Three-dimensional finite element analysis for determining subgrade reaction modulus of subgrade soils

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Abstract. The success of any pavement system is depending on the strength of the subgrade layer that represents a foundation on which unbound and surface course layers are placed. The strength of the subgrade layer is often defined in terms of a subgrade reaction modulus (Ks) which is typically obtained from the static plate load test (PLT). The PLT test is known to be laborious, time-consuming and relatively expensive, therefore several alternative methodologies for predicting (Ks) are required. The objective of this research is developing a 3D-finite element model using Plaxis 3D software to simulate the plate load tests, and comparing the finite element results with those obtained from experimental tests. Twenty-seven plate load tests were carried out on three different types of subgrade soils. The soils collected from different sites in Kerbala city and tested under static load under three degrees of compaction. The experimental results were verified numerically using the finite element method. In the numerical simulation, the Mohr-Coulomb model was used to represent the behavior of soil. The numerical and experimental results were analyzed and compared. The results showed a good agreement with experimental work, also showed the possibility of using Plaxis 3D in the simulation of the static plate load test.

1. Background
Structural elements such as concrete pavements are continuously supported by underlying soils. In the rigid pavement design process, it is suitable to assume that the intensity of the continuously distributed reaction at each point is proportional to the deflection at that point. This reaction can be represented as a modulus of subgrade reaction. The modulus of subgrade reaction (Ks) has a significant effect on the required thickness of the pavement and estimates the support of the layers below a rigid pavement surface course. The value of (Ks) depends on several factors including elastic properties of subgrade soil, dimensions of the area acted upon by the subgrade reaction, soil type, and embedment depth and type of foundation (Flexible or Rigid) Ping and Sheng (2011) [1]. The plate load test (PLT) is the direct method for determining the subgrade reaction modulus according to AASHTO T222 [2] and ASTM D 1196 [3]. The PLT test is a useful site tool in obtaining the necessary in-situ soil properties to design the pavements structures. However, there are several limitations associated with performing the plate load test; It is exceedingly time-consuming and expensive, test’s results may be evaluated only for the specific conditions under which the tests are performed, there is a difficulty in selecting a proper critical deflection
value, and it is difficult to conduct this test in narrow trenches and exploration pits because there is insufficient space.

Several researchers studied the possibility of simulating the PLT test and estimated the subgrade reaction modulus using the numerical techniques. Lee and Salgado (2000) [4] analyzed the PLT test numerically using 3D finite element program ABAQUS, to study the size effects of plate resistance for sand soil at different relative densities. They compared the experimental and numerical results and found a good agreement with a maximum error of 20% between the results. Teodoru and Toma (2009) [5] used 2D finite element model in simulation the PLT test and compared the results of numerical simulation, they showed that the modulus of subgrade reaction depends on the size of the loaded area, and on the magnitude of the load. Ziaei and Janbaz (2009) [6] studied the effects of foundation depth on the subgrade modulus for clay soil using finite element analysis, they found that the subgrade reaction modulus increases by increasing the depth of embedment of foundation. Marto et al (2012) [7] studied the effect of foundation size on subgrade reaction modulus value for sandy subgrade soil using finite element analysis. They found that when the dimension of plate increased, the modulus of subgrade reaction decreased. This was due to an increasing loaded area causing an increase in settlement. Demir et al (2013) [8] evaluated the bearing capacity of circular footing on geogrid-reinforced compacted granular fill layer overlying on natural clay, and compare the results with those from Plaxis 3D finite element. They found a very good agreement between the results. Naeini and Taherabadi (2015) [9] utilized 3D finite element model (ABAQUS) to simulate PLT test to examine the ability to determine the subgrade reaction modulus from numerical modeling without performing some plate load tests. The results showed the efficiency of FE analysis in the calculation of Ks in fine soils. Moayed et al (2017) [10] investigated the results of PLT test numerically using FLAC3D to find the effect of dimension of the model on the PLT results, they found that that the boundary conditions have no significant effect on the results and thus they are applicable to in situ conditions.

The objective of this research is to develop a finite element model to simulate the PLT surface deflection using Plaxis 3D. The FE load-deformation curve was analyzed to predict the modulus of subgrade reaction and compared with those from PLT test. The basic soil properties obtained from various laboratory tests were used as inputs into the finite element model.

2. Testing Equipment and Methods

2.1 Static Plate Load Test (PLT):

For many years, a useful site investigation tool in obtaining the necessary information about the soil to design the shallow foundation or pavement structure is the static plate load test. The plate load test is the most reliable method for obtaining various geotechnical design parameters such as bearing capacity, subgrade reaction (Ks) and modulus of deformation of soil. The interpretation of plate bearing test results requires full information on the subgrade conditions, Oh and Vanapalli (2013) [11].

In this research, the PLT was carried out according to AASHTO T222 and ASTM D1196. The testing equipment consists of 300-mm diameter circular steel plate that is in contact with the soil surface, another plate with a smaller diameter set concentric with, and on top of the bearing plate. Two or more dial gages with a sensitivity of 0.01mm were placed near the edge of the bearing plate (25 mm from the circumference) to measure deflections at different loading increments. The load is usually transmitted to the plate by a hydraulic jack acting against heavy mobile equipment. The load is applied at stages with uniform increments. The number of stages shall be enough to permit the recording of a sufficient number of load-deflection points to produce the load-deflection curve (not less than six). After each increment, the load shall be maintained until an increased in deflection of not more than 0.03 mm/min for three consecutive minutes occurs. This procedure is continued until the load capacity has been reached. Figure 1 displays a schematic diagram of the components of the PLT.
Figure 1. Schematic Diagram of the components of Plate Bearing Test

The nonrepetitive static plate load tests is widely utilized in various geotechnical applications in Europe and Asia, and it calculates the modulus of subgrade reaction ($K_s$) based on the relationship between the average normal stress and the settlement of the plate, as shown in Equation 1. As illustrated in Figure 2, the depth of influence of this test is assumed to be equal to two times the diameter of the loading plate, Barker and Alexander (2012) [12];

$$K_s = \frac{P}{\delta} \quad (1)$$

where $P$ is the contact pressure at any given point (MPa), $\delta$ is the settlement produced by the normal load applied at that point (mm), and $K_s$ is the modulus of subgrade reaction (MPa/mm) of a soil lay

Figure 2. Influence of Total Deformation in PLT

3. Experimental Testing Program

3.1. Collected Soil Samples

In this research, three types of soil were excavated and collected from different locations in Kerbala, Iraq. The basic physical properties of the collected subgrade soils are summarized in Table 1.
Table 1. Basic Physical Properties of Subgrade Soils

| Property                  | Test Results | Specification          |
|---------------------------|--------------|------------------------|
| Soil Classification       | A-1-b        | A-3                    | A-7-6 | AASHTO M 145 [13] |
|                           | SP-SM        | SP                     | CL    | ASTM D 2487 [14]  |
| OMC                       | 15.5%        | 8.75%                  | 18.5% | ASTM D 1557 [15]  |
| Max. Dry Unit Weight      | 18.85 kN/m³ | 21.35 kN/m³            | 17.20 kN/m³ | ASTM D 1557 [15] |
| Liquid Limit              | /            | /                      | 47%   | ASTM D 4318 [16]  |
| Plasticity Index          | NP           | NP                     | 24.26%| ASTM D 4318 [16]  |
| Uniformity Coefficient (Cu) | 5.25        | 1.8                    | /     | ASTM D 2487 [14]  |
| Curvature Coefficient (Cc) | 1.19        | 0.77                   | /     | ASTM D 2487 [14]  |
| Specific Gravity (Gs)     | 2.72         | 2.74                   | 2.74  | ASTM D 854 [17]   |
| CBR Soaked                | 34           | 98                     | 5.6   | ASTM D 1883 [18]  |
| CBR Un-Soaked             | 53           | 78                     | 26    | ASTM D 1883 [18]  |
| Angle of friction (ϕ)     | 38           | 36                     | /     | ASTM D 3080 [19]  |

3.2 Sample preparation:
Approximately (2 m³) of each type of soil material is required to construct a (0.6 m) thick of compacted subgrade. Each type of subgrade soil was prepared at optimum water content by using an electrical mixture with capacity (0.22 m³). Then the compacted inside the testing steel box as layers (20 cm/layer) until reaching the desired height (0.6 m). The compaction process was carried out using a compactor device, and three degrees of compaction were selected based on the number of passes of the compactor, see Figure 3. Once the subgrade is constructed its modulus and stiffness properties are measured using the static plate load test (PLT). The field moisture content and dry unit weight were obtained using sand-cone ASTM D2011 [20] and core-cutter tests method, the sequence of testing was selected as follows: three PLT, three sand cone, and three core cutter. Table 2 summarizes the total number of tests performed for each soil type collected from the field. Figure 4 describes the layout of the tests.

Table 2. Summary of Number of Experiments

| Soils Type               | Sandy soils (A-1-b) | Sandy soils (A-3) | Clayey soils (A-7-6) |
|--------------------------|----------------------|-------------------|----------------------|
| Degree of Compaction (%) | 90.0% 92.3% 98.1%   | 88.5% 89.9% 94.5% | 83.7% 87.2% 94.9%    |
| No. of Test              | PLT                  | Sand-Cone         | Core-Cutter          |
|                          | 3 3 3               | 3 3 / /            | 3 3 3                |
|                          | 3 3 3               | 3 / / /            | 3 3 3                |
4. Numerical Analysis

The finite element method is one of the most powerful ways to solve differential equations, especially when these equations are applied to complex shapes with complex boundary conditions. Nowadays, finite element analysis has been widely used to simulate different geotechnical and pavement structures, Rao (2011) [21]. In this paper, a 3D finite element program commercially known as (Plaxis– Plasticity Axisymmetry) was used to model the subgrade layer. Plaxis 3D provides a better understanding of soil behaviour under different loading conditions. The main focus of using Plaxis 3D in this study was to
create a 3D subgrade model to develop the load–deformation curve for PLT test to find the subgrade reaction modulus. Plaxis 3D provides four models; linear elastic model, Mohr-Coulomb model, hardening soil model, and soft soil creep model to allow the user to select suitable mechanical behavior of soil. In this study, the Mohr-Coulomb model was used to represent the subgrade soil behavior. This model was used based on previous studies carried by, Teodoru and Toma (2009) [5], Palix et al (2010) [22], Demir et al (2013) [8], and Ahirwar and Mandal (2017) [23]. This linearly elastic- perfectly plastic model involves five parameters as input data namely; Young’s modulus (E), Poison’s ratio (ν), cohesion (c), friction angle (ϕ), and dilatancy angle (ψ). Table 3 presents the properties of the soils.

4.1 Geometry and Boundary Conditions
In this work, the FE model was created with dimensions similar to those used in the experimental work. As shown in Figure 5, the size of the geometric model was (1.5 m width × 2.4 m length × 0.65 m deep). These large dimensions would help to avoid undesirable reflection of the scattered wave source of the static load.

To minimize the influence of the stress distribution the boundary conditions were chosen. A fixed support was used in the edges and in the bottom base of the model to prevent any movement in the horizontal direction. while the surface of the model is free in all directions, these general fixities of the boundaries are automatically imposed by Plaxis 3D.

![Figure 5. Geometry and boundary conditions of 3D Finite Element Model](image)

4.2. Mesh and Element Configurations:
The geometry model of subgrade soil layer has been divided into a fine tetrahedral element with 10-nodes called finite element mesh. Using the automatic meshing procedure, a target element size was 0.7, polyline tolerance angle was 30° and surface angle tolerance was 15°. These dimensions for finite element were selected after several analyses on different mesh size, so the surface deflection is not affected by the boundary conditions. The developed mesh has 60,106 nodes and 41,281 elements, see Figures 6 and 7.
Figure 6. Ten – nodes finite element mesh

Figure 7. Completing geometry with loading plate and developed mesh

Table 3. Materials properties

| Property                  | Soils                                      |                |                |                |
|---------------------------|--------------------------------------------|----------------|----------------|----------------|
|                           | Model                                      | A-1-b          | A-3            | A-7-6          |
| Young’s modulus (E) (kN/m²) | Mohr-Coulomb                               | 21100 - 55900  | 22360 - 84700  | 17000 - 43500  |
| Saturated unit weight γsat (kN/m³) | 18.50 – 20.34     | 19.49 – 21.72  | 18.17 - 19.97  |
| Unsaturated unit weight γunsat (kN/m³) | 16.85 – 18.55   | 18.30 – 20.39  | 14.31 – 16.46  |
| Poisson’s ratio (ν)       | 0.3                                        | 0.3            | 0.3            |
| Cohesion (c) (kN/m²)      | 0.2                                        | 0.2            | 42.15          |
| Friction angle (φ) (°)    | 38                                         | 36             | 5.58           |
| Dilatancy angle (ψ) (°)   | 8                                          | 6              | 0              |
5. Results and Analysis

5.1: Experimental Results from PLT

This section presents the results of twenty-seven of PLT test that were performed according to AASHTO T222 on three types of subgrade soils under different degree of compactions. The static plate load test is conducted by applying the load incrementally, the magnitude of maximum applied load used in this study is 50 kN (5 tonnes). The following characteristics of subgrade materials were extracted from PLT tests: δmax.: maximum settlement of the loading plate under the static load (mm). Ks: modulus of subgrade reaction in (kPa/mm). and Es: Young’s elastic modulus (MPa) determined as a function of maximum surface deflection using equation 2.

\[ E_s = \frac{\pi p D (1 - \nu^2)}{4 \delta_{max}} \]  

(2)

where \( P \) is the contact pressure at any given point (MPa), \( \delta \) is the settlement produced by the Normal load applied at that point (mm), \( D \) is the diameter of loading plate (mm), \( \nu \) is the Poisson’s ratio, and \( E_s \) Young’s elastic modulus (MPa).

For A-1-b soil, the characteristics of subgrade soil obtained from the 9 PLT test are summarized in Table 4. It was noticed that the values of the subgrade reaction modulus ranged from 313.6 to 431 kPa/mm with an average equal to 361.43 kPa/mm. Whereas the value of maximum settlement ranged from 2.7 to 6.47 mm with an average equal to 4.46 mm. The results also shown the elastic modulus varied from 21.1 to 55.9 MPa with an average equal to 32.15 MPa. Figure 8 shows the average pressure-settlement curve of the subgrade soils at A-1-b soil.

| Testing Point | δmax (mm) | Ks (kPa/mm) | Es (MPa) |
|---------------|-----------|-------------|----------|
| 1             | 4.728     | 246.4       | 22.36    |
| 2             | 3.370     | 255.6       | 31.36    |
| 3             | 2.013     | 300.0       | 52.51    |
| 4             | 2.583     | 460.0       | 57.30    |
| 5             | 2.747     | 460.0       | 53.86    |
| 6             | 2.670     | 431.3       | 55.52    |
| 7             | 1.830     | 711.3       | 80.86    |
| 8             | 1.750     | 755.2       | 84.56    |
| 9             | 1.750     | 766.7       | 84.68    |
| Average       | 2.60      | 487.38      | 58.11    |

Note: *The value of Poisson’s ratio used to determine elastic deformation moduli was assumed 0.3
Table 5. Summary of PLT measurements of A-3 soils

| Testing Point | δmax (mm) | Ks (kPa/mm) | Es (MPa) |
|---------------|-----------|-------------|----------|
| 1             | 6.03      | 138.0       | 17.50    |
| 2             | 6.20      | 138.0       | 17.00    |
| 3             | 5.77      | 135.0       | 18.40    |
| 4             | 4.20      | 186.5       | 35.20    |
| 5             | 4.08      | 181.6       | 36.30    |
| 6             | 3.90      | 172.5       | 37.90    |
| 7             | 3.44      | 230.0       | 43.01    |
| 8             | 3.40      | 230.0       | 43.52    |
| 9             | 3.42      | 246.4       | 43.26    |
| Average       | 4.49      | 184.3       | 32.5     |

Note: *The value of Poisson’s ratio used to determine elastic deformation moduli was assumed 0.3
Figure 9. an average pressure – settlement curve of PLT – A-3 soil

For A-7-6 soil the characteristics of subgrade soil obtained from the 9 PLT test are summarized in Table 6. It was noticed that the values of subgrade reaction modulus ranged from 135.3 to 246.4 kPa/mm with an average equal to 184.3 kPa/mm. Whereas the value of maximum settlement ranged from 3.4 to 6.2 mm with an average equal to 4.49 mm. The results also shown the elastic modulus range from 17 to 43.5 MPa with an average equal to 32.5 MPa. Figure 10 shows the average pressure-settlement curve of this subgrade soils.

Table 6. Summary of PLT measurements of A-7-6 soils

| Testing Point | δmax (mm) | Ks (kPa/mm) | Es (MPa) |
|---------------|-----------|-------------|----------|
| 1             | 6.03      | 138.0       | 17.50    |
| 2             | 6.20      | 138.0       | 17.00    |
| 3             | 5.77      | 135.0       | 18.40    |
| 4             | 4.20      | 186.5       | 35.20    |
| 5             | 4.08      | 181.6       | 36.30    |
| 6             | 3.90      | 172.5       | 37.90    |
| 7             | 3.44      | 230.0       | 43.01    |
| 8             | 3.40      | 230.0       | 43.52    |
| 9             | 3.42      | 246.4       | 43.26    |
| Average       | 4.49      | 184.3       | 32.5     |

Note: *The value of Poisson’s ratio used to determine elastic deformation moduli was assumed 0.3
5.2: Numerical Results from FE

Under the same loading conditions that used in the experimental work, the PLT tests were simulated numerically to find the maximum surface deflection, and to develop load-deformation curve, from the developed curve predict subgrade reaction modulus. The results for three soils are presented below:

For A-1-b subgrade soil, the results of FE analysis are summarized in Tables 7. It was noticed that maximum settlement ranged from 2.3 to 6.7 mm with an average value of 4.78 mm. Whereas the modulus of subgrade reaction \( K_s \) ranged from 287.5 to 492 kPa/mm with an average value of 343.82 kPa/mm. Figure 11 displays a typical compression load-deformation curve.

**Table 7. Summary of FEM measurements of A-1-b soil.**

| Testing Point | FEM \( \delta_{\text{max}} \) (mm) | FEM \( K_s \) (kPa/mm) |
|---------------|-----------------------------------|------------------------|
| 1             | 4.80                              | 300.0                  |
| 2             | 6.20                              | 328.6                  |
| 3             | 5.06                              | 345.0                  |
| 4             | 5.70                              | 321.0                  |
| 5             | 4.85                              | 287.5                  |
| 6             | 6.70                              | 328.5                  |
| 7             | 4.40                              | 328.6                  |
| 8             | 3.04                              | 363.2                  |
| 9             | 2.30                              | 492.0                  |
| average       | 4.783                             | 343.82                 |
Figure 11. Typical curve- compression between the experimental and the numerical simulation for surface settlement for A-1-b soil.

For A-3 subgrade soil, the results of FE analysis are summarized in Tables 8. It was noticed that maximum settlement ranged from 2.1 to 5.010 mm with an average value 3.11 mm. Whereas the modulus of subgrade reaction Ks ranged from 197.14 to 766 kPa/mm with an average value 490.47 kPa/mm. Figure 12 displays a typical compression load-deformation curve.

Table 8. Summary of FEM measurements of A-3 soil.

| Testing Point | FEM δmax (mm) | FEM Ks (kPa/mm) |
|---------------|---------------|-----------------|
| 1             | 5.01          | 197.1           |
| 2             | 4.40          | 255.6           |
| 3             | 2.68          | 363.2           |
| 4             | 3.20          | 492.8           |
| 5             | 3.10          | 431.3           |
| 6             | 2.89          | 460.0           |
| 7             | 2.25          | 690.0           |
| 8             | 2.10          | 766.0           |
| 9             | 2.40          | 758.2           |
| average       | 3.11          | 490.47          |
For A-7-6 subgrade soil, the results of FE analysis are summarized in Tables 9. It was noticed that maximum settlement ranged 3.52 to 6.2 mm with an average value 4.494 mm. Whereas the modulus of subgrade reaction Ks ranged from 135.2 to 293.6 kPa/mm with an average value 209.379 kPa/mm. Figure 13 displays a typical compression load-deformation curve.

**Figure 12.** Typical curve- compression between the experimental and the numerical simulation for surface settlement for A-3 soil

**Table 9.** Summary of FEM measurements of A-7-6 soil.

| Testing Point | FEM δmax (mm) | FEM Ks (kPa/mm) |
|---------------|---------------|-----------------|
| 1             | 6.00          | 143.7           |
| 2             | 6.85          | 135.2           |
| 3             | 5.53          | 146.8           |
| 4             | 3.98          | 222.6           |
| 5             | 4.30          | 197.4           |
| 6             | 4.18          | 181.6           |
| 7             | 3.25          | 276.0           |
| 8             | 3.80          | 287.5           |
| 9             | 3.50          | 293.6           |
| average       | 4.599         | 209.37          |
The typical output of numerical analysis is illustrated in the following figures; the geometry of 3D numerical model with circular static load of PLT test shown in Figure 14. Also, the Figure explained the
zone that effect by the load Figure 15 present the stress bulb zone (i.e. influence depth) below the PLT load.

6. Comparasion between the experimental and numerical results:

The variations between experimental and FE results were conducted using a paired T-Test method. The results for the three soils are presented below:

For A-1-b subgrade soil, the T-Test results are listed in Table 10. The results of the analysis were $[t (8) = 0.93$, probability $= 0.17 > 0.05]$ which means there is no significant variance between predicted and measured surface deflection and the mean increase value is 0.15mm with confidence interval 95%, see Figure 16. Whereas in the modulus of subgrade reaction $K_s$, the T-Test results showed that there is no significant variance between simulated and measured subgrade reaction modulus, $[t (8) = -1.49$, probability $= 0.35 > 0.05]$, the mean decreased 17.614 kPa/mm with 95% interval as illustrated in Figure 17.

### Table 10. Summary of T-Test Analysis for A-1-b Soil.

| Measurements data | No. of Samples | Mean (mm) | Standard Deviation | Paired Sample T-test Method |
|-------------------|----------------|-----------|--------------------|-----------------------------|
| $\delta_{\text{FEM.}}$ | 9              | 4.783     | 1.412              | $t_{n-1} = \frac{\bar{x}d}{[\text{std}/\sqrt{n}]}$ 0.93 Probability 0.17 > 0.05 |
| $\delta_{\text{EXP.}}$ | 9              | 4.633     | 1.421              | $t_{n-1} = \frac{\bar{x}d}{[\text{std}/\sqrt{n}]}$ -1.49 Probability 0.35 > 0.05 |
| $K_s$ (FEM)       | 9              | 343.82    | 59.84              |                             |
| $K_s$ (EXP)       | 9              | 361.43    | 32.52              |                             |

![Figure 16](image)

**Figure 16.** Predicted vs. measured maximum surface deflection for A-1-b soil
Figure 17. Predicted vs. measured modulus of subgrade reaction for A-1-b soil

For A-3 subgrade soil, the T-Test results are listed in Table 11. It was noticed that the $[t (8) = -6.0, \text{ probability } < 0.05]$ that means there is a significant variance between predicted and measured surface deflection and the mean decrease value is 0.15mm with confidence interval 95% as explained in Figure 18. Whereas in the modulus of subgrade reaction $K_s$, the T-Test result showed that there is no significant variance between simulated and measured subgrade reaction modulus, $[t (8) = -0.27, \text{ probability } = 0.75 > 0.05]$, the mean decreased 3.088 kPa/mm with 95% interval. Figure 19.

Table 11. Summary of T-Test Analysis for A-3 Soil

| Measurements data | No. of Samples | Mean (mm) | Standard Deviation | Paired Sample T-test Method |
|-------------------|----------------|-----------|--------------------|-----------------------------|
| $\delta_{\text{FEM.}}$ | 9              | 3.11      | 0.98               | $t_{n-1} = \frac{\bar{x}d}{[\text{std}/\sqrt{n}]}$ | -6.0 |
| $\delta_{\text{EXP.}}$ | 9              | 2.604     | 0.97               | Probability                | < 0.05 |
| $K_s \ (\text{FEM.})$ | 9              | 490.47    | 208.953            | $t_{n-1} = \frac{\bar{x}d}{[\text{std}/\sqrt{n}]}$ | -0.27 |
| $K_s \ (\text{EXP.})$ | 9              | 487.38    | 209.59             | Probability                | 0.75 > 0.05 |
For A-7-6 subgrade soil, the T-Test results are listed in Table 12. The results of analysis were \([t (8) = -1.03, \text{ probability } = 0.35 > 0.05]\) that means there is no significant variance between predicted and measured surface deflection and the mean decrease value is 0.105mm with confidence interval 95%, see Figure 20. Whereas in the modulus of subgrade reaction \(K_s\), the T-Test results showed that there is a significant variance between simulated and measured subgrade reaction modulus, \([t (8) = -3.47, \text{ probability } = 0.008 < 0.05]\), the mean decreased -25.125 kPa/mm with 95% interval, as illustrate in Figure 21.

### Table 12. Summary of T-Test Analysis for AL-Rofae Soil.

| Measurements | No. of Samples | Mean (mm) | Standard Deviation | Paired Sample T-test Method |
|--------------|----------------|-----------|--------------------|-----------------------------|
| \(\delta_{\text{FEM.}}\) | 9 | 4.599 | 1.235 | \(t_{n-1} = \frac{\bar{x}d}{\text{std}/\sqrt{n}}\) = -1.03 |
| \(\delta_{\text{EXP.}}\) | 9 | 4.494 | 1.171 | Probability = 0.35 > 0.05 |
| \(K_s\) (FEM) | 9 | 209.37 | 63.649 | \(t_{n-1} = \frac{\bar{x}d}{\text{std}/\sqrt{n}}\) = -3.74 |
7. Summary and Conclusions

In this research, the maximum surface settlement and the subgrade reaction modulus that was obtained from the static plate load test analyzed numerically using Plaxis3D. Comparisons have been made between the experimental and numerical results. The following conclusions based on the results are summarized below:

- The results illustrate that the subgrade reaction modulus increase with increasing the dry unit weight of soil and degree of compaction. Whereas, the increase of water content leads to decrease the subgrade reaction modulus.
The numerical analysis results with Plaxis 3D showed a good agreement with the experimental results. The T-Test indicated that in most results there is no significant variance between the experimental and numerical results data.

The finite element analysis showed a good acceptance between the measured and predicted subgrade reaction modulus. It was found that the maximum difference between the predicted and measured was 25.15 kPa/mm for clay soil (A-7-6 subgrade soil). While the minimum deference was 3.088 kPa/mm for A-3 soil. Whereas for A-1-b soil the mean difference was 17.621 kPa/mm.

Finally, the results of this work showed the possibility of using Plaxis 3D in the simulation of the static plate load test.

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