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Soil-Foundation Interaction and Its Influences on Some Geotechnical Properties of Sulaimaniyah, Northern Iraq Fine-Grained Soils Utilizing Plaxis 3D

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HIGHLIGHTS

- The 3D Plaxis is capabl of predicting the settlement of each modeled foundation.
- The utilized foundation center stresses are smaller than the foundation corner stresses.
- The soil settlement values are not dependent on the soil bearing capacity.

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ABSTRACT

Foundations of various construction projects usually can be either shallow or deep foundations. A mat foundation is one of the common shallow foundations typically utilized for various types of buildings. Foundations construct on various types of soils, which might be essential to understand the interaction scenario between them as they are two different types of materials. This study aims to discover the characteristics of the soil-foundation interaction for the suitable areas for the resettlement process in focus on a certain foundation type with a dimension of 10m x 10m x 0.5m, applied on twelve areas rich with fine-grained soil types in Sulaimaniyah governorate, northern Iraq, which suffer from some geotechnical problems such as building cracks. Application of loads was conducted in three stages; 35 tons, 70 tons, and 140 tons were directly applied on the utilized soils. The obtained results of the study prove that the 3D Plaxis is quite capable to predict the settlement of each foundation modeled on each utilized soil type. In addition, the modeling work achieved that the utilized foundation center stresses are notably smaller than the obtained foundation corner stresses. The obtained soil settlement values are not dependent on the soil-bearing capacity.

1. Introduction

Soils consider one of the most significant substances on the surface of the ground,and nearly all foundations of structures are put on it [1]. The in-situ soil stratum under the foundations of superstructures is important for bearing their forces. The weak soil stratum below foundations due to their low bearing ability can be responsible for safety issues for superstructures [2]. Most of the construction projects are put on soils. Soil is an important natural substance used in projects of construction. For that reason, soils' geotechnical properties must be critically calculated and understood [3, 4]. Soil geotechnical characteristics are important for soil foundation issues. Those characteristics should be properly figured out to be used for a successful foundation design. Fine-grained soils have some undesired characteristics, which may be unsuitable for construction purposes as soil foundations [3, 5-6]. Morecohesive soil issues, cause some difficulties for construction projects due to the availability of clay minerals, which usually exist in these soils [7]. Different building damages in various degrees are resulting from swelling procedures that happen in expansive soils, which cause volume changes due to wetting and drying states [8].

One of the most significant geotechnical issues of soils is settlement, which appears in various types and results in a risky state for superstructures' safety and sustainability. In addition, stress distribution also is important to find the exact risky area beneath superstructures' foundations. The settlement of foundations and the bearing capacity of footing are the two major criteria that govern the design of shallow foundations. However, a settlement frequently controls the design process rather than bearing capacity; this is especially true when the width of the footing exceeds 1.0 meters (3-4 ft) [9]. As a result, settlement prediction is a critical criterion in the design of shallow foundations. The shape, size, depth, and distance of the cavity from the

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loaded area all play a role in the footing's vertical settlement responses [10]. It was also revealed that if a weak layer of low stiffness is located at a shallow depth below the footing, the overall settlement of the foundation can be significantly increased.

[11], searched on the impact of foundation size considering many foundation areas such as 150 m2, 3380 m2, 600 m2, 938 m2, 1350 m2, 1838 m2, and 2400 m2. In addition, the effects of the upper structure applied load are also considered using many values such as 150 kN/m2, 200 kN/m2, and 250 kN/m2. It was achieved that there are significant differences between settlements calculated analytically and by 3D Plaxis. [12], studied the effect of raft thickness on settlement for applied pressures of 100 kN/m2 and footing embedment depths of 1.5, 3.0, 4.5, and 6.0 m by using both analytical and numerical modeling methods. It was discovered that Steinbrenner's elastic method of predicting foundation settlement produced results that were very close to those predicted by the finite element method. The thickness of the raft footing achieved has no effect on the predicted settlement.

A numerical simulation of Bangladesh soft soil was carried out by [13] using finite element software PLAXIS 3-D Foundation and SAFE V12. It has been performed to find the impact of different factors such as mat foundation thickness and modulus of elasticity, coefficient of subgrade modulus, and Poisson’s ratio on mat foundation behavior. Mat response was found to be not very sensitive to the majority of its characteristics. Mat foundation thickness and the coefficient of subgrade modulus played the most important role in this respect. In addition, [14] also utilized the criteria of Mohr-Coulomb Failure (Finite element analysis) to perform two-dimensional soil models. As square footing, the foundation is designed, and the load increase is applied until the failure of the soil model is achieved. At various places, the distribution of stress and displacement in the soil are gained, and then successfully compared with Plaxis work.

According to the previous examples on Plaxis 3D utilization to find some foundation soil changes, it has been chosen to draw the aim of this study. Plaxis 3D has been used to discover the characteristics of soil-foundation interaction for a certain foundation dimension and twelve areas around Sulaimani city, Northern Iraq, and validate them with real elastic settlement values.

2. Materials and Methods

2.1 Natural Soil Samples

The used soil samples were selected as they were considered as new resettlement areas that almost locate around Sulaimani City, Northern Iraq see Figure 1, and Table 1. The soil samples were found to be fine-grained particles with light brown color having different geotechnical parameters as shown in Table 2. The samples were collected from 1.5 – 2.0 meters depth from the natural ground level. Shelby tubes were utilized to save the natural characteristics without significant changes due to sampling and transportation. The sampling time was selected to be in the spring season to get suitable weather in terms of rainfall and temperature changes.

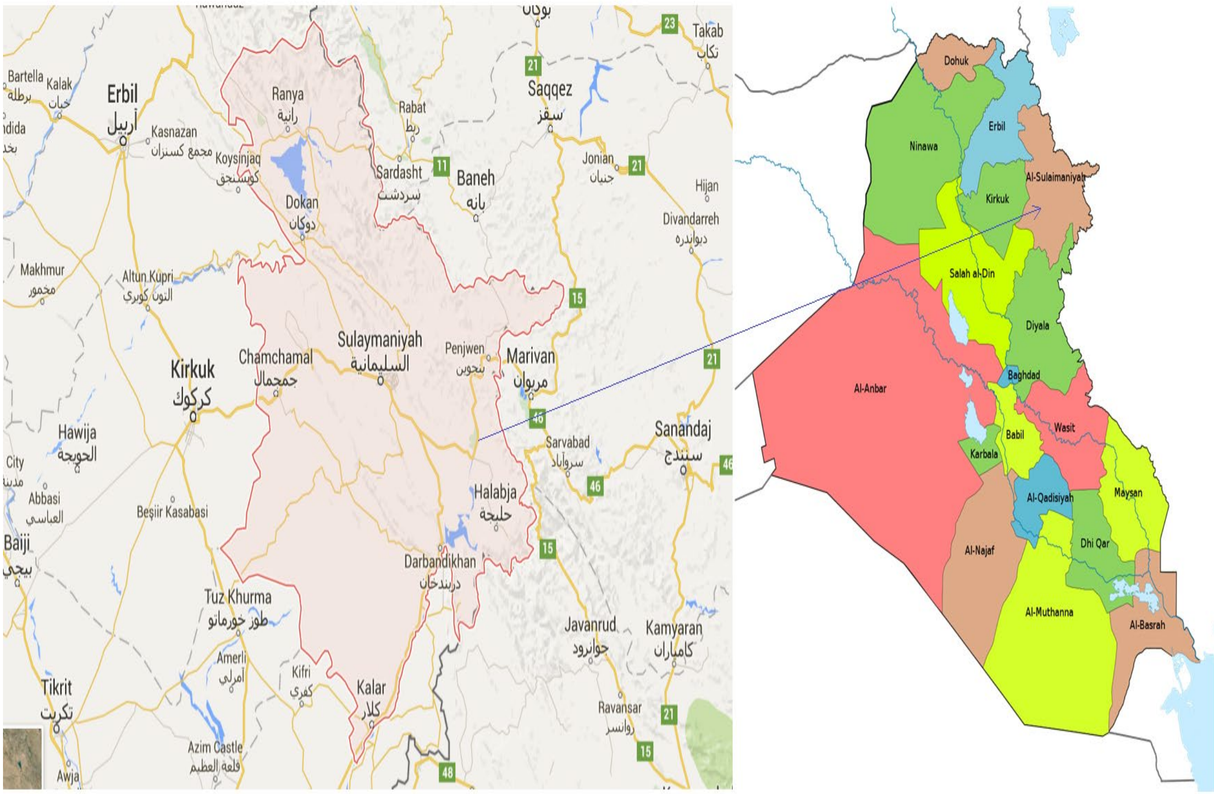

Figure 1: The chosen areas for natural soil samples collection shown on the Iraqi map

Table 1: Locations of the chosen areas for natural soils samples collection

No.	Area Name	Latitude	Longitude
1	Bakrajo	35°34'11.84"N	45°20'53.43"E
2	Khewata	35°37'34.79"N	45°24'41.94"E
3	Dabashan	35°36'29.48"N	45°28'15.31"E
4	Raparen	35°35'15.90"N	45°19'25.39"E
5	Sorga	35°39'18.90"N	45°19'53.69"E
6	Qerga	35°31'18.35"N	45°28'26.70"E
7	Qolaraise	35°36'58.85"N	45°20'13.56"E
8	Kalakn	35°36'14.51"N	45°25'18.16"E
9	Kanakawa	35°35'47.69"N	45°15'33.05"E
10	Kela Spi	35°34'23.20"N	45°16'24.74"E
11	Homara Kwer	35°33'9.76"N	45°27'31.10"E
12	Woloba	35°31'23.34"N	45°25'6.22"E

2.2 Carried out Methods

2.2.1 Laboratory Work

Various geotechnical characteristics such as shear parameters and field geotechnical properties were determined in a laboratory see Table 2 to be used for the Plaxis 3D modeling. These properties are also utilized to find the soil samples' ultimate and allowable bearing capacity using Terzhaghi bearing capacity equation with a factor of safety equal to 3.5 [15] as shown in Figure 2. The undisturbed samples were used to calculate the field density [16], cohesion and angle of internal friction [17], and Modulus of Elasticity, E [18].

2.3 Plaxis 3D Work

The interaction of the structure and its soil is based on a numerical model. Three-dimensional physical model of the structural system consisting of (1) raft; (2) soil is created. The mat foundation is modeled as a linear elastic plate element. The model created by using the above condition is analyzed by using the finite element software PLAXIS 3D to find out the settlement of the structural system. The model [19] analysis was carried out on a mat foundation with dimensions of 10m x 10m x 0.5m in addition to each mentioned soil geotechnical parameter presented in Table 2. Nine reinforced concrete columns were put on the mat foundation to represent an ordinary construction project. Four columns were put on corners, one column on the foundation center, and four columns on each side between two corner columns. Application of loads was carried out on each column in three stages; 35 tons, 70 tons, and 140 tons, which is equal to 3.5 tons/m^2, 6.3 tons/m^2, and 12.6 tons/m^2 as stresses directly on the soils. After that, from the models, settlement values were obtained for each 12 selected areas. Then, the stresses below the mat foundation center and corners were measured for each soil area to understand the responses of each area's soil to the applied loading style and value with the changes in the soil's geotechnical parameters.

The usefulness of Plaxis 3D for the current study is for the followings:

- Settlement prediction depending on in-situ soil properties and building loads. Settlement observation for the gradual loading style, which represents construction size increase.
- Highlighting the necessity of soil in-situ characteristics to decide on suitable building size. At the same time, the suitability of the selected areas for large structures.
- Discovering the most influenced places beneath the shallow foundation to find the underneath stresses that impact on the construction utilities.

3. Results and Discussion

3.1 Geotechnical Properties of the Selected Areas

The used samples were tested to obtain their geotechnical characteristics, especially those used for the soil-structure interaction modeling. Table 2 and Figure 2 present the results of the laboratory tests. The field densities of the locations are similar; however, the other characteristics are differing, which were manifested in cohesion and angle of internal friction, which then caused significant influence on the sample bearing capacity. These parameters are dependent on many factors such as soil particle sizes and shapes, void ratio, availability of impurities, etc.

3.2 Settlement due to Loads Application

After the utilization of PLAXIS 3D for all selected soil samples, Figure 3 shows the predicted settlements plotted along the y-axis, and the load is plotted along the x-axis. The linear increase with load implies an elastic behavior, the obtained results are deformed masses of soil for all the load levels applied in each of the used twelve samples. The settlement prediction is conducted for different soil layers in the various sites under the mat foundation. It is noticed that the Dabashan sample shows significantly more load-bearing capacity Figure 2, while the Qerga sample showed higher settlement Figure 3 as compared to other selected samples. The results are compiled with the finding of [20-22]. However, [11] study achieved that there are significant differences between settlements calculated analytically and by 3D Plaxis. The existence of voids in the internal structure of the soils contributes to the presence of compression index, compressible clayey soil thickness, and building structures surcharge loads, all contribute to the phenomena of settlement [23].

Table 2: The calculated geotechnical parameters for the natural soil samples

Soil Area	Field Density (gm/cm^3)	Cohesion (kPa)	Angle of Internal Friction (Degree)	Allowable Bearing Capacity (ton/m^2)
Bakrajo	1.893	33.6	24.8	56.36
Khewata	1.870	23.8	27.9	56.34
Dabashan	1.859	30.4	26.6	85.56
Raparen	1.867	35	19.6	36.11
Sorga	1.845	18.8	23.9	37.13
Qerga	1.767	25.8	25.5	48.81
Qolaraise	1.889	36.8	21.5	43.198
Kalakn	1.844	46.6	23.6	58.62
Kanakawa	1.749	27.2	28.7	60.56
Kela Spi	1.854	24.4	27.6	46.061
Homara Kwer	1.827	40	24.4	55.397
Woloba	1.858	33	23.2	46.99

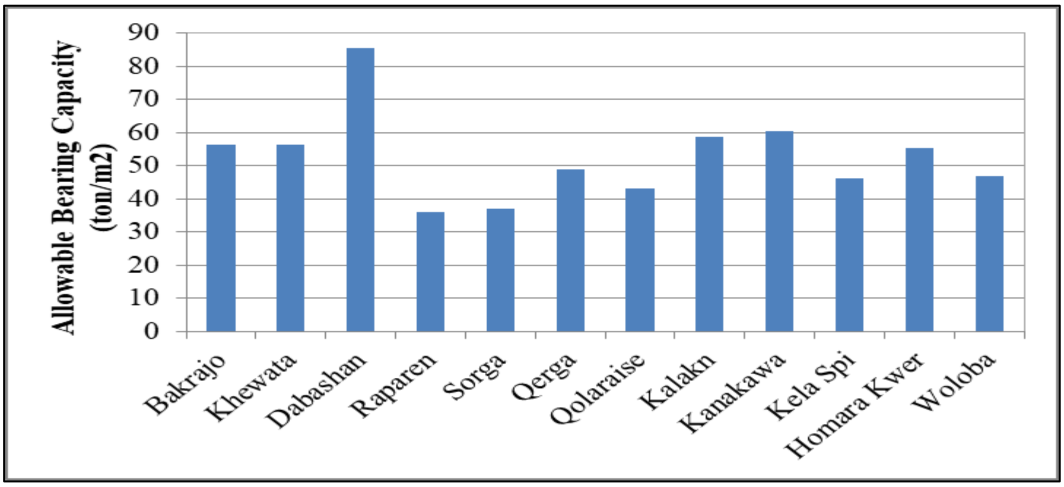

Figure 2: Allowable bearing capacity values for the utilized soil samples

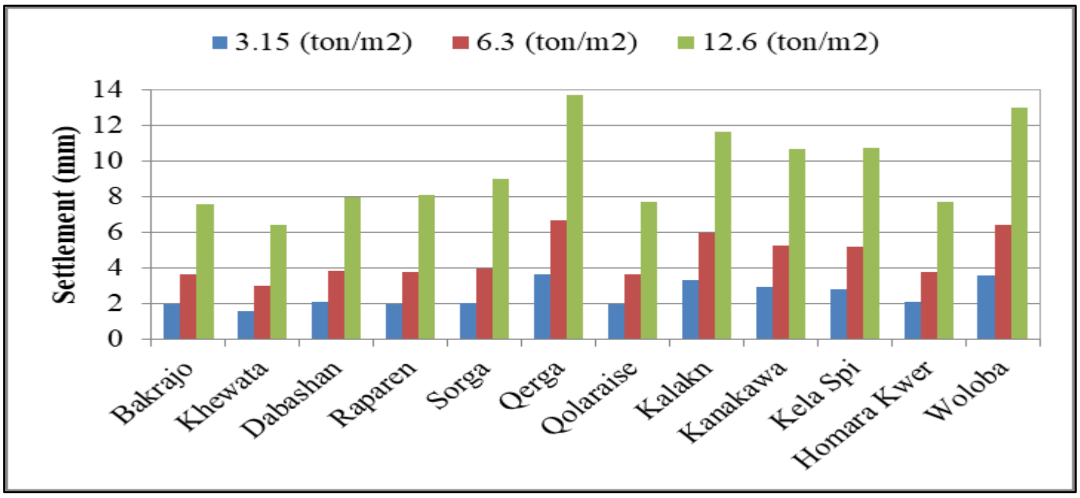

Figure 3: Comparison among the calculated settlement values for each loading applied on the soil samples

Besides the model settlement calculation, the elastic settlement was also determined. Both determined settlements were compared and critical understanding was depicted. For each loading state, the obtained settlements were compared as shown in Figures 4, 5 & 6. Almost the calculated settlement is very close to the model settlement. However, some soil types demonstrated higher differences. The found differences are in the range of 0.31% to 28.58%. The higher differences were recorded for the larger applied stresses. This may result from the changes in the soils' geotechnical characteristics, which can be noticed in the differences among the geotechnical parameter values presented in Table 2 and Figure 2. Clearly, the variations in those properties change the reaction of the sample for loading and settlement see Figures 3 – 7. The demonstrated settlement value variations that obtained mathematically and by the model in this study are dissimilar to the outcomes of [11] study, while similar to the outcomes of [12] study.

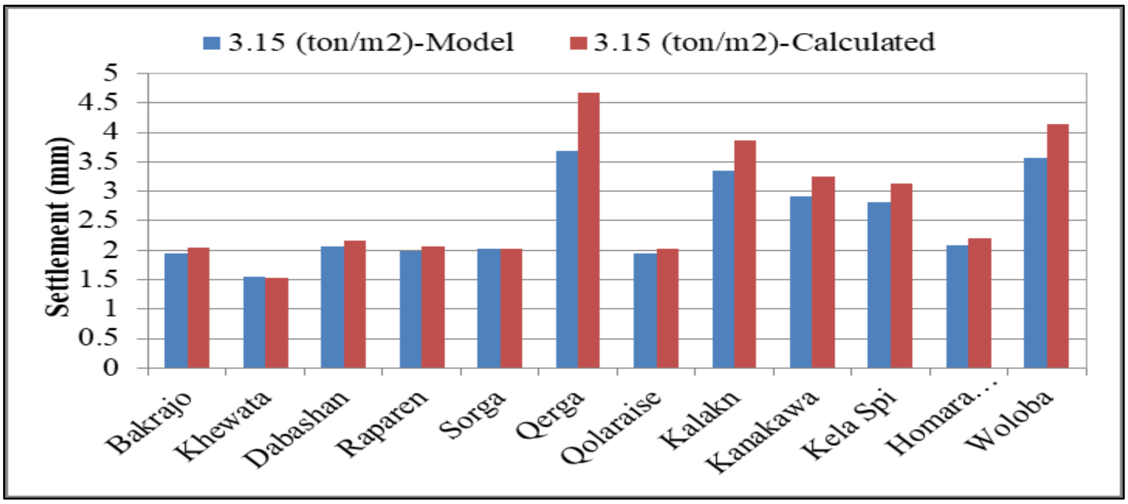

Figure 4: Comparison between the values of real elastic settlement with the values of predicted settlement by the model after subjection to 3.15 ton/m^2 stress

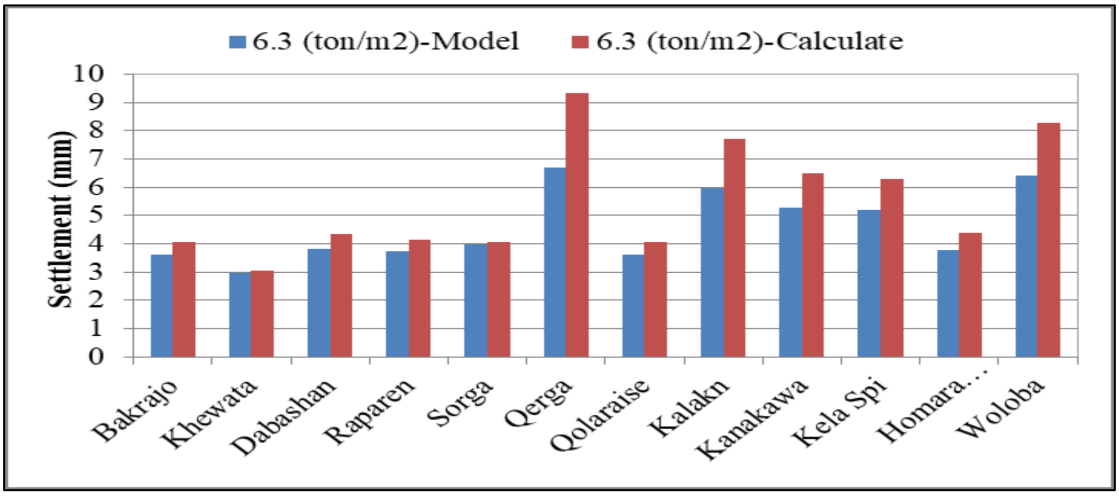

Figure 5: Comparison between the values of real elastic settlement with the values of predicted settlement by the model after subjection to 6.3 ton/m^2 stress

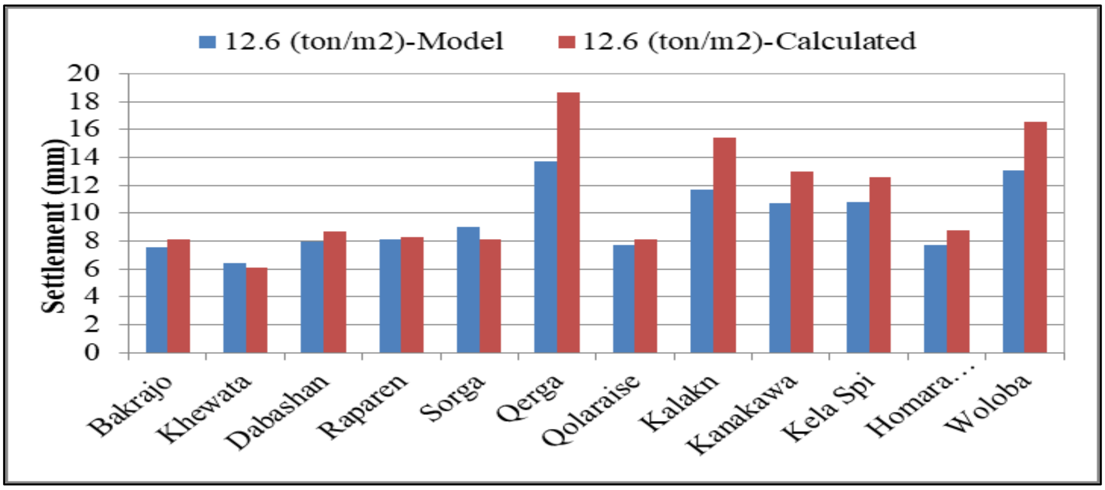

Figure 6: Comparison between the values of real elastic settlement with the values of predicted settlement by the model after subjection to 12.6 ton/m^2 stress

3.3 Stresses Below The Mat Foundations (Center and Corner)

Figure 7 shows the variation of recorded stresses under the center for each foundation under three loading systems. It is clear that Woloba and Qerga samples have the maximum value of center stress, 82.32 kPa, and 81.63 kPa respectively with the applied load of 140 tons. The minimum value of center stress can be found under the Sorga foundation up to 68.49 kPa under the same applied load. Similarly, [24] used tactile sensor technology to measure the normal pressure at various points beneath the base of a laboratory model of a rigid strip footing. The results showed that the contact stresses peak at the centerline. This visually observed distribution corresponds to the well-predicted theoretical distribution and differs significantly from the uniform distribution commonly assumed during engineering design.

The corner stress shown in Figure 8 below the Homarakwer foundation has recorded a maximum stress of 229.8 kPa at the maximum loading stage of 12.6 ton/m^2 as compared to the other foundation's stresses. This is due to the distribution of the contact stresses in general soils near footing edges being high, which tends to increase the result in the maximum bending moment at the footing. This increase should be taken into consideration during the footing design. In addition, most of the references were presenting inappropriate distribution for the contact stresses [25]. They suggested using [26] assumption, which is the uniform distribution. This tends to underestimate the maximum bending moment.

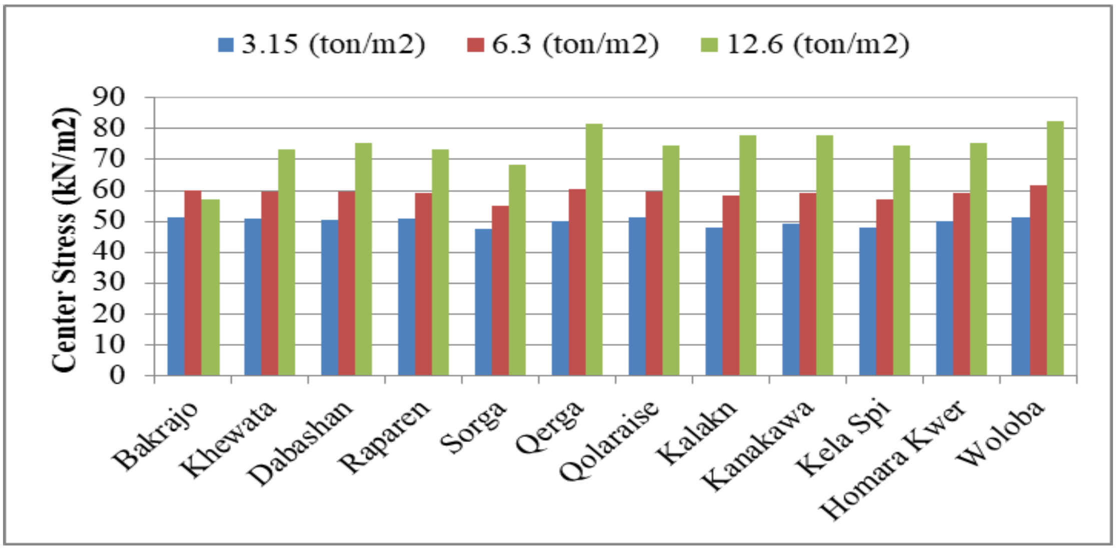

Figure 7: Comparison among the recorded stresses below the center of each foundation on each soils samples under the application of three loading systems

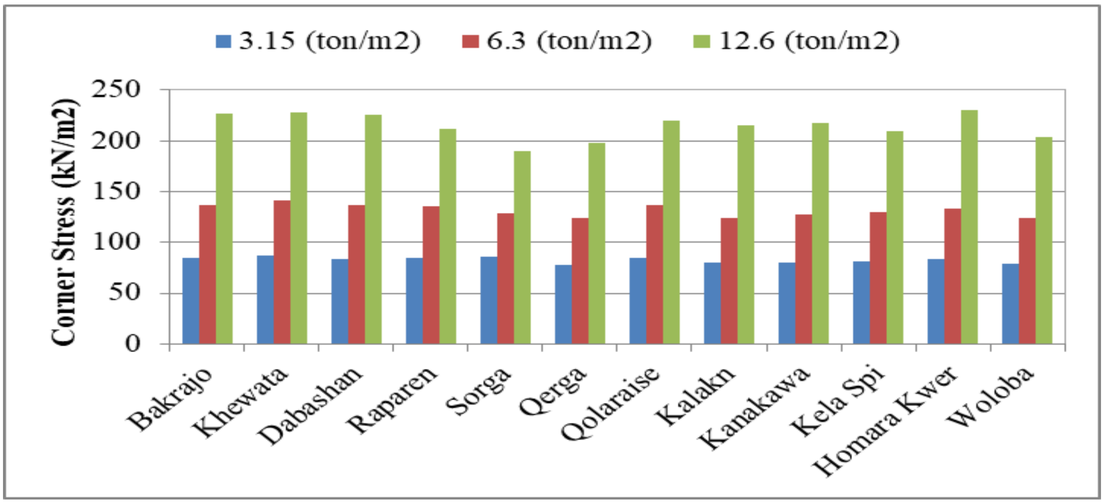

Figure 8: Comparison among the recorded stresses below a corner of each foundation on each soils samples under the application of three loading systems

3.4 Plaxis 3D Modelling Images

From Figures 9 and 10, the modeled foundation is clearly settled down. The settlement magnitude started to decrease gradually to the endpoint of surface settlement. The foundation shown in Figure 9 resisted the applied load in some way; however, it dropped to a lower elevation depending on the applied stress level. Both mid-distance and diagonal analyses in Figure 10 showed significant stress distribution below the foundation. The model is clearly successful in terms of measuring settlement, corner, and center stresses below the proposed foundation. This work was conducted to discover the surface of the soil-influenced area, which is randomly distributed around the foundation projection. Hence, the surrounding area elevation notably changed and got deeper elevation, which might be noticed by soil surface cracks after a while from the construction completion, as shown in Figure 9.

Shallow depths of the proposed foundation exhibit a larger probability of soil structure changes and causing surface depressions directly below the foundation bottom. This can result in a quick settlement. This case significantly happens in the foundation mid-width on mid-length compared to the diagonal stress distribution, which shows smaller shallow stress distribution see Figure 10.

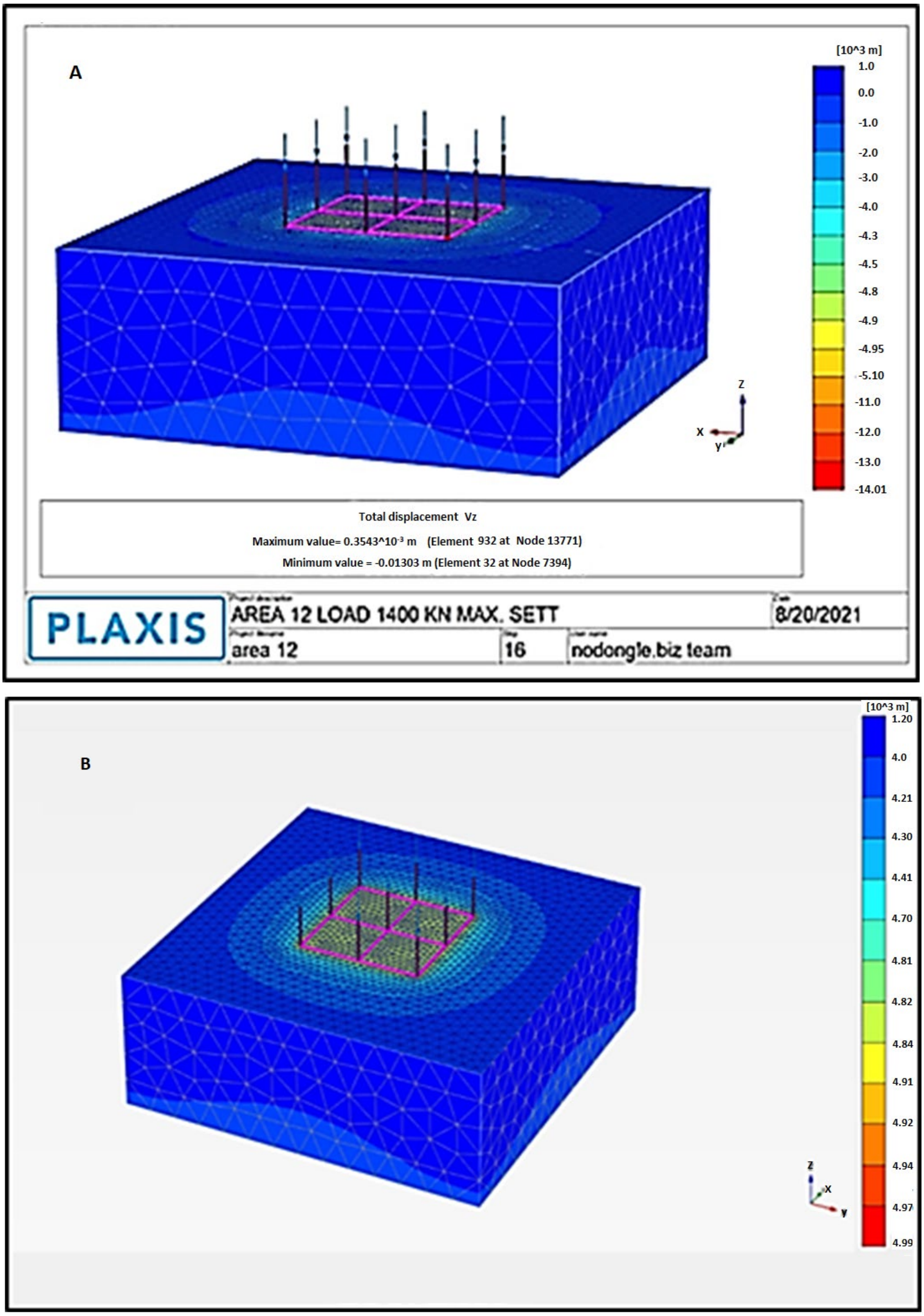

Figure 9: 3D image of the proposed mat foundation holding 9 columns and interacting with 10 m soil layer

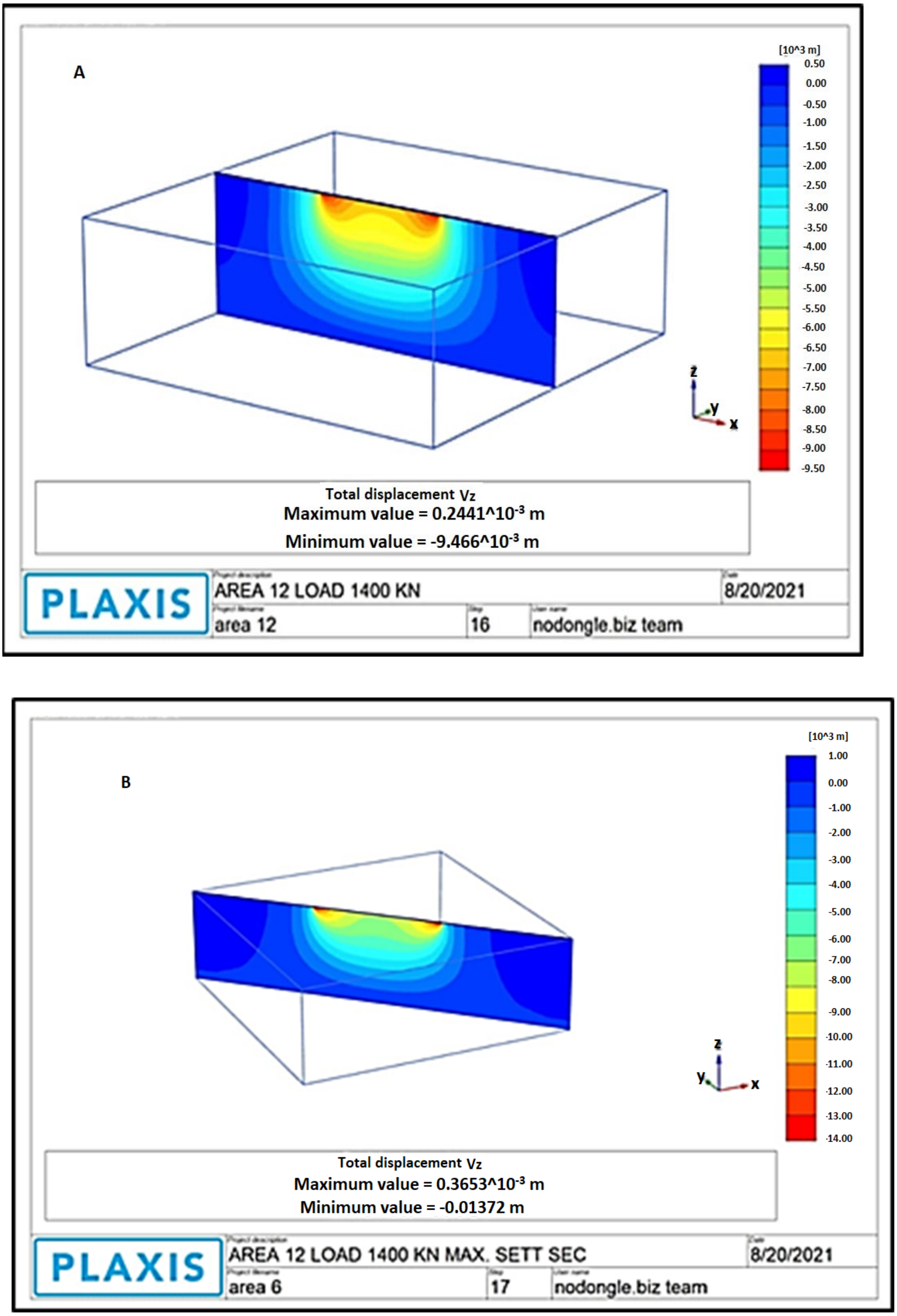

Figure 10: 3D image of the proposed mat foundation influences on the 10 m soil layer, mid-horizontal distance analysis, and diagonal analysis

4. Conclusion

- Mohr-coulomb criteria are successfully performed for mat foundations that are subjected to various loading levels.
- The Plaxis 3D work proves that with the applied loads increase, settlement increases within a similar manner for all applied loads. Plaxis 3D recognized that no significant settlement for small and medium construction, while notable settlement records for larger structures.
- The achieved settlement values do not necessarily depend on the soil's bearing capacity value.
- Stress distribution is not equal under the rigid mat foundation. The corners in the upper part were subjected to larger stresses, and then below, almost equal stress distribution. Larger foundation corner stresses are obtained compared with the mat foundation center stresses.

Author contribution

All authors contributed equally to this work.

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Data availability statement

The data supporting this study's findings are available on request from the corresponding author.

Conflicts of interest

The authors declare that no conflict of interest regarding this study.

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