American Journal of Civil Engineering
2022; 10(5): 201-212
http://www.sciencepublishinggroup.com/j/ajce
doi: 10.11648/j.ajce.20221005.14
ISSN: 2330-8729 (Print); ISSN: 2330-8737 (Online)

Finite Element Analysis of Shallow Foundation Settelment in Cohesionless Soils

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To cite this article:
Hind Nadhum Raheem. Finite Element Analysis of Shallow Foundation Settelment in Cohesionless Soils. *American Journal of Civil Engineering*. Vol. 10, No. 5, 2022, pp. 201-212. doi: 10.11648/j.ajce.20221005.14

Received: July 30, 2022; **Accepted**: October 4, 2022; **Published**: October 24, 2022

Abstract: Extreme settlement can lead to serviceability complications during shallow foundations design. Since Settlement controls the principle design criterion when it is related to the bearing capacity of soils, the estimation of shallow foundation settlement above loose sandy soils is a highly complex problem. For important structures such as bridges, power plants and earth dams, etc. settlement has to be reduced to ensure the stability of engineering structure, with another word any additional settlement could lead to successive structural damage when it exceeds the allowable. In this a model of (10×10×10) m with loose sand was used to investigate the effect of shallow various parameters by using PLAXIS 3D program which was used to solve many geotechnical problems. The program has been used to investigate effect (applied load intensity 100, 150, 200 KN, shape (circular square), width of foundations (0.75, 1, 1.5) m, internal friction angle of underlying soil (24, 33, 37) degree and effect water tables existence beneath the foundation). It was concluded that the shape, friction angle, modules of elasticity with was estimated based on a relationship which showed a good match with other available relationships predicted by powells and Water table existence which it doubles the settlement as it exist. Based on test results critical values were discussed and recommended.

Keywords: Numerical Modelling, Plaxis 3D, Elastic Settlement, Foundation Shape, Applied Load Intensity

1. Introduction

The main problem in foundation design, is continuously elevated whether to use deep foundations or shallow foundations to support any structure. It is well known that shallow foundations such as spread footing are commonly much less costly than deep foundation structures. Several empirical, semi-empirical and numerical methods have been advanced and focused on predicting shallow footings settlement. Based on several history cases. The reduction usually depends on soil conditions and the distribution of applied loads on supporting shape and size of foundation [1]. The estimation of shallow foundations settlement lying above cohesion less soils is a great challenge in geotechnical engineering.

Generally, differential sand settlement is expected to be higher than clay hence sand deposits are more heterogeneous [2]. High level of permeability for sandy soils, leads settlement to occur in a shorter time after applying loads [3]. In a typical design of shallow foundations, bearing capacity and foundation settlement [4] are two main issues. For cohesion less soil, bearing capacity is usually not a big problem. As a result, it seems that the allowable settlement governs the design [5]. Quick settlement happens due to quick structure deformation and the consequential inability to restrict the destruction and avoid further deformation, such failure can result from extreme settlement [6]. It has been concluded form many conducted researches that the settlement of shallow foundation above cohesion less soil depends on several factors, as the stress-strain behavior of underlying soil, the pressure distribution on the foundation [7], foundation size, foundation geometry, foundation rigidity, thickness of the underlying soil layer, etc.

Some factors show significant effects on the settlement, such foundation size, foundation shape, and load level and stress-strain behavior of the underlying soil layer. With the consideration of all of these factors in estimating foundation, settlement could not be possible without adopting a numerical analysis. Hence, current methods simply consider the more important factors and neglect other less important ones; the stress-strain behavior of sandy soils depends on several properties and features of in situ soil, that will be deliberated in details later.

2. Research Objective

The objective of this research is to estimate the settlement of shallow foundation lying above cohesion less soil with considering the effect of the load intensity and internal friction angle of soil, shape of foundation and effect of water table. With respect to many parameters that effects the stability of a shallow foundation, limited values of settlement are not probable to be predicted unless numerical analysis is approved, therefore an important geotechnical engineering tool named PLAXSIS 3D program has been used to analyze and predict shallow foundations settlement. Performance of a shallow foundation with various shape (square, circle) and widths (0.75, 1, 1.5) m resting above a certain loose sand soil was investigated.

The soil used in this research has a 15% relative density (R_e) and total weights, loosest unit weights are 1531 and 1889 g and (24, 33, 37) degree internal friction angle (ϕ). The settlement has been analyzed by using one of the most important tools of geotechnical engineering PLAXSIS 3D program. It is obvious that cracks appear in a structure due to foundation movement. As a result, settlement should be reduced to insure the stability of engineering structures.

3. Literature Review and Research

It has been reported that further than 40 different methods are obtainable for predicting foundations settlement underlying granular soils (Douglas, 1986). For states where the theoretical and further methods fail to offer acceptable results. Several settlement-prediction approaches in the geotechnical literature (theoretical and experimental) of shallow foundations on several types of soil [2, 8, 9]. As a result, all these presented methods ranged from only empirical to finite elements and complex nonlinear cannot reach a reliable and exact settlements prediction [10]. At current, it could be possible to analyze foundations settlement and bearing capacity by finite element approaches, and limits of equilibrium [11-14], finite difference techniques [15] have been extensively used in current years to predict the bearing capacity and settlement of foundations. Two main components of shallow foundations settlement need to be measured (elastic settlement and consolidation settlement). Elastic settlement must be carefully estimated if the foundation is resting on cohesionless soils.

For cohesionless soils case it is difficult to obtain undisturbed soil sample, which produces more difficulties in calculating the compressibility of the soil mass. This explains why a high number of settlement prediction approaches are obtainable for footings lying above sandy soils literature, much more than for clays. Douglas (1986) stated more than 40 different settlement prediction methods are used currently. The greatest challenging problem is how to estimate the non-uniform kind because it may cause to important issue such as cracking of foundation or beam, slabs, etc. Due to all difficulties in getting undisturbed samples for cohesionless soils, several methods for settlement estimating have focused on the relationships among all in situ investigations. "Settlement of footings is influenced by on various parameters, including shape and size of the footing, embedding depth, layering, soil mass non-homogeneity, type of loading conditions, and saturation degree" [16].

Settlement of a structure could be estimated by three classifications methods such as empirical method or semi-empirical method and numerical methods. In this research, a numerical method has been discussed. As mentioned before soil settlement can be divided into three types [9, 10]:

1. Immediate Settlement (Si): it is defined as settlement happened straight after of a load application, in which settlement happens after a load is applied. The amount of the settlement will be influenced the flexibility of the structural foundation and the kind of soil material on which the structure resting on. For cohesion, the immediate settlement usually is so small when compared to the consolidation settlement, therefore this settlement typically unnoticed, but it is usually careful measured for any sandy soil.
2. Primary Consolidation Settlement (Sc): This type usually happens due to gradual dissipation of pore water pressure encouraged by external applied loads. It is a time-dependent and it may very long time to occur maybe months or years.
3. Secondary Settlement (Creep) (Ss): Happens at constant actual stress due to volume change of soil. As a result, total number of settlements can be estimated by this formula St = Si + Sc + Ss. Figure 1 verifies the problem statement modeled and investigated in this research. Figures 3 and 4 illustrate types of settlement.

Settlement of a shallow foundation above any soil usually consists of two components as shown in equation 1.

$$s = s_i + s_s \quad (1)$$

Where si = immediate settlement,
ss = secondary compression.

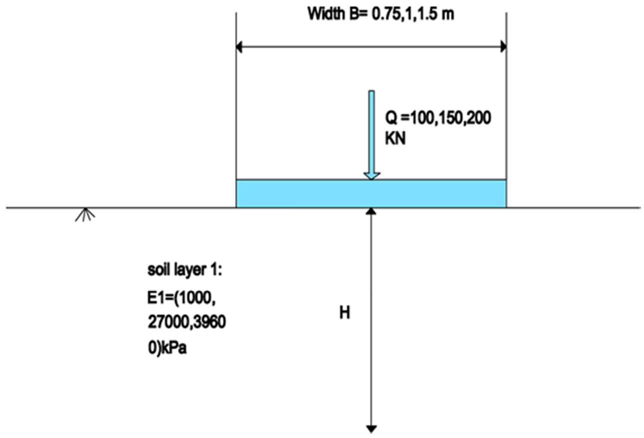


Figure 1. *Investigated problem statement.*

Factors that mainly effects the shallow foundation stability summarized in Figure 2 below.

Relevant to	Factors affecting settlement	Remarks
Foundation	Foundation size (width/diameter B)	Small footing to large raft.
	Foundation shape (L/B: length to width ratio)	Square, rectangular and circular.
	Foundation depth (D)	Shallow foundation (D/B<1)
	Foundation rigidity	
	Roughness of foundation base	
Load applied on foundation	Distribution of the load	Only vertical load is considered in this research.
	Magnitude of the load	
Underlying soil profile	Stress-strain behaviour	Linear elastic, non-linear elastic, elasto-plastic
	Bulk density (γ)	
	Depth of water table	
	Thickness of soil layer (h)	

Figure 2. *Factors mainly affecting shallow foundation settlement (Huang, Yongqing, 2011).*

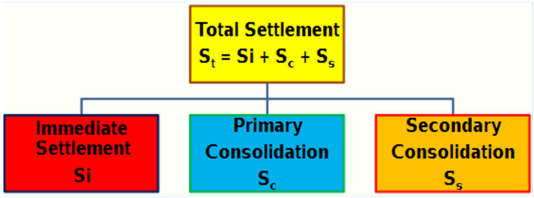


Figure 3. *Types of settlement.*

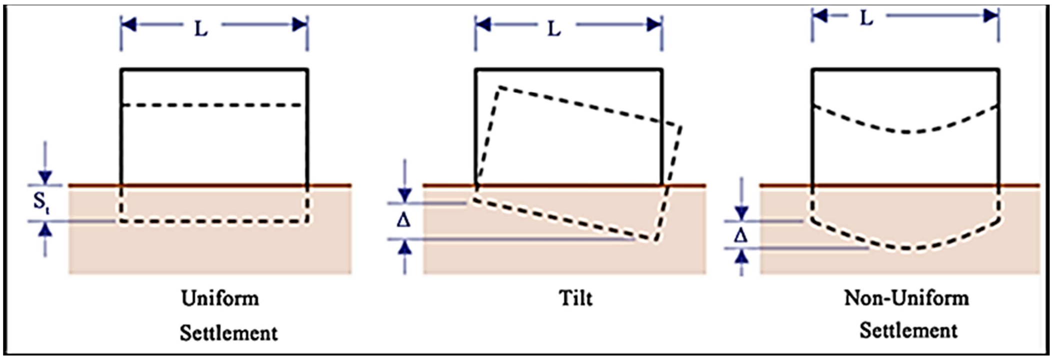


Figure 4. *Types of shallow foundation settlement (Talib, 2016).*

Terzaghi (1943) submitted that the soil toughness (Young's modulus) of saturated cohesion less soil is nearly 50% of that of the dry soil. Water table rise in cohesion less soils causes extra settlement. There are numerous details for this further settlement. Peck and Bazaraa (1969) documented the field evidence in which settlement doubles as the water table increases up to the footing level. Changes in water contents and groundwater level extremely disturb the strength and the properties of soils, thus overall structures lying on. However, geotechnical engineers abandonment this matter in furthermost cases, supposing that soil circumstances will continually stay unchanged. Which seems to be essential to use several ground improvement methods to enhance and improve the soil, and support and repair foundations [17, 18].

Floods, extreme rainfall, cyclical changes, considerably influence foundation settlement behavior, which may exceed settlement limits [19-21]. For positions where the near-surface soil is incompletely saturated through the structure's design life, the current design approach can be whichever conventional or un conservative, dependent on the variety of hydrological event. This procedure exceed the tolerable limits of settlement which may risk the structure's stability. Therefore, it is vital to estimate the extra settlements that may happen due to water changes conditions to offer an adequate margin of safety [20, 21].

4. Finite Element Program

Numerical techniques are extensively used in the current time with the development of computer knowledge. Amongst numerical approaches, FEM is possibly the most usually and commonly used technique. Typical software consists of (ABAQUS, ANASYS, and PLAXIS). Moreover, researchers and engineers also adopt FDM. However, numerical methods also have limits. The most essential limits is analysis accuracy of the modeled geotechnical problem, which depends on the adopted constitutive model and the input values determinations of those parameters. To consider the settlement of a foundation, MC model involving linear elasticity and perfect plasticity perhaps be a respectable choice. However, the choice of the adopted model is the main key.

PLAXIS is a wide-ranging program prepared to analyze many features dealing with complex geotechnical constructions. It is also used to resolve the equilibrium equations of a finite element modeling used in the present study to analyze the performance of a shallow foundation lying above on loose sandy soil, it used to offer a valuable analysis instrument for engineers who are not particular in finite element analysis. The program achieves a three-dimensional analysis of deformation and stability in geotechnical engineering. Non-linear finite element computations are to be completed without taking a long time for regular analyses. Soil is a multiphase material having properties that can change with the changing of the environment. Most of our geotechnical-engineering problems, are 3D in nature therefore, PLAXIS 3D program is an appropriate instrument for engineers that enable the user to estimate the interactions between any structural elements, such as soil, liquid, and other soil-structure-Interactions.

PLAXIS 3D is planned for three-dimensional analysis of deformation and stability in geotechnical engineering problems that may cause threatening to the stability of any structure. It is a suitable geotechnical instrument used to deal with nonlinear and complex mechanical behavior of soil and modelling the composite geotechnical construction [22]. Soil modeling for many projects is a very important matter, which may involve the modeling of constructions, moreover the interaction between the soil and constructions, which should be created. Geotechnical applications need basic Progressive models to simulate the nonlinear, time-dependent besides the anisotropic behavior of soils.

The mean objectives of PLAXIS are planned to offer functional analysis for geotechnical engineers who do not have unavoidably a numerical expert. Table 1 represents Soil properties of soil used in finite element analysis.

Table 1. *Soil properties of soil used in finite element analysis.*

Properties	Values
Cohesion (kPa)	0
Modulus of Elasticity, E (kPa)	10000, 27100, 39600
Poisson's Ratio, ν	0.25
The angle of internal friction	24, 33, 37
Density (kN/m^3)	15.5, 21, 23
Model name	Mohr-Coulomb Failure
Material	Cohession-less Soil
Condition	Drained
Model size	$10\times 10\times 10\ m$

5. Data

The data of physical and chemical soil properties used in this research is conducted by E. Hassan Abdula et al. [23] by the consistent field measurements the soil sample has been sampled from AL- NAJAF city, IRAQ exactly from a area with longitude of 44 °25′0′East and 31° 56′0′.

Figure 5 represents the grain size distribution of soil used. The references of the used database and the basic statistical information used to investigate the performance of a shallow foundation resting on loose sandy soil is summarized through Table 2. Physical properties of sand used is presented Figure 6 represent chemical properties of sandy soil used in all experiments.

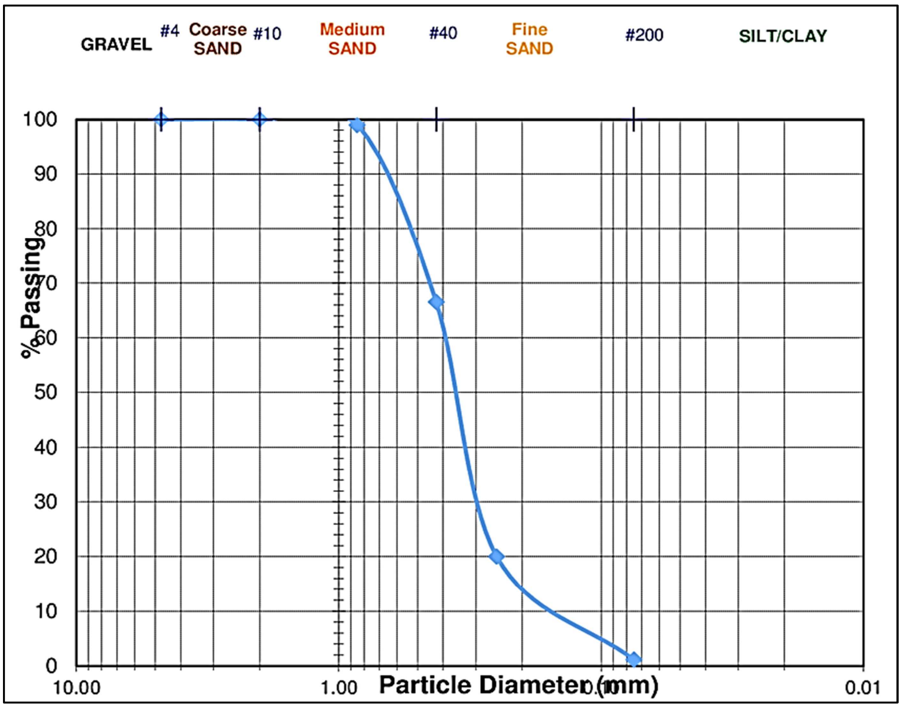


Figure 5. *Grain size distribution of soil used (Albakaa and Fakhraldin. 2022).*

Table 2. *Chemical properties of sandy soil used in the analysis (Albakaa and Fakhraldin, 2022).*

Chemical composition	Values%
SO_2	0.82
Gypsum content	1.76
T.D.S	0.54
Organic content	0.67

Index property	Value	Specification
D_{10}(mm)	0.15	ASTM D422
D_{30}(mm)	0.3	
D_{50}(mm)	0.35	
D_{60}(mm)	0.39	
Coefficient of uniformity (C_u)	2.6	
Coefficient of curvature (C_c)	1.54	
Soil classification (USCS)	SP	
Specific gravity (G_s)		ASTM D845
Maximum dry unit weight, γd max (kN/m3)	18.89	ASTM D7382-08
Minimum dry unit weight, γd min (kN/m3)	15.31	ASTM D4254 -14
Maximum void ratio, e_{max}	0.775	
Minimum void ratio, e_{min}	0.403	
Relative density, Dr (%)	15% (loose)	
Void ratio, e	0.72	
Dry unit weight, γd (kN/m3)		
Optimum water content		ASTM D698

Figure 6. *Physical properties of sand used (Albakaa and Fakhraldin, 2022).*

6. Modulus of Elasticity

A generalized correlation is established between modulus of elasticity (E) of a soil and the several engineering properties of that soil by [24]. This developed correlation is simple and can be accepted for useful estimating of Modulus elasticity for engineering application. Modules of elasticity of soil found by using this relationship was found showed a good match with other available relationships predicted by powells [25] as its shown in Figure 7.

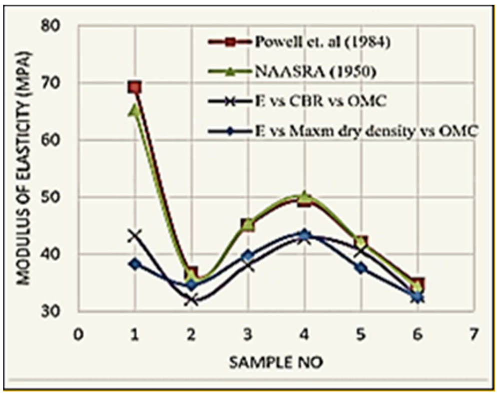


Figure 7. *Comparison analysis results (Ghosh, Datta, Chattapadhyay, 2017.*

$$E = 7000\ N^{0.5}\ \text{kPa} \quad (2)$$

Where:

E: Modulus of elasticity in KN/m^2 and N: Number of blows.

The Modulus of soil elasticity rate is estimated by using a standard relationship equation given by Bowels, (1982) through using SPT N values I an implemented equation 2. N value was found by standard relationship between N and Φ values. From (IS 6403-1981) as shown in figure 8 below.

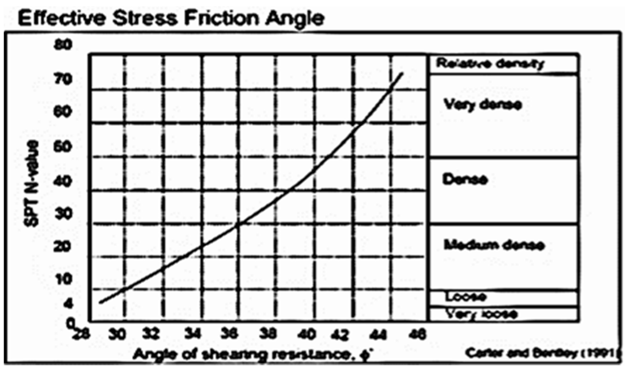


Figure 8. *Specified relationship between Value and internal friction angle.*

7. Results

7.1. Effect of Foundation Geometry

Foundation geometry is one of the essential factors that influence the shallow foundation displacement [26]. Figure 9 demonstrateds the variation of three different foundation geometry modeled cases which has analizes.. Figure 10 (a and b) shows the stress- strain diagrams of rigid square foundations, having .75, 1, and 1.5 m width (B) and 10 m soil thickness. The results shows that with increasing the square slallow founation width from .75 m to 1m and 1.5 m the settelment of 100 KN load applied over a square shallow foundation has been redused to 96%, 99% while with 150 KN load the settelment has been redused by 62%, 95% respectivily as it is clear in Figure 10 (a and b) respectivaly. This redution probebly happened due to the reduction of applied load intensity.

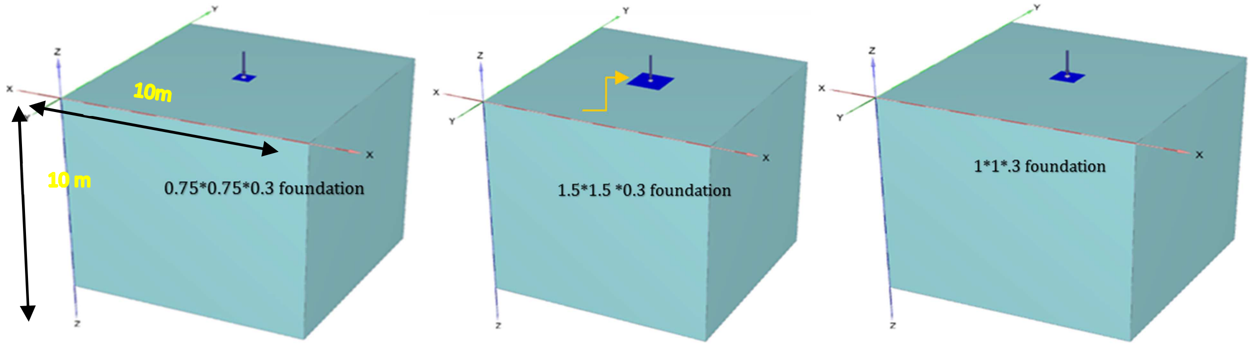
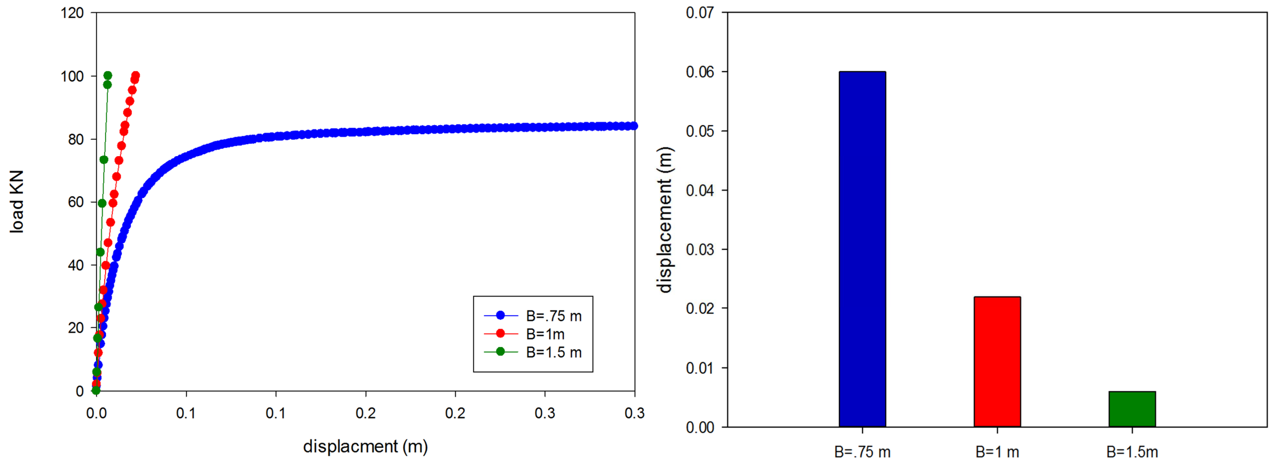
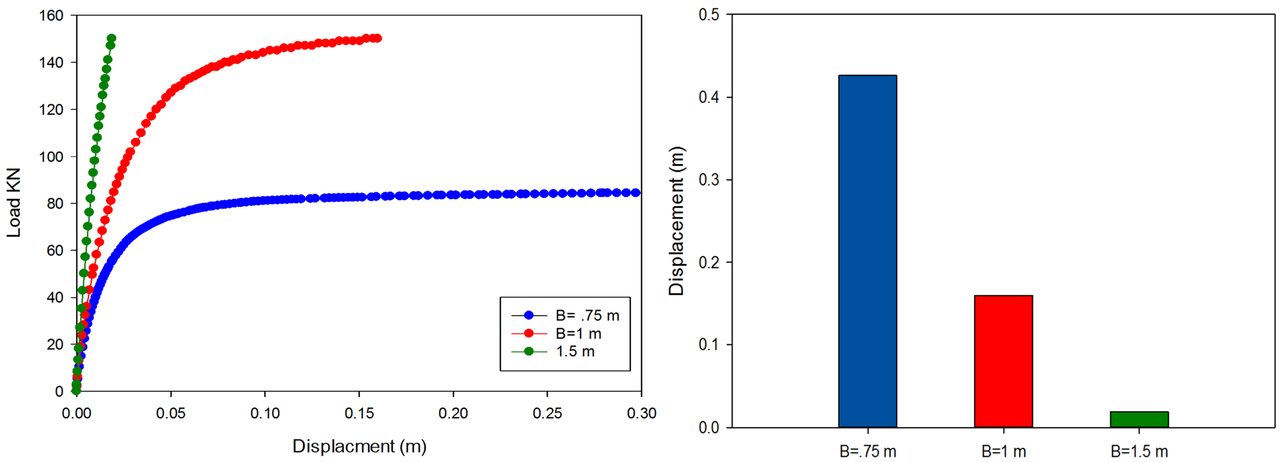


Figure 9. *Numerical analysis modeling of various investigated cases.*



(a) (b)

Figure 10. *(a and b): Effect of shallow foundation size for 100 KN load.*



(a) (b)

Figure 11. *(a and b): Effect of shallow foundation size for 150KN load.*

7.2. Effect of Friction Angle

Friction angles characterizes the particle interlocking of soil, in another way greater the interlocking between the particles, larger the friction angle should be expected and vice versa. At higher normal stress, better interlocking is to be expected. Table 2 represents the data used to investigate the effect of internal friction angle of soil.

7.2.1. Square Foundation

The effect of internal friction angle for .75 m, 1 m and 1.5 m shallow foundation when it is subjected to 150 KN applied load has been investigated. Friction angle has the most important effect on capturing the foundation displacement among all soil input parameters. Table 3 represents the data used to investigate the effect of internal friction angle of soil. Results of finite element analysis and deformed mesh of total vertical displacement for 0.75 m is foundation case is shown in figure 12.

The results of load displacement curve are, shown in figures 13 and 14 its clear that by increasing the internal friction angle from 24° to 33° and 37° the settlement of a .75 m shallow foundation decreased by 92%, 95% respectively While the settlement decreased by 89%, 94% respectively with increasing the width to 1m. Figure 13 shows the deformed mesh of total vertical displacement for 1 m foundation case. As its clear in figures 15, 16 the effect of increasing the foundation width to 1m the settlement deceased by 85%, 89% respectively.

Deformed mesh of total vertical displacement for 1 m foundation has been obtained by the numerical analysis as presented in figure 17.

Figure 18 shows that the settlement deceased by 85%, 89% respectively as the width of foundation increased to 1.5 m Figure 19 shows a comparison between values of settlement influenced by different friction angles for 150 KN load.

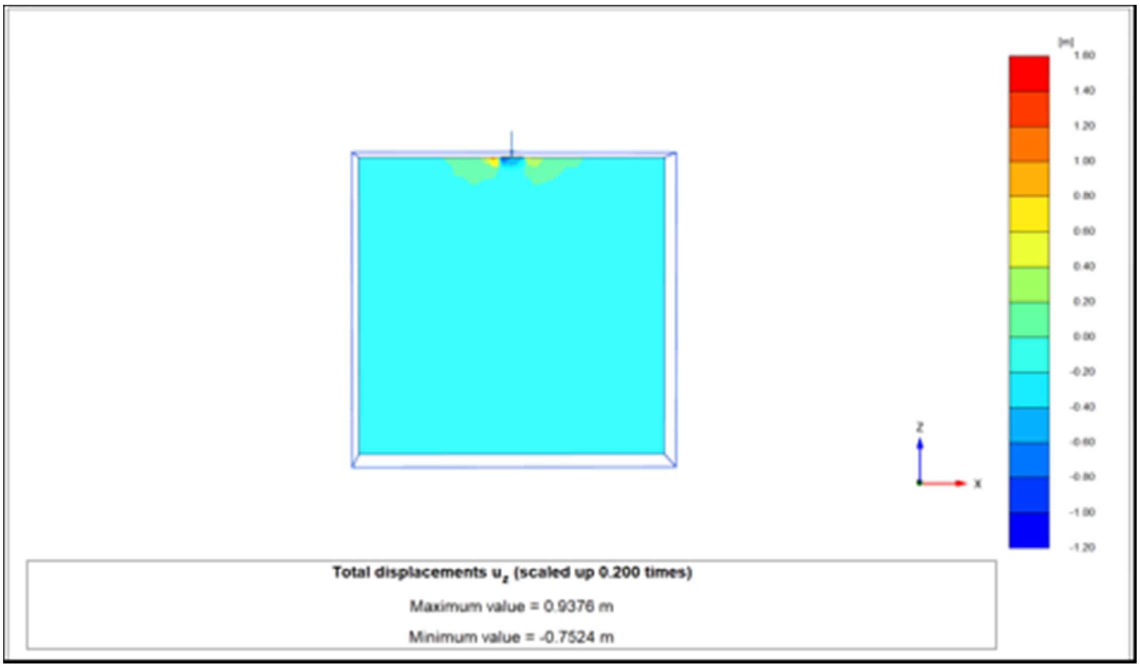


Figure 12. *Deformed mesh of total vertical displacement for 0.75 m foundation case.*

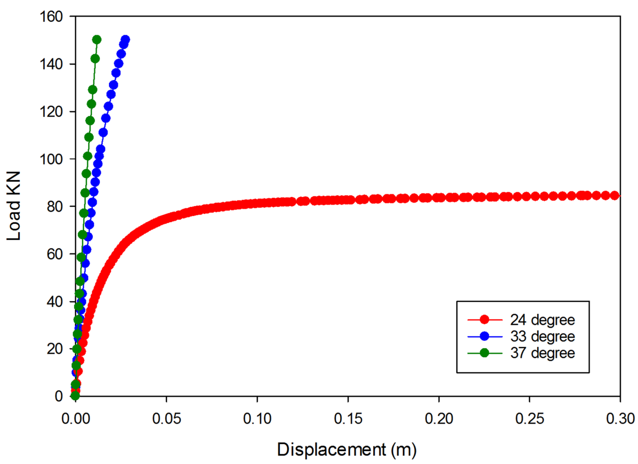


Figure 13. *Relationship between displacement and load.*

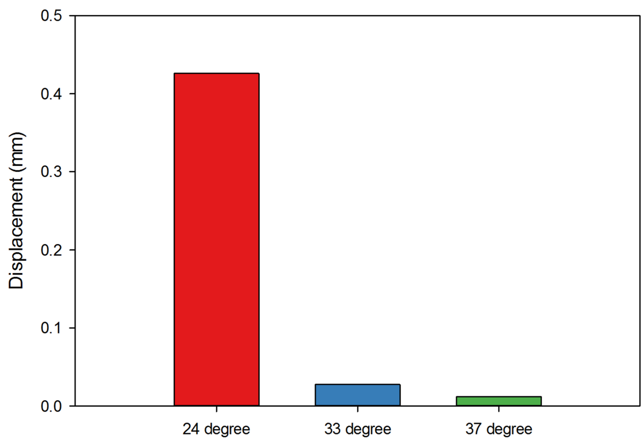


Figure 14. *Comparison between values of settlement influenced by different friction angles for 0.75m width case.*

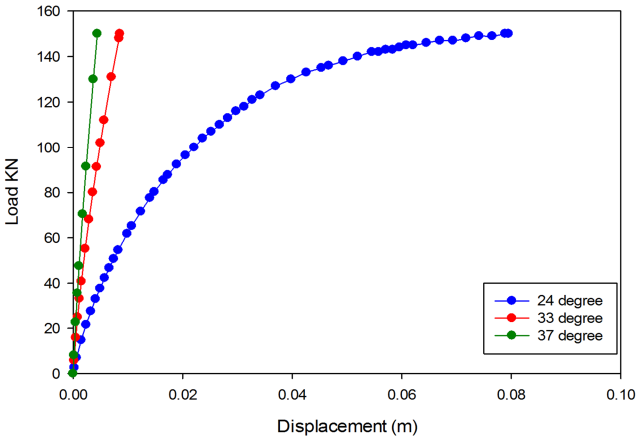


Figure 15. *Load displacement curve of 1 m foundation width case.*

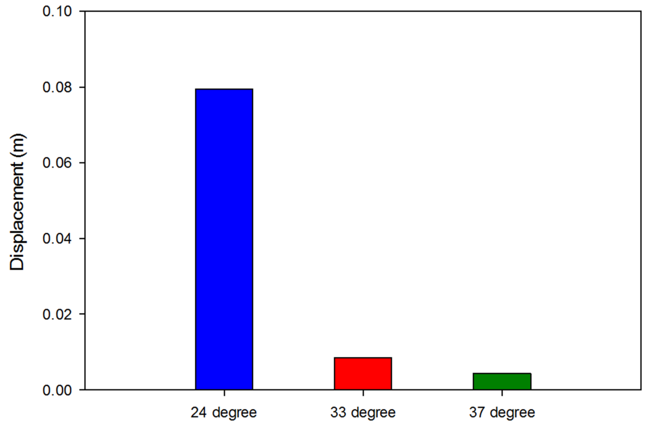


Figure 16. *Comparison between values of settlement influenced by different friction angles for 1m width case.*

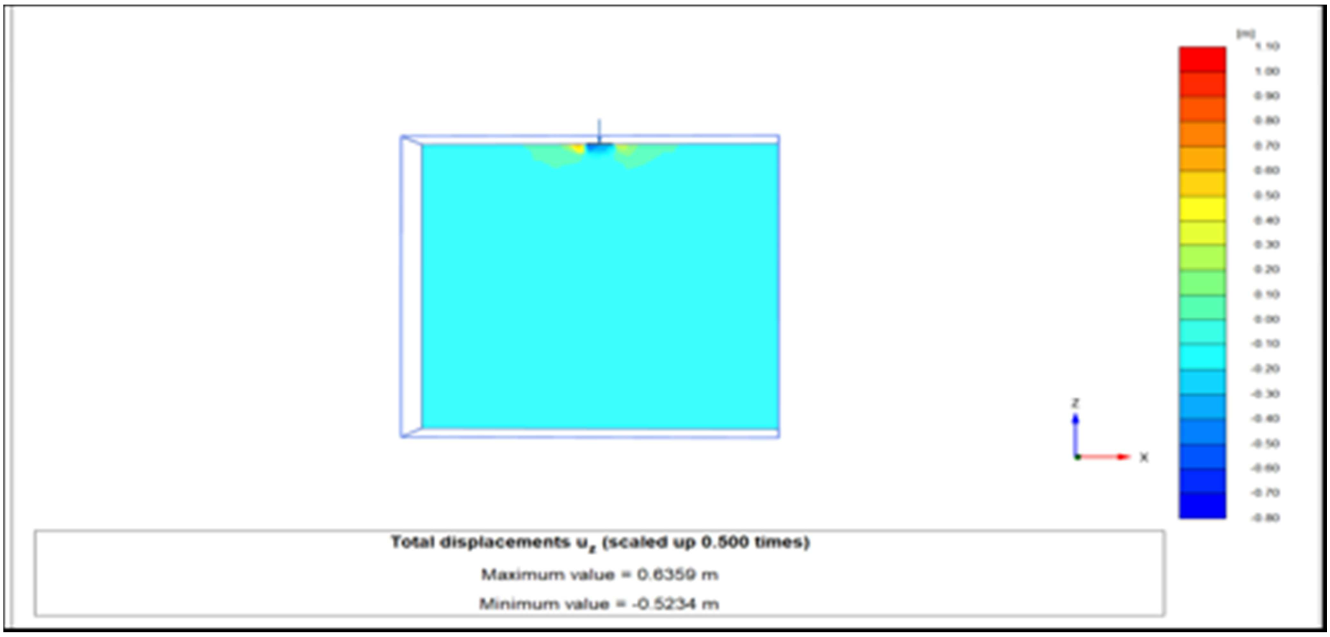


Figure 17. *Deformed mesh of total vertical displacement for 1 m foundation case.*

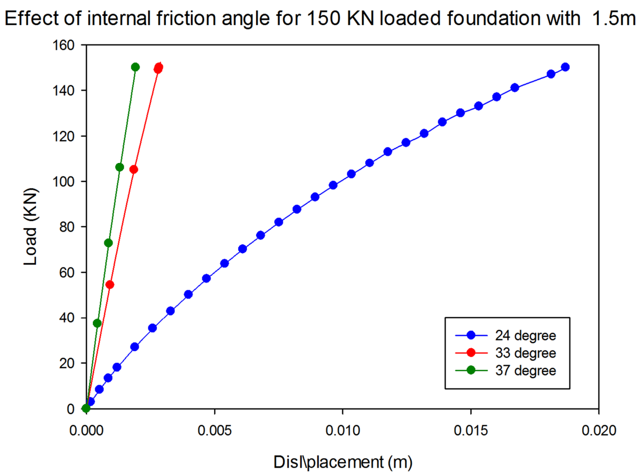


Figure 18. *Load displacement curve of 1.5 m foundation width case.*

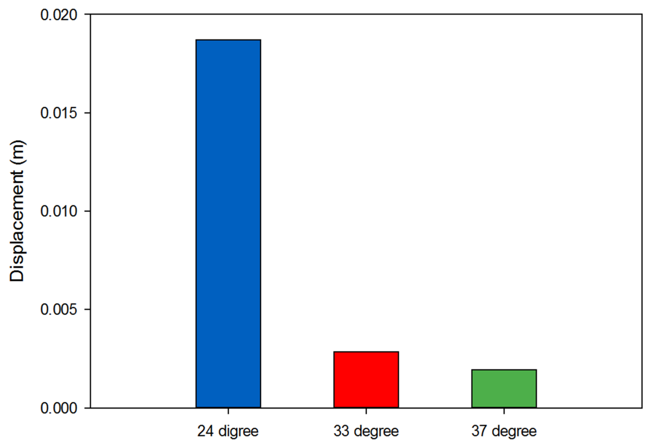


Figure 19. *Comparison between values of settlement influenced by different friction angles for 1.5 m width case.*

Table 3. *Data of frictions angle of soil used.*

Friction angle (degree)	Modules of elasticity (MPa)
24	10000
33	27100
37	39600

7.2.2. Circle Foundation

Effect of internal friction angle for 150 KN applied load on a circular shallow foundation has modeled by PLAXSIS 3D as shown in figure 20. Deformed mesh of total vertical displacement for 1 m circular foundation case has been obtained by numerical analysis as represented in Figure 21. The results shows that by increasing friction angle from 24° to 33°, 37° settlement decreased by 95%, 98%. Figure 22 illiterates the influence of internal friction angle on shallow foundation settlement for 150 KN applied load case.

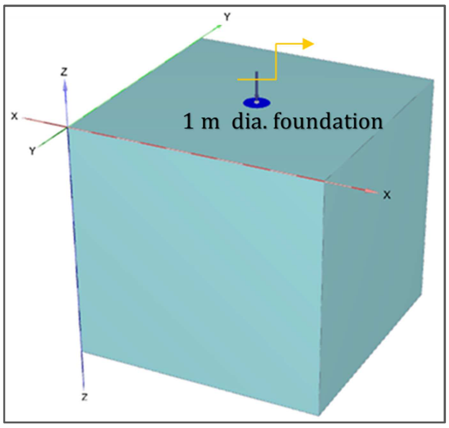


Figure 20. *Numerical analysis modeling for 1m diameter circular foundation.*

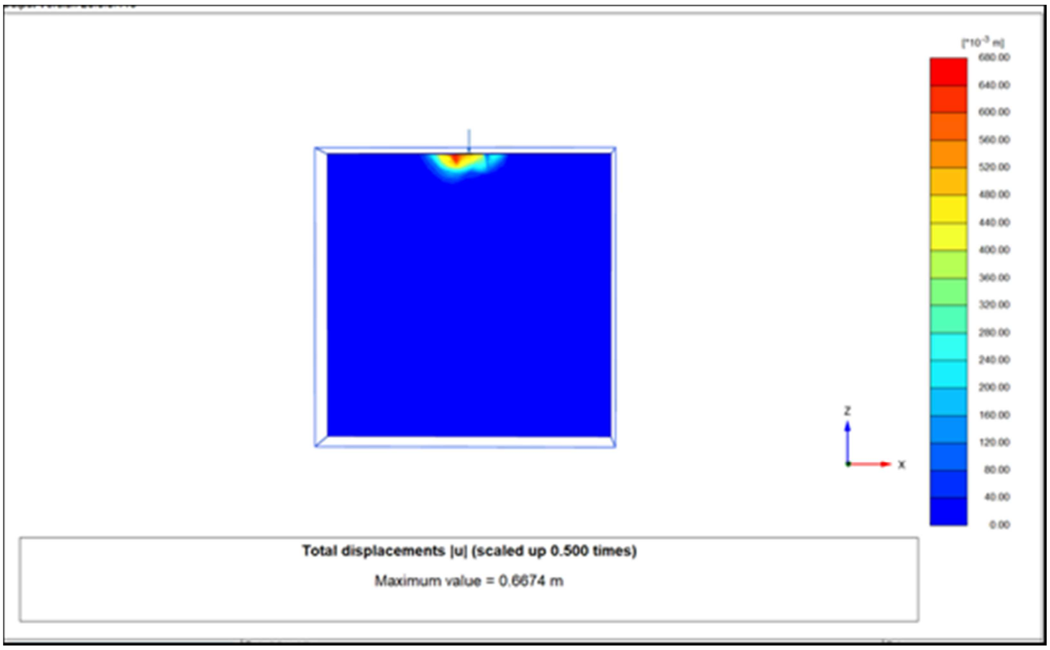


Figure 21. *Deformed mesh of total vertical displacement for 1 m circular foundation case.*

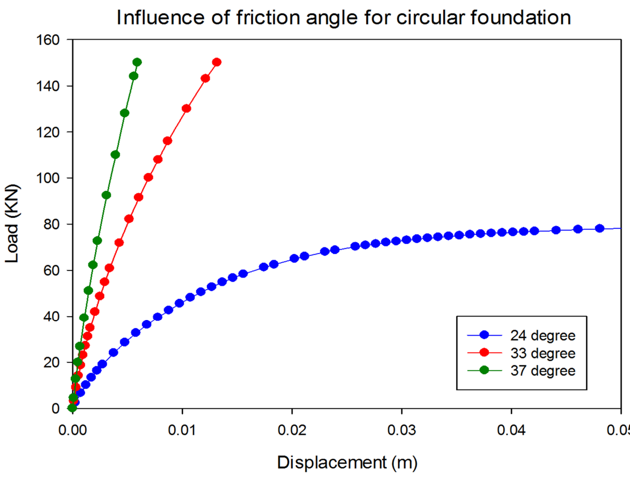


Figure 22. *Load displacement curve for internal friction angle on shallow.*

7.3. Effect of Foundations Shape

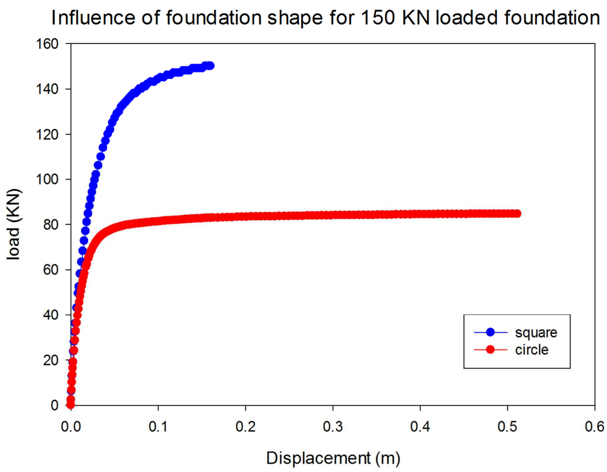


Figure 23. *Load displacement curve for shape effect on foundation performance.*

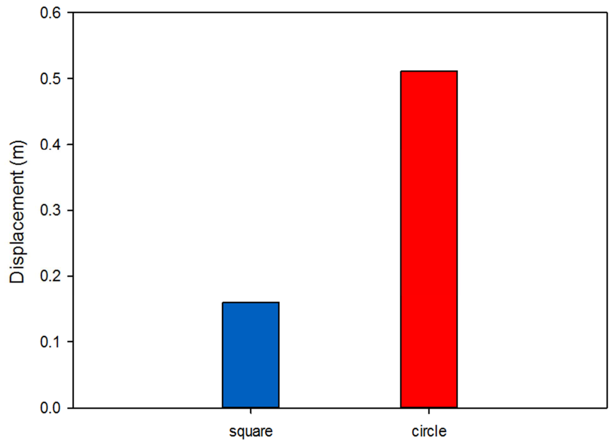


***Figure 24.** Comparison between values of settlement influenced by different shapes of footings.*

Effect of 1m shallow foundation shape for 150 KN applied load case was studies by numerical analysis and it was found that square foundation settlement is 96% less than circle one. Figures 23 and 24 represent the effect of foundation shape on the immediate settlement. It can be concluded from the obtained results the shape of foundation influences the shallow foundation settlement.

7.4. Effect of Water Tables Existence

The existence of water table can affect the structure of the supporting soil. In many situations, water table results severe damage to the structure [27]. Pumping from nearby building cause a reduction in the water level leading to great damage and cracking of nearby structures. Excavations also affects the footings stability leading to a great damage to the construction.

Future growth in water tables level underneath the structures foundation can cause extra settlements, which may threaten the stability of the constructed structure. The tolerable shallow foundations settlements are usually small (25) mm, and therefore any such further settlements has to be expected with good care. Terzaghi's (1943) suggested that the settlement of shallow foundation doubles the settlement when the water table rises beneath the foundation [28].

Settlement of shallow foundation doubles the settlement when the water table rises beneath the foundation.

7.4.1. For 1m Shallow Foundation Width

Figures 25 and 26 reflects the influence of water tables rise beneath a shallow foundation width. The results indicates that the rise of water beneath a shallow foundation increases the settlements by 96%. This result shows a good agreement with Terzaghi's suggestion as the settlement almost doubles as the water table rises under the foundation.

7.4.2. For 1.5 m Shallow Foundation width Case

Figure 27 reflects the outcomes of water table rise beneath a 1.5 m shallow foundation. The results indicates that the rise of water beneath a shallow foundation increases the settlements by 18%. This result indicates that when the width of foundation ≥ 1.5 m the effect of water table decreases. A comparison between vertical settlements due to water table rise is verified in figure 28.

7.4.3. For .75 m Shallow Foundation width Case

Figure 29 reflects the effect of water table rise beneath a shallow foundation width. The results indicates that the rise of water beneath a shallow foundation increases the settlements by 95%. Also, this results makes a good agreement with Terzaghi's suggestion as the settlement doubles with water table rise under the foundation.

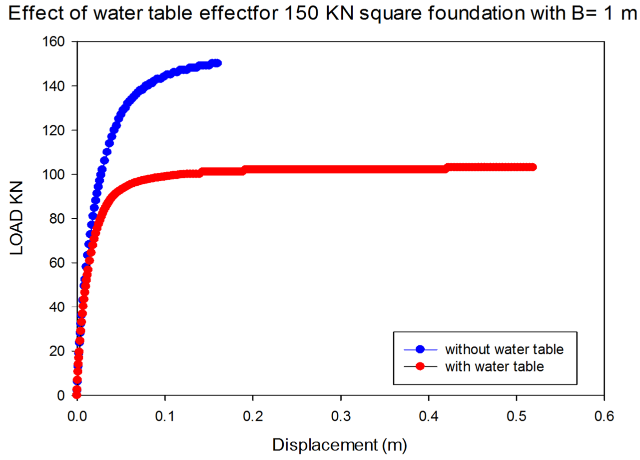


***Figure 25.** Load displacement curve water table effect for im width case.*

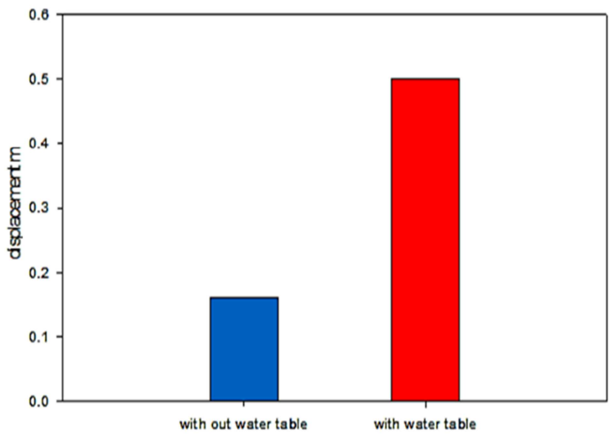


***Figure 26.** Comparison of settlement valu influenced by water table.*

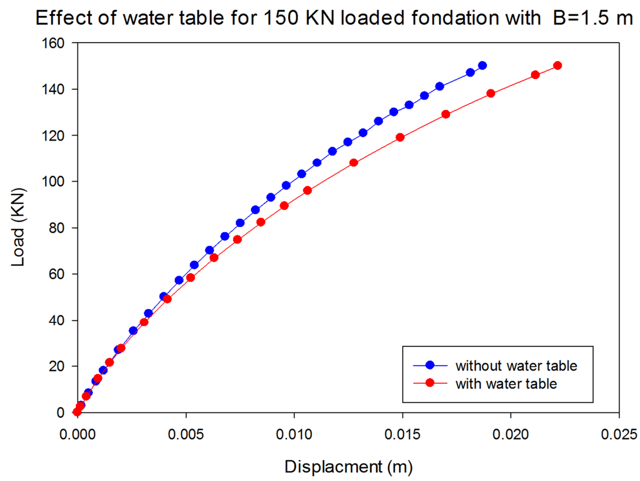


***Figure 27.** Load displacement curve water table effect for 1.5 m width case.*

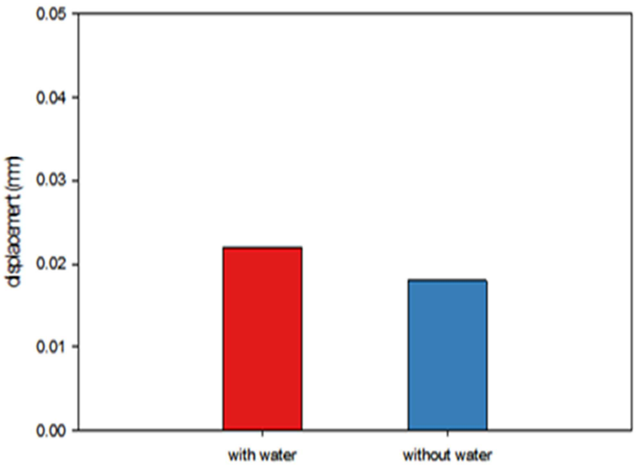


Figure 28. *Comparison between vertical settlements due to water table rise.*

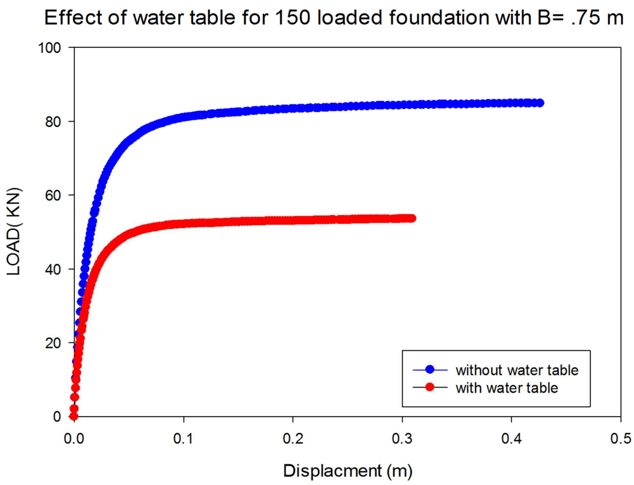


Figure 29. *Load displacement curve for water table effect (0.75 m width).*

8. Conclusion

Finite element analysis of shallow foundations settlement. Analyses were approved out by applying the Mohr–Columb model under various soils condition, loading intensity, shape and saturation degree (saturated, unsaturated). Built on the results of this research, the subsequent conclusions can be strained:

1. The footing settlement under various load intensity, decreased by increasing the width of footing, in which foundation having 0.75 m width showed maximum settlement.
2. The footing settlement beneath various shapes of footing increased, with increasing the load intensity on the shallow foundation. As a result circular shape showed maximum settlement.
3. Settlement at the center of 1m circular footing with a 150 kPa applied load increased by 96% when compared with the settlement of square foundation having the same width.
4. The footing settlement was influenced by the variation of internal friction angle. As the friction angle and modules of elasticity increases the settlement decreases for all cases.
5. All models shows that additional settlement has been observed as the water table rise under the shallow foundation, but a shallow foundation with 0.75 m width showed higher settlement.
6. When the width of foundations is ≥ 1.5 m the effect of water table decreases.
7. The settlement doubles for 0.75 and 1 m foundation wide while for 1.5 m wide case, the settlement increased by 18% only.

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