

STRENGTHENING THE RAFT FOUNDATION OF AN EXISTING RC BUILDING BY APPLICATION OF JET-GROUTING METHOD

ПОЈАЧАЊЕ ТЕМЕЉНЕ ПЛОЧЕ ПОСТОЈЕЋЕ АРМИРАНОБЕТОНСКЕ ЗГРАДЕ ПРИМЕНОМ ЦЕТ-ГРОУТИНГ (МЛАЗНОГ ИЊЕКТИРАЊА) МЕТОДЕ

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1 INTRODUCTION

A case study of soil-foundation system strengthening is presented in the paper. The studied building's RC structure (columns and slabs for vertical loads and walls for seismic loads) has been designed in 2007 and planned to be realized in the seaside city of Burgas in Bulgaria. According to the original project the building consists of 14 levels as well as 5 underground levels. The execution process has started in 2008 and has been interrupted in 2010 as only the basement part of the

building was constructed then. Due to investment intentions change it has been decided to construct the remaining superstructure and to extend it by 4 additional levels as well as to switch building's function from office to residential. In order to do so a strengthening project has been prepared. The project includes a number of measures regarding the superstructure (reparation, RC-jacketing, execution of new structural elements among others) as addition to the soil-foundation improvement.

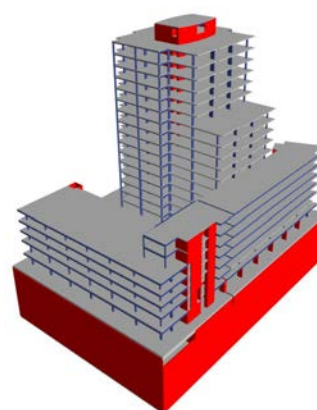


Fig. 1. Existing condition and spatial view of the structure

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The foundation of the existing part of the building consists of a raft. In order to reduce settlement due to the additional loads, [9], from the extension and for the sake of increasing the stiffness of the modulus of subgrade reaction in the numerical model it has been decided to execute jet-grouting as a hybrid soil improvement-structural strengthening measure – [18].

The operating conditions (height of 2.80 m in the basement) have made this solution as an only option.

Jet-grouting soil improvement technique (described in [1], [7] and [8]) has gained popularity, [6], during the last few decades. Its application range is wide and some typical examples include foundations, retaining structures, water barriers, tunnels among others. The jet-grouting process is recognized as a cement soil stabilization. With the aid of high pressure (400 bar) cutting jets of water or cement suspension having a nozzle exit velocity ≥ 100 m/sec eventually air-shrouded the soil around the borehole is eroded. The eroded soil is rearranged and mixed with the cement suspension. The soil-cement mix is partly flushed out to the top of the borehole through the annular space between the jet grouting rods and the borehole. Single fluid version (described in [4]) of the jet-grouting technique has been adopted for the particular project. In the single fluid system, the water-cement grout is injected into the ground through one or more nozzles. In this case, soil remoulding and subsequent cementation are both caused by the same fluid.

The adopted configuration of the 206 jet-grouting columns having a diameter of 80 cm is given on Figure 2. The execution process consists of seven major steps as follows: 1) drilling the existing raft; 2) forming the jet-grouting columns (length of 7 m and 5 m) through high-pressure injection of water-cement grout; 3) insertion of a steel pipes (ϕ 114.3x8, length of 5 m and 2.5 m) for load transfer from the raft to jet-grouting column and for the sake of increasing its compressive bearing capacity; 4) grouting the space between the raft and the pipe; 5) insertion of reinforcement in the pipe – the upper part of the reinforcement sticks out of the raft so that it could be

linked to the reinforcement of the foundation top jacketing; 6) grouting the inner volume of the pipe and execution of a 15 centimeter RC strengthening (top jacketing) of the existing raft.

2 SOIL CONDITIONS AND VERIFICATION OF JET-GROUTING COLUMN PROPERTIES

The soil conditions on site are shown on Table 1. The foundation raft is located at level +9.05 meaning that it lies on saturated Layer 3 (Pliocene clays).

Usually in practice, it is necessary to correlate the jet grouting effects (i.e., column diameter and properties) to the original soil properties (i.e., grain size, shear strength) and to the treatment procedures (i.e., treatment parameters). However, because all soils are inherently heterogeneous, the mechanical and geometrical characteristics of the columns are usually variable.

In the presented project a simple approach for verification of the jet-grouting columns' diameter has been adopted – [19]. Three test columns (TC-A1, TC-A2 and TC-A3) have been executed by three different treatment procedures. Thereafter, boreholes have been drilled in the center and periphery (at distance 40 cm from the center) of all three columns. In order to prove that a diameter of at least 80 cm is ensured, a continuous sample is taken through the whole length of the borehole – [12] and [14]. The judgment is made on the basis whether treated medium is observed through the whole sample or not. In the particular case study test columns TC-A1 and TC-A2 showed unsatisfactory results. In contrast, test column TC-A3 demonstrated a treated zone with the desired dimensions (Fig 3.).

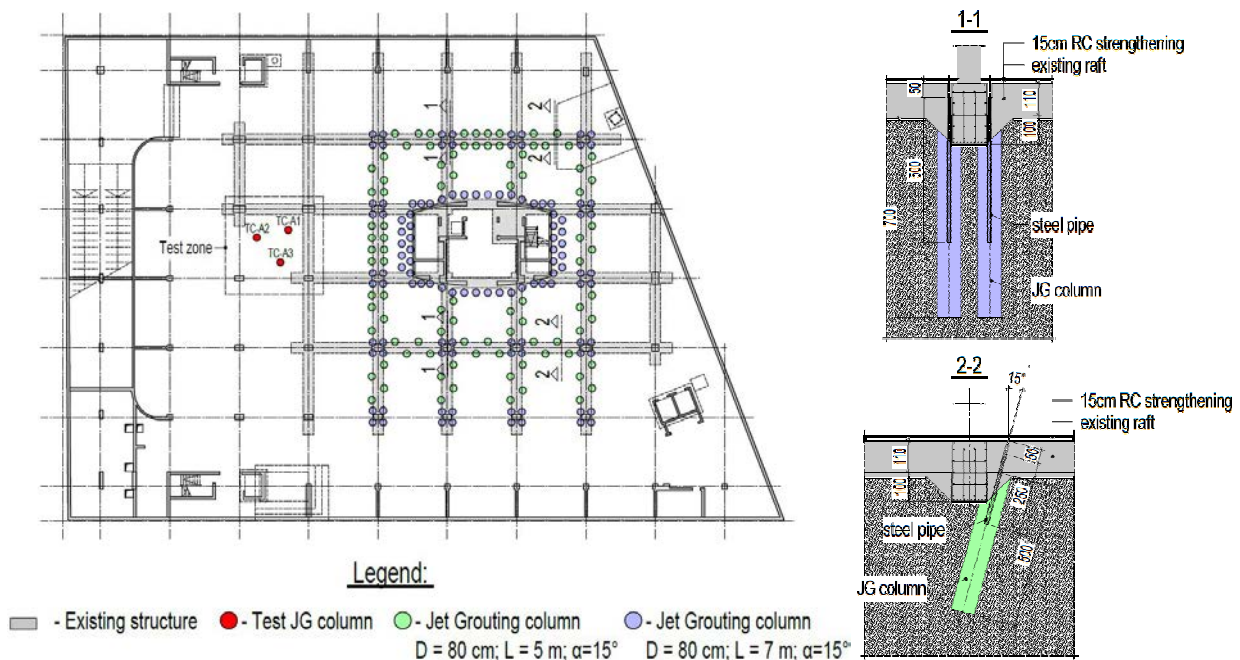


Fig. 2. Soil-foundation system strengthening approach

Table 1. Soil properties

Level [m]	Soil layer depth [m]	Soil layer height [m]	Layer number	Layer description	Characteristic values of soil parameters			
					Strength and deformability properties		Physical properties	Constitutive model parameters (HS Model)
26.60	0.00	0.80	1	Dark brown to light brown clay, Quaternary - Q	$E_{oed,100} = 4.75$ MPa $E_{oed,200} = 5.55$ MPa $E_{oed,300} = 9.10$ MPa $E_{d,100} = 9.50$ MPa $E_{d,200} = 11.10$ MPa $E_{d,300} = 18.20$ MPa $\phi'_k = 5^\circ$ $c'_k = 85$ kPa	$\gamma_{n,k} = 19.30$ kN/m ³ $\gamma_{r,k} = 19.60$ kN/m ³ $\gamma_{s,k} = 27.00$ kN/m ³ $\gamma_{d,k} = 15.20$ kN/m ³ $\gamma'_k = 9.30$ kN/m ³	$E_{50}^{ref} = 11.88$ MPa $E_{oed}^{ref} = 4.75$ MPa $E_{ur}^{ref} = 47.50$ MPa $p_{ref} = 0.10$ MPa $v_{ur} = 0.20$ $\bullet = 0.00^\circ$ $m = 1.00$ $K_0^{NC} = 0.58$	20
25.80	0.80	10.00	2	Light brown and yellow brown clay, sandy-silt with calcareous inclusions and gravel - Quaternary - Q	$E_{oed,100} = 3.20$ MPa $E_{oed,200} = 5.15$ MPa $E_{oed,300} = 11.50$ MPa $E_{d,100} = 6.40$ MPa $E_{d,200} = 10.30$ MPa $E_{d,300} = 23.00$ MPa $\phi'_k = 23^\circ$ $c'_k = 55$ kPa	$\gamma_{n,k} = 19.40$ kN/m ³ $\gamma_{r,k} = 19.92$ kN/m ³ $\gamma_{s,k} = 27.50$ kN/m ³ $\gamma_{d,k} = 15.60$ kN/m ³ $\gamma'_k = 9.40$ kN/m ³	$E_{50}^{ref} = 8.00$ MPa $E_{oed}^{ref} = 3.20$ MPa $E_{ur}^{ref} = 32.00$ MPa $p_{ref} = 0.10$ MPa $v_{ur} = 0.20$ $\bullet = 0.00^\circ$ $m = 1.00$ $K_0^{NC} = 0.58$	27
15.80	10.80	15.00	3	Pliocene clays - N ₂	$E_{oed,100} = 2.94$ MPa $E_{oed,200} = 4.39$ MPa $E_{oed,300} = 9.89$ MPa $E_{d,100} = 5.88$ MPa $E_{d,200} = 8.78$ MPa $E_{d,300} = 19.78$ MPa $\phi'_k = 17^\circ$ $c'_k = 69.3$ kPa	$\gamma_{n,k} = 18.00$ kN/m ³ $\gamma_{r,k} = 18.19$ kN/m ³ $\gamma_{s,k} = 27.50$ kN/m ³ $\gamma_{d,k} = 12.90$ kN/m ³ $\gamma'_k = 8.00$ kN/m ³	$E_{50}^{ref} = 5.88$ MPa $E_{oed}^{ref} = 2.94$ MPa $E_{ur}^{ref} = 29.40$ MPa $p_{ref} = 0.10$ MPa $v_{ur} = 0.20$ $\bullet = 0.00^\circ$ $m = 0.70$ $K_0^{NC} = 0.71$	35

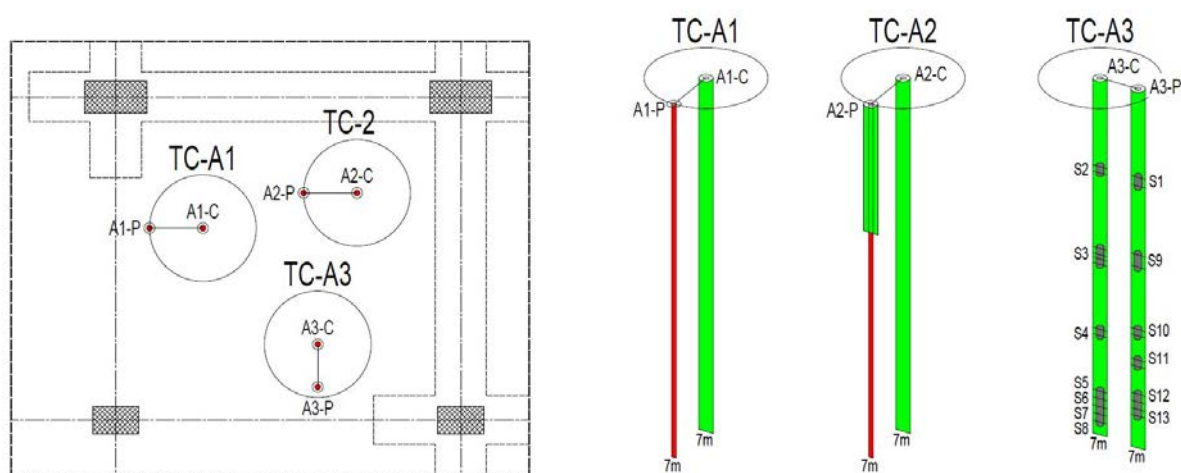
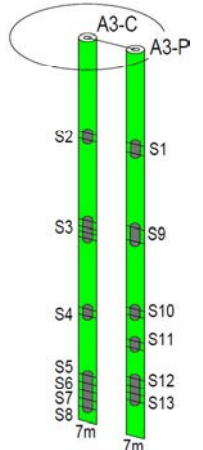


Fig. 3. Ensuring mechanical properties and column dimensions by means of test columns

Probes have been extracted from the only test column with satisfactory dimensions – in this case TC-A3. The mechanical properties (unconfined compressive strength, ultimate axial strain and deformation modulus) of the jet-grouting columns have been evaluated in the

laboratory. Due to soil's heterogeneity results show values of wide range as it could be seen on Table 2. The compressive strength varies from 3.25 MPa to 8.10 MPa – [10]. A characteristic value of 4.50 MPa has been adopted as input value for the design.

Table 2. Test jet-grouting column TC-A3 properties obtained in the laboratory

Test column TC-A3	№	Depth	Unconfined compressive strength q_u	Ultimate axial strain $\varepsilon_{u,z}$	Deformation modulus E_o
-	-	[m]	[kPa]	[%]	[MPa]
	1	0.80 - 1.00 m	3272.2 ± 163.6	0.37 ± 0.04	885
	2	0.84 - 1.00 m	4992.2 ± 249.6	0.95 ± 0.09	525
	3	2.76 - 2.90 m	4576.9 ± 228.8	0.37 ± 0.04	508
	4	4.80 - 4.94 m	8092.5 ± 404.6	0.47 ± 0.05	1722
	5	6.00 - 6.23 m	7332.4 ± 366.6	0.49 ± 0.05	1496
	6	6.23 - 6.40 m	4664.6 ± 233.2	0.96 ± 0.10	486
	7	6.40 - 6.53 m	6038.4 ± 301.9	0.48 ± 0.05	1258
	8	6.53 - 6.71 m	6099.6 ± 305.0	0.62 ± 0.06	984
	9	2.60 - 2.88 m	4985.3 ± 249.3	0.76 ± 0.08	656
	10	4.50 - 4.63 m	6258.5 ± 312.9	0.94 ± 0.09	665
	11	5.20 - 5.36 m	5837.3 ± 293.7	0.73 ± 0.07	800
	12	5.60 - 5.76 m	6873.7 ± 343.7	0.86 ± 0.09	799
	13	5.86 - 6.00 m	5790.4 ± 289.5	0.77 ± 0.08	752

3 NUMERICAL ANALYSIS AND DESIGN

The „bed of springs“ model has been adopted as an approach for consideration of the soil-structure interaction effect in numerical analysis. Soil (as physically and mechanically described medium in Table 1) has been modelled as a continuum and represented by the Mohr-

Coulomb constitutive model in SAP2000 software for the sake of evaluating the modulus of subgrade reaction. Stress which has been obtained through the analysis has been divided by the calculated settlement for the sake of determining the springs' stiffness (Fig. 4).

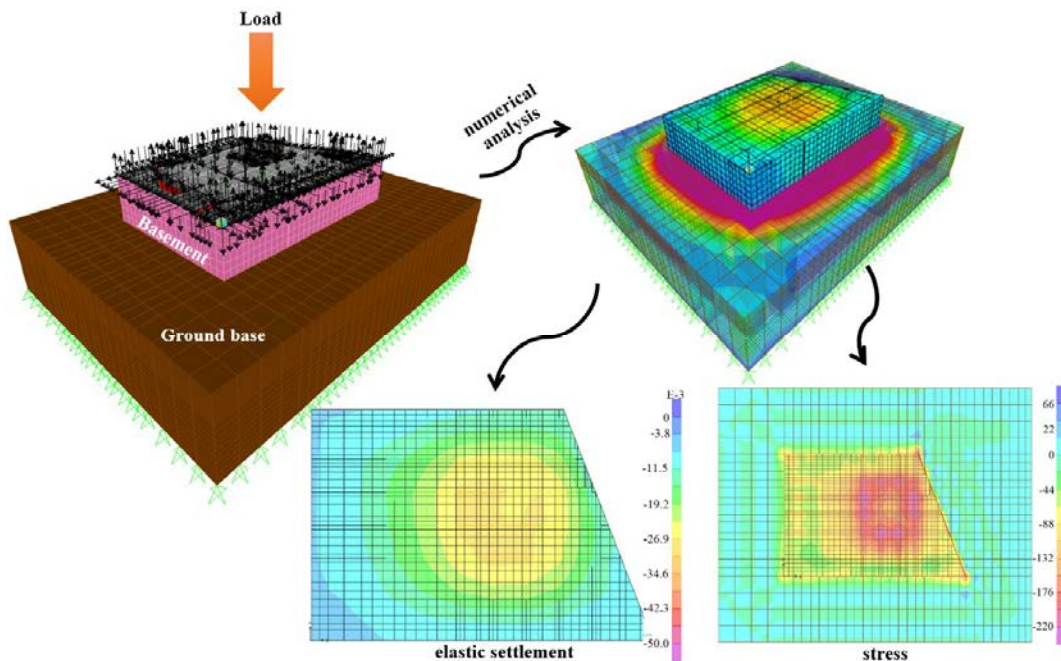


Fig. 4. Evaluation of modulus of vertical subgrade reaction through a numerical solution

The modulus of subgrade reaction of the jet-grouting treated area has been evaluated on the basis of a load-settlement relation which has been obtained through analytical procedures as well as a pile-test numerical

FEM simulation as seen in [13] in the software PLAXIS 2D by using the Hardening-Soil (HS) constitutive model (explained in details in [17]) – Figure 5.

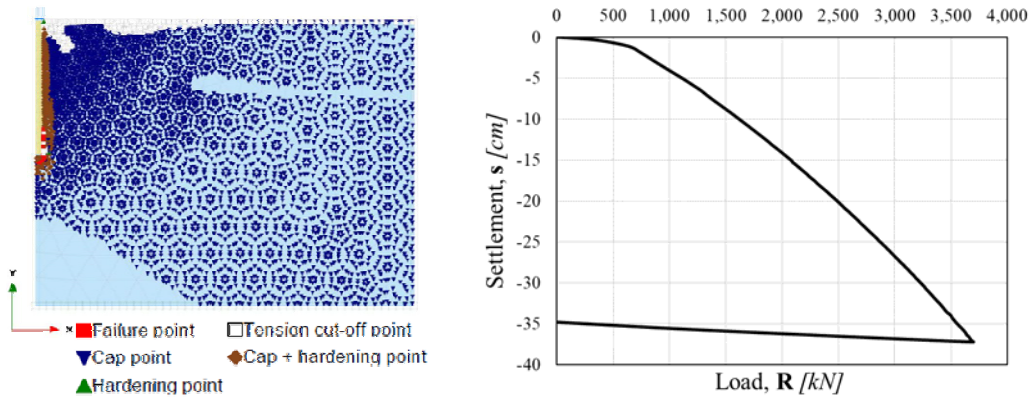


Fig. 5. Numerical FEM simulation of jet-grouting test in PLAXIS 2D

An overview of the adopted values for the modulus of subgrade reaction is given on Figure 6.

Furthermore, a 3D finite-element model which represents the superstructure in details has been developed in ETABS software. Elements from the program library have been adopted for the sake of representing the structural elements as the follows: frame elements for beams and columns, shell elements

for walls, slabs and raft foundation. The soil has been modelled by area-spring elements. A comparison of the bending moments in the raft is made between a model with evenly distributed (same stiffness) springs (existing raft) and a model which considers the soil improvement (jet-grouting) by introducing zones with stiffer springs – Figure 7.

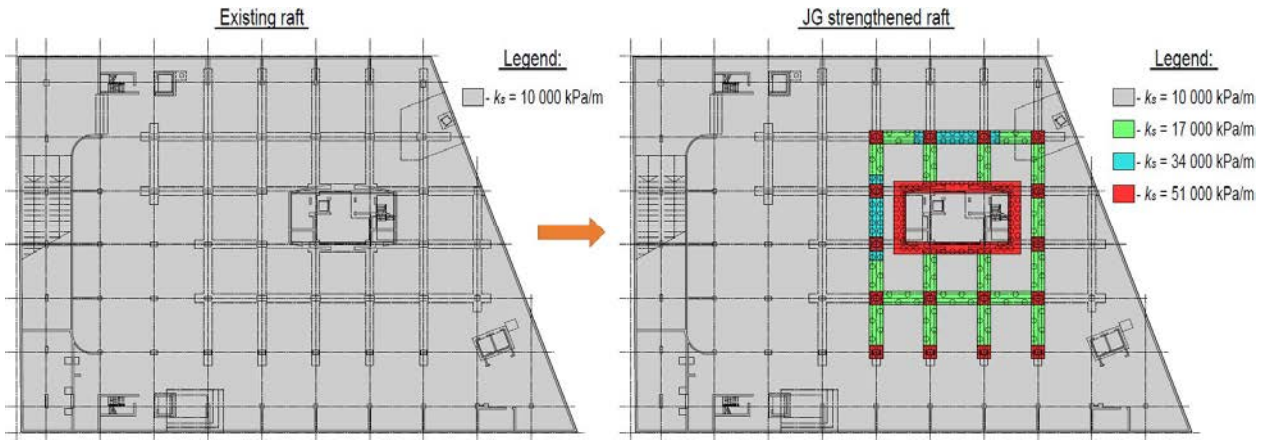


Fig. 6. Comparison of modulus of vertical subgrade reaction of the existing raft and the JG strengthened raft

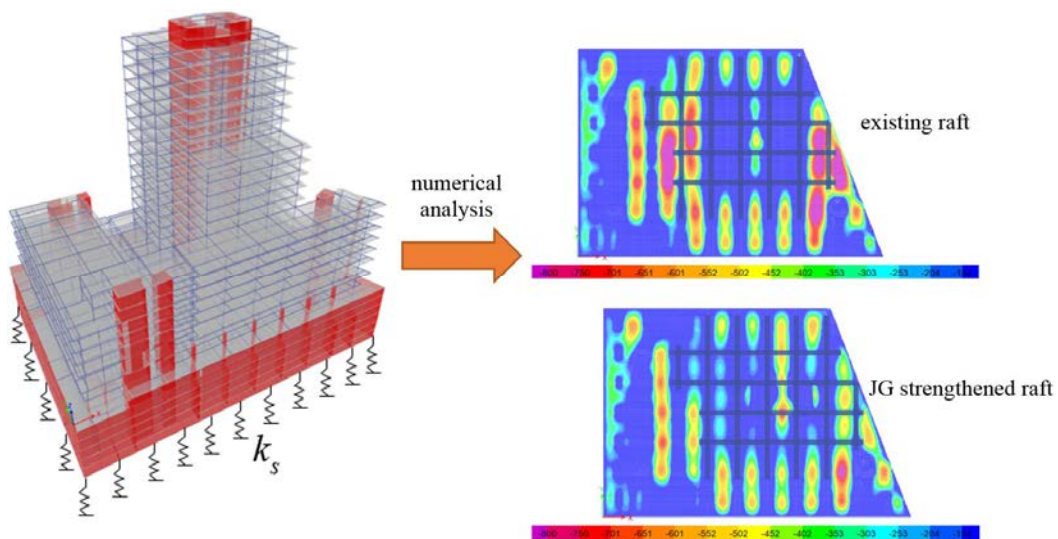


Fig. 7. 3D FEM model of the existing structure and bending moment in the raft (existing raft vs. JG strengthened raft)

A deterministic design approach (described in [5], [11], [15] and [20]) has been applied for the study. By means of such concept, which is typical in geotechnical engineering and suggested by Eurocode 7, uncertainties of the jet-grouting technique are considered by modifying actions on the structures, values of the material properties and overall bearing capacity by partial factors in order to obtain design values. For the material properties of jet-grouted elements, the characteristic values can be derived from the literature or, preferably, be taken from in-situ measurements.

Partial factors suggested by [2] and [5] are adopted in the presented study. A geometrical partial factor (g_D) of 1.15 has been chosen on the basis of available experimental information (limited) and column performance (isolated) hence design diameter (D_d) of 0.70 m has been set: $D_k / g_D = 0.8 \text{ m} / 1.15 = 0.7 \text{ m}$. A statistical analysis based on data from Table 2 has been adopted in order to set the characteristic value of unconfined compressive strength of the soil-grout column material ($q_{u,k}$) to 4 500 kPa. By application of material partial factor (g_M) of 1.5 design value of unconfined compressive strength ($q_{u,d}$) has been determined: $q_{u,d} = q_{u,k} / g_M = 4 500 \text{ kPa} / 1.5 = 3 000 \text{ kPa}$.

Thereafter jet-grouting columns have been designed in a similar to piles matter. Naturally the treated zone has a remarkable bond with the surrounding soil due to the soil-mixing technique and consequently the geotechnical resistance (jet to soil failure), GEO Ultimate Limit State (ULS) according to Eurocode 7, is typically higher than the structural one (compressive strength of the column) – STR Ultimate Limit State (ULS) according to Eurocode 7.

Characteristic structural strength (bearing capacity) of the jet-grouting column, $R_{c,k}^{int}$, is calculated on the basis of design unconfined compressive strength and columns' diameter as follows: $R_{c,k}^{int} = q_{u,d} \times \pi \times (D_d / 2)^2 = 3 000 \text{ kPa} \times \pi \times (0.70 \text{ m} / 2)^2 = 1 154 \text{ kN}$. Design structural strength (bearing capacity) of the jet-grouting column, $R_{c,d}^{int}$, has been evaluated by applying bearing capacity partial factor, g_R , of 2.2 as follows: $R_{c,d}^{int} = R_{c,k}^{int} / g_R = 1 154 \text{ kN} / 2.2 = 525 \text{ kN}$. Overall structural bearing capacity (compressive strength – STR), has been increased by 699 kN by installing a $\Phi 114.3 \times 8$ steel pipe

($f_{yk} = 275 000 \text{ kPa}$) in the jet-grouting columns: $R_{c,d} = R_{c,d}^{int} + R_{c,d}^{str} = 525 \text{ kN} + 699 \text{ kN} = 1 224 \text{ kN}$.

End-bearing ($q_{b,k} = 2 000 \text{ kPa}$) and skin friction ($q_{s,k} = 175 \text{ kPa}$) have been evaluated on the basis of the available SPT results (Table 1) and soil type according to Figure 8 – [2].

According to [2] characteristic end-bearing resistance, $R_{b,k}$, is sanctioned depending on the method through which end-bearing, $q_{b,k}$, is obtained. In the presented study end-bearing, $q_{b,k}$, is evaluated on the basis of SPT results (Fig. 8) hence partial coefficient k_{SPT} of 0.1 is adopted. Thereafter the characteristic end-bearing resistance is related to the column cross-sectional area as follows: $R_{b,k} = k_{SPT} \times \pi \times (D_d / 2)^2 \times q_{b,k} = 0.1 \times \pi \times (0.70 \text{ m} / 2)^2 \times 2 000 \text{ kPa} = 77 \text{ kN}$. Bearing capacity partial factor, g_b , of 2.0 is used in order to modify the characteristic end-bearing resistance, $R_{b,k}$, and hence to obtain the design: $R_{b,d} = R_{b,k} / g_b = 77 \text{ kN} / 2.0 = 38.5 \text{ kN}$.

The characteristic skin friction resistance, $R_{s,k}$, is determined on the basis of jet to soil contact surface (area) and skin friction, $q_{s,k}$. Design skin friction resistance, $R_{s,d}$, is obtained by adopting a bearing capacity partial factor, g^{3m}_s , for the first 3 meters of the column and another one, g^{L-3m}_s , for the remaining part as follows: $R^{L=5m}_{s,d} = [2 \times \pi \times (D_d / 2) \times 3 \times q_{s,k}] / g^{3m}_s + [2 \times \pi \times (D_d / 2) \times (L - 3) \times q_{s,k}] / g^{L-3m}_s = [2 \times \pi \times (0.70 \text{ m} / 2) \times 3 \text{ m} \times 175 \text{ kPa}] / 2.5 + [2 \times \pi \times (0.70 \text{ m} / 2) \times (5 \text{ m} - 3 \text{ m}) \times 175 \text{ kPa}] / 2.0 = 846.5 \text{ kN}$ for 5-meter long columns and $R^{L=7m}_{s,d} = [2 \times \pi \times (D_d / 2) \times 3 \times q_{s,k}] / g^{3m}_s + [2 \times \pi \times (D_d / 2) \times (L - 3) \times q_{s,k}] / g^{L-3m}_s = [2 \times \pi \times (0.70 \text{ m} / 2) \times 3 \text{ m} \times 175 \text{ kPa}] / 2.5 + [2 \times \pi \times (0.70 \text{ m} / 2) \times (7 \text{ m} - 3 \text{ m}) \times 175 \text{ kPa}] / 2.0 = 1 231.5 \text{ kN}$ for 7-meter long columns.

Overall design geotechnical resistance (jet to soil failure – GEO), $R_{p,d}$, is a sum of design end-bearing resistance, $R_{b,d}$, and design skin friction resistance, $R_{s,d}$: $R^{L=5m}_{p,d} = R_{b,d} + R^{L=5m}_{s,d} = 38.5 \text{ kN} + 846.5 \text{ kN} = 885 \text{ kN}$ for 5-meter long columns and $R^{L=7m}_{p,d} = R_{b,d} + R^{L=7m}_{s,d} = 38.5 \text{ kN} + 1 231.5 \text{ kN} = 1 270 \text{ kN}$ for 7-meter long columns.

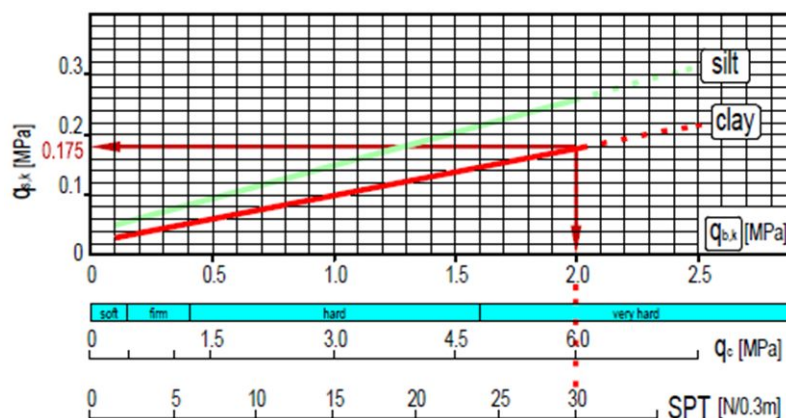


Fig. 8 Skin friction and end-bearing evaluation on the basis of soil type and SPT results – [2]

The smaller of the structural (STR) and geotechnical (GEO) bearing capacity is adopted as final design bearing capacity of the columns: $R^{L=5m}_d = \min(R_{c,d}; R^{L=5m}_{s,d}) = \min(1\ 224\ \text{kN}; 885\ \text{kN}) = 885\ \text{kN}$ for 5-meter long columns and $R^{L=7m}_d = \min(R_{c,d}; R^{L=7m}_{s,d}) = \min(1\ 224\ \text{kN}; 1\ 270\ \text{kN}) = 1\ 224\ \text{kN}$ for 7-meter long columns. In other words, geotechnical failure has turned out to be critical for the shorter (5-meter) jet-grouting bodies whereas structural failure would be critical for the longer (7-meter) ones. Design forces from the analysis are evaluated as 820 kN and 1 200 kN for the 5-meter and 7-meter columns, respectively, which means that they are smaller than their design bearing capacity.

Eurocode 7 suggests that two out of three partial factor groups (actions group, material group and bearing capacity group) which have values higher than 1.0 ought to be combined and respectively applied depending on the adopted Design Approach (either DA1, DA2 or DA3). However, as seen in the above-described procedure, due to uncertainties in the hybrid soil-structure strengthening behaviour and according to provisions given in [2] and [5] partial factors larger than 1.0 for all three groups have been accepted in the presented study.

4 PROBLEMS AND SOLVATIONS

All foundation strengthening measures have been executed in limited operation space of 2.80 m – Figure 9. The extracted material during injection and soil-mixing (reflux) has been sucked out through a pump located on the ground surface. In order to avoid filling the existing foundation with reflux, caps have been plugged in the circular raft openings right after forming each consecutive column.

The execution process has been strictly monitored. The total injected grout volume has been tracked for each column in parallel with the Injection Pressure, Rotation and Flow, [16], by means of an Injection Diagram, [3], which has been obtained directly from the jet-grouting machine (MDT – Mc 80 B has been employed for the study) software. Volume of injection grout is expected to be similar for all jet-grouting bodies. If some deviation is observed then measures ought to be taken and the Designer is informed. The monitored parameters (Injection Pressure, Rotation and Flow) should be kept constant during the whole depth of treatment. Anomaly in the diagrams would mean that the soil has not been treated evenly and in such case variation in the jet-grouting column diameter might be expected. A typical Injection Diagram for Column No. 152 is shown on Figure 10.

During the execution of the jet-grouting columns a defect has been detected in about 90 of them. Although the injection procedure has been performed all the way to the top of the raft, settlement of the columns of about 70 cm below the bottom edge of the foundation has been observed the reason for which remains unknown. In order to solve the problem the following technology has been applied: 1) the affected zone between the raft and the jet has been flushed by water under pressure through a tube in order to liquefy the grout reflux in it; 2) expandable grout MAPEI Expanjet (up to 20% volume expansion and compressive strength of 10 MPa) has been injected at 5 bar pressure. In order to ensure a closed system all neighbouring openings (except for one for reflux excess) have been sealed with a packer. In the end 50 m³ of grout has been injected additionally. The adopted approach is presented on Figure 11.

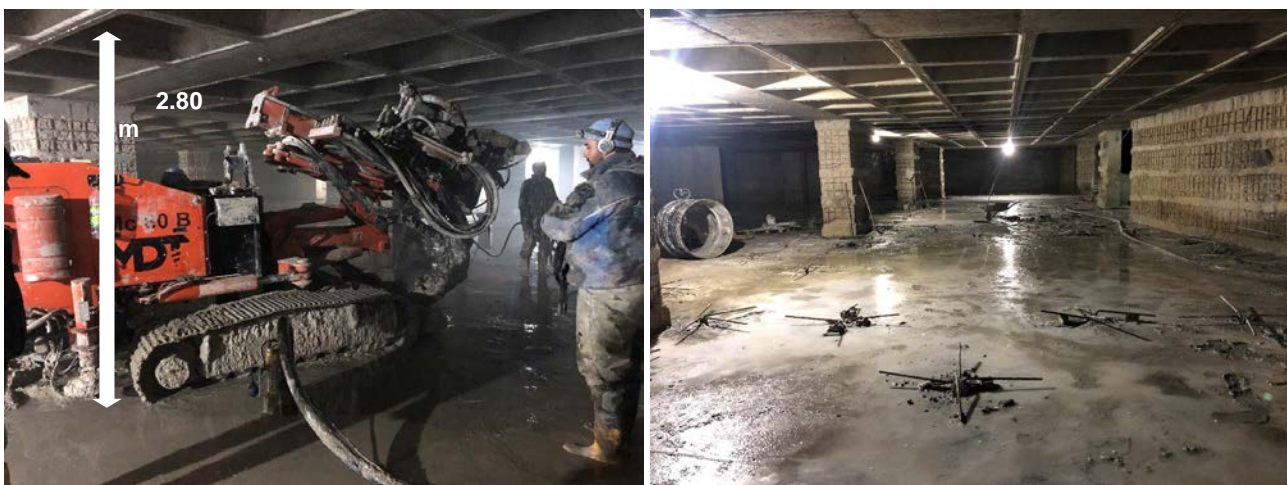


Fig. 9. Execution of the hybrid soil improvement-structural retrofitting approach by applying the jet-grouting technique

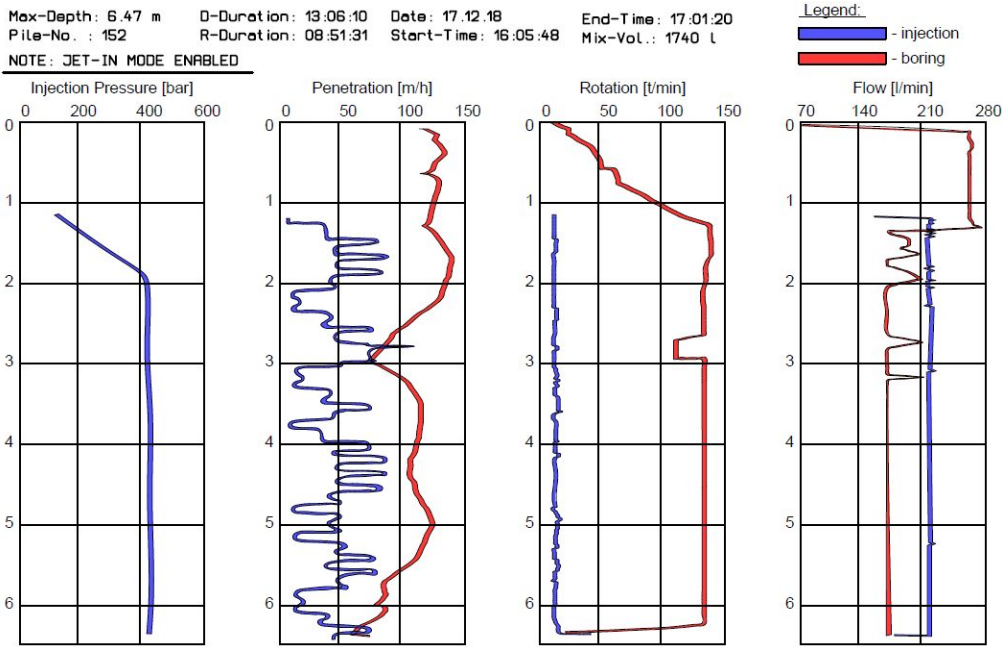


Fig. 10. Example Injection Diagram obtained directly from the "jet-grouting" machine (MDT – Mc 80 B) for Column No. 152

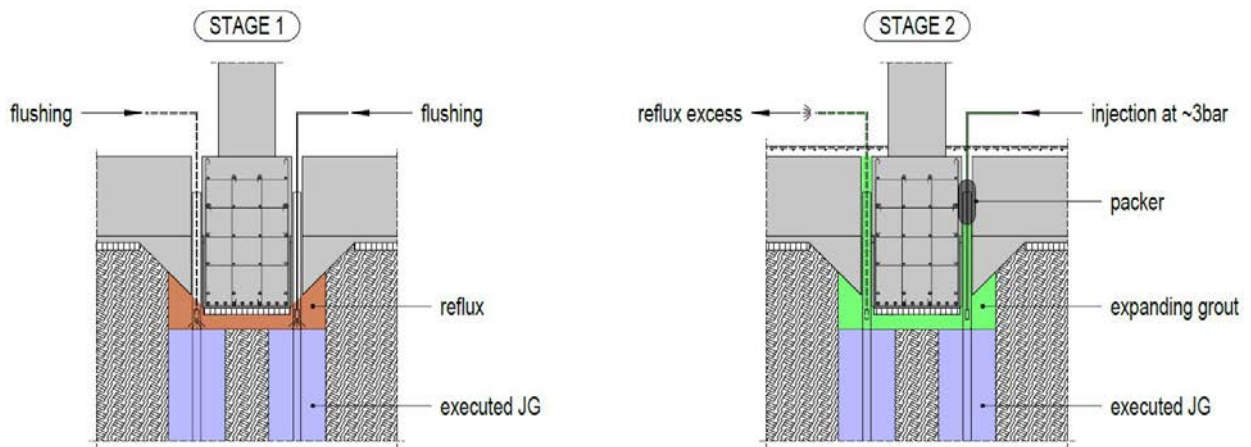


Fig. 11. Filling the void between the jet-grouting columns and the existing raft at two stages

5 CONCLUSIONS

The adopted hybrid soil improvement-structural retrofitting approach by applying the jet-grouting technique has ensured an adequate performance of the structure during and after its extension. The strengthening measure has stiffened the soil-foundation zone below the high-rise part of the building which has influenced the redistribution of the bending moments in a favourable way as well as it has reduced the expected settlement significantly. Although some defects have been detected the reparation measures have guaranteed the undisturbed exploitation of the structure.

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SUMMARY

STRENGTHENING THE RAFT FOUNDATION OF AN EXISTING RC BUILDING BY APPLICATION OF JET-GROUTING METHOD

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This paper presents the application of the jet-grouting method as a structural and ground improvement technique for strengthening the soil-raft foundation system of an existing reinforced concrete building. The structural system of the originally designed super-structure consists of columns for bearing the vertical loads and shear walls for ensuring the adequate seismic response. The building has been executed up until level zero by 2010. However, during construction, the investment intentions have been changed and the owner has decided to extend the structure by additional floors which in turn has caused the need of redesign of the building above the ground level and strengthening of its underground part. The aim of the study is to demonstrate the adopted design approach for strengthening the soil-raft foundation system *and applied* methodology for proving the predicted jet-grouting properties (diameter, length, compressive strength and elasticity modulus) as well as to outline the difficulties which have occurred during execution and the solutions of some important problems.

Key words: jet-grouting, single fluid system, raft foundation, soil improvement, foundation strengthening

APSTRAKT

POJAČANJE TEMELJNE PLOČE POSTOJEĆE ARMIRANOBETONSKE ZGRADE PRIMENOM DŽET-GROUTING (MLAZNOG INJEKTIRANJA) METODE

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U ovom radu prikazana je primena metoda džet-grouting (mlaznog injektiranja) kao tehnike za pojačanje konstrukcije i poboljšanja tla, tj. za pojačanje sistema temelja ispod postojeće armirano-betonske zgrade. Konstrukcijski sistem prvobitno projektovane nadgradnje sastoji se od stubova za prenošenje vertikalnih opterećenja i smičućih zidova kako bi se osigurao adekvatan seizmički odgovor konstrukcije. Zgrada je izvedena do nivoa nula do 2010. godine. Međutim, tokom gradnje, investicijski kapaciteti i zahtevi su promenjeni i vlasnik se odlučio da proširi tu konstrukciju dodatnim spratovima što je zauzvrat izazvalo potrebu redizajna (pre-projektovanja) zgrade iznad nivoa zemlje i pojačanje njegovog podzemnog dela. Cilj studije je pokazati usvojeni Projektantski pristup za pojačavanje sistema temelja na ravnoj ploči i primenjenu metodologiju za dokazivanje predviđenih svojstava džet-groutinga (prečnik, dužina, čvrstoća na pritisak i modul elastičnosti) kao i da se opišu poteškoće do kojih je došlo tokom rešavanja nekih važnih problema.

Ključne reči: mlazno injektiranje (džet grouting), sistem sa jednom tečnošću, temeljna ploča, poboljšanje tla, pojačanje temelja