Stress Transfer from Square Footing Model to Saturated and Unsaturated Soil

Haidar Mekkiyah[1,a], Abbas M. Kallawi[2,b], Ammar A. Sheikha[3,c*], and Mohammed Y. Fattah[4,d]

[1]National Investment Commotion, Baghdad, Iraq.

[2]University of Baghdad, Baghdad, Iraq.

[3]Department of Civil Engineering, University of Baghdad, Baghdad, Iraq.

[4]Department of Civil Engineering, University of Technology-Iraq, Baghdad, Iraq.

[a]dr.Mekkiyah.h.m@coeng.uobaghdad.edu.iq, [b]mabbas153@yahoo.com, [c]aaqassim@coeng.uobaghdad.edu.iq, [d]myf_1968@yahoo.com

*Corresponding author

Received: 1 April 2025
Revised : 1 August 2025
Accepted: 5 September 2025

Abstract. Stresses in the soil layer play a great role in geotechnical problems because it is the major parameter in all theoretical equations to calculate the deformation of soil and the stability of buildings. In this study, a set of tests is conducted to investigate the stress transfer from a square footing model (100*100) mm to the underlying soil of different properties (saturated and unsaturated with the same dry density). The soil stresses were measured using two soil transducers of 50 mm diameter and situated at different locations under the footing model. For both saturated and unsaturated soils, results showed that the soil stresses decreased when the distance below the footing was increased. The stresses measured at the center of the footing are also more than those measured at the corner of the footing for both soils tested. The trend of experimentally tested soil curves always gives a non-linear response, in comparison to linear trend curves obtained from theoretical calculations. Further, the percentage of stress transfer from the total stress on the footing during a specific period of time was larger in the saturated than in the unsaturated soil. Computed stresses in the soils were found to be lower than the measured ones. In addition, the results show that the applied stresses reach a significantly higher value for unsaturated soil, which yields a greater bearing capacity compared to that for saturated soil.

Keywords: Square footing, clay, unsaturated soil, stress transfer.

1. INTRODUCTION

In geotechnical engineering, evaluation of stresses in soil can be used in the settlement calculations (elastic and consolidation), pore water pressure, stresses within the soil due to foundation loads, underground constructions and the effects on adjacent structures [1]. Construction of a foundation changes the net stress in the soil underlying the foundation and it is usually increases depending on the load per unit area mounted [2]. The theoretical estimation of stresses transmitted to the soil under the footing or piles by equations or graphs are based entirely on the principles of the theory of elasticity [3], however, the limitations of these theories should be considered, that because the soil deposits, generally, are non-homogeneous, inelastic, and anisotropic. So, a percent of deviation can be expected when calculate the theoretical stress compared to that in field. According to this fact, the stress results could appear a difference of 25 to 30% between theoretical and actual field values [4].

Boussinesq's and Westergaard's solutions are common methods used to find the stress distribution in soil medium due to foundation loads. These stresses will be added to the existing stresses as a result of overburden pressure and any other source of stress [5,6]. Oh and Vanapalli [7] presented an approach by using a simple finite element analysis to modify the total stress approach in order to estimate the bearing capacity of unsaturated cohesive soil and concluded that Poisson's ratio effects the behavior of the stress versus settlement for both shallow foundations in unsaturated and saturated condition. Khallawi [8] investigated the transferred loads from group piles suited in saturated and unsaturated. It was shown that the transferred loads to the shaft increases when the number of the piles increases in-group tested in the three different saturated and unsaturated soil conditions. The results also show that and transferred loads reach the peak value for 3x3 group at which ≈ 10% of transfer loads goes to pile tip and the reminder loads (≈ 90 %) goes to shaft regardless of soil type shown in Figures 1 and 2, the curves are nearly coinciding at the early state of loading.

Fattah et al. [9] investigates the change in suction of soil on swelling pressure and volume change under shallow foundations. The small-scale model was used on pure bentonite and bentonite mixed with sand of different proportions these is (30, 40 and 50%). The soil model was tested with different initial water contents and dry unit weights in which they were chosen from the compaction curves. To study the effect of changes in water content on the relations of swelling with time and swelling pressure with time, large-scale model of soil with dimensions (700 × 700 × 650) mm was used to prepare the soil samples at the same initial water content and dry unit weight. The results showed that swelling pressure measured from the swelling test with a small soil sample is much higher than that from large one, the calculated swelling pressure for (60:40, bentonite: sand) model decreases to 23.2 kPa in the large-scale mode in comparison to 50 kPa in the swelling model.

Ahmed et al. [10] studied the effect of lowering water table on shallow foundation constructed over tow layer soil of clayey soil over silty sand soil and concluded that the deformation of the silty sand layer may be related to the increase of clayey soil density, while settlement of the silty clay layer induced by the increment of the effective pressure and the dissipation of pore pressure. Kim et al. [11] studied the influence of the change in matric suction as a result of rainfall infiltration on the behavior of shallow foundation settlement and concluded that soil with initial matric suction showed a strengthen effect on bearing capacity and a decrease in settlement when the matric suction increases.

Olumuyiwa [12] participates the geophysical and geotechnical approaches of subsoil assessment and shallow foundation design and found the water table of the study area differs from 4.5 to 12.3 meter which allows to a 200kPa allowable bearing capacity for design purposes of shallow foundation at 1 meter depth and an anticipated settlement varying from 9.03 to 48.2 mm. Al-Omari et al. [13] investigated the influence of transfer loads from the group piles to the underlying soil and the way of this transfer to the tip and shaft of piles tested in soil with two different conditions (saturated and unsaturated states). A 50 mm circular soil pressure transducer was used to measure the stresses. The transducer located at a depth of 0.25L (where L is the pile length = 200 mm) under the tip for all pile groups tested. The measured stresses were compared with stresses calculated theoretically from elastic theory and that estimated from conventional approximation (2V:1H). the measured stresses from experimental work show, in general, in a good agreement with two methods mentioned earlier.

In experimental work conducted by Khallawi [14], showed that the stress mechanism change as the effect of inclusion of geotextile mesh at the interface of sand layer overlying soft clay causing an approximate of double increase in the bearing capacity values of soil system compared to that unreinforced one. Further, Salih [15] study the stress distribution along soil reinforcement and its variation among the layers under different shapes and sizes of footing. The results showed concentration of stresses directly below the footing and decreased gradually to every small value at a distance (1.5B -2B). Finally, Noori [16] shows that the horizontal spacing is the most effected parameter on the stress transfer on the earth retaining wall tested in reinforced soil with a metal strips. In this study, a series of tests were conducted to investigate the load transfer from footing tested in saturated soil (degree of saturation S ≈ 90%) and unsaturated soil (S ≈ 60%) both soils with same dry density γ_d = 15 kN/m^3.and how the soil type affects the transmitted load from rigid aluminium footing (6mm thick and 100*100 mm dimensions) to the underlying soil.

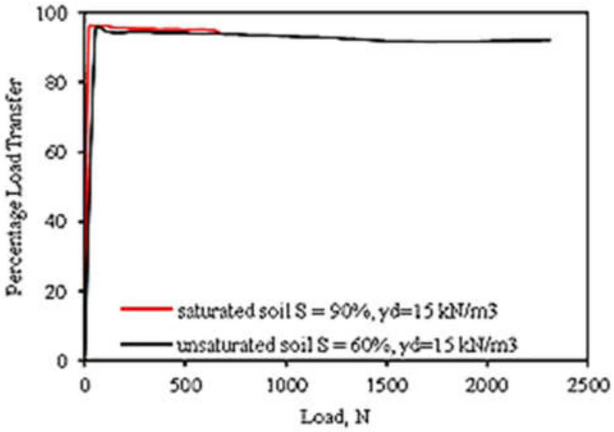

Figure 1. Comparison of load transfer to 3x3 group piles shaft in two different soil conditions (saturated and unsaturated), after [8]

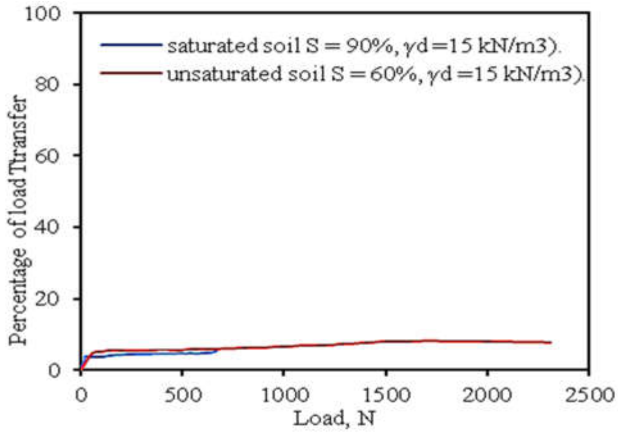

Figure 2. Comparison of load transfer to 3x3 group piles tip in two different soil conditions (saturated and unsaturated), after [8].

2. MATERIALS AND METHODS

Two types of containers were used; they are identical in dimension. The internal dimensions of the container used in the experimental work are 300 mm length, 300 mm width and 350 mm deep. The stresses below the footing model were measured with two soil pressure transducers (KDE-200 kPa) positioned at the centre and corner of the footing (footing dimensions 100 x100 mm) and the transducers were connected to a switching box through five channels. To prepare the saturated soil model the following steps are used:

- The poured soil was mixed with about 11.5% water content get a water content 12.5% (the soil has an initial water content approximately 1%), which is in the range of optimum.
- To get a uniform distribution of moisture content, the total soil mass was divided into smaller masses of 10 kg and each small soil mass was mixed gradually with water for a period of 10 minutes in order to get an approximate water content of 12.5%.
- After that, the soil was kept in nylon sheets and left 3 days as a curing period, the estimated mass of soil was spread out to a depth of 50 mm in the selected box. This quantity is compacted by using a square steel hammer of 100 mm length to give a dry density γ_d = 15 kN/m^3.
- Two pressure transducer devices (50 mm diameter) were placed below the center and corner of the footing model at different depths these are (Z/B = 0.5, 1, 1.5 and 2) where B= footing width and Z= depth below footing. After completing all soil layers, the surface of upper soil layer was, leveled, flattens, and covered with sheet nylon to prevent the evaporation. Finally, the soil model was covered with a square a plywood plate to carry a10 kPa (84 kg) a pressure load, which is mounting for 24 hours, allowing the soil model re-gaining a part of its strength. A 10 mm diameter plastic tube was used to supply water to the container. This plastic tube has two branches of the same diameter and these branches were connected to the container sides in order to ensure a gradual and a uniform saturation process when take place from the base of the container to the top surface of the model through a layer of 5 cm small gravel and perforated nylon sheet. The saturation was gradually transferred from the bottom of soil to the soil surface to expel any trapped air in the soil mass. Another 10 mm diameter tube was connected to the container side to monitor the elevation of water table during the saturation.
- The two soil pressure transducers are connected to five channel switching box which connect to the digital data logger shown in Figure 3, the whole testing system device are shown in Figure 4. The soil pressure transducers depths were located at the center and corner below the footing according to suggested by the study. Authors are suggested to present their articles in the section structure.

Figure 3. Data logger connected to five channel switching box.

Figure 4. Testing system configuration.

- On the other hand, the unsaturated soil tests models were prepared according to the previously calculated water content (w = 16.8%) which gives a degree of saturation S = 60%, as planned by testing program, and according to the soil properties. This amount of water was mixed with poured soil, following the same steps of preparing the saturated soil model (steps 1 to 4) except that on immersion of model with water.
- The soil suction of unsaturated model was measured indirectly because of the difficulties associated with direct soil suction measurements (these difficulties mentioned in. [5], this procedure of the direct preparing the unsaturated soil model for fine-grained soil from previous calculated water adopted by [17-20].

The suction of soil was measured through digital a watermark device named (900M), the logger is accompanied with seven sensors of soil moisture named (200SS – 15) and (200TS) as a sensor soil temperature these are shown in Figure 5. Seven samples of soil are prepared, with different water content for each one, the probes were inserted in the samples and the suction is checked every time in order to reach the equilibrium value of suction (on noticeable of suction with time). The results are shown in Figure 6, which gives the relationship between the water content and suction of soil suction. According to Figure 6 and soil properties the pre-calculated water content 16.8 % gives a suction value of ψ = 7.84 kPa. The soil classified according to the (USCS) as (CL-ML) containing, 38% sand, 28% silt and 34% clay. The standard compaction test showed a value of optimum moisture content (OMC) of 13.3%, and the maximum dry density of 19.1 kN /m^3, according to ASTM D 698 specification. The other clay properties are specific gravity G_s=2.68, Liquid limit LL=25%, Plastic limit=19%, and clay activity (A) = 0.19. The program consists of two sets and as follows:

- Saturated tests: The soil model prepared with dry unit weight γd ≈15 kN/m^3 and degree of saturation S ≈ 90%. Four tests with a model soil prepared in saturated conditions mentioned earlier, with two pressure transducers inserted at four different position these are Z/B= 0.5, 1, 1.5 and 2. The pressures device positioned at the same level in the soil model one at center and the other at corner below model footing.
- Unsaturated tests: Another, four soil models tested with unsaturated conditions and with identical soil pressure positions and dry unit weight γd ≈ 15 kN/m^3 and a degree of saturation S ≈ 60%.

Figure 5. Suction monitor 900M with soil and temperature probes.

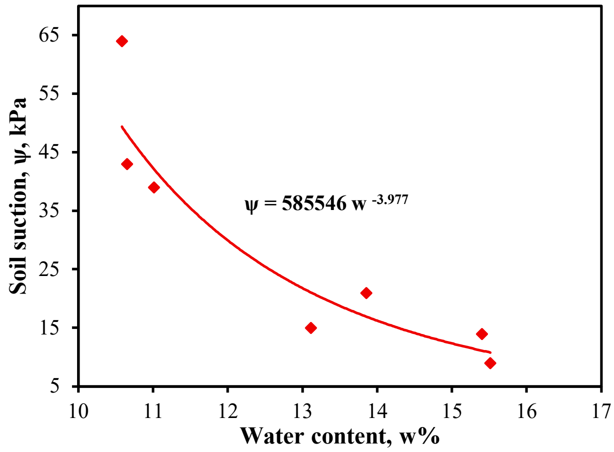

Figure 6. Relationship between the soil suction and water content obtained using a device in Figure 5.

3. RESULTS AND DISCUSSION

For the sake of comparison, the tests were divided in to two sets (saturated and unsaturated) to discuss the load transfer mechanism for the two sets. The results of saturated models are shown in Figure 7. Each part of Figure 7 includes the experimental stress results that were measured at the center and corner of the footing, and results obtained from theoretical analysis. The results of unsaturated models are shown in Figure 8. All these results obtained in Figures 7 and 8 show greater values of measured stresses compared to those obtained from theoretical analysis. It's a clear evident from all the curves obtained that the experimental measured stresses give a much more values than the value measured theoretically. Further the stresses measured at the center of the footing is also more than that measured at the corner of the footing for both soils tested, and the trend of experimental tested soil curves give always a non- linear response in comparison of a linear trend curves get from theoretical calculations. The curves of experimental works indicated a much more stresses transferred to the underlying soil compared to that for saturated one, which gives a greater bearing capacity results obtained for unsaturated soil with a range (3 to 4) times for the soil at the same dry unit weights tested.

The comparison of stresses measured at the center and corner of the footing (at different depths) for saturated soil are shown in Figure 9, while the figures for the measured unsaturated soil stresses are shown in Figure 10. All these figures give a logic results that the measured stresses decrease as the distance increase under the footing for both suited transducers (center and corner), and for both tested soils. Another more detailed comparison for the transducer at the same depth (corner and center), the stresses transferred for both soils are shown in Figure 11. In general, and for all tested footings, the percentages of stresses transferred in saturated soil were greater than the stresses transferred in unsaturated soil during specific period. This leads to indication that as the soil becomes stiffer, a reduction in the transferring stresses was found and vice versa.

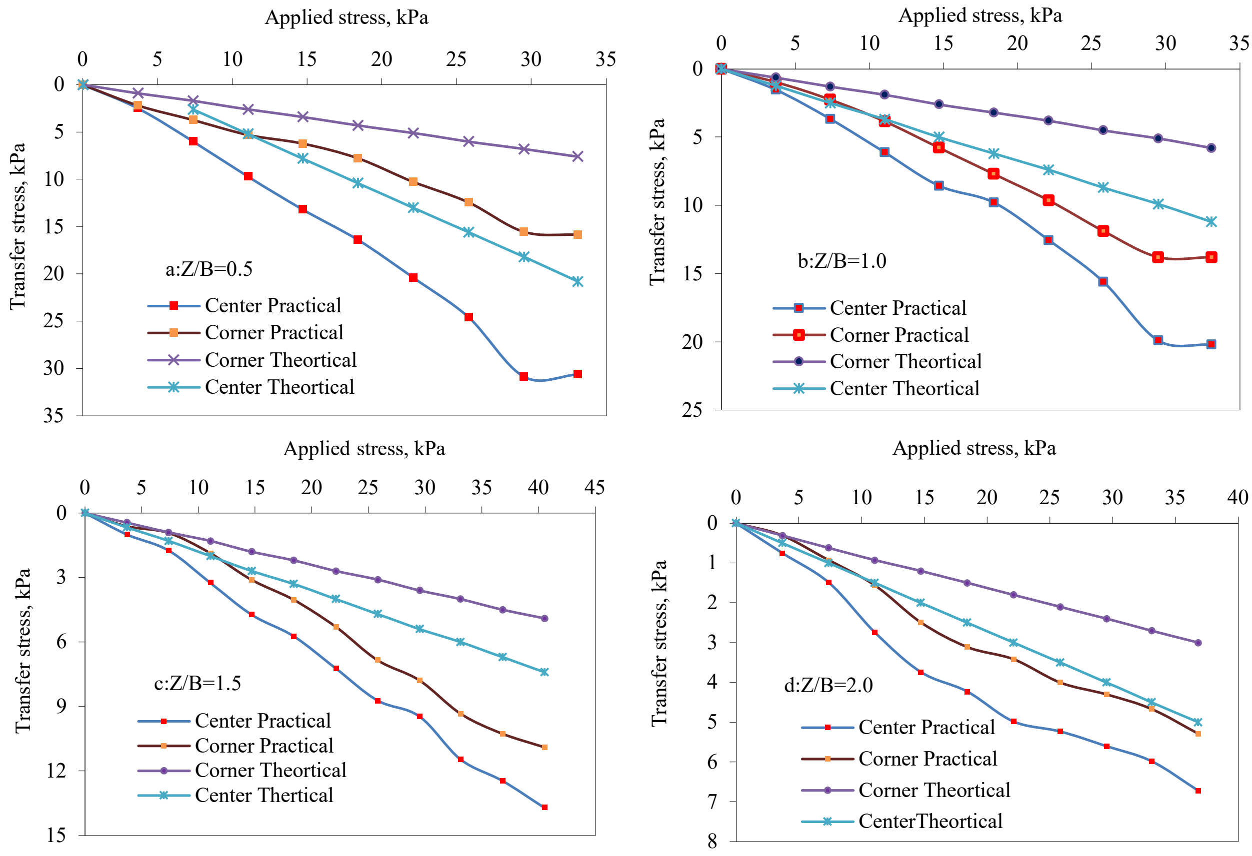

Figure 7. Stresses measured and calculated below center and corner of footing tested in saturated soil with S ≈ 90% and γd ≈ 15 kN/m³.

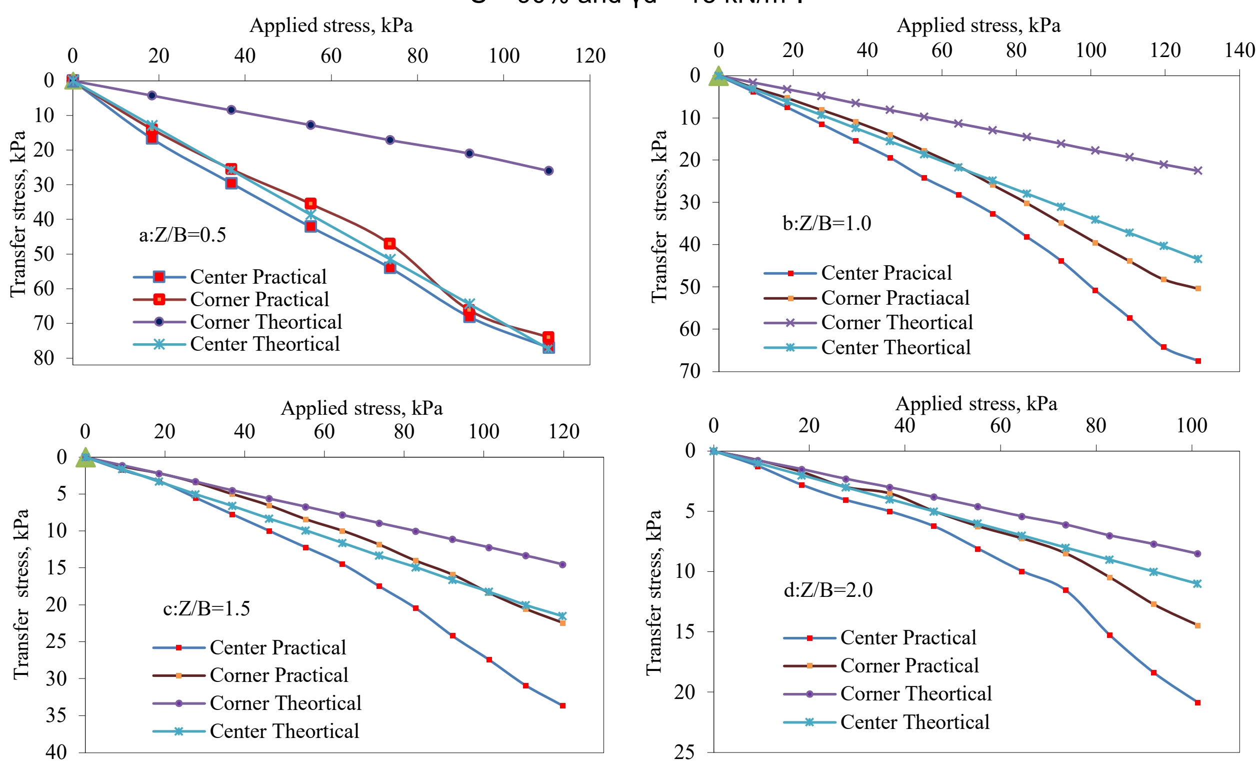

Figure 8. Stresses measured below the center and corner of footing tested in unsaturated soil with S ≈ 60% and γd ≈ 15 kN/m³.

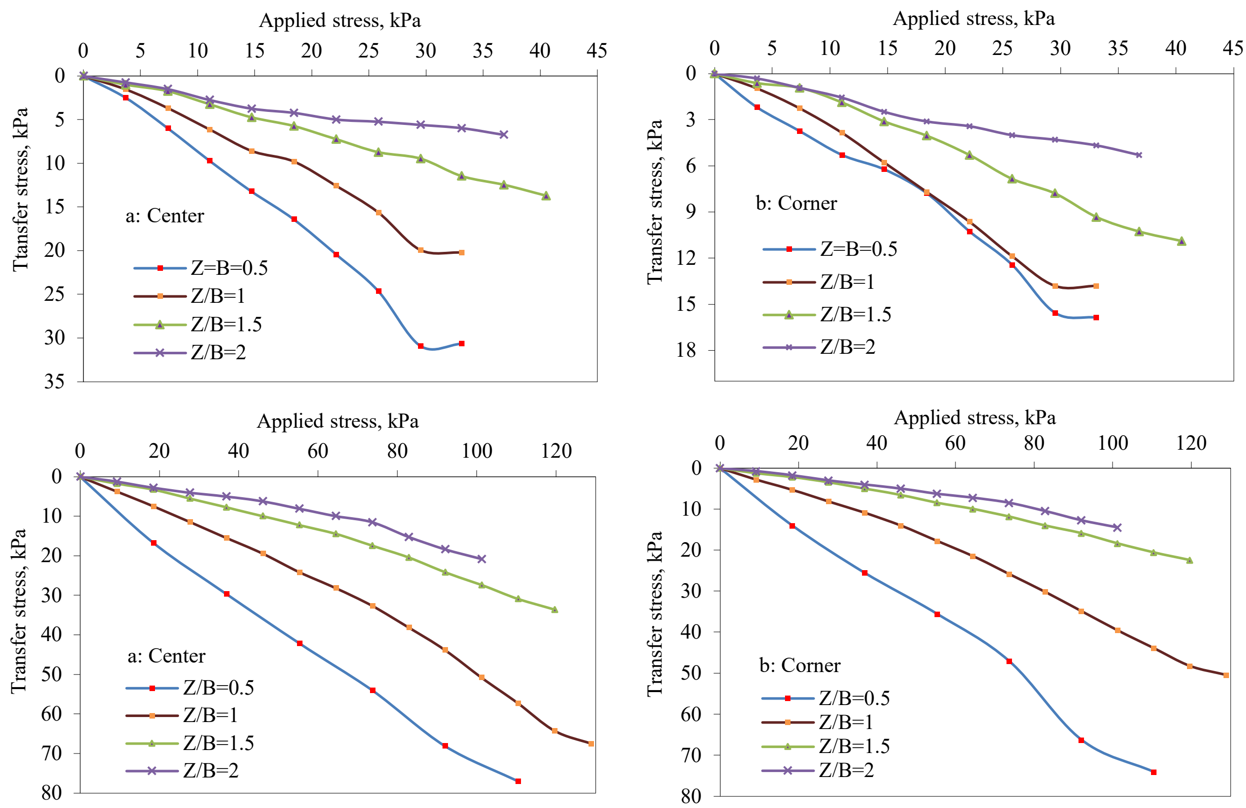

Figure 10. Stresses measured below the footing at different depths tested in unsaturated soil with S ≈ 60% and γ_d ≈15 kN/m³.

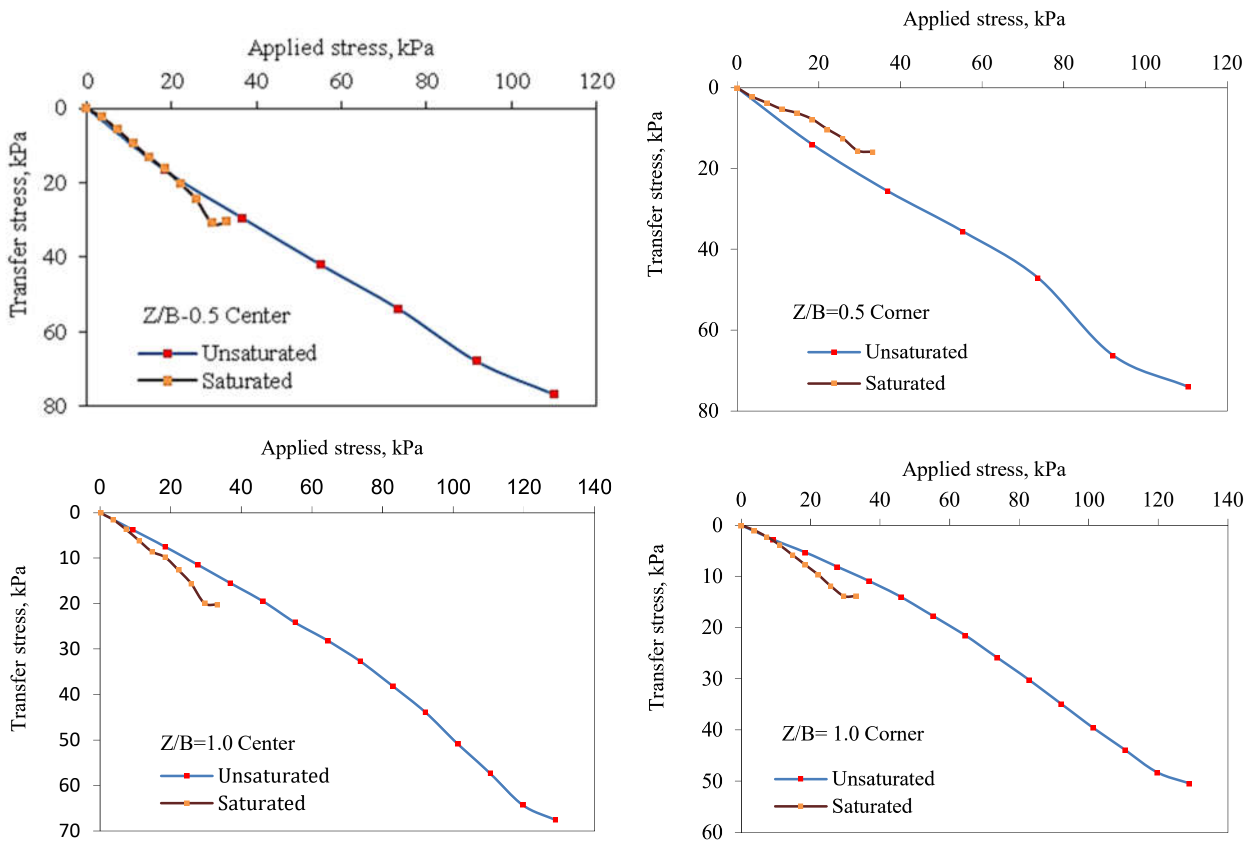

Figure 11. Comparison of stress transfer to soils measured at the same depth below the footing (corner and center).

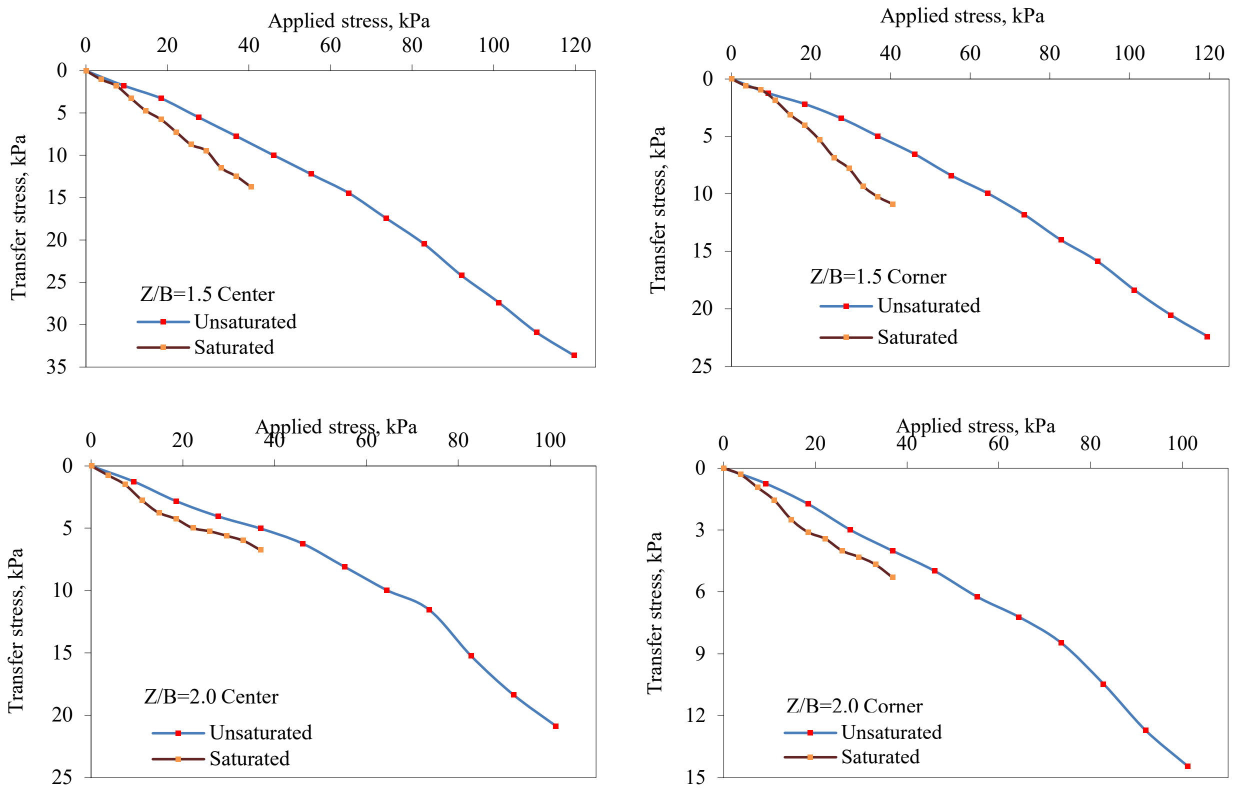

Figure 11. Continued.

4. CONCLUSIONS

Based on the results obtained, the following conclusions can be drawn:

- The experimental findings demonstrate that stress transmission into the soil diminishes with increasing depth beneath the footing, in both saturated and unsaturated conditions.
- For both soil states, the stress measured directly beneath the footing center exceeded that observed near the footing corner.
- At equal depths, saturated soils exhibited higher levels of stress transfer compared with unsaturated soils.
- The experimental measurements for both saturated and unsaturated soils indicated greater stress transfer than those predicted by conventional theoretical methods.
- A comparative assessment of saturated and unsaturated soil tests revealed that unsaturated soils mobilized higher stresses, resulting in bearing capacities approximately three to four times greater than those of saturated soils at equivalent dry unit weights.

REFERENCES

[1] Das BM. Principles of Geotechnical Engineering. Boston: Cengage Learning; 2020.
[2] Abd El Samee WN. Effect of shape and depth of shallow foundations on failure mechanism and wedge angle of sandy soil. In: Advanced Research on Shallow Foundations. 2019. p. 197–216.
[3] Pantelidis L, Gravanis E. Elastic settlement analysis of rigid rectangular footings on sands and clays. Geosciences. 2020;10(12):491.
[4] Das BM, Sivakugan N. Principles of Foundation Engineering. Boston: Cengage Learning; 2018.
[5] Rao NSV. Foundation Design, Theory and Practice. Singapore: John Wiley & Sons (Asia) Pte Ltd; 2011.
[6] Bowles JE. Foundation Analysis and Design. New York: McGraw-Hill International Book Company; 1996.
[7] Oh WT, Vanapalli SK. Modeling the stress versus settlement behavior of shallow foundations in unsaturated cohesive soils extending the modified total stress approach. Soils and Foundations. 2018;58(2):382–97.
[8] Khallawi AM. Load transfer of pile group in saturated and unsaturated clayey soil [dissertation]. Baghdad: Al-Nahrain University; 2016.
[9] Fattah MY, Salim NM, Irshayyid EJ. Influence of soil suction on swelling pressure of bentonite-sand mixtures. European Journal of Environmental and Civil Engineering. 2017;1–15.

[10] Ahmed MD, Khudair BH, Shiekha AA. Damage pattern scope prediction for well point dewatering on building foundations. IOP Conference Series: Materials Science and Engineering. 2018; 433:012034.
[11] Kim Y, Park H, Jeong S. Settlement behavior of shallow foundations in unsaturated soils under rainfall. Sustainability. 2017;9(8):1417.
[12] Olumuyiwa OF. Engineering site investigation and shallow foundation design in Ore area of Ondo State, Nigeria. RMZ – Materials and Geoenvironment. 2020;67(1):21–33.
[13] Al-Omari R, Fattah MY, Kallawi AM. Stress transfer from pile group in saturated and unsaturated soil using theoretical and experimental approaches. 2017. [Unpublished work / incomplete source].
[14] Khallawi AM. Unreinforced and reinforced sand layer overlying soft clay [dissertation]. Baghdad: University of Baghdad; 1994.
[15] Salih SM. Stress transfer and distribution in reinforcement under footings on reinforced earth [dissertation]. Mosul: University of Mosul; 1989.
[16] Noori DB. Stress transfer on reinforced earth retaining wall [dissertation]. Mosul: University of Mosul; 1985.
[17] Vanapalli S, Taylan Z. Estimation of the shaft capacity of model piles in a compacted fine-grained unsaturated soil. 2011. [Unpublished work / incomplete source].
[18] Al-Omari RR, Fattah MY, Kallawi AM. Laboratory study on load carrying capacity of pile group in unsaturated clay. Arabian Journal for Science and Engineering. 2019;44(5):4613–27.
[19] Al-Omari RR, Fattah MY, Kallawi AM. Bearing capacity of piles in unsaturated soil from theoretical and experimental approaches. IOP Conference Series: Materials Science and Engineering. 2020; 737:012101.
[20] Amin B, Majid G, Matthew T. Effects of groundwater level on seismic response of soil–foundation systems. Journal of Geotechnical and Geoenvironmental Engineering. 2020;146(10):04020110.