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Evaluation of the Bearing Capacity of a Single Pilesby NumericalsAnalysis and Various Methods

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ABSTRACT: This study focuses on estimating the predicted ultimate load of the pile that does not reach the failure, based on five methods: Chin-kondner Extrapolation, DeBeer, Shen, which estimates the value of the failure load of the pile, and by using the numerical methods. This paper compares the load results obtained from the field for the North Nasiriyah Bridge project and the results obtained from numerical methods. Plaxis3d Foundation 2020 was adopted to clarify the extent to which numerical methods can approach the behavior of the actual pile and give results that are close to the field. Four bored piles (TP1, TP2, TP3, TP4) were used in this paper, and their testing load was 60, 650, 950, 70 tons, respectively. In addition, the Mohr-Coulomb model, which considers the site's soil parameters, was employed to simulate both the mound and the soil.

1. INTRODUCTION

Because of the nature of soil as a construction material, designers in geotechnical engineering never know exactly what they're dealing with [1]. Architectural expansion and the increase in building areas at present, and the variation in the techniques of designing the piles led to the need to find alternative methods to identify the behavior of the pile and determine the safe load for it. Large numbers of soil parameters are involved in analyzing the piles' behavior, which was the reason for the doubts associated with using the accepted theories. The numerical analysis was one of the essential alternative solutions used in this study. Numerical modeling was used using plaxis3d Foundation. It was applied to a single pile drilled into the different layers of the soil of the site. The load was calculated based on plaxis3d and compared with the field results to verify the validity of the program results. Linear models are commonly used in numerical analysis. Still, this simple representation does not give a clear idea of the complex behavior of soils, as the soil is a substance with multiple deformation stages, not limited to elastic, plastic, and non-linear deformations, but also shows irreversible plastic deformations [2]. Researchers have used various analytical, experimental, and numerical-based studies over the years [3] [4]. One of the most extensively utilized geotechnical and structural analysis methodologies is the numerical simulation of structures [5].

Ahmed Majeed and Ola Haider [6] focused on representing the bearing capacity of the piles, based on the Chin Conder method, on predicting the behavior of the pile at each stage of loading until an acceptable compromise is reached. The final pile capacity is estimated using the tangential method. Each point was divided stability with the corresponding load, and the slope of this line was C_1, and the intercept with the y axis is C_2 and using the equation adopted in their study to calculate the load. An ideal curve for the field was plotting naturally and ensuring how acceptable and valid the results were. The program was repeated using the settlement obtain from Chin method. The results were very close to reality.
Shooshpasha [7] indicated that the numerical analysis results using Plaxis predicted the pile bearing capacity, and it was closer to the actual value. Harasid disagreed with the previous findings. First, the bearing capacity of a square pile was analyzed using empirical methods and numerical methods using Plaxis. Then the results are compared; the Mazurkiewicz method gave the closest carrying capacity to the field capacity [8].

The results of the substrates loading test were analyzed using a finite element based on the results of the experimental methods and the interpretation of the final bearing capacity of the field test. This study shows that Finite element technology is the most similar in producing maximum bearing capacity [9].

Krasinski presented that a numerical simulation is a useful tool in understanding the interaction of soil structure. However, it requires more research and applications for more accurate analysis. The pile was represented to transfer the loads. 81% of the total load was transferred by the pile column and 19% from the pile base. The field results do not show a perfect match with the numerical analysis results. 68% of the total load was transferred by the pile and 32% by the base of the pile. Nevertheless, the field data showed that the value of friction is less than the value obtained from the finite element.

Estimating the bearing capacity of the piles is not easy, as the traditional methods used to calculate the bearing capacity are not sufficient to understand the behavior of the pile when loads are applied to it. It neglects some effects, which in turn gives inaccurate solutions. Other reliable methods must be available to evaluate the traditional methods used and verify or validate the results. In this research, the finite element method by Plaxis3d is used to determine the piles' bearing capacity and evaluate the methods used. It helps to understand the performance of the pile more accurately. The Mohr-Coulomb analysis represented the model for a bored pile of diameter 0.3 m and 17 m. Plaxis3d and field measured load-displacement curves showed a good correlation.

The numerical method in our study provided results approaching the field and a clear description of the behavior of the substrate at each stage.

2. STATIC PILE LOAD TEST

It is one of the types of tests used to measure the bearing capacity of axially loaded piles and one of the most extensively utilized geotechnical and structural analyses [10]. The static pile load test on a single pile includes uplift force, axial compression, and lateral testing [11]. Static pile load tests are considered the most accurate method for evaluating piles' bearing capacity and settlements in many nations worldwide [12].

The tests entail gradually increasing loads at predetermined time intervals while concurrently measuring the settling at each phase. According to Standard Test Methods for Deep Foundations, an experimental system for loading test under Static Axial Compressive Load ASTM-D1143_07 [13]. Hydraulic presses achieve vertical pressing force on the pile and measure the force applied to the pile head. As a result, a load-settlement curve is produced [14]. The results (load-settlement) curve of four project piles were presented as shown in Figure 1. Figure 2 shows the details of the soil layers for borehole Points 1 and 2. Figure 3 shows the relationship between the depth of soil layers and the number of blows for the standard penetration test (SPT).

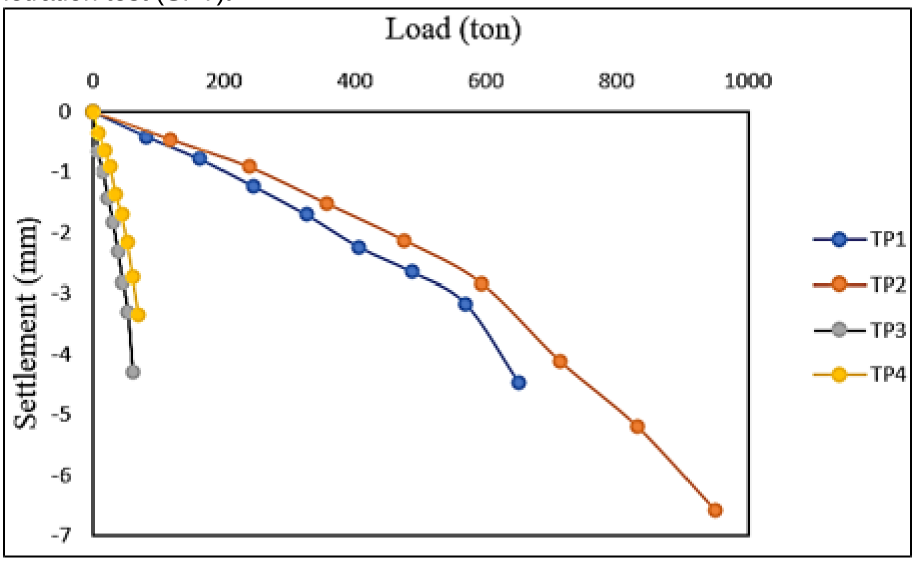

Fig. 1 Load-Settlement curve.

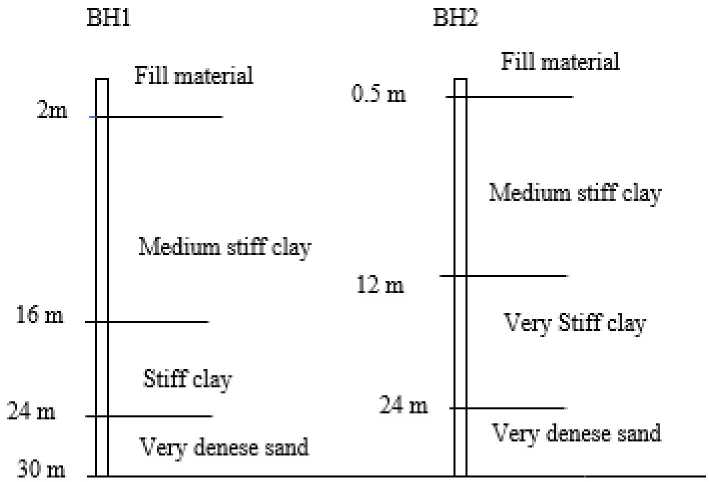

Fig. 2 profile of the soil databank test.

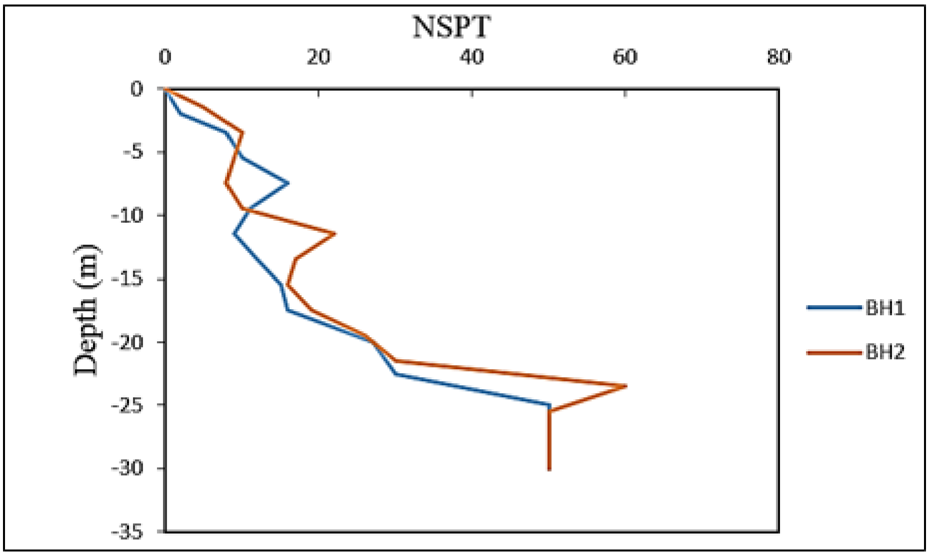

Fig. 3 SPT diagram.

3. SOIL INVESTIGATIONS AND GENERAL DETAILS OF SOIL LAYERS

Al-Iskan Interchange is a project planned and designed to be constructed in Thi-Qar, southern Iraq. Four tests borehole points with different depths were investigated. The approved test points were at depths of 30 m, 16 m, 16 m, 16 m. The samples were taken to the laboratory. All soil data were obtained, and the nature of the soil layers was determined (Table 1).SPT was performed near the pile sites and accurately depicted the geotechnical characteristics of the soil surrounding the piles.

Table 1. Details of borehole and properties of soil.

Depth (m)	0-2	2-16	16-24	24-30
Soil description	Fill material	Medium stiff clay	Stiff clay	sand
Modulus of elasticity, Es (kN/m^2)	2400	21750	51500	67200
Poisson's ratio, v	0.35	0.3	0.3	0.25

Angle of internal friction, φ	27	_	_	40.6
Cohesion, c (kN/m^2)	5	_	_	2
Angle of Dilation, ψ	0	_	_	10.6
Un drain shear strength, Su (kN/m^2)	_	43.5	103	_
Dry unit weight, γd (kN/m^3)	14	16	18.5	20
Total unit weight, γt (kN/m^3)	14	19.8	20	20

4. GRAPHICAL METHODS TO ESTIMATE BEARING CAPACITY OF SINGLE PILE

4.1 Chin-Kondner Extrapolation

The chin method for evaluating the ultimate load of the pile by dividing each movement by the applied load and plotting those results against the movement. The inverse of the slope of the straight line (C_1) extracted from the drawing represents the final load [6], as in the following equation [15]:

$$Q_u = 1/C_1 \qquad (1)$$

where

Q_u = ultimate load of the pile, C_1 = Straight Slope of the Line.

4.2 DeBeer Method

DeBeer (1968) and Deeper and Walays (1972) proposed drawing the linear, logarithmic loads curve. For the data before and after reached the ultimate load, this curve gives different slopes of the intersection axis. When the ultimate load is reached, the calculation of the two lines will become visible, one occurring before and the other after the final load [5], [16].

4.3 Shen's Method (1980)

This method assumes that it is possible to obtain the ultimate load from drawing the relationship between settlement and applied load, where the settlement is plotted against the log load. This relationship results in a curve with a linear tail where the final load is determined at the starting point of the linear tail [17].

4.4 Decourt Extrapolation (1999)

Decourt (1999) suggested a method that is similar in construction to those used in Chin-Kondner. Each load was divided with its corresponding motion to apply the method, and the resulting value was plotted against the applied load. The extrapolation load limit of Decourt is equal to the ratio between the y-intercept and the line slope [12], as follows:

$$Q_u = C_2 / C_1 \qquad (2)$$

Where

Q_u = ultimate load of the pile, C_1=Straight Slope of the Line, C_2 = y-intercept of the straight line.

4.5 *Buttler and Hoy method (1977)*

This technique draws a tangent to the point where the slope of the load settlement curve is 1.27 mm/ton.

The load value of the tangent at the point at which it intersects the tangent drawn at the source linear area, which is the root of the tangent. The origin is the ultimate at 1.27 mm/ton of slope drawn on the curve load [18].

5. EVALUATION OF A SINGLE PILE USING FINITE ELEMENT METHOD

The numerical analysis provides quick and appropriate solutions to various field problems that can be applied to other problems of a similar nature that may arise in the future. The finite element was used to calculate the bearing capacity of the piles by the Plaxis3d Foundation 2020 software. The finite element method represented four piles with lengths (17, 25, 28.5, 11.75) m and diameters (0.3, 1.50, 1.50, 28.5) m for Al-Eskan Interchange project. A representation of a single pile of 17 m in length and 0.3 m in diameter is shown in this paper. The calculations of the bearing capacity of the pile depended on the characteristics of the soil layers in which the pile was driven. The pile is defined as the linear elastic model in Table 2. The representation of the pile and the surrounding soil was based on the Mohr-Coulomb model. This model requires several soil parameters such as the angle of internal friction (φ) as well as the dilation angle (Ψ), the cohesion (C), the modulus of elasticity (E_s) and Poisson's ratio (v). Dimensions (20 × 20) m were adopted for the model in the program of this study. The model consists of a large number of nodes, each element has ten nodes, and these elements have tetrahedral shapes. Soil parameters are entered for each layer of soil. The depth is determined depending on the range of the deep the impact is in the soil. The study model consists of two things: soil and pile. First, it is necessary to consider the value of the interface ($R_{int.}$) with soil and pile. Second, it is essential to consider the interference between the soil and drive the concrete pile into the soil. Therefore the interference must be determined when creating the model and give it an appropriate value.

On the other hand, the Plaxis3d Foundation provides an important factor: the coarseness factor, which generates finer areas of the mesh close to the concrete pile in the model used. As a result, the mesh begins to coarse with increasing distance from the pile. This is due to the decrease in stresses farther away from the most significant influence near the concrete pile. Therefore, to distribute the elements in the mesh, the medium size of the distribution is adopted for all piles.

Table. 2 Details of the concrete pile.

Identification	Value
Material model	Linear elastic
Modulus of elasticity, E_p (KN/m^2)	25×10^6
Poisson's ratio	0.15
Type of material	Non-porous-concrete
Material density (KN/m^3)	25

6. THE RESULTS AND DISCUSSION

Table 3 shows the bearing capacity estimated based on the static pile load test results using five methods and the bearing capacity obtained using the finite element method. The results indicated a discrepancy in the ability predictions for the pile. The bearing capacity predicted by using Chin-Kondner and Decourt methods reached 114.8 tons, which is considered a high value compared to the results of other methods. Chin-Kondner and Decourt calculate the failure value of the pile, so the resulting values are significant. The capacity calculated by Shen was the lowest among the methods as it was 22.5 tons as in Table 3; this value is less than expected. This method's failure criterion is diving, which occurs when a pile continues to settle under a continuous weight or a little load an increase in the load. *Buttler and Hoy* gave an average value of 51 tons. Again, the value is less than expected, as the value of the test is 60 tons. DeBeer does not calculate the final load at which the pile fails but instead calculates the load at which the settlement begins to settle under a gradually increasing load. This makes the expected value less than that of Debeer does not calculate the final load at which the pile fails but instead calculates the load at which the descent begins to settle under a gradually increasing load. This makes the expected value less than that of Chin and Decourt. It is considered an average value when compared with other methods of interpretation. The last method shown in Table 3 depends in its curriculum on the finite element method by analyzing the pile and representing it within the soil medium. The numerical analysis results indicated a convergence in the calculated results from the program and the field results. The numerical analysis depends on the fundamental properties of the soil, which gives an adequate perception of the pile behavior and settlement.

Table 3. Results of bearing capacity by interpretation and numerical methods.

Piles of testing no.	Static test field (ton)	Loads obtained of interpretation methods (ton)					Loads obtained of finite element method (ton)
		Chin-Kondner	DeBeer	Shen	Decourt	*Buttler and Hoy*	Plaxis3d
TP1[1]	60	114.8	52.5	22.5	114.8	—	57
TP2[1]	650	995.8	568.7	162.5	914.5	470	470
TP3[2]	950	2040	829	237.5	2043	498	810
TP4[1]	70	195	—	26	195	56	67

The representation of the pile and the surrounding soil was based on the Mohr-Coulomb model. An effective depth of (30) m is determined for the soil. The effective depth is determined when the stress value approaches 0.01 of the total applied stress. In addition, (6D) is determined from the bottom of the end of the pile.

It is necessary to consider the thickness of the interface ($R_{int.}$) between the soil and the pile. $R_{int.}$ depends on the characteristics of the soil particles (the average of the size particles, roughness of their surfaces). The $R_{int.}$ can be represented by giving it zero value or a specific value. In the Plaxis program, it is possible to set the value of R_{int}.= 1 means no slip between the soil and the concrete pile represented as an intermediate body. In the case of zero value, this means that a full slip between the pile and the soil has occurred. The analysis will give a value for the bearing capacity greater than the actual value when using $R_{int.}$=1; the bearing capacity value is 66 tons, while the field value is 60 tons. The resulting bearing capacity by fixing the $R_{int.}$ value 0.7 is closer to the field value [19].

In a program for Plaxis, usually, a mesh convergence study should be carried out to select mesh size. Different types of inbuilt mesh are available: Very Coarse, Coarse, Medium, Fine and Very Fine the mesh is made up of elements. To verify the effect of the shape of the distribution on the bearing capacity value at the stress concentration region, the effect of each type was studied separately. The results were compared as shown in Table 4. Very fine and fine results gave more accurate results and were closer to the field value, but it has more time to analyze them, which takes more than 30 minutes. Therefore, the medium distribution was adopted in the analysis of the results for all piles. By adopting the medium distribution form, the resulting bearing capacity value had results that were no less accurate than the very fine and fine ones and at an appropriate time. The boundaries of the model are refined with an appropriate coarseness factor, which in turn works to generate finer areas of the mesh close to the concrete pile in the model use. A value of 0.7 is adopted as the coefficient of roughness for soil and 0.25 for both concrete and interface [20]. The mesh begins to coarse with increasing distance from the pile. It is due to the decrease in stresses that occurs farther away from the greatest influence near the concrete pile, as Figure 4. The convergence of the results gives a clear idea that the analysis by Mohr-Columb gives good results and is close to the field production of the Nasiriyah soil. However, understanding and selecting the appropriate material model and input parameters for the finite element is critical, and failure to do so will negatively influence the results. Therefore, the soil parameters entered into the program were chosen with great care and were determined based on laboratory results and equations to derive some of the basic soil parameters.

Table 4 Compare the results with different mesh sizes values.

Size of mesh	The (BC) resulting from numerical analysis	Node site
Very coarse	47	2920
Coarse	50	9464
Mediume	57	12051
Fine	60	16988
Very fine	62	26880

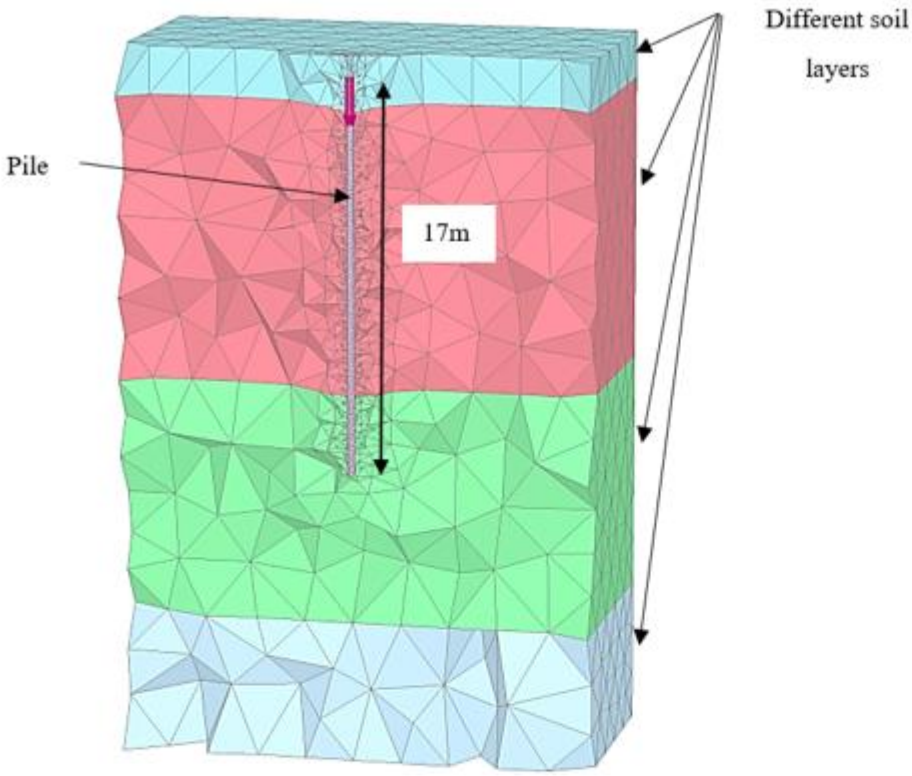

Fig. 4 Model showing the location of the coarseness factors of the model parts.

Table 5 shows the results for representing pile the load and settlement resulting from the finite element analysis. The results showed that the numerical method gates an ability and settlement close to the calculated value during the pile test.

Table 5. Results of static test load and Plaxis3d.

	Field		Plaxis3d
% Design load	Load (ton)	Settlement (mm)	settlement
0.00	0.00	0.00	0.00
25%	7.5	0.65	0.43
50%	15	1.00	0.86
75%	22.5	1.42	1.72
100%	30	1.82	2.15
125%	37.5	2.32	2.58
150%	45	2.82	3.44
175%	52.5	3.13	3.87
200%	60	4.3	4.3

Figure 5 shows the load versus settlement results for both the pile load test and the finite element solution, depending on the soil properties of the site. Again, the numerical analysis results showed convergence of the field results.

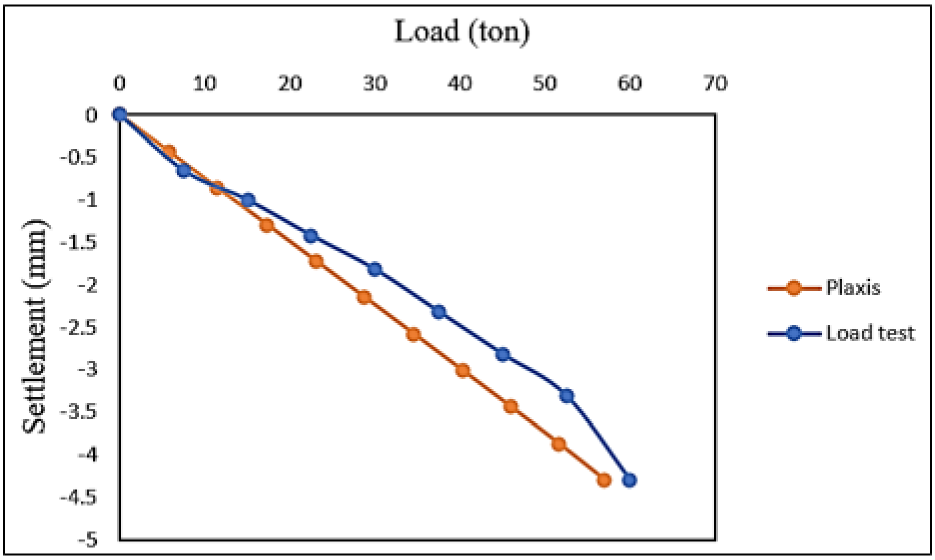

Fig. 5 comparing the results between the field and the Finite element.

The vertical deformations that occur in the soil due to the stresses generated by the pile are displayed in Figure 6 shows the contour (cross-section) of the settlement with different depths. The deformations shown in Figure 6 show the areas and areas of the soil subjected to the maximum stress, causing the failure of the pile.

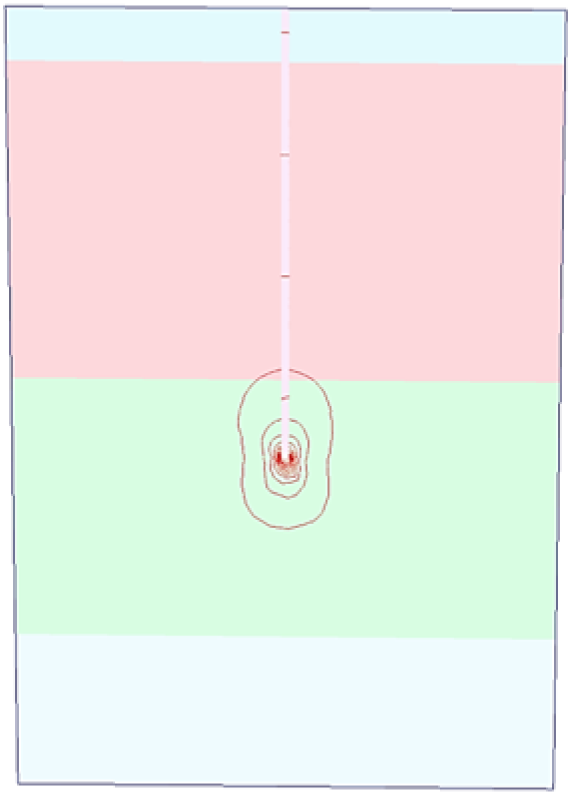

Fig. 6 Vertical deformations.

7. CONCLUSION

The results obtained from the interpretation methods used in this study were compared with the results computed by the numerical method. The pile bearing capacity value based on numerical analysis was the closest to the field. Chinn Kondener and Decourt gave an overestimated value, while DeBeer gave results more minor than the field value. The predicted values calculated by Shen were the lowest among the methods. The results of the pile bearing capacity from Plaxis3d Foundation showed reasonable expectations and closeness to the field. The value of pile capacity generated from the numerical analysis was very close to the test load value obtained from the static load test performed on-site. The results extracted by numerical analysis indicated the possibility of obtaining the required and different values accurately and the economic aspect, where the amounts spent to calculate the values in the field and save the effort expended.

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