRODUCTION

The design of ultimate bearing capacity for shallow foundations based on conventional equations by Terzaghi (1943), Meyerhof (1951), and Vésic (1973) is a common practice in the field of geotechnical engineering. The conventional equations provide corrections for different attributes contributed to shape, depth, inclined load on the footing and varying water table for seasonal climatic changes throughout a year. However, the conventional theories for saturated soils often misinterpret the bearing capacity of shallow foundations based on water table corrections. Model scale studies by various researchers (Oloo, 1994; Mohamed and Vanapalli, 2006; Rojas et al., 2007; Schanz et al., 2011) have shown that the unsaturated zone above the water table contributes significantly to the increase in bearing capacity thus making an over conservative design for shallow foundations. The increase in strength is contributed by matric suction ($u_a - u_w$), where u_a and u_w are pore air and pore water pressure, often defined as a stress state variable in the field of unsaturated soil mechanics (Fredlund and Morgenstern, 1977). The effect of matric suction can be incorporated in the study of footings by introducing Bishops effective stress parameter, total apparent cohesion (Zhan and Vanapalli, 2012) or by the incorporation of suction stress (Lu and Likos, 2004) in the conventional bearing capacity equation (Vahedifard and Robinson, 2016) analytically. Numerical studies based on total apparent cohesion approach has also been performed by various researchers (Mohamed and Vanapalli, 2006; Oh and Vanapalli, 2011; Zhan and Vanapalli , 2012) to observe the effects of unsaturated zone on the ultimate bearing capacity of shallow foundations by varying suction and average suction method. However, the effect of matric suction throughout the entire suction range for a particular soils may be quite ambiguous and hence needs to be carefully assessed for varying water table fluctuations throughout the year. Keeping the above point in view in this study an effort has been made to study the bearing capacity for a shallow circular footing on unsaturated sand along the entire suction range in commercial finite element package ABAQUS. A two dimensional axisymmetric model was analyzed to ease the computational efforts in the problem. The pore water pressures below the footing to observe the effect of loading rate on unsaturated soils. The results in the analysis were further compared with the analytical and numerical bearing capacity equations available in literature for saturated and unsaturated soils.

2 MODEL PARAMETERS

A circular rigid footing having a diameter of 0.1 m (D) resting on a sand bed was used for bearing capacity analysis (Zhan and Vanapalli, 2012). Due to symmetrical nature of the footing, an axisymmetric analysis was adopted in this study. The depth and width of the domain for 2D axisymmetric analysis in

ABAQUS was equivalent to 0.6 m and 0.45 m respectively (Vanapalli and Mohamed, 2013). The bottom of the domain was kept fixed while vertical rollers were applied on either sides of the domain.

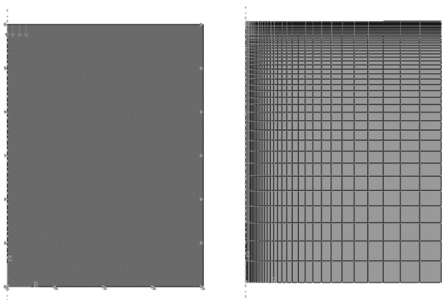

Fig 1. Bounday conditions and Meshing (*D*/100) for the axisymmetric circular footing

The sand was modelled as a Mohr-Coloumb frictional material with the properties are given in the Table 1. The elastic modulus for saturated sand was taken after Zhan and Vanapalli (2012). For unsaturated sands, the elastic modulus was modified after Oh et al. (2009) and the values for subsequent suction are shown in Table 2. The cohesion and frictional angle for unsaturated sands were kept same as saturated sands. For unsaturated bearing capacity analysis, Bishops effective parameter approach is used in ABAQUS. The effect of matric suction is incorporated by giving the soil water characteristic curve (SWCC) measured by Vanapalli and Mohamed (2013) by Tempe cell apparatus in the sorption property for material modelling. A coupled pore fluid stress analysis is thus performed using the step soil in ABAQUS in bearing capacity analysis.

Table 1. Material properties for sand

(After Vanapalli and Mohamed , 2007)

Material parameters	
Drained friction angle (ϕ')	35.3^o
Drained cohesion (c’)	0.6 kPa
Dilation angle (ψ)	3.53^o
Unit weight	16.02 kN/m^3
Saturated permeability	3E-006 m/sec
Initial Void ratio	0.63

Table 2. Elastic Properties for sand at different suctions

(After Zhan and Vanapalli, 2012)

Suction (kPa)	E_{sat} / E_{unsat} (kPa)	ν
0	4622	0.3
2	16546.76	0.3
4	25698.32	0.3
6	28748.84	0.3

3 VALIDATION OF MODEL AND MESH SENSITIVITY ANALYSIS

The bearing capacity analysis of the circular rigid footing resting on saturated soil was simulated by strain controlled loading. A geostatic step was initiated with zero pore water pressure at the nodes on the topmost part of the domain to denote water table for saturated sands. The transient consolidation stage was immediately followed after geostatic step with a maximum pore pressure increase of 0.005 kPa per increment. In order to avoid divergence of solution for purely frictional materials, the solver matrix was kept unsymmetric and automatic stabilization step with dissipated energy fraction was initiated during the transient consolidation stage. Four node axisymmetric quadrilateral, bilinear displacement, bilinear pore pressure, reduced integration and hourglass control element (CAX4RP) was used in the analysis. The pore fluid/stress element was incorporated in order to simulate the effect of pore water pressure under geostatic stress condition automatically. Equal vertical velocity was applied at the nodes beneath the footing. The loading velocity was kept at 1.44E-10 m/sec to ensure drained shearing step.

The mesh sensitivity analysis for saturated soil of the entire domain was performed using five different mesh sizes as shown in the Figure 2. The variation of vertical pressure with the vertical settlement for the circular footing resting on sand was compared for all the five domains to determine the mesh sensitivity. Finer mesh was adopted near the base of the footing to take care of stress concentration which increases with the distance from center of the footing. The maximum mesh size was kept *D*/2 for every case while the minimum mesh size was varied from *D*/20 to *D*/200 to study the mesh convergence.

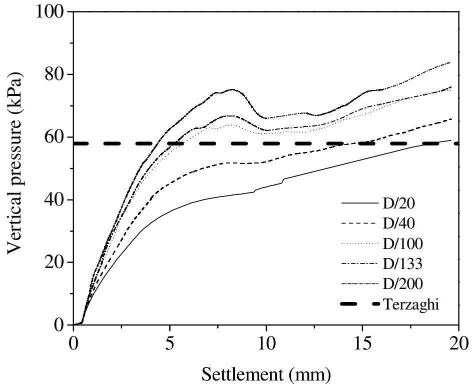

Fig 2. Mesh convergence analysis and Validation

It is seen from Fig 2. that a mesh size of *D*/100 is sufficient to get a reasonable numerical result. A comparison of the numerical result obtained from ABAQUS with Terzaghi's Bearing capacity equation for the same problem is also shown in Fig.2. The numerical analysis shows an ultimate bearing capacity of 66 kPa which is close to 58 kPa obtained from Terzaghi's Bearing capacity equation.

4 FOOTING AT VARIED WATER TABLE DEPTHS

The water table was varied at three different depths for the axisymmetric circular rigid footing on sand according to Mohamed (2014). The average suction for three different depths of water table corresponded to 2, 4 and 6 kPa respectively. The water table was simulated at a particular depth by imposing a boundary condition of zero pore water pressure at the nodes for the given depth. The water table corresponding to 2, 4 and 6 kPa was 0.2, 0.35 and 0.6 m respectively as reported by Mohamed (2014). The suction values at specific depths as measured by Mohamed (2014) was provided at the initial stage. The unsaturated property of the soil was given in accordance with the SWCC of sand measured by Tempe cell apparatus (Vanapalli and Mohamed, 2013). The SWCC was incorporated in the finite element software ABAQUS using the table for sorption to simulate the Bishop's effective stress formulation $\bar{\sigma}$ as shown in the equation below.

$$\bar{\sigma}^* = \sigma + \left(\chi u_w + (1-\chi)u_a\right)\boldsymbol{I}$$

where χ is a factor depending on saturation and is assumed to be equivalent to the saturation of the medium, σ is the total stress while u_a and u_w are pore air and pore water pressure respectively. A geostatic step was initiated followed by a transient consolidation step in the analysis. The rate of loading during transient consolidation analysis was assumed to be same as the validated model study on saturated sands. The initial time step was assumed to be 1 instead of 8000 as for partially saturated pore fluid stress analysis a much lower increment is advisable in order to avoid divergence in the solution. A comparison of the circular footing at varied water table depths is shown in Fig. 3.

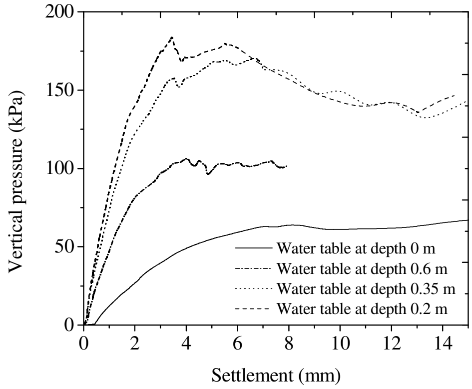

Fig 3. Vertical Pressure vs Settlement curve for different water table depths

A comparison of the pore water pressures at different depths vertically below the footing surface for different water table locations is shown in Fig. 4. The results show that the pore water pressure shows some variations from the hydrostatic profile the maximum suction is observed at the top layer near the footing.

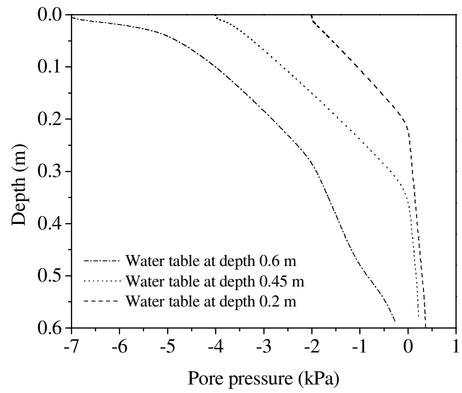

Fig 4. Pore pressure profile for different water table depths below the footing

The ultimate bearing capacity for varying water table depths increases to about three folds with the increase in water table depth. The drained analysis step is ensured from the little or no variation in pore water pressure from geostatic conditions in unsaturated conditions.

5 COMPARISON WITH ANALYTICAL EXPRESSIONS

Analytical expressions for footings resting on unsaturated soil due to varying water table depths developed by many researchers are in use (Oloo et al., 1997; Mohamed and Vanapalli, 2006; Vahedifard and Robinson, 2016).In the present study, the analytical expression developed by Vahedifard and Robinson (2016) as well as the conventional bearing capacity equation by Terzaghi (1943) incorporating water table correction factors for varying water table depths are compared with the numerical results. Figure 5 shows a comparison of ultimate bearing capacity estimated by all the three methods. It is observed that the analytical method by Vahedifard and Robinson (2016) predicts higher ultimate bearing capacity compared to the FEA while Terzaghi's equation predicts lower bearing capacity compared to the same.

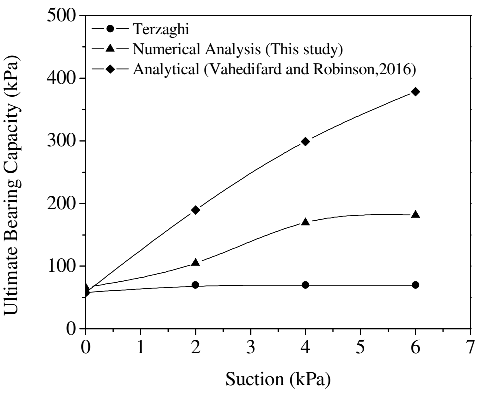

Fig54. Comparison of bearing capacity analysis by different methods for varying water table

6 CONCLUSION

A comparison of the ultimate bearing capacity for a circular footing resting on sand for varying water table fluctuations is shown in this study. It is observed that for varying water table depths almost 66 % to 175% increase in bearing capacity is observed. The bearing capacity analysis used in practice is thus highly uneconomic as additional factor of safety of two to three is used over the conventional ultimate bearing capacity. From the study, it may be concluded that the factor of safety used in conventional practice may be reduced as there is a subsequent increase in bearing capacity during water table fluctuations. The above study does not take into account the effect of unsaturated flow in soils. Also, the above studies are solely based on numerical methods and thus caution must be employed while dealing with the water table fluctuations on footing.

REFERENCES

Fredlund DG, Morgenstern NR (1977) Stress state variables for Unsaturated Soils. Soil Mechanics and Foundations Divison ASCE 103 (5): 447-466.

Lu N, Likos WJ (2004) Unsaturated Soil Mechanics. John Wiley and Sons, New Jersey

Mohamed, F. M. O. and Vanapalli, S. K. (2006). Laboratory investigations for the measurement of the bearing capacity of an unsaturated coarse-grained soil In the Proceedings of the 59th Canadian Geotechnical Conference, Vancouver, BC: 219– 226.

Mohamed, F. M. O. (2014) Bearing Capacity and settlement behavior of footings subjected to static and seismic loading conditions in unsaturated sandy soils Ph.D. Thesis, University of Ottawa, Canada

Oh, W. T. and Vanapalli, S. K. (2011) Modeling the applied vertical stress and settlement relationship of shallow foundations in saturated and unsaturated sands Canadian Geotechnical Journal, Vol. 48, 425-438

Oloo, S. Y. (1994) A Bearing Capacity Approach to the Design of Low Volume Traffic Roads Ph.D. Thesis, University of Saskatchewan, Canada

Oloo, S. Y., Fredlund, D. G., and Gan, J. K. M. (1997). Bearing capacity of unpaved roads. Canadian. Geotechnical. Journal., 34(3), 398–407

Rojas, J. C., Salinas, L. M., and Seja, C. (2007) Plate-load tests on an unsaturated lean clay,.Experimental unsaturated soil mechanics. Springer-Verlag, Berlin Heidelberg, Germany, 445-452.

Schanz, T., Lins, Y. and Vanapalli, S. K . (2011) Bearing capacity of a strip footing on an unsaturated sand Unsaturated Soils. Edited by Antonio Gens. CRC Press. 1195-1200

Vahedifard, F., Robinson, J.D. (2016) Unified method for estimating the ultimate bearing capacity of shallow foundations in variably saturated soils under steady flow Journal of Geotechnical and Geoenvironmental Engineering, 142 (4),

Vanapalli, S. K., and Mohamed, F. M. O. (2013). Bearing capacity and settlement of footings in an unsaturated sand. International Journal of GEOMATE-2013 (Geotechnique, Construction Materials and Environment Japan, Vol. 5, No. 1 (9): 595-604.

Zhan, Y.-G., Vanapalli, S.K (2012) Some aspects on numerical modeling of model footing test on saturated and unsaturated sands Electronic Journal of Geotechnical Engineering, 17 U, pp. 2833-2850