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Subsoil stabilized by polyurethane resin injection: FEM calculation

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Abstract:

The soil injection technology using an expandable polyurethane resin is one of the most efficient modern techniques that have been actively used in recent years for soil stabilization and foundations lifting. There are many advantages of using this technology, such as the rapid and strictly controlled process of lifting foundations, ease of use, high mobility and the lightweight of injectable foaming resin in addition to the independence of the physical and mechanical properties of resin from groundwater level, which allow the application of the proposed technology in a variety of geotechnical conditions and projects of various specificities. As part of the study of this technology in the world, very few theoretical and practical studies have been conducted. Most of these studies are focused mainly on the process of raising the foundations and monitoring of this technology. Thus, various monitoring methods have been developed around the world to control the injection process and to provide adequate tracking and a sufficient degree of visualization of the foundations lifting process in various geotechnical situations. Nevertheless, the application of this technology in the field of the soil stabilization and foundation strengthening has so far had certain limitations due to the lack of sufficient scientific theoretical and experimental justifications for the combined behavior of the composite (soil-resin) and the absence of an advanced calculation method, that allows predicting the altered characteristics of the treated soil massive after its injection by the expandable resin. The article demonstrates the results of a developed calculation method for predicting the averaged characteristics of the strengthened massive of a soil base after its injection by an expandable resin, based on theoretical and practical evidence obtained as a result of field and laboratory experiments, utilizing different approaches of the finite element method. The obtained by the developed calculation method results have been compared to the results of in-situ plate load tests obtained from field experiments without the injection of the resin and after its inclusion into the massive of the investigated soil to verify its accuracy.

1 Introduction

Soil strengthening and regulating the settlement of the foundations is an urgent actual technical task during reconstruction. There are various methods used to strengthen the foundations and stabilize the settlement of existing buildings and structures. Each method has its area of application, based on the functions it implements, the availability of its use in the conditions of a particular project, and in accordance with the scope of the problem and the degree of strengthening required.

In world practices, one of such effective modern methods that have been actively used in recent years to raise the foundations is the soil injection technology using expandable polyurethane resin, consisting of two components. There are many advantages of using this technology, such as the fast and strictly controlled foundation lifting process, which becomes possible due to the resin's rapid hardening process. Its use for almost all types of soils is possible because the proposed polyurethane composite does not contain any particles whose dimension can be limited by the treated soil's porosity. Besides, the ease of use, high mobility, and the lightweight of the injectable expandable polyurethane resin, in addition to the independence of its physic-mechanical properties from the groundwater level, which facilitates the application of this technology in various complex geotechnical conditions [1], [2], [11], [3]–[10][12].

As part of the study of the soil injection technology using expandable polyurethane resin globally, very few theoretical and practical studies have been conducted. Most of these studies are focused mainly on the process of raising the foundations, which is why various monitoring methods have been developed around the world to control the injection process and to provide adequate tracking and a sufficient degree of visualization of the foundations lifting process in various geotechnical situations [1]–[3], [9], [11], [13]–[16]. However, the combined behavior of the composite (soil-resin) has not been sufficiently examined to allow the application of this technology for soil stabilization and foundation strengthening reliably. Also, the lack of an advanced calculation method that allows predicting the altered characteristics of the treated soil's massive after its injection by the expandable resin is another restriction of the technology application in foundation strengthening practices [1]–[4], [8], [11], [15], [17]–[20].

In this regard, a calculation method of the bearing capacity and the settlement for the foundation soils strengthened by an expandable resin is developed to improve the design practices and further improve the application of this technology in the field of foundation's soil strengthening, as well as to increase its efficiency and operational reliability based on theoretical and practical evidence obtained to achieve the purpose of this research.

2 Materials and Methods

According to the author's previous researches [1], [11], the improvement of soil characteristics after its injection by an expandable resin is a controlled parameter. It depends on the distribution pattern and the resin's actual density formed in the massive of the treated soil and on the specifications of the treated soil. Therefore, in order to determine the best design parameters and further improve applicability and increase efficiency, as well as the operational reliability of the soil injection technology using an expandable resin in the field of foundations strengthening, the following aims were set:

1. Development of a calculation method of the bearing capacity and settlement conditions for the foundation soils, strengthened by an expandable resin, Considering the resin's distribution patterns in the massive of the injected soil.

2. Validation of the developed method by comparing the obtained numerical modeling results with pre-fulfilled normative field plate load tests results carried out during previous field investigations before and after the soil injection by the expandable resin.

Numerical solutions based on the finite element analysis approaches and well-known constitutive models were adopted for developing the proposed calculation method. The developed calculation method is a system of a virtual laboratory triaxial test of the composite (soil-resin) based on separately obtained laboratory characteristics of soil and resin. The obtained results are compared to the pre-fulfilled normative field plate load test to verify the accuracy of the developed method. The field and laboratory investigations results before and after the injection process were published in previous articles [1], [11].

The developed calculation method consists of mainly four phases:

Phase (1): The modeling of the soil triaxial test according to the initial soil parameters, pre-determined without the inclusion of the resin.

Phase (2): The modeling of the resin triaxial test according to its properties, pre-identified by the actual density of the resin, formed in the massive of the injected soil. In this phase, the actual parameters of the injected resin required for the composite (soil-resin) simulation, according to its pre-measured density, are selected. The resin used in this model is called (MC-Montan Injekt LE), whose properties for various densities and expansion ratios controlled by the amount of the injected resin were established and introduced in the author's previous article [11].

Phase (3): The modeling of the composite system (soil-resin) triaxial test through the inclusion of the resin elements into the soil's layer according to its verified geometrical parameters and actual volume formed in the massive of the investigated soil considering the expansion ratio of the resin. The actual propagation, geometrical parameters, and the properties of the injected resin in the massive of the investigated soil were determined previously and introduced in the author's previous articles [1], [11]. At this step, the altered characteristics of the composite (soil-resin) are determined.

Phase (4): The triaxial test modeling for the soil layer (without the resin's inclusion) is performed using input parameters that are equivalent to the composite's obtained output parameters. Consequently, a soil model without the resin's inclusion, whose characteristics are equivalent to the soil with resin's inclusion, is obtained.

Finally, the field plate load tests implemented previously before and after the soil injection by the expandable resin have been simulated using the software Plaxis 2D. The results obtained by the proposed calculation method are compared to the in-situ plate load test results to verify the accuracy and ensure the developed calculation method's reliability. The field plate load tests were carried out previously at different sandy soil depths underneath an experimental concrete foundation before and after its injection by an expandable polyurethane resin during a full-scale field experiment, the data of which were published in a previous article [1].

2.1. Background of the field and laboratory investigations.

A sandy soil base underneath an experimental concrete foundation (3*3 m) has been injected by net 180 liters of the resin (MC-Montan Injekt LE) in the mode of hydrofracturing up to the depth 2 m. The results of the sand's field investigations utilizing plate load tests have shown a significant improvement in the soil's physic-mechanical properties after its injection by the expandable resin. The injection process and the soil field investigations before and after the injection of the non-cohesive soil by the expandable resin were described in a previous article [1].

Moreover, the distribution patterns of the resin propagation in the massive of the injected soil were identified in-situ, found that the injected resin spreads in the massive of the investigated sand, forming solid walls of foamed hardened plates along the entire injection depth, surrounding the injected sand, and connecting along the edges at a distance of about 30-50 cm. Thus, the injected sand and the resin plates form a single homogeneous environment. According to the field measurements, the average thickness of the resulting resin formed in the massive of the investigated soil is around 1-2 cm, as shown in Figure 1.

Figure 1. The distribution patterns of the resin propagation, which formed in the massive of the sandy soil after the injection process [1]**.**

Furthermore, a laboratory investigation of the resin physic-mechanical properties for various densities formed based on its volumetric expansion ratios controlled by the amount of the injected resin was carried out previously. The relationships between the resin's density and its mechanical characteristics were established and introduced in a previous article [11].

2.2. Further laboratory investigations.

During the field trials, twenty-five resin samples (3 * 3 and 6 * 6 cm) were extracted from the injected site to determine the resulting material's average density after the injection process, as shown in Figure 2.

Figure 2. The resin samples, extracted from the injection site after the injection process of the field experiment.

Each sample was suitably prepared, and the thin layer of the soil directly contacting the resin was carefully removed. The density of each resin sample is determined using the following formula:

$$\rho = m/V \qquad (1)$$

Where: ρ – The sample's density; m – The measured weight of the sample; V – Sample's volume.

Table 1 shows the measured densities of each tested sample and the average density of the resin formed in the injected soil's massive.

Table 1. The average density of the resin formed in the injected soil's massive.

Sample, №	Weight, gm	Volume, cm^3	Density, gm/cm^3
1	2.700	14.848	0.182
2	3.273	18.000	0.182
3	3.053	16.240	0.188
4	3.526	20.460	0.172
5	3.437	18.750	0.183
6	3.706	19.200	0.193
7	3.516	19.008	0.185
8	2.394	12.600	0.190
9	2.975	16.074	0.185
10	1.938	9.800	0.198
11	2.836	15.552	0.182
12	3.058	17.670	0.173
13	2.520	13.950	0.181
14	3.194	18.254	0.175
15	4.869	25.725	0.189
16	3.563	18.240	0.195
17	2.227	12.250	0.182
18	2.108	11.712	0.180
19	2.990	16.660	0.179
20	4.095	22.050	0.186
21	11.945	60.51	0.197
22	14.137	75.52	0.187
23	11.853	59.53	0.199
24	14.101	75.58	0.187
25	9.100	52.22	0.174
The average density of the resulting material			0.184

The resulting resin's density, formed in the injected massive of the sandy soil during the injection process of the field investigations, is determined. The actual density of the resin formed in the soil massive is equal to 0.184 gm/cm^3. However, the density of the resin in the liquid state is 1.1 gm/ cm^3. A comparison of the resin's density in the liquid state with its density formed in the massive of the investigated sand after the injection process during the field experiment proves that the resin underwent a six-fold expansion compared to its initial volume.

Moreover, the resin's consumption was recorded during the monitoring of the injection process of the field experiment. It was found that the net amount of resin injected into the soil mass was about 180 liters, which represents 1% of the total volume of injected sand. Moreover, the amount of the injected resin was recorded at each injection point in two stages. The first stage is the fixation of the consumption rate required for the soil strengthening process until the initial lifting occurs and is fixed. The second stage is the resin's volume required to lift the experimental foundation, which immediately follows the soil's stabilization process. The resin consumption required to strengthen the injected sandy soil was recorded in a volume of approximately 123 liters, and 57 liters were spent for raising the experimental concrete foundation to the pre-specified level. Consequently, the amount of the resin required to strengthen the investigated soil exceeded almost twice the amount required for the experimental foundation lifting process up to the level of 1 cm. Table 2 shows the resin consumption necessary for the soil strengthening and foundation lifting separately at each injection point and the total consumption for lifting and strengthening separately.

Table 2. The resin's consumption at each injection point, recorded during the in-situ injection.

Injection point	The volume required to strengthen the soil, (liters)	The volume required to raise the foundation, (liters)	Loss (liters)
Point 1	22	9	3
Point 2	19	7	2
Point 3	37	17	7
Point 4	17	13	3
Point 5	28	11	5
Total	123	57	20

Consequently, according to the resin consumption rate determined during the injection process, it was found that the resin's actual volume required to strengthen the soil is 4% of the total volume of the injected soil. In comparison, 2% of the volume was required to raise the experimental foundation to a preset level of 1 cm, considering the resin expansion ratio, obtained and identified by its actual density formed in the massive of the investigated sand.

2.3. The investigation of the soil mechanical properties using a laboratory triaxial compression test

Soil samples were extracted during the field investigations using the borehole soil sampling method. Six cylindrical samples were prepared and tested using a consolidated drained triaxial compression test in the laboratory environment to determine the mechanical properties of the investigated sand before its injection by the expandable resin. The investigated soil's normative mechanical properties are identified as given in the tables (3, 4). The graphical analysis of the investigated sand's triaxial test is shown in Figure 3.

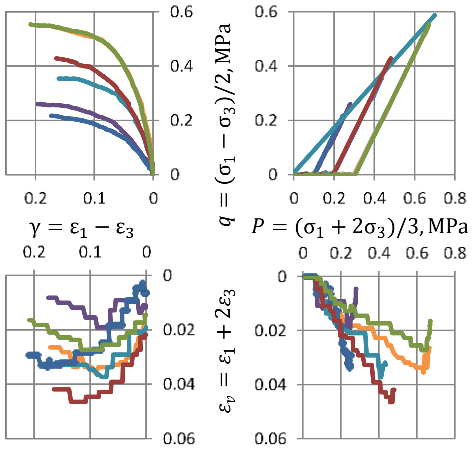


Figure 3. The graphical analysis of the investigated sandy soil, as determined by the triaxial compression test.

Table 3. The calculated strength parameters of the investigated soil.

The angle of internal friction, φ, degrees	The soil cohesion, *c*, kPa
40.5	6.921

Table 4. The deformation characteristics of the investigated soil.

No of the sample	failure stress in the chamber, MPa	Deformation modulus E, MPa	Volumetric strain modulus K, MPa	Shear modulus G, MPa	Poisson's ratio, ν	The angle of dilatancy, degrees
1	0.100	7.958	12.76	2.85	0.40	5.7
2	0.196	17.834	12.77	7.04	0.27	4.5
3	0.303	29.810	18.30	12.13	0.23	6.7
4	0.108	8.701	10.84	3.18	0.37	6.9
5	0.198	16.648	13.13	6.46	0.29	3.7
6	0.305	27.375	24.95	10.39	0.32	5.9
The average value		18.054	15.458	7.009	0.31	5.6

2.4. Calibration of the obtained soil properties for the determination of the optimum parameters for the simulation process

The triaxial test allows for obtaining the soil's mechanical characteristics accurately. Nevertheless, in cases where the finite element method is used for solving complex geotechnical problems, the correct selection of the soil input parameters used for a particular model is essential to ensure their reliability, as well as to so that these parameters correspond to the actual behavior of the soil under loading during the numerical simulation processes.

In light of this consideration, the laboratory triaxial compression tests were simulated using the FEM-models software to select the optimum soil parameters required for the modeling process. The triaxial laboratory tests simulation results to identify the modeling parameters for the studied sand are shown in Figure 4.

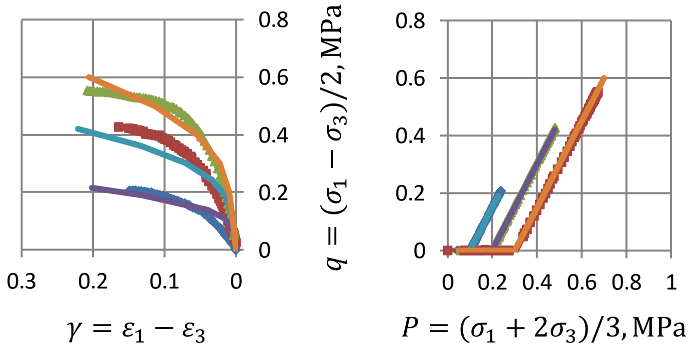


Figure 4. The triaxial tests' simulation results to select the modeling parameters of the studied sand using the FEM-models program.

The modeling parameters of the investigated sand, obtained by simulation of the triaxial laboratory test results using the FEM-models software, are shown in Table (5).

Table 5. The obtained model parameters.

The parameter of the model	Units	Value
Modulus of elasticity (deformation)	kPa	18975
Initial compression pressure	kPa	100
Final pressure during compression	kPa	200
Initial volumetric stress	kPa	200
Initial deformation modulus	kPa	60000
Poisson's ratio	----	0.30
Specific gravity	kN/m^3	18
Specific cohesion	kPa	6.921
The angle of internal friction	degree	40.5
The angle of internal friction during unloading	degree	40.5
Shear strain at failure	%	0.15
indicator of the degree	----	8

Moreover, the obtained modeling parameters were verified by simulating a triaxial test using the Plaxis 2D software, as shown in Figure 5.

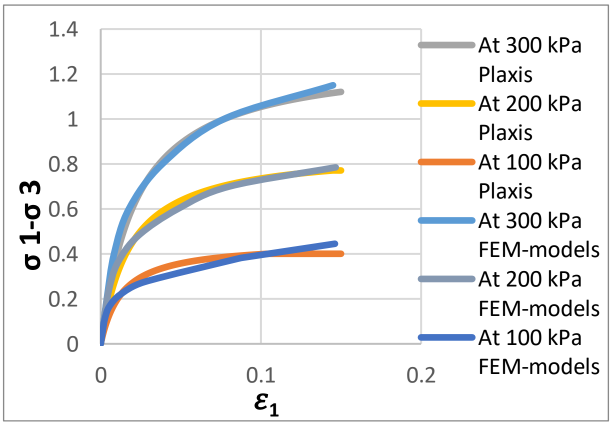


Figure 5. The simulation and verification of the triaxial compression tests, carried out using the Plaxis 2D program compared with the simulation in the environment of FEM-models software according to the given parameters.

2.5. Development of a calculation method of the bearing capacity and the settlement for foundation soils, strengthened by an expandable resin.

2.5.1. A virtual triaxial laboratory test for the soil without resin inclusion

A triaxial laboratory test model is built in the FEM-models software using the generalized elastic-visco-plastic model built in the mentioned program. The model's design scheme is a virtual laboratory triaxial test system consisting of elements of one soil layer exposed to a triaxial hydrostatic pressure of 100 kPa, as shown in Figure 6. The model's geometric parameters are (1 * 1 * 2 m), and the depth of the model is 2 m, which corresponds to the injection's actual depth of the field trials. The soil input parameters of this phase are the sandy soil model parameters, which are given in Table 5. The results of the stresses generated in the investigated soil layer without the resin inclusion are shown in Figure 7.

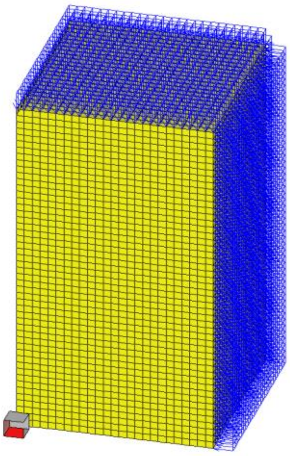


Figure 6.The design scheme of the virtual laboratory triaxial compression test without the inclusion of the resin

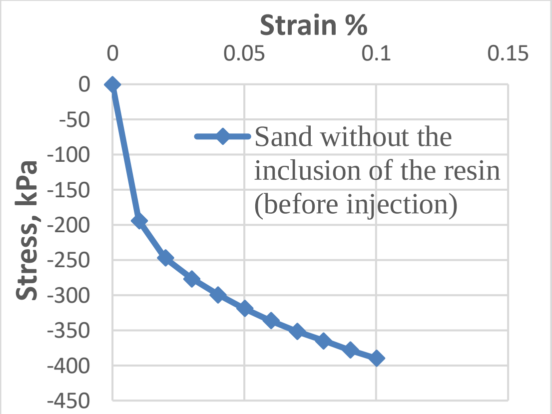


Figure 7.The results of the stresses generated in the soil's massive without the inclusion of the resin

2.5.2. A virtual triaxial laboratory test of the injected resin

A triaxial test model for the expandable resin is built according to identical boundary conditions of the soil model. Consequently, the virtual triaxial compression test is applied to the resin to select its optimum model parameters according to its stress-strain state obtained during the laboratory investigations, which corresponding to its previously identified actual density formed in the massive of the injected soil obtained during the field investigations. The stress-strain states of the used resin for various densities and expansion ratios, controlled volumetrically by the expandable resin amount, were achieved and introduced in a previous article [11].

The design scheme of the virtual laboratory triaxial test of the resin is shown in Figure 8. The simulation results of the resin's stress-strain state corresponding to its actual density, formed in the massive of the injected soil, are given in Figure 9.

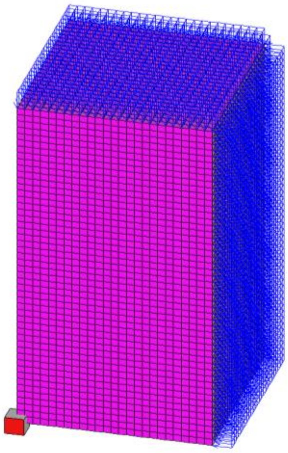


Figure 8.The design scheme of the virtual laboratory triaxial compression test of the expandable resin

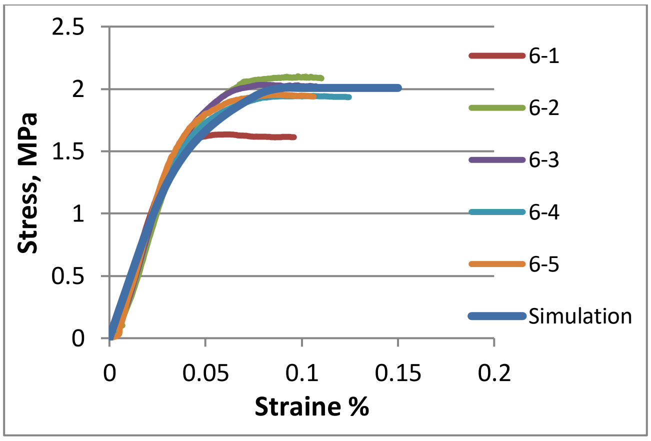
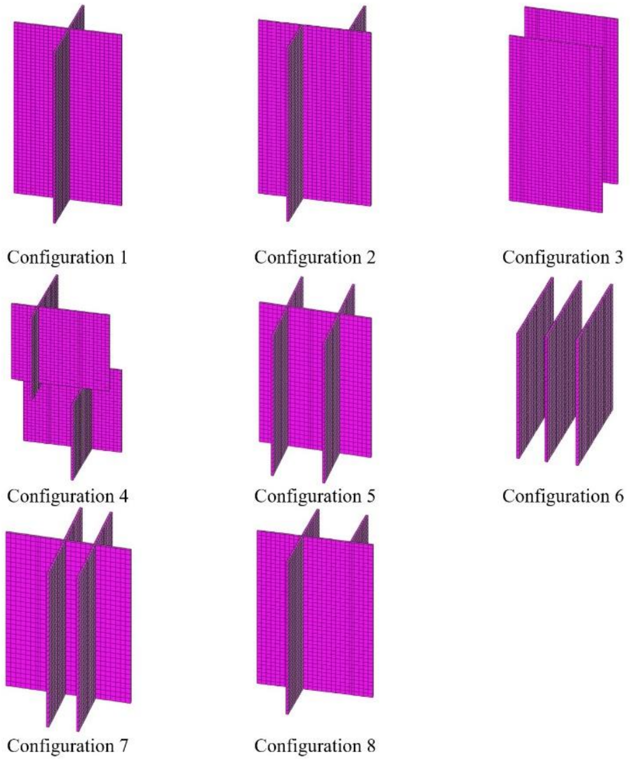


Figure 9. The simulation results of the stress-strain state of the expandable resin, according to its actual density, formed in the massive of the injected sand obtained during the field investigations

2.5.3. A virtual triaxial laboratory test of the composite (soil with the inclusion of the resin)

At this stage, a virtual triaxial laboratory test model is simulated, consisting of a composite system (soil-resin). The resin elements are included in the soil layer according to its geometric parameters, and the actual distribution patterns of its propagation in the massive of the injected soil pre-identified during the field investigations, as shown in Figure 1.

Various configurations of the resin distribution patterns (with an average layer thickness of 1 cm and a distance between resin plates of 30-50 cm) are incorporated in the design scheme as part of the virtual laboratory triaxial test of the composite (soil-resin), as shown in Figures (10, 11). The average volume of the included resin in the composite system is constant. It makes up 4% of the total soil volume, which corresponds to the resin's actual volume consumed to strengthen the investigated sandy soil, as pre-identified during the field and laboratory investigations.



Configuration 1

Configuration 2

Configuration 3

Configuration 4

Configuration 5

Configuration 6

Configuration 7

Configuration 8

Figure 10. The pre-specified distribution patterns of the resin, incorporated in the design model of the composite system (soil-resin)

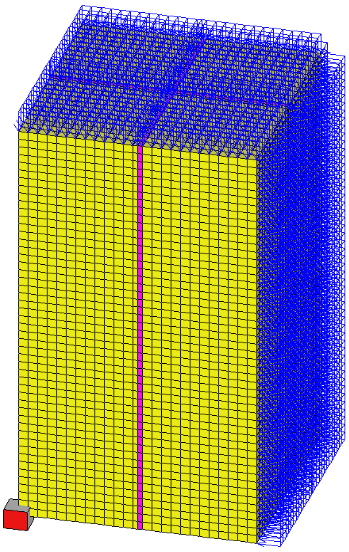


Figure 11.The design scheme of the virtual laboratory triaxial test of the composite system (soil with resin inclusion)

3 Results and Discussion

3.1. Determination of the averaged parameters of the resulting composite (soil with the inclusion of the resin).

As a result of the numerical calculations of the composite system (soil-resin) for various distribution patterns of the resin propagation, the averaged characteristics of the resulting composite are obtained. The average generated stresses in the composite system of all the pre-specified resin propagation patterns after its inclusion into the soil layer compared to the generated in the soil layer stresses before the resin inclusion at a triaxial pressure 100 kPa, are give in Figure 12.

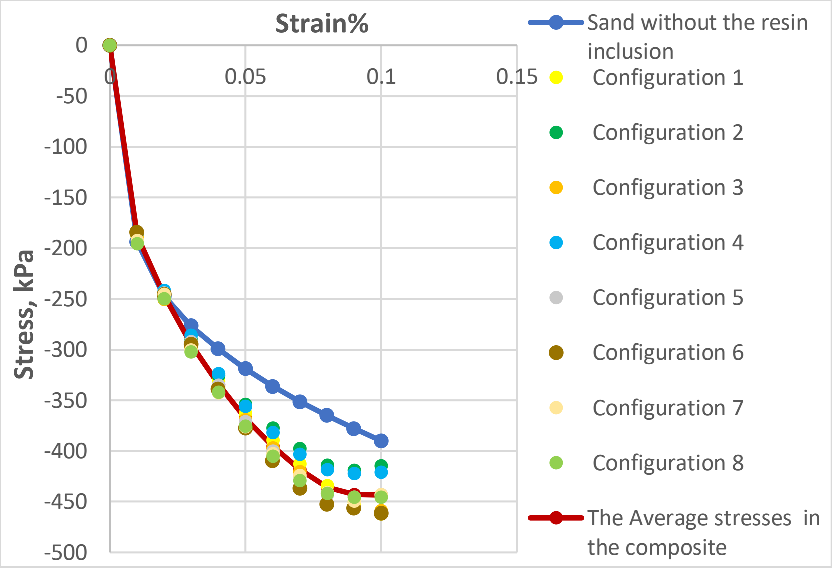


Figure 12.The generated stresses before and after the inclusion of the resin in the soil layer. The red graph represents the average stresses of the composite (soil-resin) for all the pre-determined distribution patterns of the resin propagation when subjected to a triaxial pressure of 100 kPa.

The virtual triaxial laboratory test of the composite (soil-resin) is repeated for each pre-specified distribution pattern of the resin propagation under a triaxial pressure of 300 kPa. The average stresses generated in the composite system for all the pre-specified resin propagation patterns after its inclusion into the soil layer at 300 kPa are given in Figure 13.

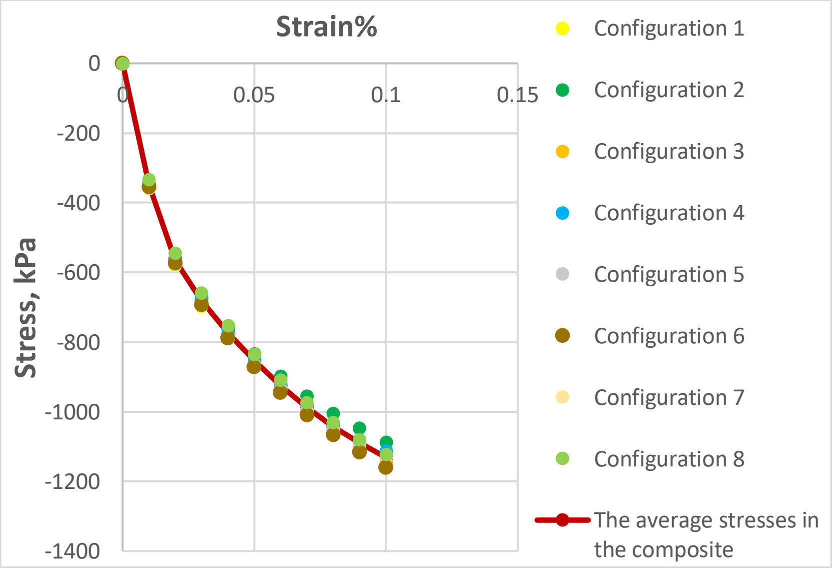


Figure 13.The generated stresses in the composite system for each pre-specified distribution pattern of the resin propagation under a triaxial pressure of 300 kPa. The red graph represents the average stresses in the composite for all the pre-determined distribution patterns of the resin propagation when subjected to a triaxial pressure of 300 kPa

Consequently, the averaged characteristics of the composite (soil-resin) are obtained utilizing the mohr-coulomb failure criteria and p-q diagram using the following formulas:

$$C + M\left(100 + \frac{\sigma 100}{3}\right) = \frac{\sigma 100}{2} \tag{2}$$

$$C + M\left(300 + \frac{\sigma 300}{3}\right) = \frac{\sigma 300}{2} \tag{3}$$

Where: $M = \frac{3 \sin \varphi}{3 - \sin \varphi}$; $\sigma 100 -$ the ultimate stress at 100 kPa; $\sigma 300 -$ the ultimate stress at 300 kPa.

As a result of the numerical calculations, it becomes obvious that the injection of the soil by an expandable polyurethane resin leads to the appearance of specific cohesion in the massive of the injected non-cohesive soils (justified by the inclusion of the resin), which in turn leads to a corresponding increase in the bearing capacity of the foundations on the natural basis. The average calculated specific cohesion value of the composite and the limit cohesion boundary values for the pre-specified distributions pattern of the resin propagation are given in Table 6.

Table 6. The calculated values of the modified cohesion for the composite system (soil-resin).

The calculated cohesion	Configuration	Value, kPa
Minimum	2	11.551
Average	Average graph	18.059
Maximum	6	22.458

3.2. Determination of the specified soil parameters of a homogeneous environment equivalent to the soil with the inclusion of the resin

At this stage, a virtual laboratory experiment is simulated, consisting of only soil (without the inclusion of the resin) according to the obtained averaged characteristics of the composite (soil-resin). Consequently, a soil model without the resin inclusion is obtained, the characteristics of which, however, are equivalent to the soil with the resin inclusion. The generated stresses in the soil layer without resin inclusion when modeling a homogeneous soil medium equivalent to the soil with the resin's inclusion are shown in Figure 14.

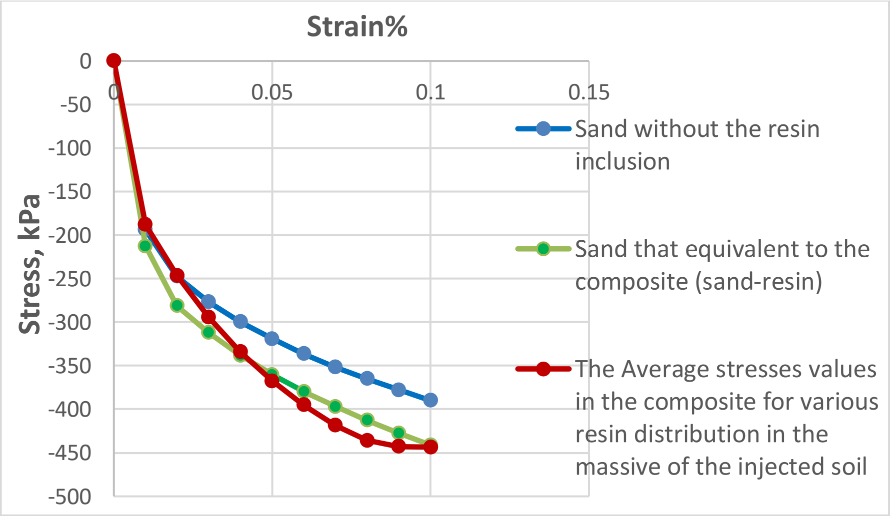


Figure 14.The resulting stresses in the soil layer without the resin inclusion in a homogenous environment equivalent to the soil with the resin inclusion

3.3. Validation of the developed calculation method by comparison with the results of the field plate load tests using Plaxis 2D software

In the Plaxis 2D software, an axisymmetric model of field plate load test is constructed using the Hardening Soil Model under homogenous conditions of the field plate load tests to ensure the accuracy of the developed calculation method results. The design model scheme is a single-layer sandy soil tested with a circular plate of 600 cm^2. The plate was subjected to a distributed vertical load of a uniform medium and under a homogenous environment of the field conditions.

3.3.1. The modeling of the field plate load tests of the investigated sand without its injection by the expandable resin, at depths of 0.4 and 1.2 m

The field plate load tests without the soil injection by the expendable resin at depths of 0.4 and 1.2 m are simulated according to the initial soil characteristics without the resin inclusion. The input parameters used are the model parameters obtained using the soil laboratory triaxial test, given in Table 5. The comparison of the load-settlement relationships of the in-situ plate load test and its simulation at the investigated depths are shown in Figures (15, 16).

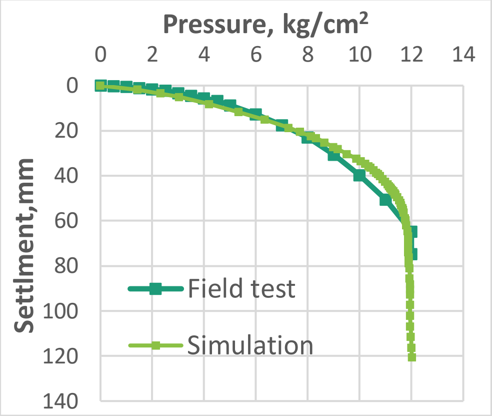


Figure 15. The plate load tests simulation results for the investigated sand without its injection by the resin, at a depth of 0.4 m

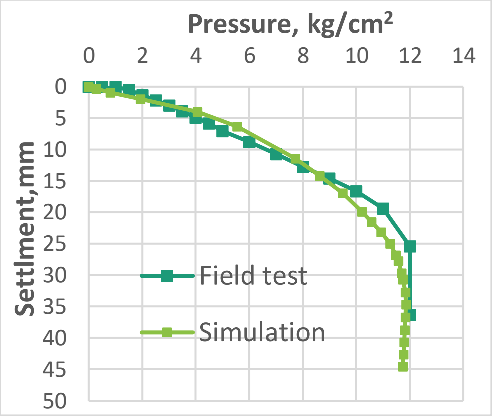


Figure 16. The plate load tests simulation results for the investigated sand without its injection by the resin, at a depth of 1.2 m

Focusing on the figures (15, 16), The ultimate critical loads when simulating the plate load test for the investigated soil without its injection by the expandable resin (using the initial parameters of soil without the resin's inclusion) were 12, 11.8 kg/cm^2 at the studied depths of 0.4 and 1.2 m, respectively. These results are consistent with the actual results of the field plate load tests of the soil before injection, in which the ultimate critical load was 12 kg/cm^2 at the investigated depths.

3.3.2. The modeling of the field plate load tests of the investigated sand after its injection by the expandable resin, at depths of 0.4 and 1.1 m

The field plate load tests for the investigated sand after its injection by the expendable resin at depths of 0.4 and 1.1 m, respectively, are simulated according to the output characteristics of the composite (soil with the resin inclusion). The input parameters used are the model parameters obtained using the numerical calculations of the developed calculation method. The comparison of the load-settlement relationships of the in-situ plate load test and its simulation at the investigated depths are shown in Figures (17, 18).

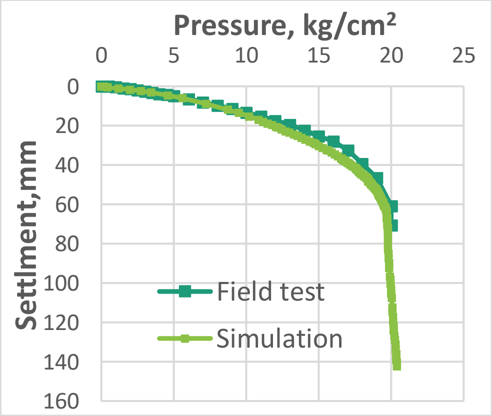


Figure 17. The plate load test's simulation results for the investigated sand after the injection process, at a depth of 0.4 m.

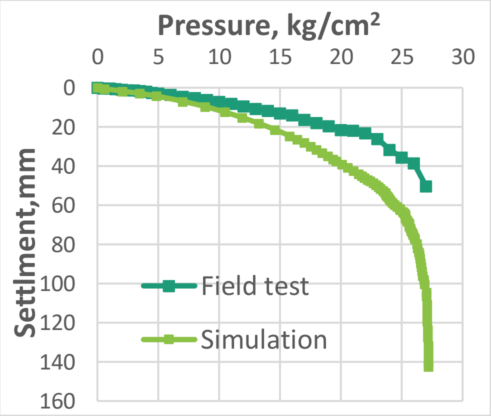


Figure 18. The plate load test's simulation results for the investigated sand after the injection process, at a depth of 1.1 m.

Focusing on figures (17, 18), The ultimate critical loads when simulating the plate load test for the investigated soil after its injection by the expandable resin (using the output parameters of the composite model) were 20.3 and 27.2 kg/cm^2 at the studied depths of 0.4 and 1.1 m, respectively. These results are consistent with the actual results of field plate load tests of the injected soil, in which the ultimate critical loads were 20 and 27 kg/cm^2.

A comparative analysis of the results of the numerical prediction of the averaged characteristics obtained for the investigated soil with the actual plate load test results indicates the effectiveness of the proposed calculation method for predicting the altered soil characteristics after its injection by an expandable polyurethane resin, as shown in figures (15- 18). Consequently, the obtained modified soil parameters after its injection by the resin and the developed equivalent model are employed to establish the modified bearing capacity and the settlement conditions for the foundation soils, strengthened by an expandable resin in field applications.

4 Conclusions

1. A calculation method of the bearing capacity and settlement for the foundation soils, strengthened by an expandable resin, has been developed, which improves the design practice, increasing the efficiency and operational reliability of the injection technology using an expandable resin in the field of foundations strengthening.

2. The results of numerical modeling confirmed by the results of field plate load tests have shown that the injection of the non-cohesive soils by an expandable polyurethane resin leads to the appearance of specific cohesion in the massive of the injected soils (justified by the inclusion of the resin), which in turn leads to a corresponding increase in the bearing capacity of the natural basis.

3. A comparison of the numerical calculations of the averaged characteristics of a sandy basis injected by an expandable polyurethane resin with the results of field plate load tests was carried out, the accuracy and reliability of the developed calculation method were verified. The comparison results have shown that the altered parameters of the injected massive obtained using the proposed calculation method are sufficient to be used in the field applications.

4. The distribution patterns of the resin's propagation in the massive of the injected soils play an essential role in the altered properties of the treated soil after the injection process. Even though the propagation of the resin in the soil environment is a random phenomenon, the developed calculation method allows predicting the averaged characteristics of a homogenous soil equivalent to the composite (soil-resin) considering various distribution patterns of the resin's propagation. Thus, it allows ignoring the effect of the random spread of the resin on the obtained results.

5. The mechanical properties of the resulting material formed in the soil's massive after the injection process play an essential role in the gained soil strengthening results. Consequently, it depends on the resin's density, formed in the massive of the injected soils, which controlled volumetrically by the amount of the injected resin. Thus, the developed calculation method can provide a reasonable visualization control over the resin's consumption rate required to gain the desired strengthening results in a homogenous injection environment.

6. The developed calculation method can be used to justify other soil stabilization techniques that form inclusion in the soil's massive.

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