In The Name of God

K. N. Toosi University of Technology
Faculty of Civil Engineering

Thesis Submitted in Partial Fulfillment of the
Requirements for the Degree of Master of Science (M.Sc.)

Experimental Study of Foundation Settlement on Unsaturated Sand With PIV Technique

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September 2019

اظهارنامه دانشجو

اینجانب **حسین خیاطیان** دانشجوی دوره **کارشناسی ارشد** رشته **مهندسی عمران** گرایش **ژئوتکنیک** دانشکده **مهندسی عمران** دانشگاه **صنعتی خواجه نصیرالدین طوسی** گواهی می‌نمایم که تحقیقات ارائه شده در پایان‌نامه با عنوان:

مطالعه آزمایشگاهی نشست پی بر بستر ماسه غیراشباع با استفاده از تکنیک PIV

با راهنمایی استاد محترم **جناب آقای دکتر حسن قاسم زاده** توسط شخص اینجانب انجام شده است. صحت و اصالت مطالب نگارش شده در این پایان‌نامه مورد تأیید اینجانب می‌باشد. در مورد استفاده از کار سایر محققین به مرجع مورد استفاده اشاره شده است. همچنین گواهی می‌نمایم که مطالب مندرج در پایان‌نامه تاکنون برای دریافت هیچ نوع مدرک یا امتیازی توسط اینجانب یا فرد دیگری در هیچ جا ارائه نشده است و در تدوین متن پایان‌نامه چارچوب مصوب دانشگاه به طور کامل رعایت شده است.

امضاء دانشجو:

تاریخ:

حق طبع، نشر و مالکیت نتایج

۱. حق چاپ و تکثیر این پایان‌نامه متعلق به نویسنده و استاد راهنمای آن می‌باشد. هرگونه تصویربرداری از کل یا بخشی از پایان‌نامه تنها با موافقت نویسنده یا استاد راهنما یا کتابخانه دانشکده مهندسی عمران دانشگاه صنعتی خواجه نصیرالدین طوسی مجاز می‌باشد.

۲. کلیه حقوق معنوی این اثر متعلق به دانشگاه صنعتی خواجه نصیرالدین طوسی می‌باشد و بدون اجازه کتبی دانشگاه به شخص ثالث قابل واگذاری نیست.

۳. استفاده از اطلاعات و نتایج موجود پایان نامه بدون ذکر مرجع مجاز نمی‌باشد.

This thesis is dedicated to ***my parents***

for their love, endless support and encouragement.

ACKNOWLEDGEMENTS

I am very grateful to my supervisor ***Dr. Hasan Ghasemzadeh*** *for his guidance, encouragement,valuable advice and suggestions throughout this research program.*

I would like to thank my friends for helping me purchase and set up various materials and facilities required for the research program. I appreciate from ***En. Reza Fami Tafreshi*** *who helped me to performe the experiments.*

Finally, I thank the faculty and staff in Civil Engineering Department for providing support to my graduate study.

Abstract

One of the issues in geotechnical society is the study of engineering behavior of unsaturated soils. In most relationships of bearing capacity of unsaturated soils, the rigid soil mass is assumed and the influence of changes in matric suction, porosity ratio and degree of saturation has not been considered. In practical projects dealing with unsaturated soils, using of the conventional equations provided for dry or unsaturated soils, lead to conservative results and consequently lead to non-economic design of structures. In this research, a device has been designed and developed to examine unsaturated soil bearing capacity. Chamber of which is insulated against air and water. This feature makes it possible apply the suction to the sample. Chamber has the transparent glass walls that give us the opportunity shoot during tests and then do image processing. The soil used in the study is Jajrud sand and the foundation is 2 cm thick steel with dimension of $25 \times 25\ cm^2$. Saturation levels were 0%, 25%, 50%, 75% and 100% and the unsaturated experiments were performed in two methods which are different in sample preparation, likewise, in the method of the implementing the experiment. In all experiments the loading rate was *2 mm / min* and during the experiment 2 Hz frequency shooting was performed for image processing (PIV technique). The results of the experiments show that the decrease of saturation (suction increase) causes increase the bearing capacity up to 68% more than the saturation sample and up to 55% more than the dry sample. The results of the experiments are compared with the analytical relationship of bearing capacity of unsaturated soil, proposed by Ghasemzadeh and Akbari, and the maximum difference is 25%. Also, according to the results of image processing, it can be inferred that the failure mode is general shear failure mechanism for the dry, saturated and unsaturated samples. The active wedge angle of the unsaturated soils, as shown by Ghasemzadeh and Akbari, is $\frac{\pi}{6} + \frac{7}{8}\varphi'$, which is 65°.

Keywords: Soil Bearing Capacity, Foundation Settlement, Unsaturated Soil, Degree of Saturation, Image Processing, Shear Failure mechanism, Active Wedge Angle of Soil

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Chapter 1 : Introduction and Overview

1-1 Introduction

One of the important subjects in geotechnic is the study of engineering behavior of unsaturated soils, and the results of researches and studies in this field are published annually in articles and books. Soil mechanics is a combination of the application of mechanical and hydraulic principles to soil engineering issues. In 1944, assuming complete soil saturation, Terzaghi developed a framework for interpreting soil mechanical behavior using the principle of effective stress[1].Nowadays, the same assumption is followed in many scientific and practical purposes. About 33 percent of the world's soils are in arid and semi-arid regions; therefore, groundwater levels are far below ground level. Soil above ground level is unsaturated. In many areas of these arid and semi-arid regions, shallow foundations are above groundwater level and in direct contact with unsaturated soils.

Unlike saturated soil mechanics, in unsaturated soils the pore water pressure is negative. In unsaturated soil problems, there are more than two phases. For this reason, it is now becoming crystal clear that it is not possible to ultimately interpret the behavioral characteristics of unsaturated soils using classical theories and codes of conduct applied to saturated soils. The behavior of unsaturated soils is hugely more complicated than unsaturated soils[2].Generally, three phases are considered for unsaturated soils: solids, water, and air. However, some scholars also consider a fourth phase for these soils called contractile skin or air-Water interface[3]. Classical soil mechanics and geotechnical engineering regularly assume that soil is either dry (0% saturated) or saturated (100% saturated), while in dry and saturated cases, there are only two specific, limited soil conditions. In other words, dry and saturated soil conditions are only two specific cases of the general circumstances of unsaturated soils with a saturation of zero and 100%[4]. It can be said that the world of soil mechanics is separated by the level of water. Below the water level, the soil is saturated and its behavior is justified by the effective stress parameter $(\sigma - u_w)$. While the soil is unsaturated above the level of water where two independent stress variables, namely net normal stress $(\sigma - u_a)$ and matric suction $(u_a - u_w)$, should be used to express the relationships and justify their behavior that σ is stress, u_a is pore air pressure and u_w is pore water pressure[3, 5].

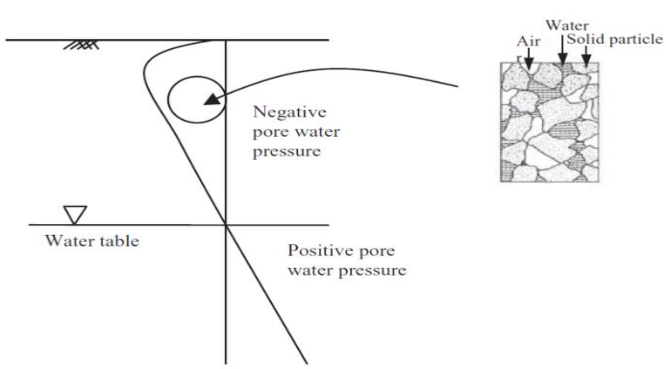

Figure (1-1): Scheme of pore water pressure profile in saturated and unsaturated soils[6]

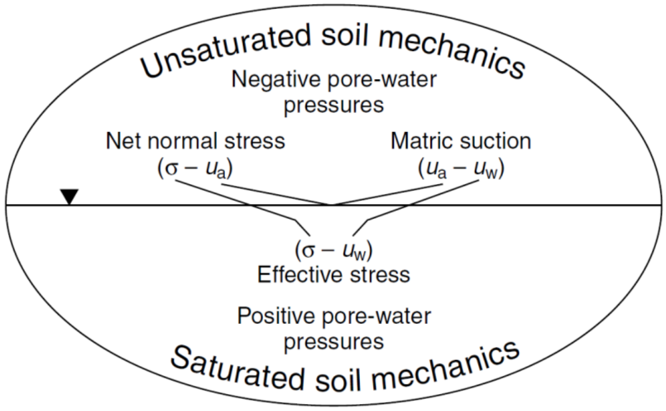

Figure (1-2): Division of soil mechanics world by water level surface[7]

1-2 Problem statement

Shallow foundations design is one of the most critical issues in geotechnical engineering. The two critical parameters for a proper design of shallow foundations are bearing capacity and settlement of the foundation. As mentioned, the surface layers are often above the underground water level, and the soil in these areas is unsaturated. The stresses caused by loading on these foundations are distributed in the unsaturated soil areas. Therefore, to calculate the bearing capacity and settlement of these foundations, the regular and classical equations of soil mechanics cannot be used and the impact of significant factors that exist on unsaturated soil including capillary forces should be considered. However, in everyday engineering problems, the foundations are designed with the hypothesis that the soil is saturated so that the design approach is conservative both for bearing capacity and settlement. That is, the estimated bearing capacity is less than the actual value, and the calculated settlement is higher than the correct amount. As long as there is no specific framework and criteria for analyzing the behavior of unsaturated soils, these non-economical and straightforward methods are used to solve engineering problems.

1-3 Purpose of the research

The purpose of this study was to model the physical bearing capacity of unsaturated soil and to investigate the failure of this soil by particle image velocimetry (PIV) technique. A unique device has been developed to carry out the experiments in this study, which is fully described in Chapter 3.The principal distinction between this study and the recent laboratory researches which investigate the bearing capacity of unsaturated soils is in the method of generating and measuring suction during the experiment. General outline on recent researches conducted in this area is presented in Chapter 2.

1-4 Research questions

Among the important questions that are posed and the purpose of this study is to investigate how they are answered are as follows:

1- What is the impact of suction on the ultimate bearing capacity and saturation of Jajroud sand?

2- Is the failure mechanism of Jajrud sand different from unsaturated to dry and saturated soil?

3. Are the results of the bearing capacity tests performed with the air pressure applied different from those without the air pressure tests?

4- In the unsaturated bearing capacity tests, how suction variation in height is?

1-5 Research Methodology

The research method in this study is to design and manufacture a suitable bearing capacity apparatus for unsaturated samples first, and then bearing capacity tests on dry, saturated and unsaturated samples with degrees of 0, 25, 50, 75 and 100% is conducted. In order to process the images of the experiments, photographs were taken during all experiments.

1-6 Research necessity

Most of the soils in the world due to weather and geographical conditions situated between dry and saturated state, without no exception in Iran. Understanding the relationships governing the behavior of unsaturated soils can provide the maximum resistance capacity of these soils. One of the important requirements of this study is to investigate the bearing capacity of Jajrud sand in dry, saturated and unsaturated state, which ultimately enables us to better understand the resistance behavior of this soil in different conditions.

1-7 Outline of the Thesis

This research generally consists of 5 chapters:

In the first chapter, an introduction to the research is presented, which includes the research field, the problem statement, and the purpose of the study.

In the second chapter, a review of studies on the bearing capacity of shallow foundations in saturated soils and failure mechanisms in shallow foundations are presented. Finally, researches and experiments on the calculation of bearing capacity in unsaturated soils are reviewed.

The third chapter introduces the tools, equipment, and materials used in this study. This chapter first discusses the design of the device required for conducting research experiments, and then introduces the specifications of the equipment used in this device. Lastly, the materials used for the research as well as the method of sampling and preparing these samples for testing are mentioned.

Chapter 4 firstly discusses the experiments and their details and then examines the bearing capacity of the soil in three phases, including dry, saturated, and unsaturated. At the end of this chapter, the results of the experiments are evaluated, analyzed, and interpreted.

In chapter 5, the findings of this study are summarized and concluded, and suggestions that may be useful for further research are offered.

Chapter 2 : Literature Review

2-1 Introduction

The two core characteristics required for the proper design of shallow foundations are the bearing capacity and soil settlement. Structures such as silos, bridges, multi-story buildings, dams, retaining walls, and other significant infrastructures can be constructed on the shallow foundations based on sandy soils with a safe and affordable design. In general, shallow foundations are designed to transport loads safely from structure to soil under a limited settlement as reported in the bylaws. The bearing capacity of the shallow foundations is calculated using the methods proposed by Tarzaghi (1943)[1] or Mirhoff (1951)[8], assuming soil is saturated. However, the bearing capacity estimated in standard field experiments is greater than the bearing capacity calculated by analytical and empirical methods. In this chapter, the bearing capacity of the unsaturated soil in various forms and its collapse mechanisms that was studied, are considered.

2-2 The bearing capacity of saturated soils

Many empirical and theoretical studies have been conducted to investigate the bearing capacity of soils, some of which will be discussed below. In most of these studies, researchers have sought to provide a framework for explaining or calculating the bearing capacity of saturated soils and have neglected the effect of texture suction on the bearing capacity of unsaturated soils. The results of several experiments show that the bearing capacity of shallow foundations in unsaturated soils is usually higher than the bearing capacity calculated by conventional equations. Using these ordinary equations will lead to conservative designs. In this section, a summary of essential studies by Terzaghi to understand the bearing capacity of saturated soils is reviewed.

2-2-1 Terzaghi

According to Terzaghi, the surface of failure for the ultimate loading for a strip foundation can be shown as in figure (2-1). The failure zone in this figure can be divided into five zones, containing one region (I) and two pairs of regions (II) and (III)[1].

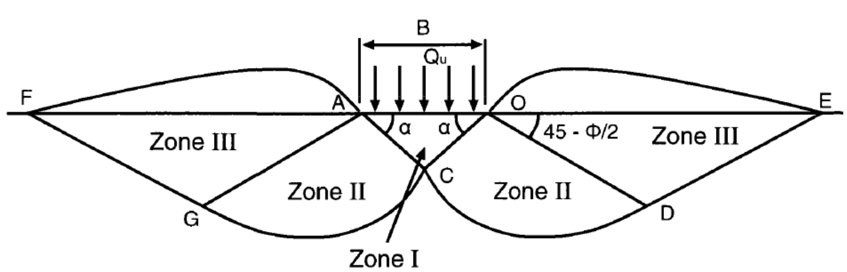

Figure (2-1): Bearing capacity failure of soil under strip foundation[1]

The triangular area (I) below the foundation is considered part of the foundation and, due to friction and cohesion between the foundation and the soil, penetrates like a wedge in the soil. Area (II) lies between Area (I) and Area (III) and is known as the quarter-sawed area because the shear pattern lines in this area extend from the outer edge of the foundation. Zone III is similar to passive Rankine state, and a shear pattern is created in these regions. Using the Limit Equilibrium Method, Terzaghi expressed the final bearing capacity of a strip foundation using Equation (2-1). Accordingly, the bearing capacity of the soil is dependent on the dimensions of the foundation, specific weight, and shear strength parameters C' and φ'.

$$q_u = c'N_c + qN_q + 0.5\gamma BN_\gamma \tag{2-1}$$

Where:

$q_u =$ Ultimate bearing capacity, kPa

$c' =$ Effective cohesion, kPa

$q =$ Effective overburden pressure, kPa

$B =$ Foundation's width, m

$\gamma =$ The specific weight of soil, kN/m^3

$N_c =$ Bearing capacity factor related to the cohesion

$N_q =$ Bearing capacity factor related to the overburden

$N_\gamma =$ Bearing capacity factor related to the specific weight of soil

Table (2-1) summarizes bearing capacity factors based on different internal friction angles. In this table, the values of N_q and N_c are based on Terzaghi's proposed equations, and the values are calculated based on Kumbhojkar's studies[9]. Kumbhojkar's studies show that the measured bearing capacity is in a better relationship with the bearing capacity calculated with his proposed N_γ. Terzaghi also introduced the form factor to consider the effect of the foundation shape on the bearing capacity as shown in table (2-2). Finally, Terzaghi's proposed equation for bearing capacity, taking into account the shape factor, will be as follows:

$$q_u = c'N_c\zeta_c + qN_q + 0.5\gamma BN_\gamma\zeta_\gamma \tag{2-2}$$

Table 2-1: Bearing capacity factors

Φ'	N_c	N_q	N_γ	Φ'	N_c	N_q	N_γ	Φ'	N_c	N_q	N_γ
0	5.70	1.00	0.00	17	14.60	5.45	2.18	34	52.64	36.50	38.04
1	6.00	1.1	0.01	18	15.12	6.04	2.59	35	57.75	41.44	45.41
2	6.30	1.22	0.04	19	16.57	6.70	3.07	36	63.53	47.16	54.36
3	6.62	1.35	0.06	20	17.69	7.44	3.64	37	70.01	53.80	65.27
4	6.97	1.49	0.10	21	18.92	8.26	4.31	38	77.50	61.55	78.61
5	7.34	1.64	0.14	22	20.27	9.19	5.09	39	85.97	70.61	95.03
6	7.73	1.81	0.20	23	21.75	10.23	6.00	40	95.66	81.27	115.31
7	8.15	2.00	0.27	24	23.36	11.40	7.08	41	106.81	93.85	140.51
8	8.60	2.21	0.35	25	25.13	12.72	8.34	42	119.67	108.75	171.99
9	9.09	2.44	0.44	26	27.09	14.21	9.84	43	134.58	126.50	211.56
10	9.61	2.69	0.56	27	29.24	15.90	11.60	44	151.95	147.74	261.60
11	10.16	2.98	0.69	28	31.61	17.81	13.70	45	172.28	173.28	325.34
12	10.76	3.29	0.85	29	34.24	19.98	16.18	46	196.22	204.19	407.11
13	11.41	3.63	1.04	30	37.16	22.46	19.13	47	224.55	241.19	512.84
14	12.11	4.02	1.26	31	40.41	25.28	22.65	48	258.28	287.85	650.87
15	12.86	4.45	1.52	32	44.04	28.52	26.87	49	298.71	344.63	831.99
16	13.68	4.92	1.82	33	48.09	32.23	31.94	50	347.50	415.14	1072.80

Table (2-2): Terzaghi's proposed shape factor for calculating bearing capacity

shape factor	square foundation	strip foundation	circular foundation
ζ_c	1.3	1	1.3
ζ_γ	0.8	1	0.6

Other researchers, such as Meyerhof, Vesic and Hansen, also proposed relationships for calculating soil bearing capacity, which is the difference in the amount of coefficients suggested for using those relationships. Table (2-3) shows the suggested values of Meyerhof, Vesic and Hansen for the N_c, N_q and N_γ coefficients. The notable point is that the N_c and N_q coefficients presented by these researchers are the same and their relationship is different in the N_γ coefficient.

Table (2-3): Meyerhof, Vesic and Hansen's proposed Bearing capacity factors[10]

ϕ	N_c	N_q	$N_{\gamma(H)}$	$N_{\gamma(M)}$	$N_{\gamma(V)}$	N_q/N_c	$2\tan\phi(1-\sin\phi)^2$
0	5.14*	1.0	0.0	0.0	0.0	0.195	0.000
5	6.49	1.6	0.1	0.1	0.4	0.242	0.146
10	8.34	2.5	0.4	0.4	1.2	0.296	0.241
15	10.97	3.9	1.2	1.1	2.6	0.359	0.294
20	14.83	6.4	2.9	2.9	5.4	0.431	0.315
25	20.71	10.7	6.8	6.8	10.9	0.514	0.311
26	22.25	11.8	7.9	8.0	12.5	0.533	0.308
28	25.79	14.7	10.9	11.2	16.7	0.570	0.299
30	30.13	18.4	15.1	15.7	22.4	0.610	0.289
32	35.47	23.2	20.8	22.0	30.2	0.653	0.276
34	42.14	29.4	28.7	31.1	41.0	0.698	0.262
36	50.55	37.7	40.0	44.4	56.2	0.746	0.247
38	61.31	48.9	56.1	64.0	77.9	0.797	0.231
40	75.25	64.1	79.4	93.6	109.3	0.852	0.214
45	133.73	134.7	200.5	262.3	271.3	1.007	0.172
50	266.50	318.5	567.4	871.7	761.3	1.195	0.131

2-3 The bearing capacity of unsaturated soil

The bearing capacity measured from field tests is usually higher than predicted by classical theories [1, 11, 12]. These results show that the contribution of suction in calculating soil bearing capacity is ignored[2]. Modifications to the bearing capacity of the Terzaghi equation for various modes of groundwater level are also being considered to investigate the effect of positive pore water pressure. In other words, the effect of negative pore water pressure has not been observed independently in the form of specific equations. Accordingly, the generalization of the design method used in saturated soils to unsaturated soils results in conservative analyzes with less bearing capacity and more settlement. Although significant developments have been created over the past 30 years in understanding the engineering behavior of unsaturated soils, no specific framework has yet been established for interpreting and assessing the bearing capacity of unsaturated soils. This section reviews some of the most critical studies on the bearing capacity of unsaturated soils.

2-3-1 Broms

Broms's 1964 study provided a method for evaluating the bearing capacity of flexible pavements in unsaturated soils and was one of the first studies conducted on unsaturated soils[13]. This method assumed that the rupture would occur in the saturated bed of the soil. According to this method, the bearing capacity is a function of the degree of saturation(S_r), the apparent cohesion(c) and the angle of internal friction of the soil(φ). The results of Broms studies show that the decline of saturation degree from 100% to 90% in fine silt and clay soils grows the bearing capacity of these soils by 2 and 8%, respectively. Also, according to his research, the bearing capacity of the bed soil decreases with increasing degree of saturation. Figure (2-2) illustrates the equation between vehicle tire pressure and wheel ultimate load with different saturation degrees. From this graph, which shows the results of Broms research, it can be concluded that the degree of saturation has a significant