Evaluation on the SPT Based Design Approach for Shallow Foundations

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Abstract. This research evaluated four SPT-based design equations used to estimate the carrying capacity of shallow footing. Using different methods, two plate load tests performed on silty clay and clay soil in Nasiriyah have been used to obtain the ultimate load-carrying capacity. Further, this study aims to utilize the finite element method based on Plaxis 3D foundation software to simulate the behavior of load settlement of the foundation with actual dimensions. It was concluded that the numerical analysis methods showed a good convergence to the actual test results, where the numerical results were 67 and 65 ton/m^2 for two projects, respectively. The field values were 70 ton/m^2 for projects with a number of possibilities in determining the failure areas of the soil to give a sufficient picture of the load expectations. The boundary of the influence zone obtained by the finite element method has functioned as an influence zone proposed for a new proposed equation which gave a good convergence with the measured bearing capacity values.

Keywords: Shallow foundation, plate load test, Finite element method, Ultimate bearing capacity.

1. INTRODUCTION

The design of shallow foundations requires satisfying two criteria: the first is the adequacy of a shallow foundation to withstand the applied load without failure, and the second is that the settlement shall be within the permissible limits [1]. The bearing capacity and the settlement of the soil beneath the foundation determine how well a foundation performs [2]. Mainly, two approaches are available to design shallow foundation theoretical and empirical equations [3]. The theoretical methods are those based on elasticity, plasticity, and upper and lower limits. The empirical approach is based on experimental and field studies such as standard penetration test (SPT) [4-6]. The best method of estimating the bearing capacity was by measuring the load settlement curve using a plate load test (PLT). The PLT is the best method to quantify the load-carrying capacity for the soil at shallow depth from the load-settlement curves [7]. However, in many cases, we need to compute the bearing capacity in the preliminary phase, which needs a fast and simple equation based on the field test. A full-scale axial stress test is frequently the most effective method for eliminating uncertainty and determining the best foundation design [8,9].

Field testing (e.g., standard and cone penetration tests) is frequently favored over laboratory experiments in the geotechnical site exploration program [4]. The safe and economical size of the footings may be determined by the structural engineer using this safe bearing capacity [10]. A considerable amount of research has been performed during the last two decades to evaluate the SPT-based design methods and analytical approaches. A comparative study on analytical and empirical approaches has been reported by Tahmid [11] in the study achieved on soil at various locations in Dhaka city. They found that the analytical approach gives bearing capacity more than that obtained by the SPT empirical equations. An empirical equation may give values overestimated compared to PLT results [12].

Basak [12] explained the results obtained from the calculations of the bearing capacity of shallow foundations using equations based on SPT. Values were slightly overestimated for loads bearing shallow foundations through pressure gauge tests and, according to recommendations, the IS code using SPT and lab testing results. Waheed [13] evaluated and simulated the foundations' bearing capacity values using Plaxis 3D with many patterns, such as Mohr-Coulomb and others, by hardening and softening. The representation of soil using the hardening soil model is more realistic and gives better results. Salahudeen [14] used many traditional empirical/analytical methods and numerical modeling and evaluated the bearing capacity and the foundations' characteristics for the foundations' geotechnical preliminary design. The analytical/empirical approaches of determining the allowed bearing pressure and settlements of shallow foundations that yielded acceptable results were shown in the numerical analysis using Plaxis2D, a finite element code. Dev [15] gave a demonstration of gravelly soils that are difficult to sample and that require on-site tests, such as the Standard Penetration Test (SPT) and Conical Penetration Test (CPT). In addition, the plate test was applied to conclude that the test was the most appropriate in such circumstances. Soleimanbeigi [16] predicted the ultimate bearing capacity of shallow foundations on reinforced cohesionless soils by artificial neural networks. The results are then compared to standard methods, revealing a significantly higher level of accuracy. Akpila [17] set a comparison of SPT-based bearing capacity calculation methods for shallow foundations on sand. Perry's method yielded higher results, followed by Meyerhof's modified method, then Meyerhof's method.

Although the studies mentioned earlier evaluated the empirical equation based on SPT to compute the bearing capacity, very few studies considered the soil in Nasiriyah. The soil belongs to Mesopotamian soil, which is classified as alluvial soil. Unfortunately, Nasiriyah lacks the formulas and methods for estimating the value of bearing capacity, which is proper with the region's soil in southern Iraq. The studies did not give a clear view of the estimation of the bearing capacity of the southern region. Further, these equations may give different results because of the uncertainty in the boundary of the influence zone and the wide range of soils that may be encountered with SPT. Therefore, the aim of this study is to evaluate the SPT-based bearing capacity equation for shallow foundations for soil in Nasiriyah. This employs several objectives:

- Estimating the ultimate bearing capacity from plate load test using four methods.
- Estimating the bearing capacity of shallow foundations using nine methods based on SPT.
- Indicating the influence zone of stress and estimating the bearing capacity of shallow foundation using the finite element method.
- Evaluating the SPT-based design approach applied on the boundary of the influence zone by comparing with an ultimate bearing capacity of obtained plate load test results.

These groups are empirical equations based on SPT and numerical analysis based on the finite element method; both were compared with real PLT.

2. STUDY AREA

The study area considered in this research was Nasiriyah City, the center of Thi-Qar Governorate, located in southern Iraq within a flat plane (the Mesopotamian Plain), Figure 1. Holocene deposits, comprising floodplain sediments, river sediments, swamp sediments, and Aeolian deposits, all of the Mesopotamian sediments, cover the city's floor [18,19]. Two selected sites in Nasiriyah constitute the field of study.

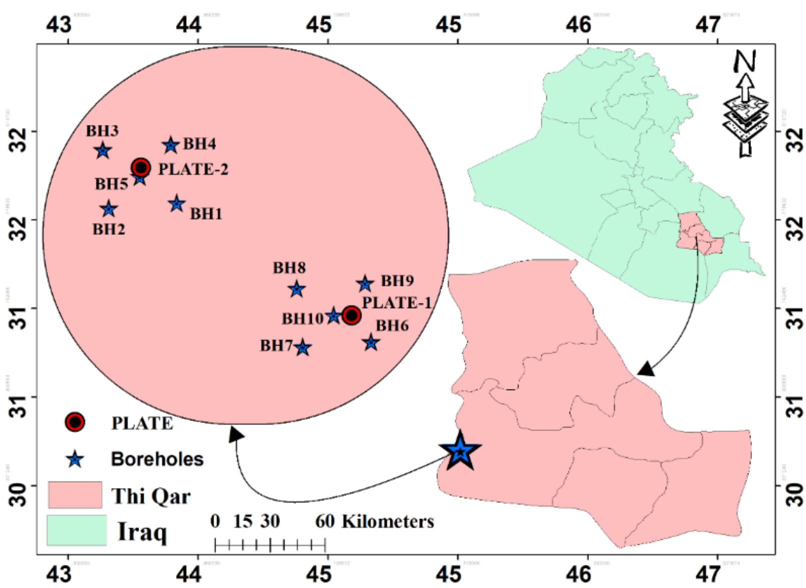


Figure 1: Map of Nasiriyah city and location of boreholes and PLT locations.

3. METHODOLOGY

Field and laboratory experiments were considered to characterize the soil with depth after the selection of the study site. The SPT is usually carried out using the test procedure described in ASTM D1586 [20]. SPT N values were measured at (1.5) m intervals at a depth where disturbed soil samples were obtained from boreholes. In this paper, the bearing capacity was calculated by three groups:

1. PLT.
2. Methods based on SPT
3. Numerical method by Plaxis3D.

Figure 2 shows the diagram of the methodology.

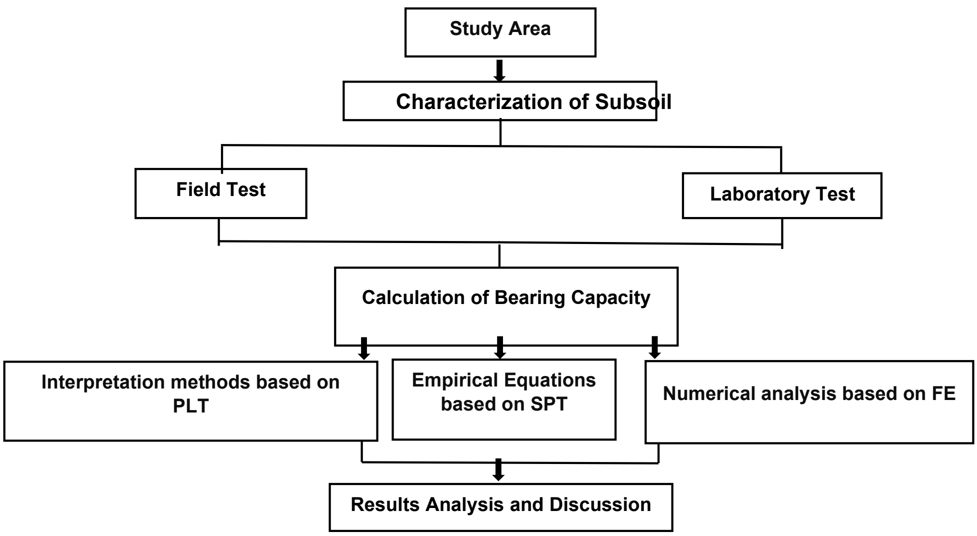


Figure 2: Methodological Flow Diagram.

3.1 Group One: PLT-Based Load Carrying Capacity

The most reliance test used to estimate the bearing capacity of shallow foundations is the PLT. In spite of that, the influence zone of applied stress through the PLT is within about 1.5 to 2 of the width of the plate, which represents a restriction in including the soil under the foundation in design. The test can give an acceptable estimation within this depth. Moreover, for the thick soil type and homogeneous soil, this defect has not affected the results of bearing capacity. For foundation design, there are numerous ways to determine the bearing capacity. One of the most widely used approaches is the PLT. It is divided into two categories based on how the test is conducted: testing to shear failure or testing based on operating pressure at a specified permitted settlement. Figure 3 depicts the PLT curves obtained for various soil types when loaded to shear failure [21].

The typical curve of PLT depends on the type of the supported soils. Four types of curves can be recognized, as presented in Figure 3.

- Curve A is typical for non-cohesive soils that are loose to medium in texture. This curve appears to be a straight line at first, but it flattens out as the weight increases. There is no obvious shear breaking point.
- For cohesive soils, Curve B is usual. This may not be perfectly straight initially, but as the settlement grows, it leans toward the settlement axis.
- Curve C is indicative of soils that are partially cohesive.
- Curve D is typical of non-cohesive, dense soil.

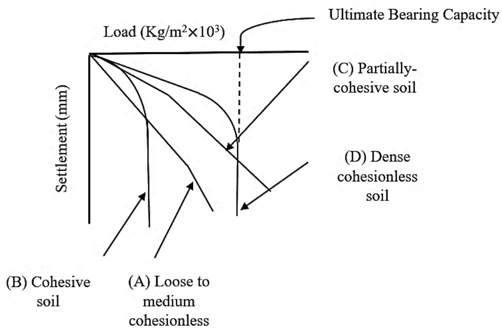


Figure 3: Types of PLT curves.

During performing the PLT, the settlement is recorded for every load applied on the tested plate, and then the curve of load versus vertical settlement is drawn. The ultimate capacity of the plate can be estimated using different methods since the failure point is not clear in most cases. Four interpretation methods can be utilized to estimate the ultimate bearing capacity of the loaded plate. The first method of interpretation of the ultimate load-carrying capacity was developed by DeBeer (1968). This curve shows different slopes of the intersecting axis for the data both before and after the maximum load. The computation of the two lines will be evident when the maximum load is attained, with one occurring earlier and the other following the last load [22]. In the second method, Tangent's method, the load-settlement graph's curve is parallel to the beginning and plastic states, which represent the initial and elastic states, respectively. The load's value, defined by the intersection of these two lines, is ultimately responsible [23]. The hyperbolic method, which is so called because a reasonable model is chosen to compare the stress to the settlement, and the value corresponding to the upper limit pressure is fixed, was also used as a third method [24]. Finally, the simplest method chooses the footing stress corresponding to the specific relative settlement value, called the 0.1 B method [25].

3.2 Group Two: SPT Based Methods

The bearing capacity of a shallow foundation can be estimated based on the number of blows measured through SPT. There are many methods have been developed for this purpose. They are widely used to estimate the bearing capacity of shallow foundations. The approach of empirical equations is used to determine the bearing capacity of soil when the other design methods are not applicable or to evaluate the bearing capacity computed based on strength parameters obtained from laboratory tests. The SPT value is used exclusively in this calculation. Table 1 refers to a set of methods proposed by some researchers to estimate the bearing capacity of the shallow foundation, which has been applied in this paper.

Table 1: Empirical equation for soil bearing capacity analysis.

Method	Bearing capacity (kPa)	Limitations
Meyerhof (1956) (26)	$q_a=12N\times k_d$ $q_a=8N(\frac{B+0.305}{B})^2\times k_d$	B≤1.22 B>1.22
Meyerhof (1974) (11)	$q_u=(N/4)\times K_d$	___
Bowles (1988) (26)	$q_a=20N\times k_d$ $q_a=12.5N(\frac{B+0.305}{B})^2\times k_d$	B≤1.22 B>1.22
Bowles (11)	$q_u=(N/2.5)\times K_d$	___
Terzaghi and Peak (1967) (26)	12.5N	Fine grained soil
Teng (1969) (27)	$q_a=34.3(N-3)\,(\frac{B+0.3}{2B})^2\times k_d\times k_w$	___
Terzaghi and Peak (1948) (28)	$q_a=35\times k_d\times k_w(N-3)\times(\frac{B+0.3}{B})$	For saturated soil
Parry (1977) (29)	$q_u=0.24N(\frac{D_f+0.13B}{D_f+0.75B})$ $q_u=0.24N$	$D_f/B<1$ $D_f/B>1$
Sanglerat (1972) (30)	$q_u=25N$ $q_u=20N$	Clay Silty Clay
Sivrikaya and Togrol (2006) (30)	$q_u=8.66N_{field}$	___

3.3 Group Three: Numerical Method

The Plaxis3d foundation application is used in this research to undertake numerical modeling of the behavior of a shallow foundation. Plaxis3d is a computer program that is specifically intended to assess geotechnical difficulties. It is a three-dimensional application for simulating deformation analyses of various foundations and geotechnical issues. This tool automates the creation of two and three-dimensional meshes, allowing the user to quickly produce a final three-dimensional model based on material attributes. The load-settlement curves for the foundation models analyzed by the finite element method from the models are compared with the experimental findings to verify the reliability of the modeling using the program for estimating soil behavior. The dimensions of the plate in the numerous models were (2 ×2) m with a depth of 0.025 m. Table 2 shows the data entered into the program to calculate the bearing capacity of the soil for the first. Table 3 shows the characteristics of the plate metal used in the field.

Table 2: The parameters of the soil profile for Project 1.

Project No.	**Project1**	
Depth (m)	**0-3**	**0-3**
Soil description	Clay	Clay
Modulus of elasticity, Es (kN/m^2)	30000	45000
Poisson's ratio, v	0.3	0.3
Cohesion, c (kN/m^2)	50	70
Dry unit weight, γ_d (kN/m^3)	18.9	18.9
Total unit weight, γ_t (kN/m^3)	20	20

Table 3: Details of the plate.

Identification	**Value**
Modulus of elasticity, E_p (kN/m^2)	20×10^3
Depth (m)	0.025
Poisson's ratio	0.26
Type of material	Elastic
Material density (kN/m^3)	78.5

4. RESULTS AND DISCUSSIONS

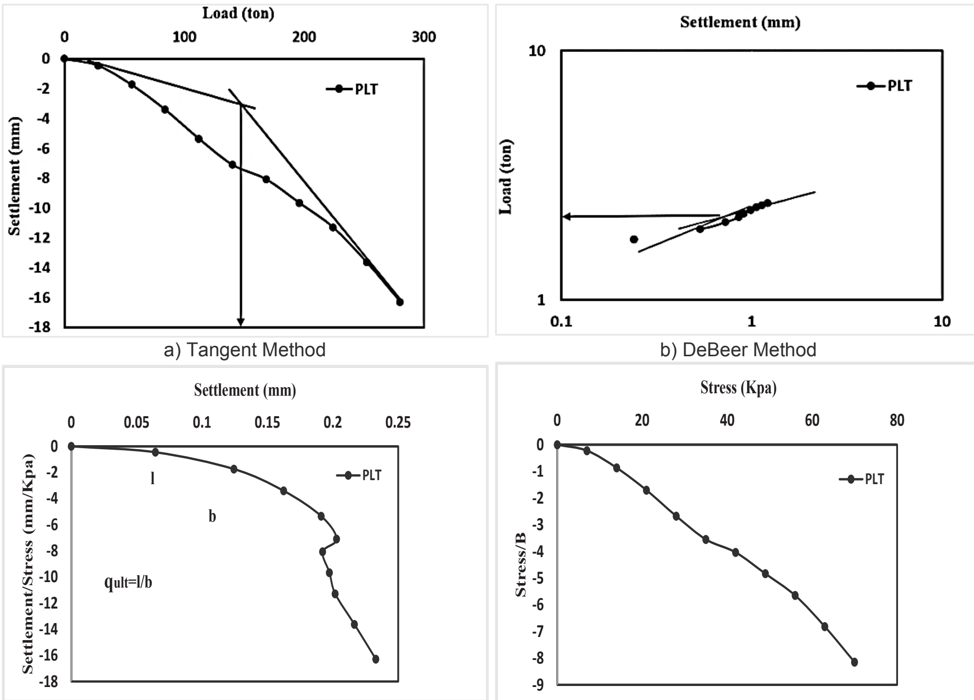
4.1 Plate Load Test Results

The four interpretation methods described in the methodology have been used to obtain the ultimate bearing capacity of soil from the load settlement curves measured through PLT. They are treated graphically based on the results of the field test. Note that the values of ultimate bearing capacity obtained based on PLT cannot be used directly for foundations with actual dimensions. They may be revised according to criteria depending on the type of soil. In clayey soil, the ultimate bearing capacity of the plate load test equals the ultimate bearing capacity for the proposed foundation [32]. Since the soil layers of the two projects are clay, the bearing capacity of the actual shallow foundation can be considered similar to the results obtained from the interpreting methods. Mathematically, the value of ultimate bearing capacity can be expressed as [32]:

$$\mathrm{qus(Fd)} = \mathrm{qus(Pd)} \tag{1}$$

Where $q_{us(Fd)}$ (ton/m^2) represents the ultimate bearing capacity of the proposed foundation and $q_{us(Pd)}$ (ton/m^2) means the ultimate bearing capacity of the plate load test.

Figure 4 shows the graphical presentation of applying the four-interpretation method for PLT at project 1. It is clearly observed that the result of ultimate bearing capacity has different values. Table 4 refers to the results of four interpretation methods. The four approved method to determine the ultimate bearing capacity (measured value) verify three convergent values and shows a very low value using 0.1B method. The average value of the first three methods was (32) ton/m^2. Regarding project two, the results for the first three interpretation methods were also convergent, while the last one was low compared to others.



a) Tangent Method

b) DeBeer Method

c) Hyperbolic Method

d) (0.1B) Method

Figure 4: Graphical methods for project 1.

Table 4: Results of interpreting methods for two projects.

Method	Tangent	DeBeer	The Hyperbolic method	0.1B method
Ultimate Bearing Capacity (ton/m^2) (Project 1)	35	20	40	7
Ultimate Bearing Capacity (ton/m^2) (Project 2)	53	33	39	9

4.2 SPT Results

The design empirical equations presented in section 3 have been used to compute the ultimate bearing capacity of a square (2 x 2) m shallow foundation. All the previously mentioned equations have been implemented, and their results are presented. The results of applying the design equations are shown in Table 5. Table 5 consists of seven columns that show each method adopted in this study, the predicted load estimated by equations, the boundary of the failure influence zone that, if it is considered, assessment of the predicted to measured ratio, average N, and final evaluation for each method. It is observed that the ultimate bearing obtained from these equations depicts a discrepancy result. Meyerhof (1956) and Sivrikaya (2006) methods indicated values of lower prediction of soil bearing capacity (17, 15) in t/m^2 units compared with the other mentioned methods. These equations are subject to a comparison with the field test to ensure the acceptability of the values. Comparing with the lower value of the bearing capacity obtained from PLT based on the interpretation methods, which was (32) ton, reveal that these methods are conservative methods and can be used safely. The seventh column refers to the underestimated evaluation of these two methods.

Teng's method obtained the highest value of ultimate bearing capacity, which is a value that exceeded the field result by a large amount. Often, one of the reasons for these results is not to specify the failure area and depth, which negatively affects the acceptability of the results. Further, the value of the fifth column Indicates that the result is far from the actual value. According to these results, using this equation may be not suitable based on this study. The results computed using Terzaghi & Peack (1984) and

Terzaghi & Peack (1967) showed a clear convergence, but they still indicate failure with a value higher than the actual result. High failure expectations give a risk to the design. Meyerhof (1956) and Sanglerat (1972) methods showed that the expectations of the failure value were not the most fortunate of the above, as they were not close in the appropriate amount to the actual values and did not give an acceptable safety factor for the building.

The ultimate bearing capacity obtained by applying Bowel's equation (1988) showed closer value to the field than methods, as mentioned in the previous paragraphs, making it more acceptable. So, the value of predict/measured was underestimated and close to the actual value compared to the previous methods. The fifth column's result must make the design equation proposed by Meyerhof (1974) the most acceptable compared to others. Meyerhof (1974) obviously represented the best convergent to the measured value based on the effective depth selected in this method but showed overestimated results. The diversity of the results of these empirical equations may be attributed to equations used due to various reasons, including the neglect of some equations, the boundary of influence zone or the uncertain influence zone boundary.

Table 5: SPT equations results.

Item	Design method	Predicted (ton/m^2)	Influence zone	Predicted to measured	Average N	Evaluation
1	Meyerhof (1956)	17	Twice the foundation width (33)	0.5	5	Underestimate
2	Bowles (1988)	25	___	0.6	7	Underestimate
3	Meyerhof (1974)	38	0.5B-2B (34)	1.2	5	Overestimate
4	Bowles	82	___	2.5	7	Overestimate
5	Parry (1977)	46	0.75B below the proposed base (34)	1.4	3	Overestimate
6	Teng (1969)	139	___	4	7	Overestimate
7	Terzaghi and Peak (1967)	110	___	3	7	Overestimate
8	Terzaghi and Peak (1984)	115	___	3.5	7	Overestimate
9	Sanglerant (1972)	45	___	1.4	7	Overestimate
10	Sivrikaya (2006)	15	___	0.46	7	Underestimate

4.3 Numerical results

Besides the theoretical and experimental studies, a numerical study was also conducted. Plaxis3d has been applied to the soil data previously mentioned in Tables 2 and 3. The general mesh of two models for projects is illustrative in Figure 5 with dimensions (12×12) m and depth (10) m. In addition, the ultimate bearing capacity was determined at the center of the finite element model at the number node (8363).

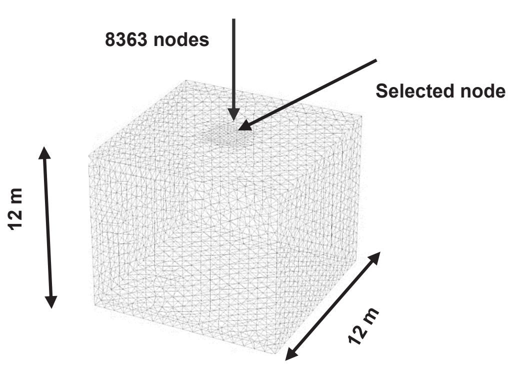
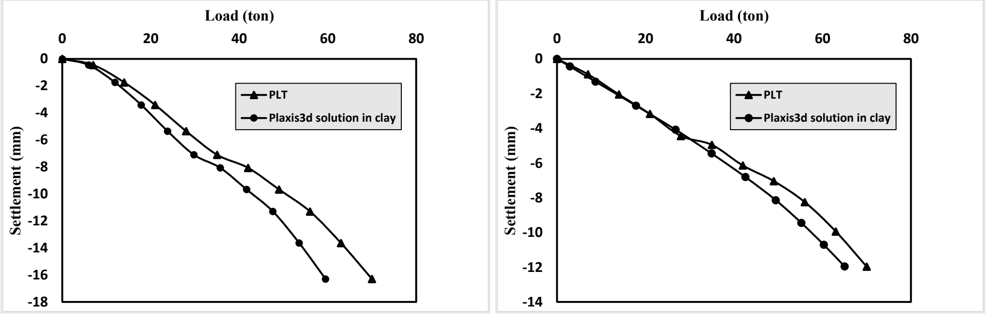


Figure 5: General mesh of the model.

Figure 6 represents the data obtained from the numerical analysis of load versus settlement, which shows the convergence between the numerical results and the field results, as this result is considered a verification of the numerical method. The results obtained from the finite element method confirm the actual results compared to the measured bearing capacity (Table 6). Convergence refers to the precision of the finite elements in order to produce the most reasonable result.

Table 6: Finite element results.

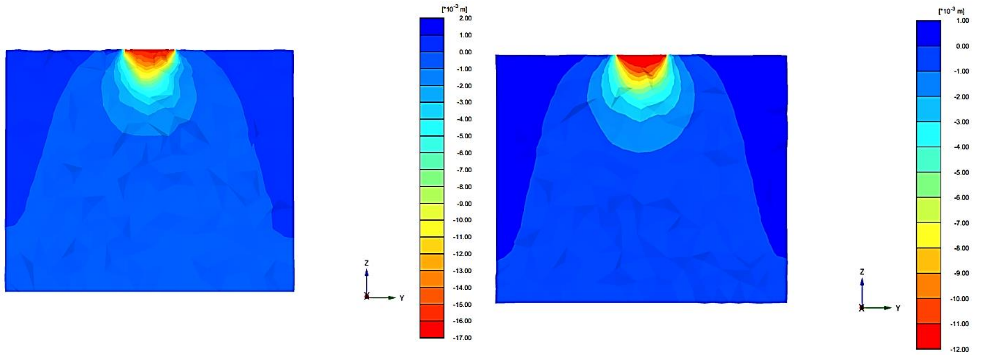
Projects	Ultimate bearing capacity (ton/m^2)
Project 1	67
Project 2	65



(a) (b)

Figure 6: Load-Settlement behavior for PLT and Plaxis3d in clay for two projects: a) Project 1 and b) Project 2.

The failure zone, or the area affected by the loading stresses of the soil, is one of the most important topics because of its obvious impact on the reliability of the results, which was studied in the research. The finite element method using Plaxis3d software accurately determined the affected areas and failure areas in the soil. Figure 7 (a, b) refers to the areas of failure in determining the depth affected by the stresses for each of the clay for both projects, and this gives the possibility to identify and know the affected area for each type of soil for the city of Nasiriyah. Thus, it is possible to propose the influence depth for clay based on the finite element method. Although the Meyerhof (1974) method was the most reliable method to predict the ultimate bearing capacity, these equations can be developed using the proposed effective depth in this study. The average failure depth illustrated in Figures 7 (a,c) is 3.4 m under the base. It should be used instead of the effective depth of Meyerhof equation. Table 7 shows the results based on the new effective depth. The ultimate bearing capacity based on the proposed limitation of the effective depth gave a good evaluation.



(a) (b)

Figure 7: Project 1 a) boundaries of the failure zone in clay, Project 2 b) boundaries of the failure zone in clay.

Table 7: Results of Meyerhof (1974) based on the proposed effective depth.

Item	Design method	Predicted (ton/m^2)	Proposed the influence zone	Predicted to measured	Average N	Evaluation
1	Meyerhof (1974)	30	3.4 below the base	0.91	4	good convergent

4. CONCLUSION

In this paper, the most important methods based on SPT that were used to predict the ultimate bearing capacity of shallow foundations have been evaluated. The evaluation has been performed by comparing results obtained by SPT-based design equations with actual results of PLT and then using the finite element method. The ultimate bearing capacity of a square shallow foundation computed by using Meyerhof (1956), Bowles (1988), and Sivrikaya (2006) methods, utilizing SPT from a real site, revealed an under-estimate prediction. Teng (1969) equation had the highest prediction of bearing capacity value. Depending on the failure zone proposed by Meyerhof (1974), the best prediction of the ultimate bearing capacity compared to other methods was obtained. As an important practical rule, determining the failure area plays a key role in enabling the theory to draw more accurate value conclusions. In contrast to the results obtained by Meyerhof's design method, the design method developed by Bowles, Terzaghi, and Peek (1967), Terzaghi and Peck (1984) and Sanglerant (1972) gave overestimated results. Moreover, the ultimate bearing capacity obtained by using Parry (1977) showed an overestimated value, which may be attributed to the influence zone criteria assumed in his method. Another solution for similar problems using Plaxis3D has been performed in this research. The results of the numerical analysis had a convergence with the results of the field, as they simulated reality to obtain a clear convergence in the value of the bearing capacity of the soil. In addition to that, the available capabilities are available to determine the depths of failure for the foundations, and this is what was worked on in this study. Based on that, values for the depths of failure were taken for the shallow foundation. This solution technique gave an advantage to study the deformed soil below the footing. It is concluded that the depth of influence zone of stresses below the shallow foundation was 3.4 m for clayey soil. As a ratio to the width of the foundation, it is equal to 1.7B. Finally, the depth of the proposed foundation, based on the finite element method, was employed in calculating the bearing capacity of the soil in the Meyerhof equation, where the equation gave values close to the actual values.

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