

# LABORATORY FOOTING TEST ON PARTIALLY SATURATED SANDY SOIL

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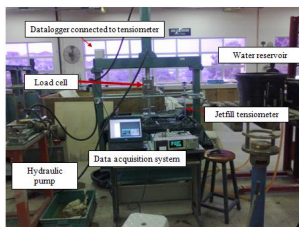
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## Graphical abstract



## Abstract

Conventional analysis and design of shallow foundation are based on the assumption that the soil is under fully saturated condition. However, shallow foundations are typically constructed near the ground surface where the soil is under partially saturated condition. Therefore, more research to investigate the behaviour of shallow foundation in unsaturated soil is very essential in order to aid engineers in making good analysis and design. This paper presents a series of laboratory footing tests conducted on unsaturated sandy soil. A specially designed test tank was fabricated for the test. Square footings of two different sizes (100 mm x 100 mm and 150 mm x 150 mm) were used and loaded on Rawang sand which has residual suction value of 10 kPa. The measured values of matric suction of the soil in the test tank were in the range of 0 to 30 kPa. Based on the results, it was observed that bearing capacities of shallow foundation under fully saturated condition were the lowest compared to soil under unsaturated conditions. The highest values were measured at matric suction equals to residual suction (i.e 10 kPa). Furthermore, the relationship between the bearing capacities of shallow foundation with the matric suction was observed to be non-linear.

Keywords: Shallow foundation, bearing capacity, unsaturated soil, suction

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## 1.0 INTRODUCTION

Understanding the behaviour of fully saturated and fully dry, fine-grained and coarse soils is less complicated compares to understanding the behaviour of unsaturated soils [1]. Incorporating the effect of matric suction is essential in interpreting the behaviour of shallow foundation in unsaturated soils. Neglecting the contribution of matric suction to the bearing capacity of unsaturated soil may lead to over-design of shallow foundation. In most cases, the design of shallow foundation considers the soil to be in fully saturated condition even though the water table is well below ground level [2]. Due to this reason, estimation of the bearing capacity of shallow foundations using the conventional approaches may not be reliable leading to uneconomical designs.

Since the past five decades, very limited theoretical research work is reported in the literature with respect to the interpretation of the bearing capacity of unsaturated soils. Most researches were focusing in the field of saturated soil mechanics and attempting to improve the bearing capacity factor, which frequently indicted as one of the cause of irregularity between the theoretical and experimental values.

In this study, specially designed equipment was fabricated in order to observe the behaviour of model footing under saturated and unsaturated condition. Two different footing sizes (100 mm x 100 mm and 150 mm x 150 mm) were used and loaded on a compacted sandy soil with matric suction range from 0 – 30 kPa.

## 2.0 BACKGROUND

Matric suction plays a significant role in the development of shear strength in soil. The neglect of the increase shear strength due to matric suction can lead to substantial under-estimation of bearing capacity [3]. Ignoring the influence of capillary stresses in the bearing capacity would be equivalent to ignoring the influence of reinforcement in the design of reinforced concrete [4]. Vanapalli and Mohamed [5] conducted laboratory investigations to measure the bearing capacity of an unsaturated coarse-grained soil using specially designed test tank. The measured values were compared with the proposed bearing capacity equation for unsaturated soil [6]. However, the matric suctions applied in the test range only from 0 to 10 kPa. This shows the need to investigate the effect of higher matric suction values to the bearing capacity of unsaturated soils.

## 3.0 EQUIPMENT AND PROCEDURE

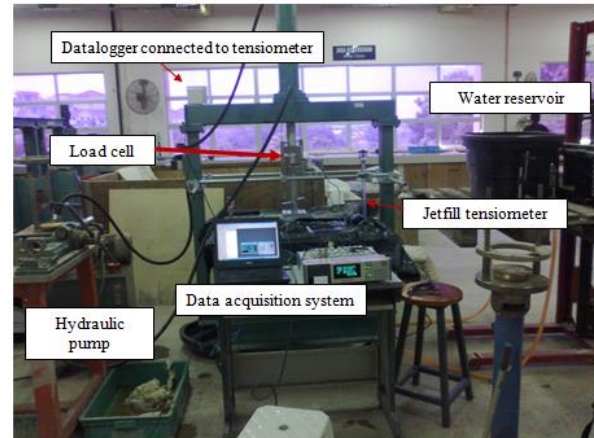
### 3.1 Test tank

Figure 1 shows the test tank designed and fabricated at the Faculty of Civil Engineering, Universiti Teknologi MARA, Shah Alam, Malaysia. The test tank is a 1000 mm x 1000 mm x 600 mm steel box with supporting beams and steel base. The tank was constructed using 10 mm thick steel. The dimensions of the tank were specially designed in order to provide clear distance between the footing edge and the sides of the tank to avoid the influence of the boundary effects of the stress bulb zone. The depth of the tank was deeper than the expected depth of the stress bulb below the model footing. An electrically operated and mechanically controlled loading system was used to load the model footings. Two drainage pipes with valves connected to the bottom of the test tank were used in monitoring the water level. A water supply pipe of 20 mm in diameter was used to control the amount of water supplied to the tank. The water supply pipes facilitate to saturate the soil gradually and uniformly from the base of the tank to the surface (i.e., the saturation was progressed from the bottom to the top of the soil surface). Both saturation and desaturation conditions were achieved successfully in the tank using this system. Linearly Variable Displacement Transducers (LVDTs) were attached to the vertical loading arm and the tip of the LVDT was placed directly on the surface of the model footing. A load cell capable of measuring 100 kN was mounted on the loading arm. Both the LVDT and the load cell were connected to a data acquisition system.

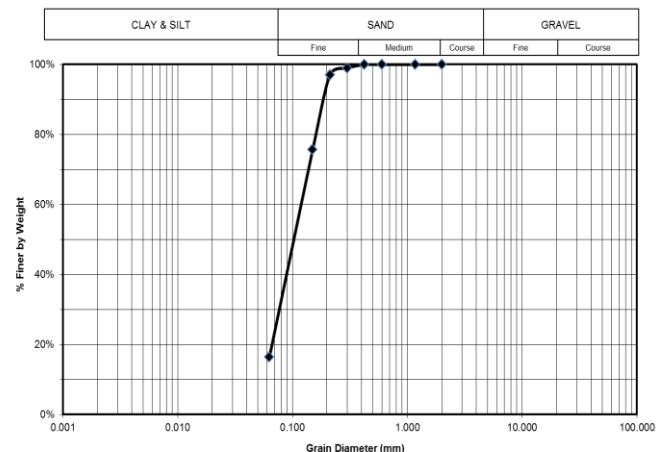
### 3.2 Test Material

Rawang sand was used as test material in this study. The soil classification tests of the used material are performed based on BS 1377: 1990 (British Standard: Methods of Test for Soils for Civil Engineering Purposes).

The tests included particle density, particle size distribution, and compaction characteristics. Rawang sand is poorly graded sand with grain sizes range from 0.08 mm to 0.20 mm in diameter (Figure 2). The soil was collected from a quarry in the district of Rawang, Selangor. Table 1 shows the summary of results from the properties tests.



**Figure 1** Specially designed equipment for laboratory footing test at the Faculty of Civil Engineering, Universiti Teknologi MARA, Shah Alam, Selangor



**Figure 2** Particle size distribution curve of Rawang sand

**Table 1** Physical characteristics of Rawang sand

Soil physical properties	Description
Gravel content	0 %
Sand content	83.6 %
Silt content	16.4 %
Clay content	0 %
Specific gravity	2.56

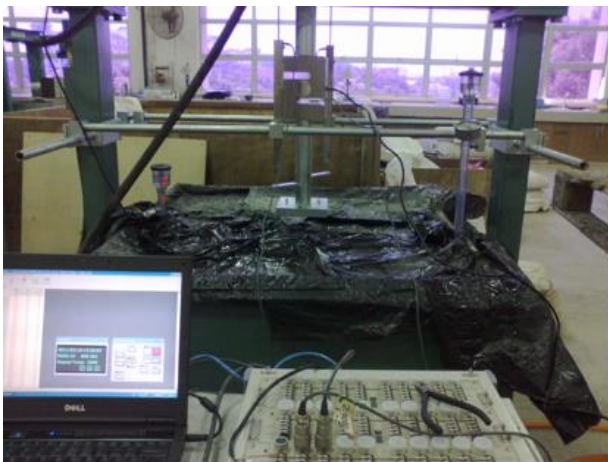
### 3.3 Procedures

The soil was poured into the tank and compacted on 10 layers of 50 mm each in order to achieve the target height of 500 mm. Hand compactor was used to

compact the soil and relative density of 50 - 70 % was achieved in every series of footing test.

The specially designed tank can accommodate test under fully saturated and unsaturated conditions. For saturated condition, the water table was slowly raised from the base of the tank through the bottom aggregate layer. This technique facilitated escape of air from bottom to the surface layers of the soil in the tank gradually to ensure a fully saturated condition. The water level were inspected periodically by observing the water level in the water supply tank. The supplier valve was closed once the water level reached the soil surface in the tank. The bearing capacity of the saturated soil was measured by loading the footing gradually at a rate of 1 mm/min. All tensiometers were indicating zero suction values after saturation and during the testing period.

For unsaturated condition, the soil in the tank was first saturated as detailed in the previous section. The water table was then lowered down by opening drainage valves, to different levels of depth from the soil surface to achieve different suction values. Equilibrium conditions with respect to suction value in the stress bulb zone (i.e., depth of  $1.5B$ ) were achieved in a time period of 7-10 days (Figure 3). The bearing capacity of the soil using this technique was measured under different average suction values and with the same loading rate as the saturated condition.

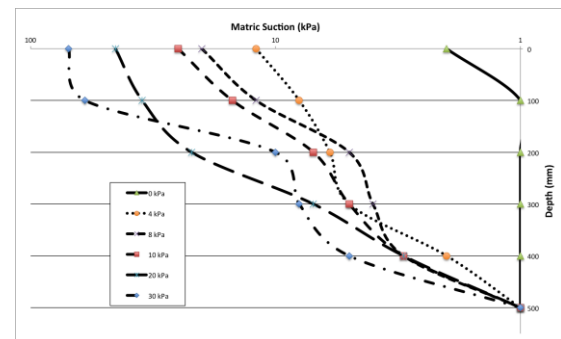


**Figure 3** Dark plastic cover used to cover the surface of the tank during the equalization stage

At the end of test series, a sampling tube was pushed into the soil in order to obtain samples for the verification of the soil matric suction with the Soil Water Characteristic Curve (SWCC) of the Rawang sand (Figure 4). The graph in Figure 5 shows the matric suction profile with respect to different depths.



**Figure 4** Sampling tube to collect soil samples for the verification of matric suction



**Figure 5** Matric suction profile with respect to different depths

#### 4.0 SOIL WATER CHARACTERISTIC CURVE OF RAWANG SAND

In this study the pressure plate extractor (Soil Moisture Equipment Corp.) [7] was used to apply suction values between 5 - 500 kPa using the axis-translation technique (ATT) [8] as stated in [9]. Figure 6 shows the photo of the pressure plate extractor used. The SWCC curve for Rawang sand is shown in Figure 7. The key parameters of a typical SWCC curve are the air-entry value and the residual suction. The air-entry value is the matric suction value where the air starts to enter the largest pores in the soil, which cause the desaturation of the soil. The residual suction is the matric suction where additional water is removed from the soil. The air-entry value and residual suction value for Rawang sand were 5 kPa and 10 kPa respectively. These values are typical values for coarse-grained soils.



Figure 6 Pressure plate extractor (Soil Moisture Equipment Corp.) [7]

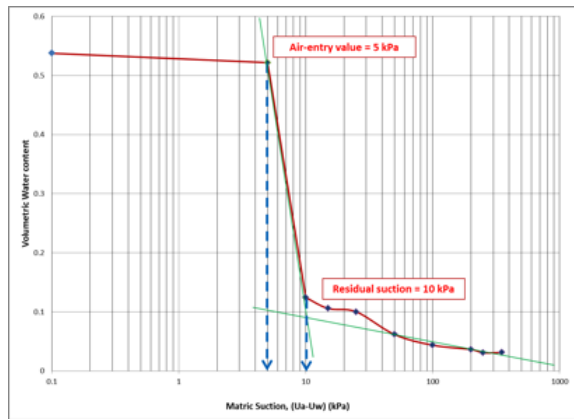


Figure 7 Soil Water Characteristics Curve for Rawang sand

### 5.0 RESULTS AND DISCUSSIONS

Figure 8 and 9 show the results of the footing tests for 100 m x 100 mm and 150 mm x 150 mm.

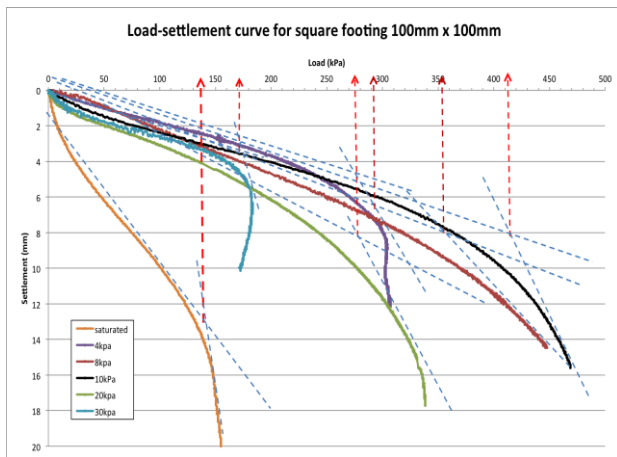


Figure 8 Load versus settlement curves of 100 mm x 100 mm footing test under different matric suctions

The failure mechanisms observed from the load-settlement curves, show patterns of local shear failure to general shear failure as described by [10]. These curves show that the densities of the compacted soil vary from medium to dense densities. Ultimate bearing capacities were obtained using the Tangent Intersection Method [11].

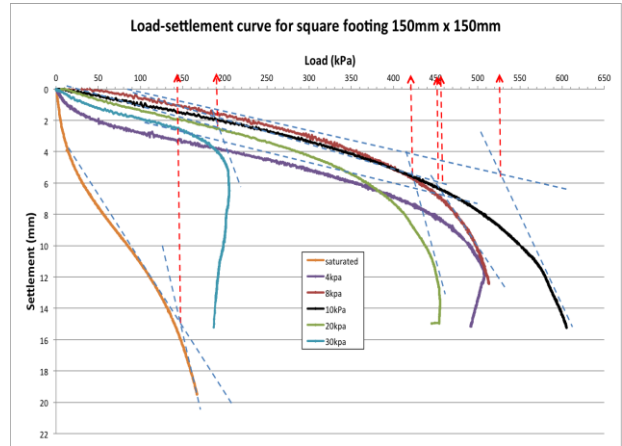


Figure 9 Load versus settlement curves of 150 mm x 150 mm footing test under different matric suctions

From the test series, it was observed that soil under fully saturated condition produced the lowest bearing capacity values (135 kPa for 100 mm footing and 140 kPa for 150 mm footing). The highest bearing capacity values were measured for soil under matric suction equals to residual suction (i.e. 10 kPa) which are 410 kPa and 525 kPa for 100 mm footing and 150 mm footing respectively. These values show the contribution of matric suction to the bearing capacity of unsaturated soil is approximately 4 times more than the bearing capacity of soil under fully saturated condition. This also proves the role of suction in increasing the shear strength of unsaturated soils.

However, the bearing capacity values start to drop as the matric suction in the soil increase beyond the residual suction. This can be observed for soil under matric suction of 20 kPa and 30 kPa. It can be concluded that the contribution of matric suction becomes lesser as the soil approach fully dry condition.

Summary of the results from the footing test is shown in Table 2 and Figure 10.

Table 2 Measured bearing capacity

Matric Suction (kPa)	Bearing Capacity (kPa)	
	100 mm x 100 mm	150 mm x 150 mm
0	135	140
4	290	455
8	350	450
10	410	525
20	225	420
30	170	190

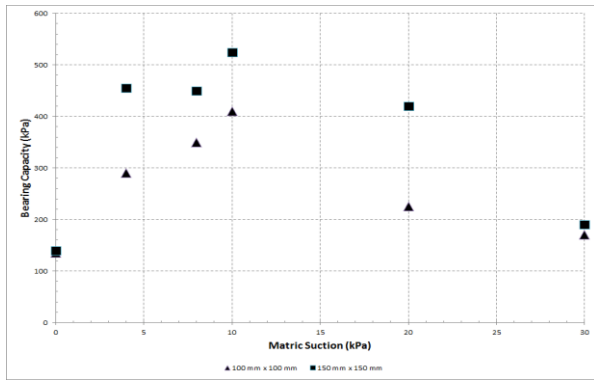


Figure 10 Variation of measured bearing capacity with respect to matric suctions

Another important observation is the non-linear relationship between the bearing capacity values with respect to matric suction. Past researchers tried to explain this behaviour using the SWCC curve of soil whereby, the relationship between the degrees of saturation or the water content (volumetric or gravimetric) with the matric suction is non-linear. However, this behaviour is due the true soil behaviour, which is non-linear. The result validates the curved-surface soil shear strength model by Md Noor and Anderson [12].

The model shows the nonlinearity of the soil shear strength with respect to both net stress and matric suction (Figure 11).

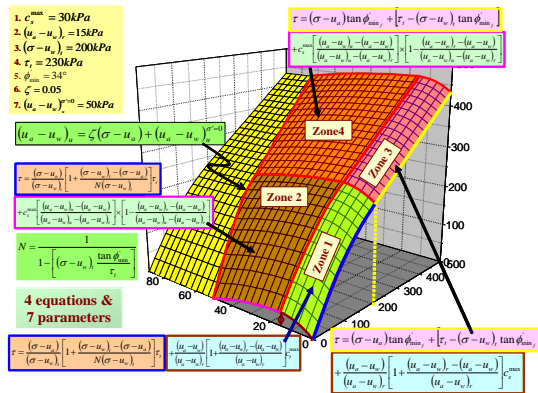


Figure 11 Curvilinear soil shear strength envelope by Md Noor and Anderson (2006)

### 6.0 CONCLUSION

This study proves the significant role of matric suction to the bearing capacity of shallow foundation in unsaturated sandy soil. Further test series using fine-grained or real soils are needed in order to establish a comprehensive behaviour of shallow foundation in unsaturated soils. The following are the conclusions based on the study:

1. The behaviour of the shallow foundation with respect to the variation of matric suction is observed to be non-linear.
2. The highest measured bearing capacity is observed to be when the soil is under matric suction equals to the residual suction. The bearing capacity drops when matric suction exceeds the residual suction value. It can be concluded that the bearing capacities of soil are low when the soil is fully wet (i.e. matric suction is zero) or fully dry.
3. Furthermore, there is a need to improve the conventional bearing capacity equation in order to incorporate the non-linear behaviour of soil.
4. The outcome of the study is very useful to help geotechnical engineer to have a better understanding in the analysis and design of shallow foundation.

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