Proceedings of the 20th International Conference on Soil Mechanics and Geotechnical Engineering– Rahman and Jaksa (Eds)

Vertical displacement of bored piles group for project of LRT using numerical analysis

Déplacement vertical d'un groupe de pieux forés pour un projet LRT par analyse numérique

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ABSTRACT: This paper presents the finite element modeling of bored piles in clay and sandy soils in which piles are subjected to static compressive and lifting loads is presented. The thickness of bored piles was investigated by interpretation methods and supporting equations. For modeling we used data from load tests of bored piles at the LRT construction site. This study discusses the drilling mechanism of piles subjected to compression and lifting using two-dimensional finite element method analysis (FEMA) based on the Midas-GTS NX program (Midas, 2014). This article discusses the problem of the bearing capacity of piles with defects in the pile body. Field tests were conducted using a non-destructive Cross-hole Sonic Logging method (CSL). According to the results of the field tests and pile modeling has been given that more than 20 % of piles are with defects. Field data results and data of numerical modeling were confirmed also as on the recommendation by Bjerrum.

RÉSUMÉ: Cet article présente la modélisation par éléments finis de pieux forés dans des sols argileux et sableux, dans l esquels les pieux sont soumis à des charges statiques de compression et de levage. L'épaisseur des pieux forés a été étu diée par des méthodes d'interprétation et des équations à l'appui. Pour la modélisation, les données des essais de charge des pieux forés sur le chantier de construction du TLR ont été utilisées. Cette étude traite du mécanisme de forage de pieux de compression et de levage à l'aide de l'analyse par éléments finis 2D (FEMA) basée sur le logiciel Midas-GTS NX (Midas, 2014). Cet article traite du problème de la capacité portante des pieux en cas de défauts dans le corps du pieu. Des essais sur le terrain ont été menés à l'aide de la diagraphie sonique inter-puits non destructive (CSL). D'après les résultats des tests grandeur nature et de la modélisation des pieux, il a été constaté que plus de 20% des pieux présentent des défauts. Les données de terrain et les simulations numériques ont également été validées sur la recommandation de Bjerrum.

KEYWORDS: pile, defect, test, method, soil, ultrasonic

1 INTRODUCTION

The construction public transport system LRT (Light Railway Transport city was constructed in Nur-Sultan. LRT is an overhead road with two railway lines. At the first stage of construction included the construction of overhead road (bridge) with 22,4 km length and 18 stations which are under process. The foundation of bridge is the bored piles with cross-section 1.0÷1.5 m and length 8÷55 m. Design bearing capacity of piles is 4500÷12000 kN. For boring of soil used a Chinese drilling rigs Zoomlion without casing. To maintain the walls of boreholes in sand and gravel soils to use a polymer slurry. In these conditions, very important to control integrity of concrete body of each bored piles. For checking integrity applying two methods - Low Strain Method and Cross-Hole Sonic Logging.

This study discusses about of the bored pile mechanism subjected to compression and uplift loads using the two-dimensional finite element method analysis (FEMA) based on the Midas-GTS NX program (Midas, 2014). This article is decided the task of the bearing capacity of piles with defects respectively 10%, 20%, and 30% in the pile body. The data of pile defects were obtained from in-situ tests (one of three with an acceptable defect) based on which the task was simulated on the Midas-GTS NX program.

Numerical models of a three bored pile located in clayey and sandy layers were examined. The Mohr-Coulomb model was presumed for soils, and the concrete bored pile was assumed to be linearly elastic. Cases of pile foundation models with various defects were created to analyze the simulation results by parameters "defect percentage" for three combinations of defective pile groups. The results of pile modeling and field tests confirm that piles with defects over 20% have a low bearing capacity and are not allowed for exploitation. Details of the observations are discussed below.

2 EXPERIMENTAL DATA OF CSL TEST

2.1 *Cross-Hole Sonic Logging*

CSL method is an accurate, cost-effective, and non-destructive that means of investigating the integrity of concrete in drilled shaft foundations. CSL establishes the homogeneity and integrity of concrete in a deep foundation and identifies anomalies, such as voids or soil intrusions, within the structure.

Ultrasonic logging, on the other hand, is intrusive and necessitates the prior installation of access tubes (usually two or more) in the pile, which is shown in Figure 1. Before the test they have to be filled with water (to obtain good coupling) and two probes are lowered inside two of the tubes. One of these probes is "an emitter" and the other "a receiver" of ultrasonic pulses. Having been lowered to the bottom, the probes are then pulled simultaneously upwards to produce an ultrasonic logging profile. The transmitter produces a series of acoustic waves in all directions. Some of these waves do eventually reach the receiver. The testing instrument then plots the travel time between the tubes versus the depth. As long as this time is fairly constant, it shows that there is no change in concrete quality. If the travel time suddenly increase at any depth may indicate a weakness at this depth. The number of access tubes cast in the pile concrete is a function of the pile diameter, the importance of the pile and, of course, economic consideration. A good rule of thumb is to specify one tube per each 30 cm of pile diameter. For best effect, the tubes should be equally spaced inside the spiral reinforcement and rigidly attached to it by wire or spot welding. Tubes are extended below the reinforcement cage, they have stabilized by suitable steel hoops [Zhussupbekov and Shakirova *et.all* 2018 & Zhussupbekov *et. all* 2019*]*.

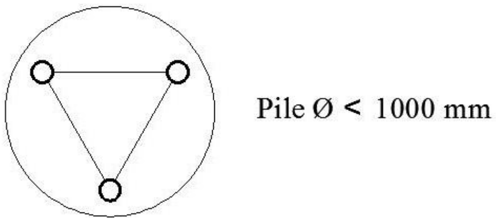

Fig. 1 Typical Access Duct Configuration

Everybody with experience in reinforced concrete construction has encountered columns that, upon dismantling of the forms, exhibit air voids and honeycombing. Although these columns may have been cast with good-quality concrete, in properly assembled forms and with careful vibration, they still exhibit defects. Cast-in-situ piles are also columns, but instead of forms made of wood or metal we have a hole in the ground. This hole may pass through layers of dumped fill, loose sand, organic matter, and ground water, which may be fast flowing or corrosive. Obviously, such conditions are not conducive to a high-quality end product.

2.2 *Interpretations of test data*

Usually the report includes presentation of Cross-Hole Sonic logs for all tested tube pairs including:
- Presentation of the traditional signal peak diagram as a function of time plotted versus depth.
- Computed initial pulse arrival time or pulse wave speed versus depth.
- Computed relative pulse energy or amplitude versus depth.

A Cross-Hole Sonic Logging will be presented for each tube pairs. Defect zones, if any, will be indicated on the logs and their extent and location discussed in the report text. Defect zones are defined by an increase in arrival time of more than 20 percent relative to the arrival time in a nearby zone of good concrete, indicating a lower pulse velocity [ASTM Standard D 6760 2002, White *et. all* 2008, Zhussupbekov and Shakirova *et.all* 2019 & Zhussupbekov and Shakirova *et.all* 2019]. The same procedure, which is carried out in two dimensions on a single profile can be used in three dimensions for the whole piles.

A tomography is a mathematical procedure that is applied to the Cross-hole Sonic Logging (CSL) data, providing the user with a visual image of shaft's internal defects. The procedure involves solving a system of equations based on the first arrival times (FAT) in order to calculate wave speeds at various points within the shaft. Wave speeds of tomography distributed throughout the shaft are directly proportional to density, indicating concrete quality. For visual imaging are used a program PDI-TOMO is an extension of the CHA-W software designed for superior tomographic analysis results from CHAMP data with increased efficiency for the user. The field test result of the integrity of bored pile shows in Table 1 and defects on the pile body as shown in Figure 2.

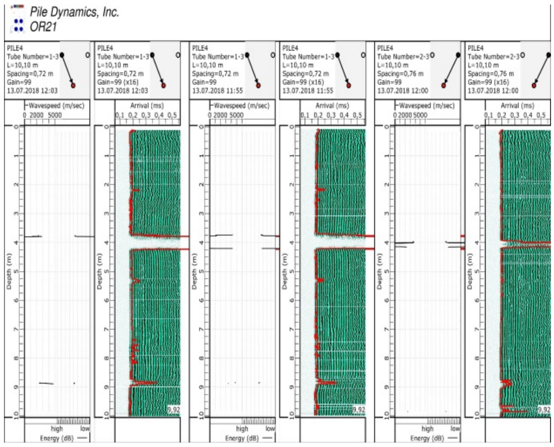

Fig. 2 Three Ultrasonic Profile of one pile OR21-4

Table 1 The result of the integrity of bored pile

Number pile	Pile diameter, (m)	Pile length, (m)	Speed of wave, (m/c)	Concrete class	Comments
Station 115-116, OR21-4	1.2	10.1	1565	B35	Anomaly at depth defected 3.75:4.75 m

3 NUMERICAL MODELING

3.1 *Analysis in Midas-GTS NX*

Finite element analysis has gained popularity in the design of geotechnical structures since the 2000s. There are many computer packages available at present. The functions of the Midas-GTS NX analysis are similar to other geotechnical engineering software such as PLAXIS, FLAC, etc. The two-dimensional FE analysis can provide any displacement component at the nodes of the structural system. It can further reveal the stresses at the nodes, and any of the elements. However, it should be noted that the stresses revealed at the nodes need to be carefully used. The Midas-GTS NX analysis is the main tool used in carrying out this study.

3.2 *Results of numerical modeling of pile group in program Midas-GTS NX*

Clayey and sandy strata were both assumed. A soil stiffness was increased with the layer's depth. The effects of the ground water table and pore water movements were neglected in the modeling. Mohr-Coulomb failure criterion was assumed for the soils. As shown in the results, clayey soils were dominated by the undrained shear strength. Sandy soils were controlled by the internal friction angles. The internal friction angles of the sandy layers were averaged in the analysis for the interpretations. Linear elastic material was assumed for the concrete piles.

The numerical models and the material properties of the bored piles used in this study can be found in Table 2.

Table 2 Properties of bored pile

Number pile	Pile length, (m)	Pile diameter, (m)	E_s, MPa	Poisson is ratio	ρ, (t/m^3)
Station 115-116, OR21-4	10.1	1.2	3*10^4	0.18	2.4

Table 3 Soil parameters for modeling

Depth, h (m)	Soil types	Soil density, ρ, (t/m^3)	c, kPa	φ, (^{0})	E_s, MPa
0.6-5.20	Bulk soil	1.87			70
5.20-9.80	Loam	1.90	40	26	77
9.80-14.10	Sand stone	1.95	0	40	126
14.10	Gravel sand	2.00	0	32	217
Average value					122

For the Midas-GTS NX analysis, the contact elements between the pile and soils were guided by a simple elastoplastic model. The frictional stiffness (*Kt*) of the contact element was presumed equal to the Young's Modulus of the soils (*Es*). For the frictional strength of the element, if the piles were in clays, the adhesions (c_a) between the pile and the soils were related to the undrained shear strength of the clayey soils (S_u). All parameters of soil layers shown in Table 3.

A Figure 3 shows the typical FEMA mesh used in the study. A uniformly distributed load was applied on top of the bored pile. 150 MN were the maximum loads applied for compression and lift is shown in Figure 4. Significant boundary conditions shown in Figure 5. The stability and convergence of the numerical solutions were ensued by enlarging the size of FEM zone. Depicts the appropriateness of the solutions with respect to the size of the FEM zone for pile in clays.

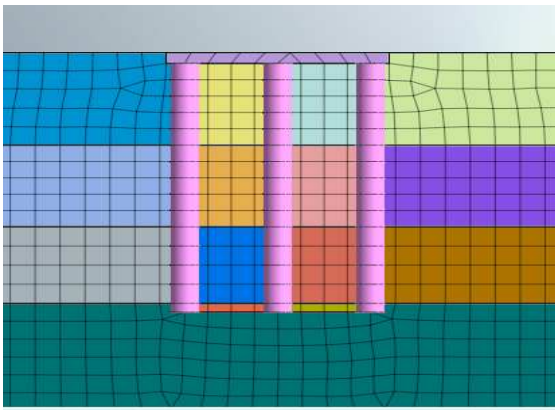

Fig. 3 FE mesh used in the Midas analysis

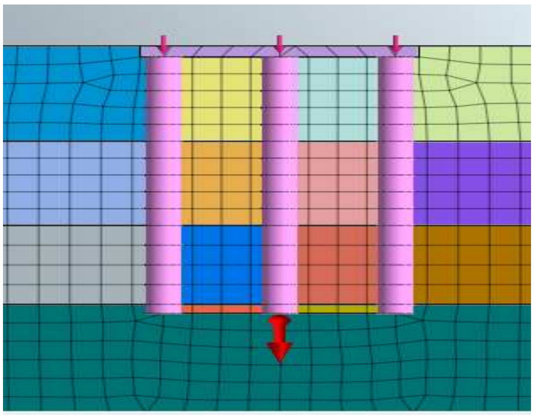

Fig. 4 Static load gravity, force

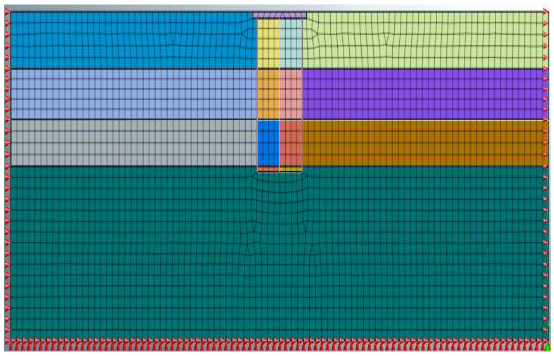

Fig. 5 Boundary conditions

Cases of pile foundation models with various defects were created to analyze the simulation results by parameters "defect percentage" for three combinations of defective pile groups. We considered the bearing capacity of piles with defects respectively 10%, 20% and 30% in the pile body, respectively, as shown in Figures 6,7,8,9.

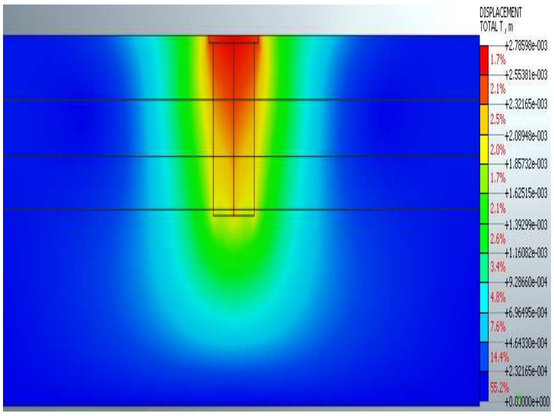

Fig. 6 Vertical displacement of bored pile groups ("good" pile)

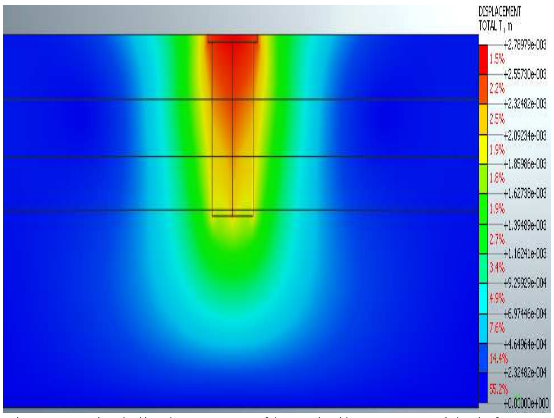

Fig. 7 Vertical displacement of bored pile groups with defect 10%

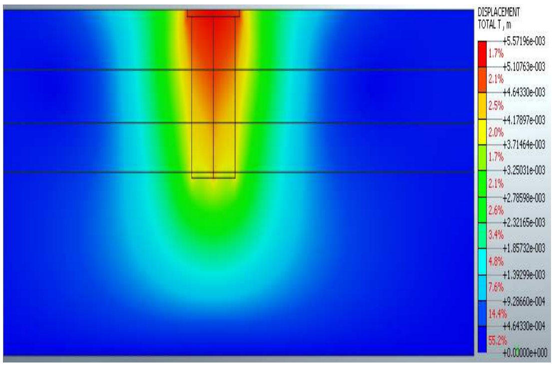

Fig.8 Vertical displacement of bored pile groups with defect 20%

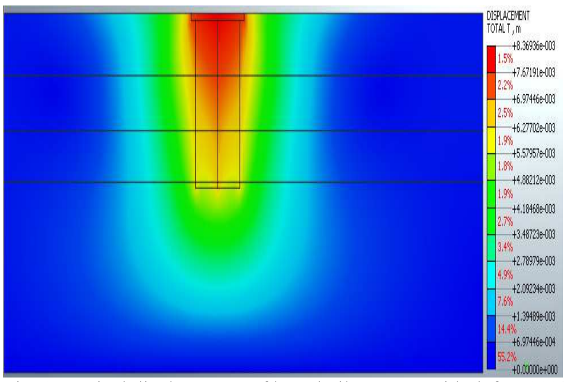

Fig. 9 Vertical displacement of bored pile groups with defect 30%

The analysis results show that for piles with 30% defects, the maximum vertical displacement is 25.107 mm, exceeding the permissible value (limit 25 mm). Consequently, a pile of more than 20% defects will have a low bearing capacity.

Table 4 Cases of pile group foundation models with 10 percentage defects

Case study	Defect 10 %	Good pile	Maximum vertical displacement, mm	Limit, 25 mm
1-1	0	Pile 1,2,3	8.355	OK
1-2	Pile 1	Pile 1,2	8.359	OK
1-3	Pile 1,2	Pile 1	8.363	OK
1-4	Pile 1,2,3	0	8.367	OK

Table 5 Cases of pile group foundation models with 20 percentage defects

Case study	Defect 20 %	Good pile	Maximum vertical displacement, mm	Limit, 25 mm
1-1	0	Pile 1,2,3	8.355	OK
1-2	Pile 1	Pile 1,2	11.140	OK
1-3	Pile 1,2	Pile 1	13.927	OK
1-4	Pile 1,2,3	0	16.713	OK

Table 6 Cases of pile group foundation models with 30 percentage defects

Case study	Defect 30 %	Good pile	Maximum vertical displacement, mm	Limit, 25 mm
1-1	0	Pile 1,2,3	8.355	OK
1-2	Pile 1	Pile 1,2	13.939	OK
1-3	Pile 1,2	Pile 1	19.523	OK
1-4	Pile 1,2,3	0	25.107	N.G.

Bjerrum (1963) recommended the limiting angular distortion, β_{max} for various structures [Amir, J.M. & Amir, E.I. 2009]. The differential settlement and the angular distortion can cause structural distress when they are excessive. The angular distortion is defin ed as the ratio of the differential settlement between two adjacent foundations to the span length.

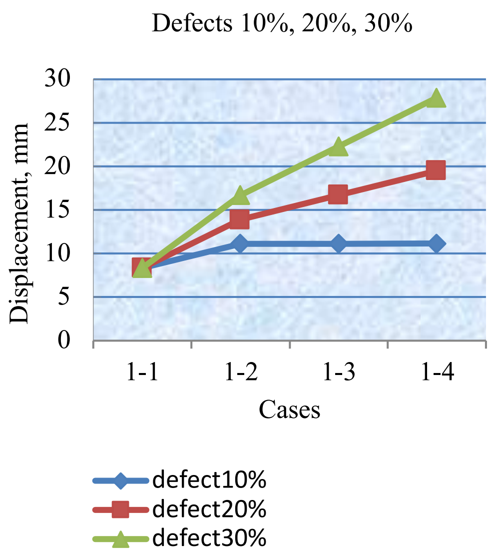

Fig. 10 Results of the pile displacements with various defects

The European Committee for Standardization has also provided limiting values for serviceability and the maximum accepted foundation movements.

The serviceability limit state can be threatened when the angular distortion reaches a specific value in the range of 1/300 to 1/500. These limiting values are larger than those provided by Terzaghi and Peck (1948), who suggested an allowable settlement limiting value of 25mm for isolated foundations and 50 mm for rafts. Field data results and data of numerical modelling were confirmed also as β_{max} in [Branagan & Associates 2002]. For the piles with 10 and 20 percentages of defects the rules are made, and for piles with 30 percentage defects the rule do not decided. The piles with more than 20 percentage (see Fig. 10) of defects had been low bearing capacity of piles.

4 CONCLUSION

This study presents the examples of using the two-dimensional FEMA for modeling of bored piles that have undergone compression and lifting. The results of field tests and modeling of piles, as well as on the recommendation by Bjerrum showed that piles with more than 20% defects have a low bearing capacity. Those piles are not approved for exploitation.

On the basis of investigations are given following recommendations: if defects of piles founded near top of piles needed to take a coring from pile body and analyze the concrete strength parameters at the laboratory, and secondly, if the length of the piles is deep needed to conduct a static test of pile with defects or improve the group piles by additional pile.

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