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Evaluation of Numerical Modeling of Jet Grouting Design Using in situ Loading Test

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***Abstract*—**Jet grouting (JG) is one of the methods of improving and increasing the strength and bearing of soil in which the high pressure water or grout is injected through the nozzles into the soil. During this process, a part of the soil and grout particles comes out of the drill borehole, and the other part is mixed up with the grout in place, as a result of this process, a mass of modified soil is created. The purpose of this method is to change the soil into a mixture of soil and cement, commonly known as "soil-cement". In this paper, first, the principles of high pressure injection and then the effective parameters in the JG method are described**.** Then, the tests on the samples taken from the columns formed from the excavation around the soil-cement columns, as well as the static loading test on the created column, are discussed. In the other part of this paper, the soil behavior models for numerical modeling in PLAXIS software are mentioned. The purpose of this paper is to evaluate the results of numerical modeling based on in-situ static loading tests. The results indicate an acceptable agreement between the results of the tests mentioned and the modeling results. Also, modeling with this software as an appropriate option for technical feasibility can be used to soil improvement using JG.

***Keywords*—**Jet grouting column, Soil improvement, Numerical modeling, In-situ loading test.

I. Introduction

INJECTION of slurry of under high pressure was introduced in Japan in the early 1970s. During the past years, with the development of equipment and injection knowledge, various injection methods have been developed under pressure. Pressure injection provides conditions that modify the shape, size and characteristics of the soil mass. In this method, with the advanced tools, the buried columns of soil and cement mixes are produced by special pumps at high speeds (800 to 900 km/h) and high pressure (300 to 700 bars) at the site. In fact, the injection improves the physical and mechanical properties of the mentioned organization, thereby reducing the permeability and deformability of the layers and increasing their resistance [1], [2].

Now JG has become a fast-method with diverse application as one of the most popular methods of soil improvement [3], including the cases mentioned in [4]-[6]. The pressure injection is capable of improving all types of soils, from sand and gravels to very sensitive clays.

In the JG method, first, a low-diameter rod is drilled in the ground at high speed. When the rod reaches the desired depth, air, water, and injection mixtures are injected into the soil using the pump at high speed and pressure through the nozzles at the tip. In this method, rod rotates at high speed during injection and moves upward at low speeds. This operation can damage the soil structure and completely mix with the soil. On the other hand, high injection pressure also increases the density of soil and creates a homogeneous and rigid environment in the soil. The soil-cement column has a strength range of 20 to 200 kg/cm^2 and an elastic modulus of about 2000 MPa. In general, there are three distinct types of pressure injection (Single Fluid, Double Fluid and Triple Fluid). The choice of one of these three methods depends on the soil, application and soil-cement properties [7], [8]. It is important to note that according to the results of [9], the uniaxial compressive strength of the column implemented in the Single Fluid is greater than other JG injection methods, due to the higher consumption of the cement and the lower water/cement ratio. The result of the JG column in Single Fluid has a higher elastic modulus and shear modulus.

In this paper, a project in the south of Iran is investigated and evaluated. The main objective of this paper is to investigate: (1) Perform modeling of JG using software PLAXIS and (2) Evaluation of numerical modeling results using static loading test results. This test has been carried out after the implementation of the jet column, which is presented in part of the paper. Then, we use the results of this in situ test to evaluate the modeling.

II. Effective Factors in the Operation of JG

A. Compressive Strength of JG Column

One of the important parameters for designing the columns of this method is the uniaxial compressive strength of the mixture of soil and cement obtained from this method. After the construct trial columns on the project site and core sampling at different depths of the column, the 28-day resistance of the samples can be obtained and the initial design is modified accordingly.

According to [10], 'specifications of Soilcrete (which means JG) columns that are achieved from the JG procedures from a diameter and strength point of view, depend on JG parameters such as grout pressure, lifting speed, rotating speed, number and diameter of nozzles, cement /water ratio and specifications of local soil'.

B. Elasticity Modulus of JG Column

Another important parameter in the design of JG columns is to calculate the modulus of elasticity of these columns. This

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parameter is similar to the compressive strength of the soil and is, in fact, a function of the compressive strength of the columns. In various references, such as in [3], the modulus of elasticity is expressed as a coefficient of uniaxial compressive strength:

$$E = \beta . q_u \quad (1)$$

The value of β coefficient varies according to the soil's type, which is included in coarse-grained soils including sand and sandy gravel in the range of 1000-1200 and in fine-grained soils including clay to silty sand, this coefficient is between 100 and 200. Therefore, the exact value of this parameter should also be verified in each project using the test.

C. Specific Gravity

Specific gravity for JG columns is a function of soil specific gravity, slurry density, volumetric ratio of soil and slurry, also void ratio. This item should also be corrected by testing, but it is suggested as a preliminary estimation in different references that the single and double fluids should be considered to be similar to the specific gravity of the surrounding soil.

D. Soil Behavioral Model

In the case of behavioral model of JG columns, two models have been suggested in different references. The proposed model is the first to use the Tresca model, which is purely dependent on the uniaxial compressive strength of the columns and is similar to the behavioral model of a weak concrete element. In this model, the coefficient of friction for the column is not considered, or in the other words, the effect of the confining pressure or the coefficient of friction against the cohesion of the element is ignored. In this model, the compressive strength is merely a function of cohesion [3]:

$$\tau = C_T \quad (2)$$

The C_T value is obtained from a uniaxial compressive strength test.

The second proposed model is the use of the behavioral model of Mohr Coulomb, which is a function of effective stress, friction angle and cohesion [3]:

$$\tau = C_{MC} + \sigma_1 \tan(\varphi_{MC}) \quad (3)$$

The relationship between the parameters of these two behavioral models given the fact that the C_T value is obtained from the uniaxial compressive strength test, according to Fig. 1, this is as follows:

$$C_T = C_{MC} . \tan(\pi/4 + \varphi_{MC}/2) \quad (4)$$

Due to the degradation of soil structure in the JG system, no relationship can be made between the angle of friction of the soil before and after the JG, and the only way to calculate the friction angle and jet column cohesion is by using the triaxial test. Due to the need for a high confining pressure in practice, this test is difficult to achieve. Therefore, due to the fact that in JG, the cohesion of the JG is much higher than the confining stress. Using Tresca's behavioral model is an option for modeling. However, due to the limitations of existing software such as the PLAXIS, we can use (3) and the uniaxial compressive strength and estimate the friction angle using the behavioral model of Mohr Coulomb in software.

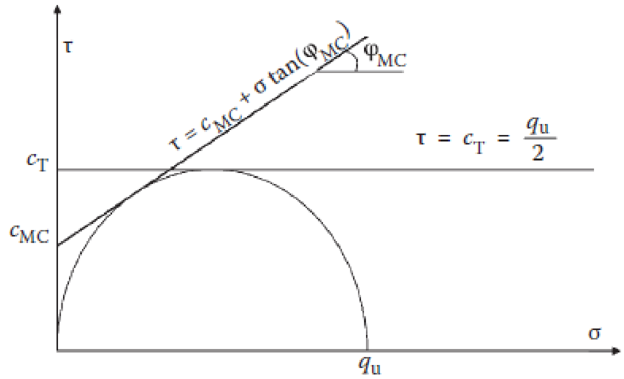

Fig. 1 Two proposed failure models for JG columns

III. Quality Control of JG Columns

There are various methods for controlling the quality of JG columns to reach the diameter and the optimal resistance during and after the implemented. There is always an element of uncertainty with the JG technique regarding quality control on site. This is in reality the main issue for every contractor [11]. The executional valid standard for JG is the EN12716 which provides various suggestions, recommendations and requirements for a proper quality control [12].

A. How to Control the Diameter of the JG Columns?

Initially, the designer proposes the limit values for effective parameters to reach the computational diameter based on the relationships presented in the references. At the beginning of the project, before the start of the main column, some test columns are executed in which the effective parameters in the formation of the column diameter including the injection pressure, nozzle type and diameter, the rate of increase and the amount of discharge (volumetric flow rate) are set according to the designer's opinion. Here, commonly (5)-(7) for calculations of diameter have been mentioned [3]:

$$D_{min} = 1.128\sqrt{P . V_g . \lambda_E} \quad (5)$$

In this case, P is the injection pressure, V is the injection rate and λ is the energy coefficient.

For fine-grained soils:

$$D_m = D_{ref} . \left(\frac{\alpha_E . \Delta^* . E_n'}{7.5 . 10}\right)^{\beta} . \left(\frac{q_c}{1.5}\right)^{8} \quad (6)$$

For coarse-grained soils:

$$D_m = D_{ref} . \left(\frac{\alpha_E . \Delta^* . E_n'}{7.5 . 10}\right)^{\beta} . \left(\frac{N_{SPT}}{1.5}\right)^{8} \quad (7)$$

The effective parameters in these relationships are the diameter and number of nozzles, slurry discharge, slurry density, water/cement ratio, slurry outlet velocity, and so on. After the trial columns, after a specified time period (48 to 72 hours), the columns excavated and the diameter of the columns is measured as shown in Fig. 2. In this project, the diameter was measured up to a depth of 8 m using a cement rings system (with special rings and a large diameter).

By comparing the computational relationships and the measured diameters on the site, the experimental coefficients in (5), (6) are accurate and the method of execution is corrected. Using the results of calculating a diameter of 8 m above, if there is a layer at lower depths that gives less probability of forming a smaller diameter, the method of execution is proportional to the results obtained.

Another method of diameter control is the use of the combined method of shear wave testing and PIT that the experience of this testing in the South of Iran project has led to satisfactory results. PIT is a non-destructive testing technique for assessment of structural integrity of column type foundations, which is very common because of its ease and cost. It is also possible to use a continuous coring method at the edges of the JG column to control the diameter in depth.

Fig. 2 Measuring the diameter and using the cement rings

B. How to Control the Strength?

One of the methods for controlling the core strength of JG columns is to perform uniaxial compressive strength test on it and to study the stress-strain curve to calculate the modulus of elasticity. Table I shows the results of uniaxial tests on loadable specimens.

TABLE I
RESULTS OF UNIAXIAL LOAD TEST ON JG CORING SPECIMENS

Raw	BH NO.	Depth (m)	Level	Strata Type	Age (day)	C.S (kg/cm^2)
1	1	2	Level 1	SC-SP	28	33.4
	2	4	Level 2	SC	28	37.2
2	3	2	Level 1	SC	28	39.4
	4	5	Level 2	SC	28	42.3
	5	10	Level 3	SC	28	45.8
3	6	7	Level 1	SC	28	46.1
	7	9	Level 2	SC	28	47.6

A static loading test similar to a pile can also be performed on JG columns.

Static loading test is an in-situ type of loading test that is used to determine the bearing capacity of deep foundations in geotechnical research. In the project presented in this article, the method of testing on the basis of the Standard Test Method [13] is carried out, as shown in Fig. 3. The results of this test are shown in Fig. 4.

Fig. 3 Static loading test in south of Iran project

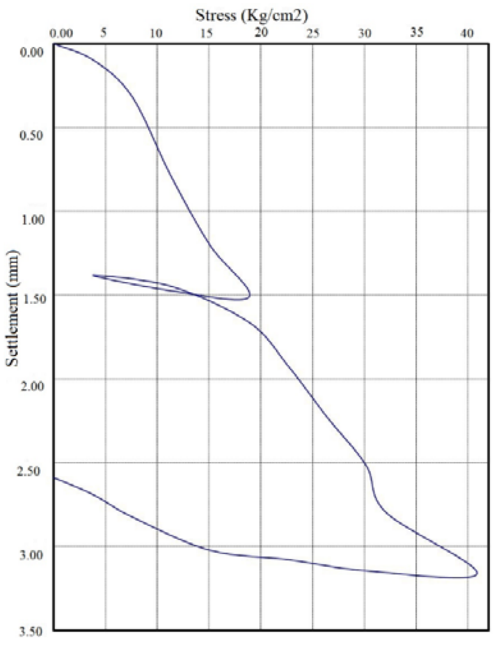

Fig. 4 Typical results of static loading test

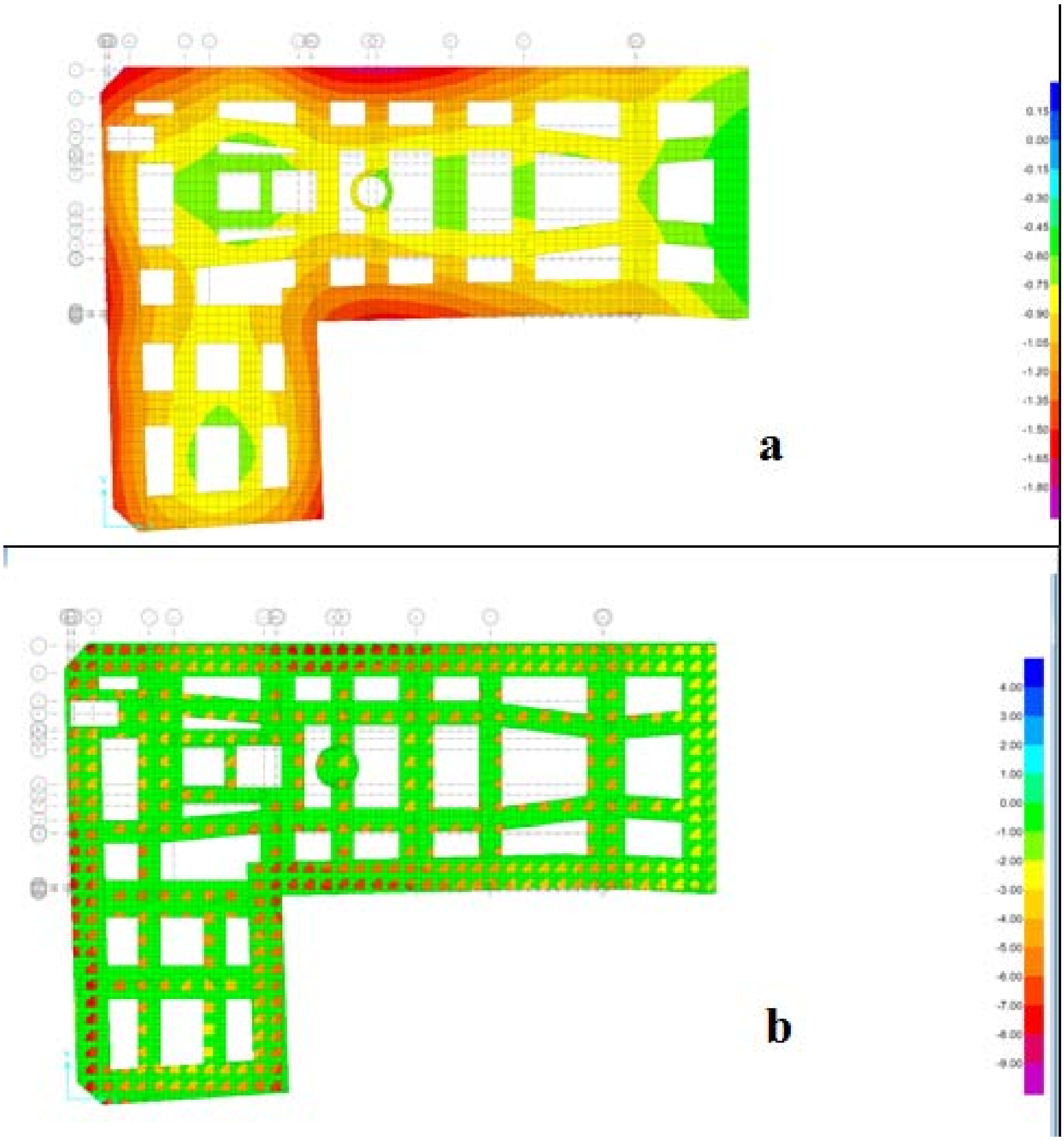

Fig. 5 The status of stresses below the foundation under the service load (a) before the improvement, (b) after the improvement

TABLE II
SOIL PROPERTIES

Layer	Depth (m)	USCS	φ (Deg)	C kN/m^2	γ_{sat} kN/m^3	E kN/m^2
1	0.0-3.0	SC-SP	32	1	17.2	2.06E+04
2	3.0-6.0	SC	32	1	18	1.30E+04
3	6.0-9.0	SC	32	1	18.5	2.15E+04
4	9.0-12.0	SC	32	2	18.5	1.50E+04
5	12.0-22.0	CL	30	31	19.3	8.00E+03
6	22.0-24.0	SM-SP	33	1	20	2.15E+04
7	24.0-36.0	SM-SP	33	1	20	2.00E+04

IV. GEOTECHNICAL PROFILE OF THE PROJECT

The project studied in this research is related to a region of southern Iran. Based on field observations and in situ and laboratory tests, submerged tissue mainly consists of sandy layers including brown clay and brown silt. The soil properties are given in Table II.

V. ANALYSIS AND CALCULATION OF PROJECT IMPROVEMENT PLAN

A. Control the Soil Bearing Capacity

In order to control the soil bearing capacity of the underlying foundation, modeling with the desired improvement in the SAFE program (finite element software) is carried out. After analyzing the stresses and deformations in the software, the amount of elastic and consolidation settlement created with values allowable settlements are compared. According to the geotechnical studies, the soil bearing capacity is 0.52 kg/cm^2. In Fig. 5 (a), the status of stresses below the foundation is shown before the improvement operations in the SAFE program under the service load. As can be seen, most of the stresses below the foundation are greater than the allowable stresses in the soil, so it is essential to accomplish improvement operations. Fig. 5 (b) shows the status of stresses below the foundation after the improvement operation under the service load.

In accordance with the soil bearing capacity (0.52 kg/cm^2) and also the examination of SAFE files (Fig. 5), the need to improve the soil to control the settlements against the static and dynamic loads seems to be necessary.

B. Model Evaluation with Static Loading Test Results

Despite the high use of JG in geotechnical engineering, the choice of basic design assumptions is complicated, based on simple assumptions. Therefore, a static loading test is often used to confirm the initial assumptions.

At first, modeling in PLAXIS with initial assumption of a compressive strength of 25 kg/cm^2 is done as shown in Fig. 6. From the static loading test (Fig. 4) for a load of 65 tons, the elasticity modulus value is obtained at 3750 kg/cm^2, which is equivalent to compressive strength of 25 kg/cm^2 according to (1). So, the initial design is correct in the model and does not require correction.

Since a static loading test is performed on a single column, modeling also needs to be done on a column in order to compare the results of the model with the test. According to Fig. 7, the modeling is done on a column. In order to evaluate the model based on the static loading results, modifications of the elasticity modulus against the settlements are presented in Fig. 8. As shown in Fig. 8, the settlement changes in the in-situ loading test show slightly larger values than the numerical modeling, but these trends are similar and close. Therefore, this software can be used to design JG column in soil improvement projects.

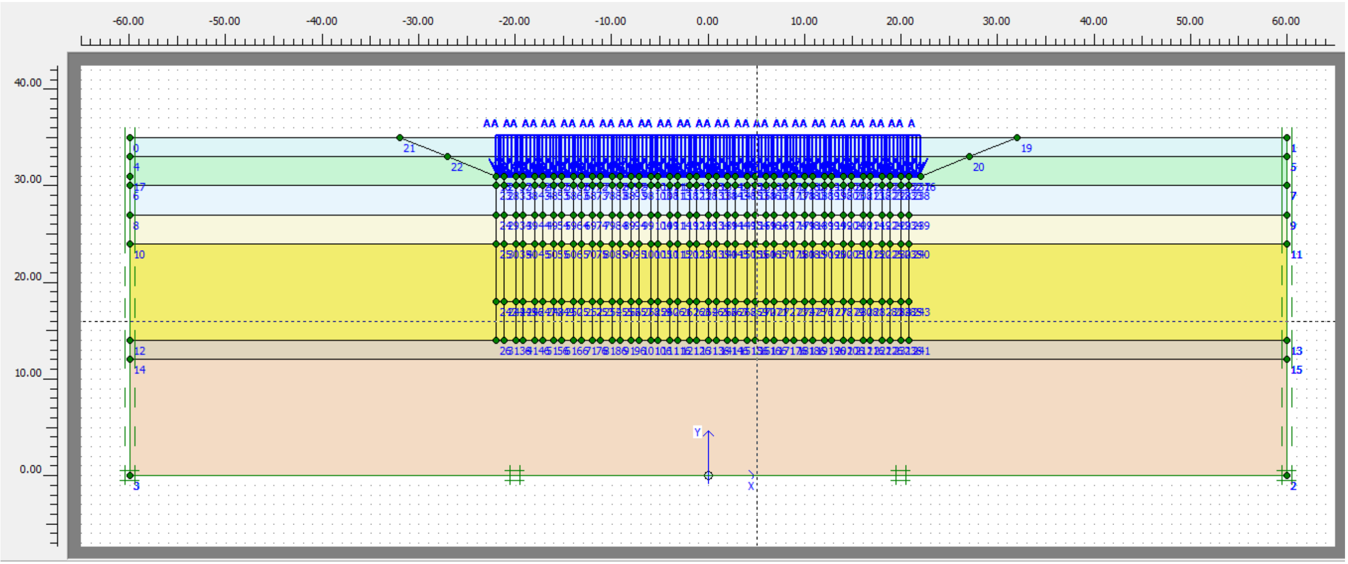

Fig. 6 Numerical modeling in PLAXIS software using in-situ loading test

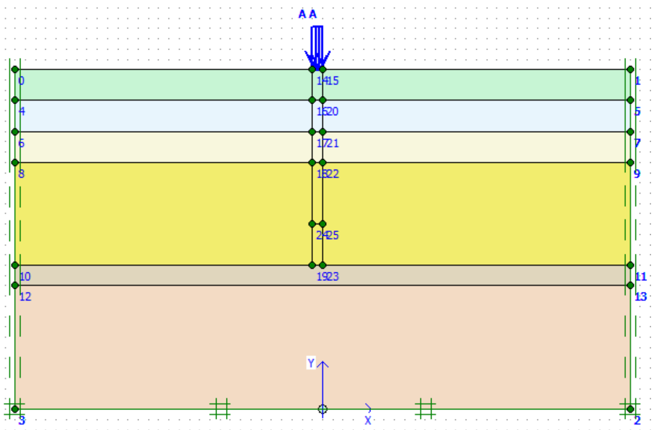

Fig. 7 Numerical modeling in PLAXIS software for a column JG

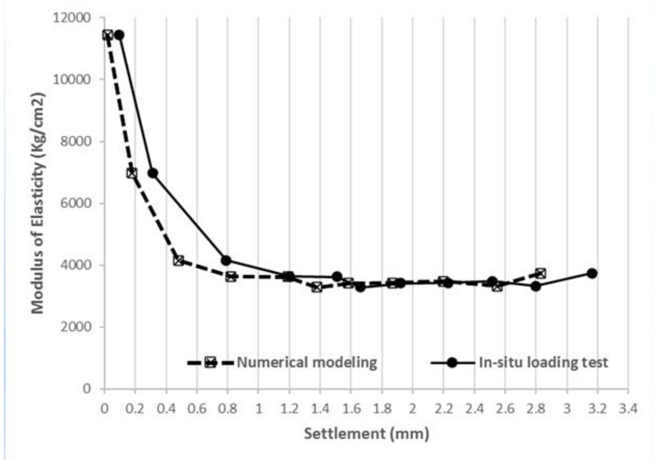

Fig. 8 Modifications of the elasticity modulus against the settlements for numerical modeling and in-situ loading test

VI. Conclusion

JG method is an economical method for a variety of works that is applicable to most soils. In this method, the resistance of the soil-cement column is designed in which a column of soil-cement is obtained with low permeability and high strength. This resistance depends on several factors. In the implementation work, the use of finite element software is used to design a JG. The results obtained from the static loading test on the jet column indicate that numerical modeling using the Mohr Coulomb behavioral model, with the uniaxial compressive strength and friction angle, is acceptable.

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