IJE TRANSACTIONS A: Basics Vol. 32, No. 10, (October 2019) 1429-1436

International Journal of Engineering

Journal Homepage: www.ije.ir

Experimental and Numerical Modeling of the Effect of Groundwater Table Lowering on Bearing Capacity of Shallow Square Footings

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PAPER INFO

Paper history:
Received 09 April 2019
Received in revised form 15 July 2019
Accepted 12 September 2019

Keywords:
Bearing Capacity
Experimental Model
Numerical Modeling
Groundwater Table
Unsaturated Soils

ABSTRACT

The lowering of the groundwater table causes the area above the water table to become unsaturated and capillary phenomena to appear in this zone. This means that the bearing capacity of shallow footings will be influenced by capillary stress or matric suction. In this research, the effect of groundwater table lowering on the bearing capacity of a shallow square model footing on dense sand has been investigated by conducting plate load tests under different groundwater table conditions. Numerical simulations of the experiments also were performed using the finite element software Optum G2. The results of the experiments showed that lowering of the water table increased the matric suction. At a suction 0.5 to 4.5 kPa, the ultimate bearing capacity in the soil increased non-linearly from 2.5 to 4-times the bearing capacity of the saturated state. Numerical simulation of the experiments by assuming cohesion due to matric suction for the upper part of the groundwater table predicted the same behavior. Very good agreement was obtained between the predicted bearing capacity and the measured values.

***doi**: 10.5829/ije.2019.32.10a.12*

NOMENCLATURE

u_a	Pore air pressure (kPa)
u_w	Pore water pressure (kPa)
c'	Effective cohesion (kN/m^2)
q_{ult}	Ultimate bearing capacity (kN/m^2)
N_c , N_q , N_γ	Bearing capacity coefficients
q	Surcharge (kN/m^2)
B	Width of footing (m)
$(u_a - u_w) = \Psi$	Matric suction (kPa)
$e = V_v/V_s$	Void ratio of soil
$G_s = \gamma_s/\gamma_w$	Specific gravity of soil particles
C_u , C_c	Uniformity and grading coefficients
$D_r = (e_{max} - e)/(e_{max} - e_{min})$	Relative density (%)
p_a=101.3	Atmospheric pressure (kPa)

Greek Symbols

σ	Normal stress (kPa)
φ'	Internal friction angle of soil (°)
φ^b	Friction angle related to matric suction (°)
τ	Shear strength of soil (kN/m^2)
γ	Unit weight of soil (kN/m^3)
κ_{BC}	Bearing capacity fitting parameter
ζ_c , ζ_γ, ζ_q	Shape factors of footing
ψ	Dilation angle (°)
γ_{sat}	Saturated unit weight (kN/m^3)
γ_{unsat}	Unit weight of unsaturated zone (kN/m^3)
σ_3	Minimum principal stress

1. INTRODUCTION

In parts of the planet located in dry or semi-arid climates, the surface soil is in a dry or unsaturated state. With the lowering of the groundwater table (GWT) and in the presence of air and fluid phases, capillary phenomena occur in the soil pores above the groundwater table and causes capillary stress. Capillary stress affects various soil properties, including shear strength. Fredlund et al. [1] proposed Equation (1) for calculating the shear strength of unsaturated soil using the stress state variables of $(\sigma - u_a)$ and $(u_a - u_w)$, which denote net normal stress and matric suction, respectively.

$$\tau = c' + (\sigma - u_a)tan\varphi' + (u_a - u_w)tan\varphi^b \qquad (1)$$

The third term on the right side of Equation (1), due to

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Please cite this article as: Z. Safarzadeh, M. H. Aminfar, Experimental and Numerical Modeling of the Effect of Groundwater Table Lowering on Bearing Capacity of Shallow Square Footings, International Journal of Engineering (IJE), IJE TRANSACTIONS A: Basics Vol. 32, No. 10, (October 2019) 1429-1436

desaturation of the soil or capillary stress which is independent of normal stress, the shear strength has increased. This term denotes apparent cohesion in which desaturation of the soil increases soil cohesion. Several researchers have used plate load tests at laboratory scale or *in situ*; they have concluded that, under unsaturated conditions, the bearing capacity of the footing compared to saturated conditions has significantly increased [2-6]. Vahedifard and Robinson [7] presented a unified method for estimating the ultimate bearing capacity of shallow foundations resting on variably saturated soil under steady flow. Their study showed that the ultimate bearing capacity for shallow foundations in variably saturated soil under different flow conditions could be estimated rather well by taking into account the role of matric suction. Vanapalli and Mohamed [4] extended and developed Terzaghi's bearing capacity theory to estimate the ultimate bearing capacity of shallow footings in unsaturated soil as shown in Equation (2):

$$q_{ult} = [c' + (u_a - u_w)_b(tan\varphi' - S^{\kappa_{BC}}tan\varphi') + (u_a - u_w)_{AVR}S^{\kappa_{BC}}tan\varphi']N_c\zeta_c + qN_q\zeta_q + 0.5\gamma BN_\gamma\zeta_\gamma \quad (2)$$

where $(u_a - u_w)_b$ denotes the matric suction related to the air entry value (AEV) and is extracted from the soil-water characteristic curve (SWCC), $(u_a - u_w)_{AVR}$ denotes the average measured matric suction for the effective depth of the footing, S denotes the degree of saturation corresponding to the average matric suction obtained from SWCC, and κ_{BC} is a fitting parameter for bearing capacity, which is a function of the soil plasticity index with a recommended value of 1 for granular soil [4].

In Equation (2), the effect of soil desaturation on the bearing capacity is affected by the degree of saturation and matric suction. The expression added to the effective cohesion as shown in Equation (3) is called the apparent cohesion (c_{ap}).

$$c_{ap} = (u_a - u_w)_b(tan\varphi' - S^{\kappa_{BC}}tan\varphi') + (u_a - u_w)_{AVR}S^{\kappa_{BC}}tan\varphi' \quad (3)$$

Numerical modeling of geotechnical problems to predict behavior or verify experiments is a conventional approach [8, 9]. Its accuracy depends on the accuracy of the soil parameters, the boundary conditions selected and the use of appropriate failure criteria for the soil. A suitable constitutive model for unsaturated soil, such as Barcelona Basic Model, requires special and expensive experiments, such as for triaxial testing with suction control capability [10]. In recent years, researchers have numerically modeled the problem of bearing capacity of footings in unsaturated soil using classic soil behavior models such as the Mohr-Coulomb constitutive model by considering the different semi-empirical relationships for apparent cohesion to determine the matric suction effects on soil behavior [11, 12].

Ghorbani et al. [13] investigated the behavior of unsaturated soil under a rigid strip footing subjected to static loading in both fully saturated and unsaturated soil using an extended modified cam clay model. Tang et al. [14] investigated the bearing capacity of shallow foundations in unsaturated soil using the elastic perfectly plastic Mohr-Coulomb model. Oh and Vanapalli [15] used the elastic perfectly plastic model with the Mohr-Coulomb yield criterion in finite element software (Sigma/W; GeoStudio 2012) to simulate the vertical stress versus surface settlement behavior of model footing in unsaturated cohesive soil.

The present study investigated the effect of groundwater lowering on the bearing capacity of shallow square footing in dense sand. In order to demonstrate the ability of Equation (3) to simulate the effect of desaturation on the bearing capacity by numerical modeling, plate load testing was performed using a model of a square footing of 10 cm in width at laboratory scale for different groundwater table levels and by measurement of the matric suction using tensiometers. The experimental test models were simulated numerically using Optum G2 FE software and its results were compared with the test results.

2. PROPERTIES OF THE TESTED SOIL

Experiments in this research were conducted on soil obtained from Goomtape-Sufian area of Iran. Figure 1 shows that the soil is poorly graded clean sand.

The specific gravity and maximum and minimum void ratio of this sand were extracted based on ASTM standards. The shear strength parameters measured were the effective residual internal friction angle (φ'_{res}), effective cohesion (c') and peak internal friction angle (φ_p^{ds}). These were obtained by performing consolidated drained direct shear tests at a constant speed of 1 mm/min on compacted samples. Because the average void ratio of compacted sand in the bearing capacity test tank described in section 4 was about 0.6, the direct shear tests were performed at the same void ratio. Table 1 presents the physical and mechanical properties of sand.

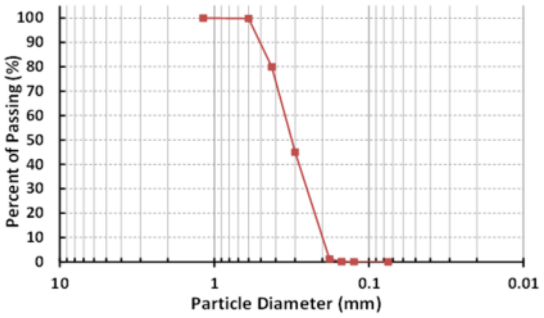

Figure 1. Goomtape-Sufian soil grading curve

TABLE 1. Physical and mechanical properties of tested soil

Parameter	Value	Parameter	Value
G_s	2.636	e_{max}	0.775
C_u	1.75	e_{min}	0.523
C_c	0.89	c'(kpa)	0
USCS	SP	φ'_{res}(°)	33.6
D_{50}(mm)	0.32	φ_P^{ds}(°)	38.5

USCS: Unified Soil Classification System

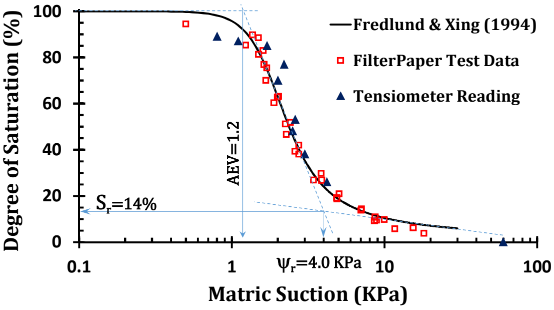

Figure 2. Characteristic soil-water curve for tested sand

3. SOIL-WATER CHARACTERISTIC CURVE

The water retention curve, or SWCC, in unsaturated soil mechanics describes changes in the matric suction versus changes in the water content or degree of saturation of the soil. At any point above the groundwater table, the effective stress will be greater than the total stress, as the pore water pressure in these partially saturated soils is actually negative. This is primarily due to the surface tension of the pore water in the voids throughout the vadose zone, which causes suction on the surrounding particles (matric suction). By lowering the groundwater table, the degree of saturation decreases, the binding of the water becomes stronger and, at small potentials, the water is strongly bound in the smallest of pores, at contact points between the grains, and as film bound by adsorptive forces around the particles. Therefore, the properties of unsaturated soil, including the hydraulic and strength properties, will be affected by matric suction and could interpreted using SWCC.

For the sand used in this study, the data of the SWCC was extracted using the filter paper method with Whatman #42 filter paper sheets according to ASTM D5298 [16]. The Fredlund and Xing [17] method was used to find the best curve fitted to the measured data. Figure 2 shows the characteristic curve. In this figure, in addition to the extraction points of the filter paper method, the points recorded by the tensiometers were used. According to SWCC, the AEV for this soil was about 1.2 kPa, the residual matric suction (Ψr) was 4.0 kPa and the residual degree of saturation (*S_r*) was estimated to be 14%.

4. TEST SETUP AND EXPERIMENTS

The test setup shown in Figure 3 was specially designed to carry out the bearing capacity experiments in the laboratory. The device has a soil tank with a length, width, and depth of 1 m made of steel plate of 6 mm in thickness. Five tensiometers (2100F, Soilmoisture) were attached to this device in order to measure the matric suction in the soil body. The water table level in the test tank could be adjusted to the desired level using a drainage valve on the bottom. The variation in matric suction according to depth in the unsaturated soil zone below the model footing was measured by the tensiometers. The test tank was filled with dried sand in 2.5 cm layers that were spread uniformly and then compacted using a hand compactor.

In order to control the soil density during the filling of the tank, three small aluminum molds of 5 cm in diameter and 2.5 cm in height were placed every 5 cm in the final 30 cm of the thickness. Figure 4 is a schematic representation of the arrangement of the tensiometers and the locations of the sampling molds in the soil tank. The water entered the soil tank through the bottom valve. When the water level met the level of the soil surface, the soil was considered to be completely saturated and submerged. The water level could be decreased by drainage through the bottom valve to desired elevation, causing the soil above the groundwater table to become unsaturated.

After adjusting the water level to the desired position, tensiometers probes were installed at five levels from the soil surface to the water table and the soil surface was covered with nylon plates to prevent surface evaporation. At least 24 h were required to stabilize the tensiometers pressure gauge. It was then possible to begin bearing capacity test for the provided condition with suction measuring using installed tensiometers. In order to investigate the effect of groundwater lowering on bearing

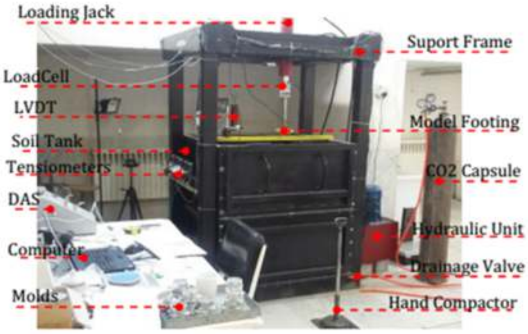

Figure 3. Test equipment and features

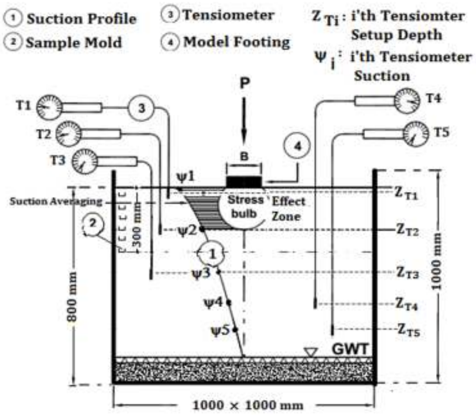

Figure 4. Schematic view of tensiometers and sampling mold arrangement

capacity, the experiments were carried out at four groundwater table levels relative to the soil surface: GWT = 0, GWT = -100, GWT = -300 and GWT = -500 mm.

The loading of the model footing was done using a square steel plate of 100 mm in width and 20 mm in thickness, the bottom of which was covered with a sandpaper sheet to create a rough footing. The loading speed was set to 0.016 mm/s, as was done in the direct shear test. To ensure the repeatability of the tests, all experiments were performed three times and the average of the three was used as the result of the tests for later analysis. After each loading test, the sampling molds embedded in the soil (three molds at every 50 mm) were carefully removed and the properties of the soil were prepared for each test. These were wet density, dry density, void ratio, and relative density at the different depths.

Tables 3 and 4 show the void ratios and wet densities at different depths at different groundwater table levels in the test tank, respectively. Figure 5 shows the matric suction profiles recorded at each groundwater table position from the soil surface to the water level as derived from the data and the readings of the five tensiometers.

TABLE 3. Measured soil void ratio at various depths

Depth of Mold Placement (mm)	GWT= 0 mm	GWT= - 100 mm	GWT= - 300 mm	GWT= - 500 mm
50	0.609	0.602	0.595	0.602
100	0.579	0.571	0.574	0.577
150	0.579	0.586	0.584	0.590
200	0.584	0.593	0.579	0.589
250	0.587	0.593	0.592	0.607
300	0.571	0.575	0.574	0.592

TABLE 4. Soil wet density (g/cm^3) at various depths

Depth of Mold Placement (mm)	GWT= 0 mm	GWT= - 100 mm	GWT= - 300 mm	GWT= - 500 mm
50	2.02	1.98	1.86	1.72
100	2.04	2.04	1.98	1.76
150	2.04	2.03	1.99	1.75
200	2.03	2.03	2.00	1.79
250	2.03	2.03	2.01	1.80
300	2.04	2.04	2.04	1.90

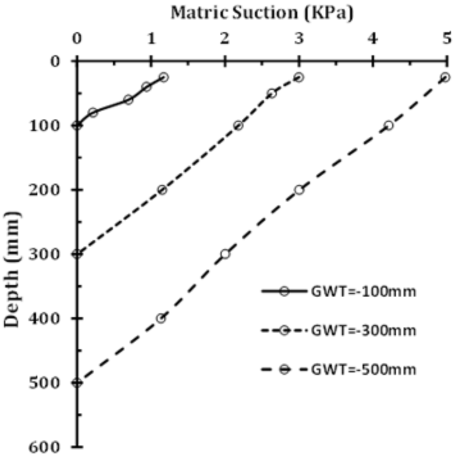

Figure 5. Matric suction profiles in soil tank

Because at different groundwater table levels, the void ratio, unit weight, and matric suction of the soil will vary, a good approach to finding a comparable value for these parameters in different test modes is to calculate their average values at effective depth of footing. Vanapalli and Mohamed [4], Zhan and Vanapalli [12] used 1.5B as the effective depth for a square footing.

Table 5 shows the results of weighted averaging of the measured void ratio, relative density, and matric suction in the zone of the effective depth of the model footing under different test modes. Based on the results of all experiments, the average values for the void ratio and relative density were 0.595 and 71.5%, respectively. These values indicate the high density of the soil compacted in the tank.

TABLE 5. Parameter averages at effective depths

Parameter	GWT= 0 mm	GWT= - 100 mm	GWT= - 300 mm	GWT= - 500 mm
$\bar{e}$	0.599	0.594	0.590	0.596
$\overline{Dr}$ (%)	69.8	71.8	73.4	71.0
$\overline{\Psi}$ (Kpa)	0.00	0.53	2.45	4.40

5. RESULTS OF MODEL FOOTING TESTS

Three plate load tests were conducted under each condition and the change in the load applied to the model footing versus the settlement and mean load-settlement curve of the average results were processed. By dividing the calculated load into the footing area, the stress on the bottom surface of the footing was obtained and the change in applied stress versus induced settlement was plotted. The maximum stress was expressed as the ultimate bearing capacity (q_{ult}). The resulting curved shape was caused by the presence of a peak point and revealed the high density of the compacted soil and general shear failure of the model footings. Figure 6 shows the curves for the bearing capacity under different experimental conditions. The suction value for each curve was the weighted average matric suction in the zone of the effective depth of the model footing obtained from Table 5.

6. NUMERICAL MODELING OF EXPERIMENTS

To verify the results of the model footing experiments and investigate the apparent cohesion, instead of desaturated soil, the physical model shown in Figure 4 was simulated in Optum G2 as the two-dimensional axisymmetric model shown in Figure 7. For this purpose, a 100 ×100 mm square footing was modeled with same area as the circular footing with a 56.52 mm radius. To refine the elements, a zone of 2B in the horizontal direction and 1.5B in depth around the footing was created. The rigid plate option was used to create a rigid footing with a coefficient of $R_{in} = 1$ (no friction reduction between the bottom of the footing and the soil). A 6-node triangular Gaussian element was used as the mesh. The footing was loaded to 20 mm of settlement by uniformly increasing the stress on the surface of footing in 100 increments using the multiplier elastoplastic analysis option. For soil, the elastoplastic behavior was considered to be the Mohr-Coulomb failure criteria.

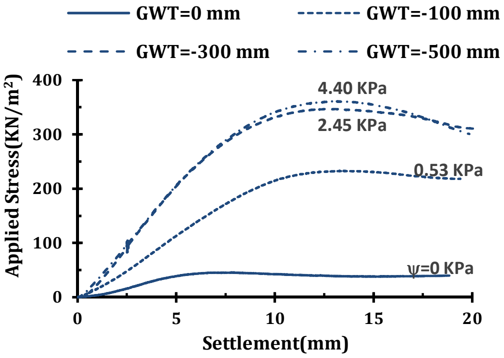

Figure 6. Bearing capacity curves of footing.

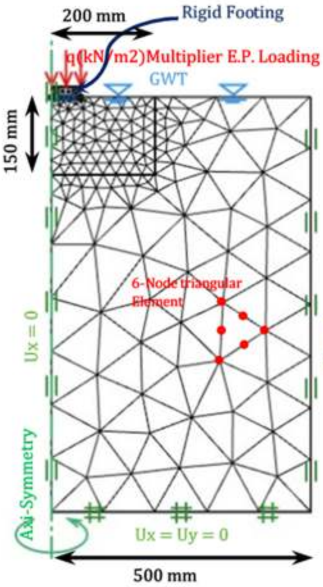

Figure 7. FE model created in Optum G2

The material properties required for numerical modelling were selected in the manner described here and were applied to the FE models. The unit weight of the compacted soil below the water table was equal to the saturated unit weight of 20 kN/m^3 and the average unit weight for the unsaturated zone above the water table was taken from Table 4. For the sand above the water table, the average apparent cohesion in the zone of effective depth caused by desaturation of the soil was calculated using Equation (3) for different GWTs.

The internal friction angle in the triaxial condition was estimated using Equations (4) and (5) as proposed by Kulhawy and Mayne [18].

$$\varphi_P^{psc} = tan^{-1}(1.2tan\varphi_P^{ds}) = 43.67° \tag{4}$$

$$\varphi_P^{tr} = \varphi_P^{psc}/1.12 = 43.7/1.12 = 39.02 \cong 39^{\circ} \tag{5}$$

The calculated value for φ_P^{tr} matched that estimated by Equation (6) as proposed by Meyerhof [19] using an estimated relative density of 71.5% of compacted soil in the test tank.

$$\varphi_P^{tr} = 28 + 0.15Dr = 38.73 \cong 39^{\circ} \tag{6}$$

Because of the friction angle obtained from the direct shear test of 33.6° was equal to the friction angle of the critical state of the soil, the dilation angle of the sand in the test tank was estimated to be about 11° using Equation (7) as proposed by Bolton [20].

$$\varphi_P^{tr} = \varphi_{CV} + 0.5\psi_{max} \;\Rightarrow\; \psi_{max} = 10.8 \cong 11^{\circ} \tag{7}$$

The modulus of elasticity for soil was estimated proposed by Janbu [21] using Equation (8):

$$E = k.p_a(\frac{\sigma_3}{p_a})^n \qquad (8)$$

Parameter n was assumed to be 0.5 as recommended for sand in the Optum G2 manual [22] and the k coefficient was determined using sensitivity analysis by comparing the initial slope of the bearing capacity curves obtained from numerical analysis and the slope of the experimental bearing capacity curves under all test conditions. The Poisson's ratio was considered to be 0.3. The soil parameters used in FE analysis are shown in Table 6. The development of the shear failure mechanism is shown in Figure 8 and demonstrates the adequacy of the effective region for element refinement. The form of the rupture represents the occurrence of general shear failure of the footing.

Figure 9 shows the measured and predicted bearing capacity curves in different test modes. This figure shows good agreement between the simulated and measured behavior.

7. ANALYSIS OF RESULTS

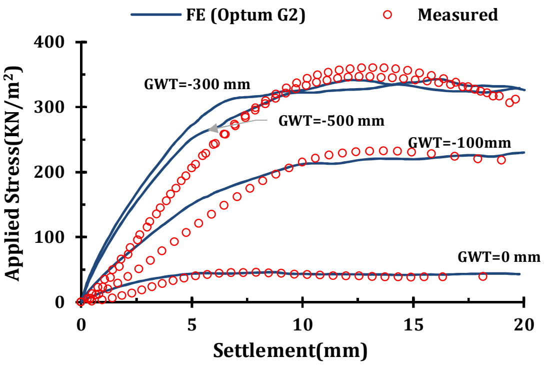

Figure 9. Comparison of measured and simulated bearing capacity curves

TABLE 7. Measured ultimate bearing capacity under different groundwater table conditions

Parameter	GWT= 0 mm	GWT= - 100 mm	GWT= - 300 mm	GWT= - 500 mm
$q_{ult,m}$ (kN/m^2)	46	233	347	361
$q_{ult,m}/q_{ult,sat}$	0.5	2.55	3.80	3.95

Table 7 presents the measured values of the ultimate bearing capacity ($q_{ult,m}$) and the ratio of these values to the ultimate bearing capacity in the saturated state ($q_{ult,m}/q_{ult,sat}$) for different test modes. These values were used to investigate the effect of groundwater lowering on the ultimate bearing capacity of the footing. The ultimate bearing capacity in the saturated state was considered to be approximately twice that in the submerged condition. As seen, a lowering of the groundwater table and change the soil state from saturated to unsaturated, increased the matric suction at the effective depth. This change of soil state increased the ultimate bearing capacity 2.55 to 3.95 times.

Figure 10 shows the variation in the measured ultimate bearing capacity of the model footing versus the average estimated matric suction. The predicted values for ultimate bearing capacity at each test condition also

TABLE 6. Soil parameters used in FE analysis

Parameter	GWT= 0 mm	GWT= - 100 mm	GWT= - 300 mm	GWT= - 500 mm
$\bar{c}_{ap}$ (kN/m^3)	0	0.64	1.39	1.47
φ (°)	39	39	39	39
ψ (°)	11	11	11	11
$\bar{\gamma}_{sat}$ (kN/m^3)	20	20	20	20
$\bar{\gamma}_{unsat}$ (kN/m^3)	20	19.78	19.18	18.12
n	0.5	0.5	0.5	0.5
k	160	300	550	500
ν	0.3	0.3	0.3	0.3

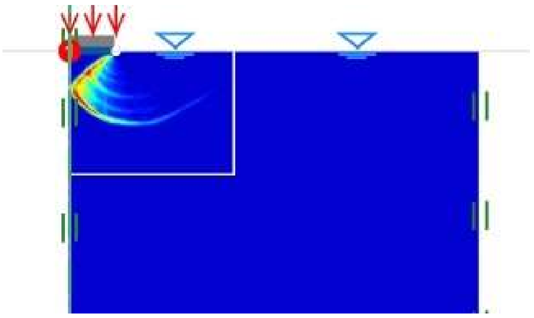

Figure 8. Development of shear failure under the footing (GWT = 0)

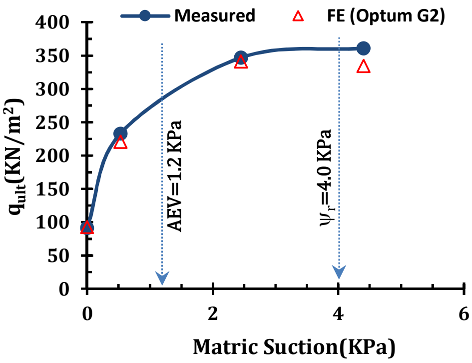

Figure 10. The variation of ultimate bearing capacity with matric suction

are shown. It can be seen that the bearing capacity increased nonlinearity as the suction increased such that when the matric suction approached and passed the air entry value (1.2 kPa), the rate of increase in bearing capacity decreased. As the residual matric suction (4.0 kPa) was approached, an increase in bearing capacity stopped. There was very good agreement between the values estimated by FE modeling and the measured value shown in the figure.

8. CONCLUSION

In this research, the bearing capacity of shallow square footing on dense sand under saturated and unsaturated conditions was studied using plate load tests at laboratory scale (model footing) under different groundwater conditions using a physical modeling apparatus. Numerical modeling was used in Optum G2 FE software. The results of the experiments show that as the water table lowered, matric suction increased in soil and the ultimate bearing capacity increased from 2.55 to 3.95 times the ultimate bearing capacity of the saturated condition. The bearing capacity increased nonlinearly as the suction increased such that when the matric suction approached and passed the air entry value, the rate of increase in bearing capacity decreased. As the residual matric suction was approached, an increase in bearing capacity stopped. Numerical simulation using the Mohr-Coulomb failure criteria by application of apparent cohesion instead of matric suction using Equation (3) for the upper area of the water table, very good estimated the measured ultimate bearing capacity.

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Experimental and Numerical Modeling of the Effect of Groundwater Table Lowering on Bearing Capacity of Shallow Square Footings

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PAPER INFO

Paper history:
Received 09 April 2019
Received in revised form 15 July 2019
Accepted 12 September 2019

Keywords:
Bearing Capacity
Experimental Model
Numerical Modeling
Groundwater Table
Unsaturated Soils

چکیده

پایین رفتن تراز آب زیر زمینی سبب غیراشباع شدن ناحیه بالای تراز آب و بروز پدیده موئینگی در این ناحیه می شود. بنابراین ظرفیت باربری پی های سطحی بایستی متاثر از مکش بافتی شرایط غیراشباع خاک باشد. در این تحقیق تاثیر افت تراز آب زیرزمینی بر ظرفیت باربری پی با انجام آزمایش بارگذاری پی مدل مربعی واقع بر خاک دانه ای متراکم در شرایط مختلف تراز آب زیرزمینی و نیز شبیه سازی عددی آزمایشهای انجام شده در نرم افزار اجزای محدود Optum G2 بررسی شده است. نتایج آزمایشهای این تحقیق نشان می دهد که با پایین بردن تراز آب زیرزمینی، مکش بافتی در خاک افزایش یافته و در محدوده مکش بافتی ٠/٥ تا ٤/٥ کیلوپاسکال، ظرفیت باربری نهایی در خاک مورد مطالعه بصورت غیرخطی از ٢/٥ تا ٤ برابر ظرفیت باربری حالت اشباع افزایش می یابد. شبیه سازی عددی آزمایشها با لحاظ کردن چسبندگی ظاهری ناشی از مکش بافتی برای ناحیه بالای تراز آب زیرزمینی نیز رفتار مشابهی پیش بینی کرده و همخوانی بسیار مناسبی بین مقادیر برآورد شده ظرفیت باربری به روش عددی با مقادیر اندازه گیری شده بدست آمده است.

doi*: 10.5829/ije.2019.32.10a.12*