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THE NUMERICAL CALCULATIONS OF INFLUENCE OF UNDERPINNING ON FOUNDATIONS SETTLEMENT

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Abstract: The paper presents numerical calculations of the influence of implementation technology for underpinning the footing on settlement, with the use of finite element method. Three cases of underpinning methods were taken for calculations, depending on the diameter of the jet grouting column and the order of works. The intensity of settlement of the base of the footing foundation is significantly influenced by the growth of Young's modulus and the jet grouting column with time, until its complete curing and reaching final technological parameters.

1. INTRODUCTION

The problem of constructing continuous footings and bases of foundation is particularly important when constructing new structures in the neighbourhood of existing buildings, in strongly urbanized areas. It is also of importance in the case of saving and protection against further degradation of historical objects or objects excluded from use, the only possibility for which is their modernization and change of the function, which is connected with an increased burden on the foundations. The reinforcement of the base is required also in the case of deep excavations under the building, and consequently the impact on the existing foundations, especially when there is a need to enhance the exploitation values of existing buildings or industrial constructions. Examples of constructions built inside buildings may be the construction of reinforced concrete chambers under the mechanism of railway wheel drop in the wagon halls, waterproof reinforced concrete chambers of swimming pools in hotels and villas, or underground garages or car parks, etc.

With the construction of foundations a change of soil parameters beneath the foundations takes place. These include mechanic parameters: angle of internal friction φ, cohesion c, modulus of soil deformation E_o, modulus of soil compressibility M_o, Poisson's coefficient ν. Also physical parameters are changed, such as: unit weight of the soil γ, total porosity n, void ratio e. If binding materials, e.g., Portland cement, are injected to the ground, the natural or anthropogenic loose soil changes into solid. This results in accepting for engineering calculations bearing capacity or settlement of columns, the elastic modulus E (Young's modulus) instead of the modulus of soil deformation E_o, as in the case of loose media.

For the purpose of soil reinforcement, different technologies can be applied, such as vibro-exchange (gravel columns, sand columns, etc.), deep soil mixing (columns DSM) or jet grouting (Zielińska and Bzówka [18], Borges et al. [2], Voottipruexa et al. [16], Asgari et al. [1]).

Each of these methods can be implemented to strengthen the basis of various manufacturing technologies. This article presents and comments on the differences in reinforcement efficiency of the substrate, which occur as a result of using different technologies, with the method of injecting high-pressure jet being in the focus.

2. JET GROUTING TECHNOLOGY

Nowadays, jet grouting is more and more often applied in the process of soil hardening under foundations, due to which it is possible to form individual quarter-, half-, and full columns, one- and two-sided lamellas (Fig. 1), palisades and injection walls and lids protecting from the pressure of water, e.g., in the case of foundations made below the ground water table (Bzówka [6]). The application of jet grouting technologies not only allows stabilization or compensation of settlement, but also active lifting of the existing foundations of buildings including buildings important for their cultural, historical or economic values (Topolnicki [15], Chernyakov [7]).The problems related to jet grouting, both in terms of carrying out injection, as well as estimating material parameters of cement-ground mixture and measuring jet grouting columns (defining the bearing capacity and settlement) have been addressed by Zielińska and Bzówka [18], Bukowski and Rymsza [4], Topolnicki [15], Rawicki and Żmudziński [13], Bzówka [5], Coulter and Martin [8], Malinin et al. [9], Modoni et al. [12], Modoni and Bzówka [11], Wanik and Bzówka [17], Shen et al. [14]) and many others not mentioned in this paper.

Some most important data for designer of building constructions are, e.g., loading, physical and technological parameters of cement-ground mixture, from which jet grouting columns are formed and assumptions of a method of calculating bearing capacity, settlement and results of calculations. Final settlement of the jet-grouting column depends not only on the parameters of the column, the way and size of the given load, method of its estimation, but also on the data about the surrounding ground base (Borges and Marques [3]) as well as technology of carrying out work, the influence of which will be presented in further part of the paper.

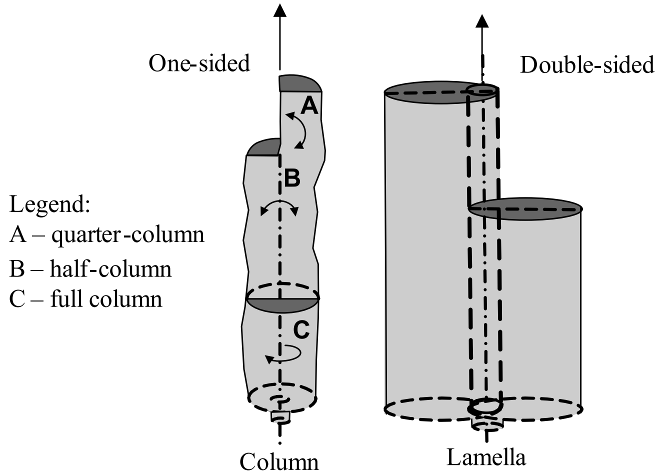

Fig. 1. Elements of jet grouting – the column and lamella (Bzówka [6])

The idea of a classical jet-grouting method (Bzówka [6]) consists in making a borehole with a drill rod to a depth appropriate for a given column or lamella. The diameter of the borehole is about 0.1 m. In the further stage, the machining of the ground is performed by a thin stream of water or the grout of pressure ranging from 15 MPa to 70 MPa. After making the ground the petrification and formation of column takes place under the pressure ranging from 2–5 MPa.

The hardened grout is mixed with the insitu soil to produce a soilcrete. The strength parameters of the latter are sometimes characterized by a considerable spread of values, e.g., Young's modulus E, for which the value of variability coefficient v was found to be about 30%, according to Rawicki and Żmudziński [13]. In their study, they used 15 samples taken from piles' core. The piles were formed by high-pressure injection in order to reinforce the foundation footing of a hall and a flyover nearby Cracow. The value of variability coefficient v for elastic modulus E was for all the columns $v = 27.7\%$, standard deviation $s = 0.735$ GPa and the mean value of elastic modulus $E = 2.86$ GPa. One should emphasize that all the columns, with mean length of 10 and 11 m, were implemented when applying the grout to jet-grouting in the ratio $c/w = 1.2$. The soil base is formed of silt and clay earthwork (thickness 4.1 m), loess-like sediments (thickness 8.6 m), in the upper part consisting of hard plastic silt ($I_L = 0.16$), and in the lower part – silt hard plastic clays ($I_L = 0.24$). Below these layers there were humid sands of thickness ca. 1.7 m, and then, subsequently silty clays and sandy clays as well as compact clays of the mean value of the degree of plasticity ($I_L = 0.16$). The measure of the differentiation of the distribution of the feature of Young's modulus E for individual columns of jet grouting analyzed separately is presented in Table 1 based on the studies of Rawicki and Żmudziński [13].

Table 1

Mean values of Young's modulus E, standard deviation s, and coefficient of variation v for jet grouting columns mixture of the tests referred to in the article (Rawicki and Żmudziński [13])

Number of a jet grouting column	Mean values of Young's modulus E	Standard deviation s	Coefficient of variation v
	(GPa)	–	(%)
1H	3.3	1.1521	34.4
2H	3.4	1.1942	35.1
3E	2.9	0.2754	9.6
4E	2.3	0.6267	27.0

Some different conclusions referring to the influence of the type of soil that is a component of the soil-cement material were formulated by Bzówka [5], based on the strength testing of cylindrical samples, with the height, h, to diameter, d, ratio of 2:1, cut from the grouting column. There were investigated the following series of samples:

- series A – samples cut from the part of the column with medium sand as the soil component of grouting material,
- series B – samples taken from the part of grouting column made by mixing cement grout with soil component: mean sand/silty loam,
- series C, D, E – samples designed for technological studies, obtained from the part of jet grouting column consisting of silty loam in the soil-cement mixture.

In Table 2, the results of studies of parameters from paper [5] are shown, both for one-axis and three-axis compression. Based on experimental results the author stated that the influence of the type of soil on the parameters of Coulomb-Mohr's model for columns formed with the jet grouting method is "small, nevertheless visible". A very important conclusion made in the article is the fact that the rigidity of soil-cement material is between 5 and 8 times smaller than the rigidity of concrete, the measure of which is Young's modulus *E*.

Table 2

Mean values of Young's modulus *E*, friction angle *φ*, Poisson's ratio *ν* and the cohesion *c* for jet grouting columns mixture of the tests referred to in the article (Bzówka [5])

Number of series of a jet grouting column	Mean values of Young's modulus *E*	Friction angle *φ*	Poisson's ratio *ν*	Cohesion *c*
	(MPa)	(°)	(–)	(kPa)
Series A and B	5630	56	0.17	3640
Series C, D and E	4720	52	0.20	3530
Series A–E	5490	57	0.18	3320

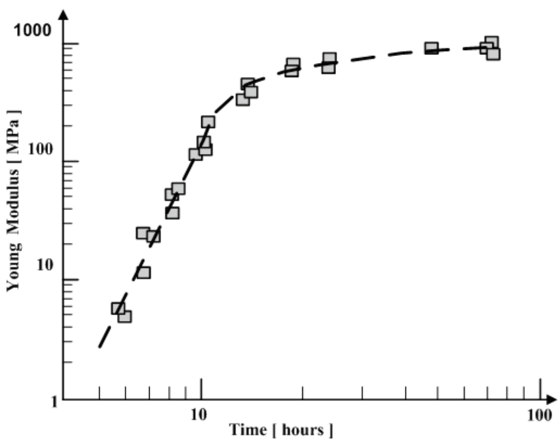

Fig. 2. Young's modulus *E* of the grout as a function of time (after Coulter and Martin [8])

Different values of Young's modulus *E* for jet grouting columns are noted not only as a result of making columns in different soils, compact or loose, but also as a result of changes during the hardening of soil-cement-ground material, as presented in Fig. 2 (Coulter and Martin [8]). The graph of changes in Young's modulus with time, illustrated in Fig. 2, is given on a logarithmic scale, while the graph presented in Fig. 3 is transformed – by the authors of this paper – into the scale of the function of Young's modulus vs. time obtained by Coulter and Martin [8]. Due to such a procedure, a curve was plotted, from which other 17 numerical values of elastic modulus *E* were taken.

Changes were recorded during the time span starting 2.5 hours after the column had been formed and terminated after about 70 hours until a complete setting of the cement-soil material (Table 3).

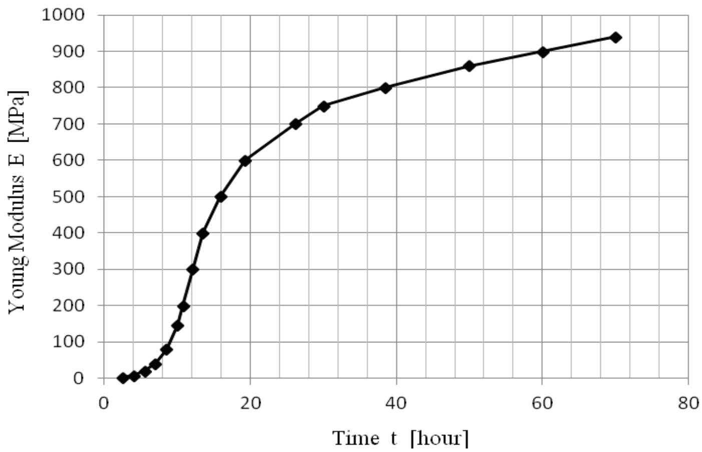

Fig. 3. Transformed function from Fig. 2

Table 3

Values of Young's modulus E adopted in numerical calculations based on Fig. 3, from the tests performed by Rawicki and Żmudziński [13]

Time t (h)	Young's modulus E (MPa)
2.5	3
4	8
5.5	20
7	40
8.5	80
10	146
10.8	200
12.1	300
13.5	400
15.9	500
19.3	600
26.1	700
30	750
38.5	800
50	860
60	900
70	940

3. NUMERICAL SIMULATION OF THE TECHNOLOGY USED FOR THE CONSTRUCTION OF FOOTING

The paper presents a numerical simulation of the influence of technology applied on the settlement of foundation in a two-layer base. Plaxis 8.2 program which is a finite element package was used for numerical calculations. The jet grouting column and the co-operating ground were assumed to work in a plane state of strain. A footing of dimensions 3.0 m × 3.0 m, and the point load of 1000 kN was taken for the settlement analysis. For jet grouting column, a model of isotropic body, linearly-elastic material of Young's modulus values *E* (MPa) changing with time according to Table 3 was accepted, and yet the volume weight of cement-soil material was assumed to equal $\gamma = 22$ kN/m^3 and Poisson's coefficient $\nu = 0.25$. Soil was described with the condition of the Coulomb–Mohr state associated with the law of plastic flow. Basic geometric parameters of layers are presented in Table 4. The area was divided into triangular 15 node finite elements with the contact layer on the border of soil–jet grouting column. The scope of the model in the numerical analysis makes up a rectangle of width 50 m and depth 30 m. The mesh consists of 1234 elements and 10148 nodes, the dimension of an average element being about 1.1 m. Numerical models of the footing of the foundation are illustrated in Fig. 4.

Boundary conditions were selected according to typical models applied in the calculations of geotechnical issues and include knot jointed movable supports for vertical side edges and knot jointed not movable supports for the lower edges base of the model (Bzówka [6]).

Table 4

Basic parameters of soils used in numerical calculations

Layer	The level of compaction I_D	Young's modulus E (MPa)	Poisson's ratio ν (–)	Cohesion * c (kPa)	The internal friction angle φ (°)	Angle of dilatation Ψ (°)	The thickness of the layer (m)
Fine sand	0.6	57000	0.3	1	31	0	5
Medium sand	0.7	110000	0.3	1	34	0	5
* minimum value of cohesion is required by the program							
Foundations		Axial stiffness EA (kPa/m)		Bending stiffness EI (kPa/m)		Poisson's ratio ν (–)	
Spread footing: 3.0 m × 3.0 m × 0.5 m		47850000		1206218.8		0	

Numerical analysis of the settlement of jet grouting column was done assuming asymmetric and symmetric technology of work performance. The symmetric and asymmetric models included first making a ground column under the gravity centre of the foundation, with three different diameters of the jet grouting columns: 1.0 m (marked

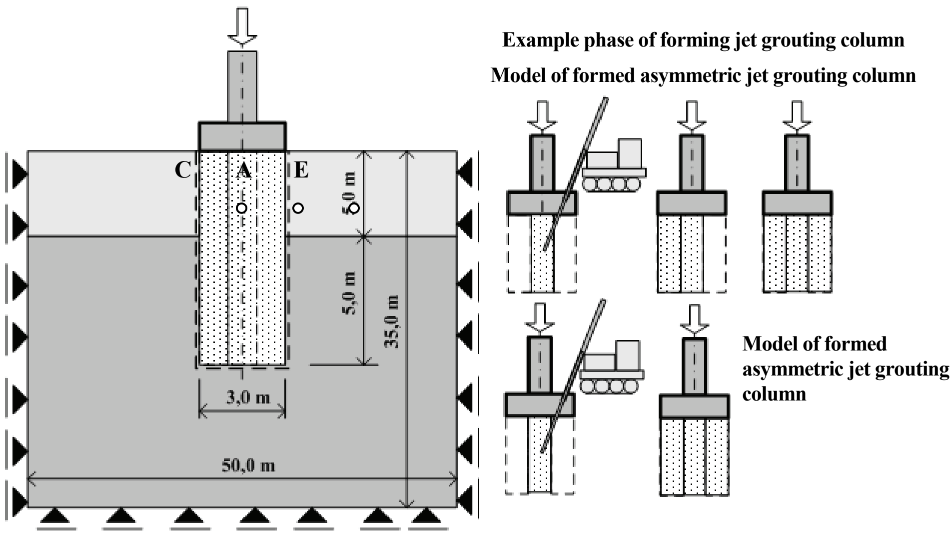

Fig. 4. The numerical model of jet grouting column formed in the central part of the foundation with external columns to be filled with soilcrete material, with foot-points: A, C, E, where the settlement was calculated (the model is not to scale)

yellow in Fig. 4), 0.5 m and 2.0 m, respectively. The diameters of extreme columns were identical and adjusted to the width of the foundation equalling 3.0 m, due to which it was possible to obtain the settlement of the footing at the exchange of the whole mass of the subsoil under the foundation. The settlement of points situated under the gravity centre of footing – point A and extreme points, situated on both sides of the side edges on the footing – points C and E were analyzed (Fig. 4). For the numerical calculations it was assumed that the length of jet grouting column equals 10.0 m. In the further part of the model prepared every diameter of particular jet grouting columns, was given a variable – according to the increase of time – value of Young's modulus E, given in Table 3. In the case of symmetric technology, extreme (outer) columns were simultaneously given values of growing direct elasticity moduli E. Due to such an approach, the authors succeeded in forming the columns under the whole footing in 34 stages, while the implementation of jet grouting columns took place after 17 stages. In the case of an asymmetric model, at the beginning the growing values of Young's modulus E (according to Table 3) were given for extreme column on the left. For obvious reasons, only after getting settlement for central column (hardened after 17th stage – the value of the column modulus was E = 940 MPa) and extreme left (which reached the value of Young's modulus E = 940 MPa – in 34th stage) the process of the formation of extreme right jet grouting column, which in numerical calculations was, like in the case of earlier stages, given to the material of the column growing values of direct elasticity modulus E (Table 3). This way, with asymmetric technology, 51 stages of the exchange of ground for the foundations of the reinforced concrete footing are obtained by the implementation of jet grouting columns.

It should be emphasized that the settlement in a given stage was the beginning of calculations for the subsequent stage of settlement, with the increased value of Young's modulus *E*, simulating the hardening of the cement-soil material and improvement of the mechanical properties of the column.

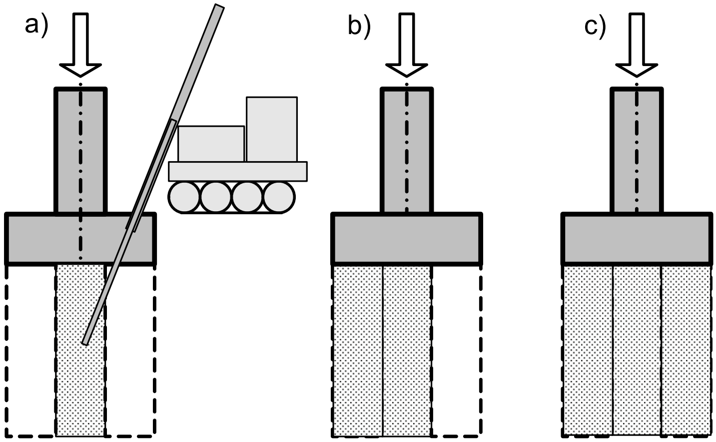

Fig. 5. Asymmetric technology of ground reinforcement under the spread footing, (a) stage 2 – pd1, (b) stage 19 – pd1, (c) stage 36 – pd1

In Fig. 5, the asymmetric technology of making column is illustrated. As one can see from the figure, in each of the stages the same value of Young's modulus E = 8.0 MPa is assigned to another jet grouting column, which is 4 hours after making the column (according to Table 3). It is worth noticing that in the numerical model in stage 19, the central jet grouting column has already hardened and achieved maximal value of direct elasticity modulus E for the cement-soil material, i.e., E = 940 MPa, while in stage 36, the same value of Young's modulus is acquired by the left outer column, while the right one is still hardening.

Similarly, one can present a symmetric model of the ground base reinforcement by jet grouting columns, as illustrated in Fig. 6.

Abbreviations pd1, pd1s stand for the jet grouting column of 1 m in diameter. Symbol pd1 refers to the column made by asymmetric technology of soil hardening, while pd1s is a column made by symmetric technology. In the same way pd2 and pd2s refer to the start of making the jet grouting column of 0.5 m in diameter – stage 1, then making external columns of 1.25 m in diameter on both sides of the central column. Symbol pd2 means asymmetric technology of making a column, while pd2s – symmetric technology of making a column. Finally, pd3 refers to making the central column of 2.0 m in diameter in the axis of the foot and external columns of 0.5 m in diameter are made using asymmetric technology, and in pd3s – central column has 2.0 m diameter, and external columns of diameter 0.5 m each, are formed using symmetric technology.

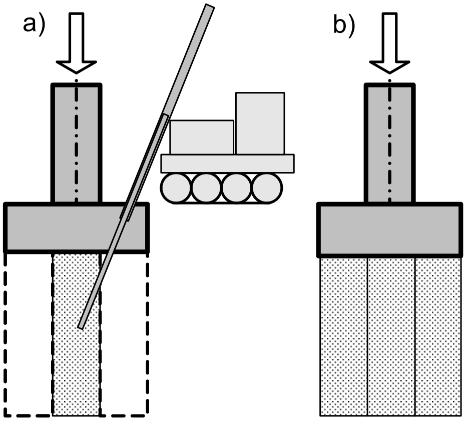

Fig. 6. The numerical model of symmetric technology of jet grouting column formation, (a) stage 2 – pd1s, (b) stage 19 – pd1s

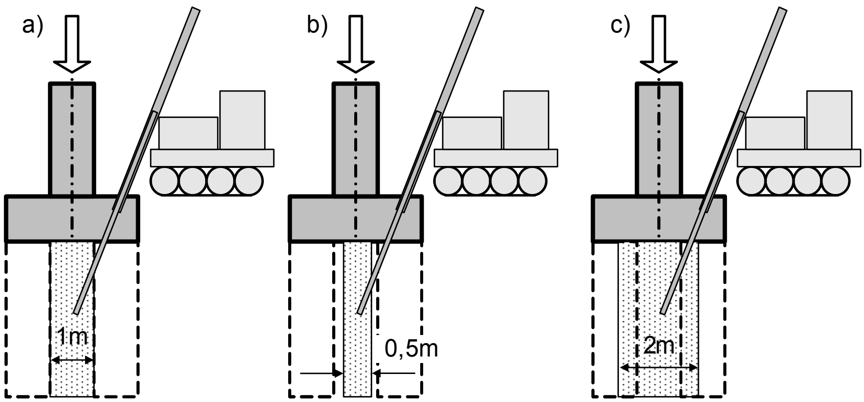

Fig. 7. Examples of the diameters of jet grouting columns formed with asymmetrical or symmetrical technology of ground reinforcement under the spread footing:
(a) the diameter of the central and external columns is 1 m – stage 1 – pd1 or pd1s,
(b) the central column diameter is 0.5 m, and the external ones are 1.25 m each – stage 1 – pd2 or pd2s,
(c) the central column diameter is 2.0 m, and the external ones are 0.5 m each – stage 1 – pd3 or pd3s

Examples of the analyzed cases of reinforcement of the subsoil by different models of the jet grouting column diameters, both for the symmetric and asymmetric technology of the works, are given in Fig. 7.

4. RESULTS OF NUMERICAL CALCULATIONS

Based on the results of numerical calculations the conclusion can be made that the influence of the technology of underpinning on the settlement of the foundation footing is significant. First of all, using a symmetric method, reduces values of the foundation inclination; see points C and E – Fig. 8. Moreover, the intensity of the settlement can be controlled by the scope of injection, which is shown in the graph of Fig. 9. The largest settlement of the foundation base – point A – is observed when making a broad central column (diameter 2.0 m – curves marked pd3s), as presented on the graph of settlement, Fig. 9. In this case, there is practically no influence of settlement due to the formation of two outer columns at the same time, because rapid growths of the settlement of the footing are not recorded anymore. It is completely different with the central jet grouting column being only 0.5 m in diameter, where settlement is the smallest, however forming simultaneously two outer columns contribute to the rapid growth of settlement (curves pd2s), though the final value is still smaller than in the case of forming columns of diameters 1.0 and

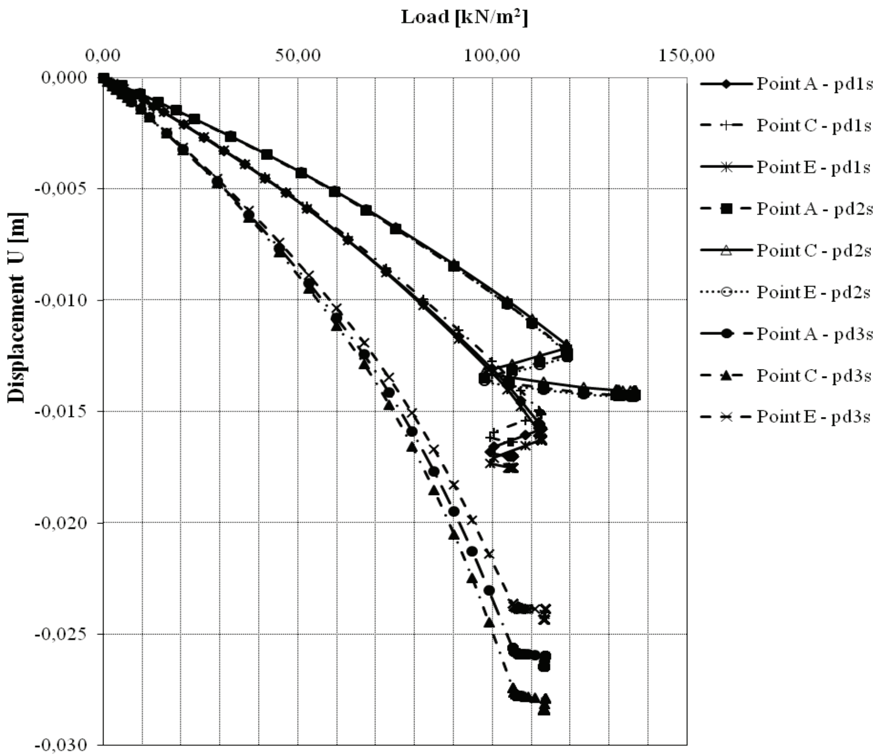

Fig. 8. The theoretical settlement curves of jet grouting column: symmetric technology of jet grouting column formation

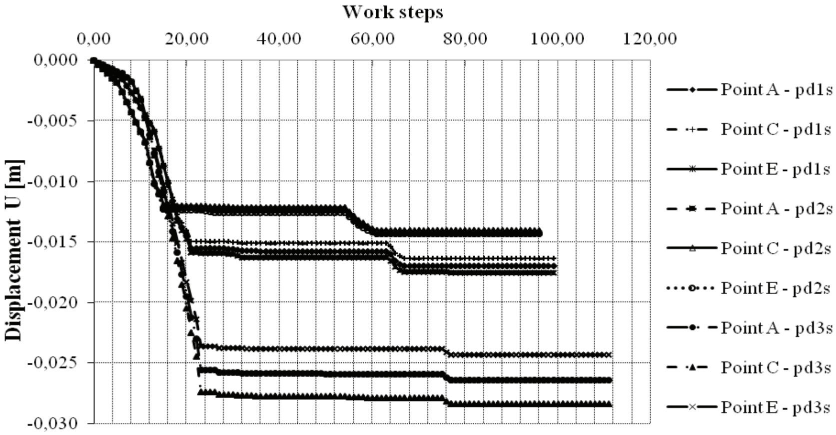

Fig. 9. The theoretical settlement curves of jet grouting column: symmetric technology of jet grouting column formation depending on work stages

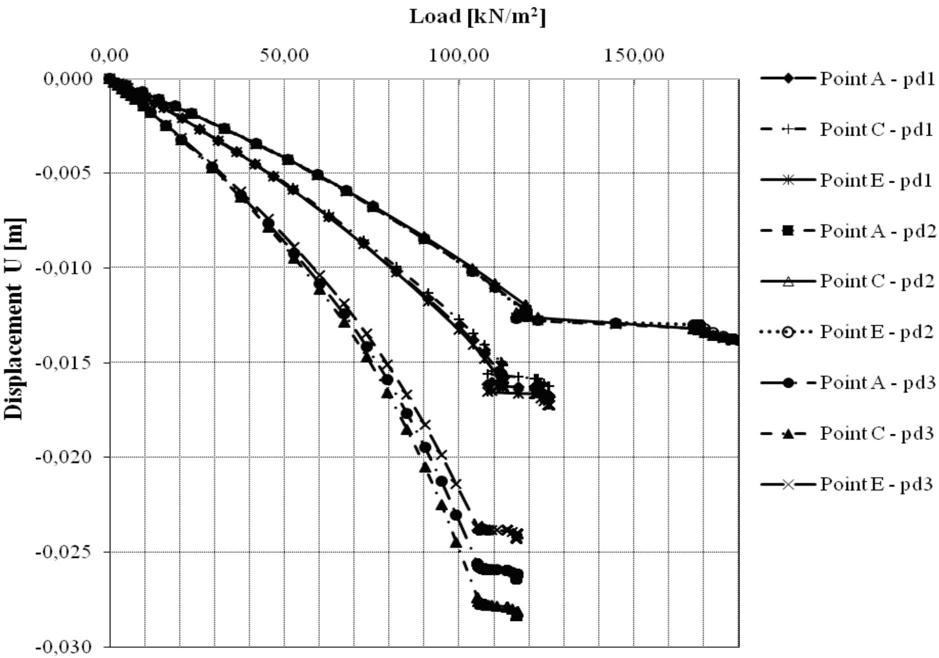

Fig. 10. The theoretical settlement curves of jet grouting column: asymmetric technology of jet grouting column formation

2.0 m. This proves the stabilizing function of the central column, which, after reaching the full strength works as a pile. Based on the graph (Fig. 9) one can also see the importance of soil lumps cooperating with the formed and hardened cement-soil material in the jet grouting column using suitable technology. Widening the scope of underpinning of the foundation can contribute to the growth of settlement, which fact should be accounted for. A rapid growth of settlement during the formation of outer columns, even when a symmetric technology of ground exchange is employed, is a result of insufficient load capacity of the central column as the soilcrete material used for its formation has already hardened because it occurs at the end of phase 17 and the beginning of phase 18, i.e., at the moment the outer columns have the lowest value of Young's modulus E = 3.0 MPa (time t = 2.5 hours). After that period the settlement is practically not changing. One should bear in mind a very important conclusion drawn by Bzówka J. [5] that rigidity of cement-soil mixture is from 5 to 8 times lower than that of concrete.

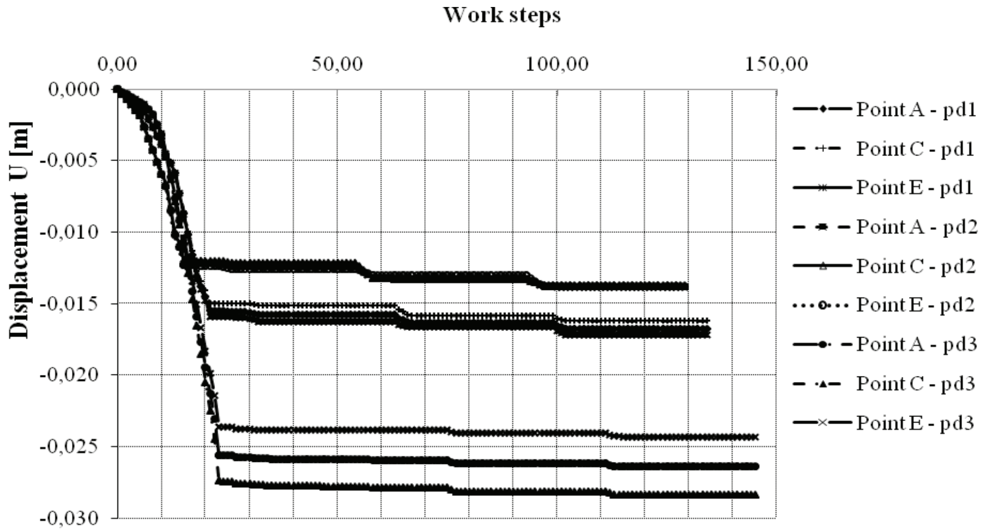

Fig. 11. The theoretical settlement curves of jet grouting column: asymmetric technology of jet grouting column formation depending on work stages

In the case of underpinning the footing with columns of identical diameter, equal 1.0 m (curves pd1s in Fig. 9), an intermediate value of final settlement is obtained, compared to the case of central columns of 0.5 m and 2.0 m in diameter.

A comparison of settlement obtained when using asymmetrical technology of forming jet grouting columns is presented in Figs. 10 and 11. In Figs. 12, 13 and 14, calculation curves of settlement have been plotted for both asymmetrical and symmetrical technology applied, with settlement values taken from curves pd1 and pd1s in Figs. 12 and 13, and from pd2 and pd2s curves in Fig. 14.

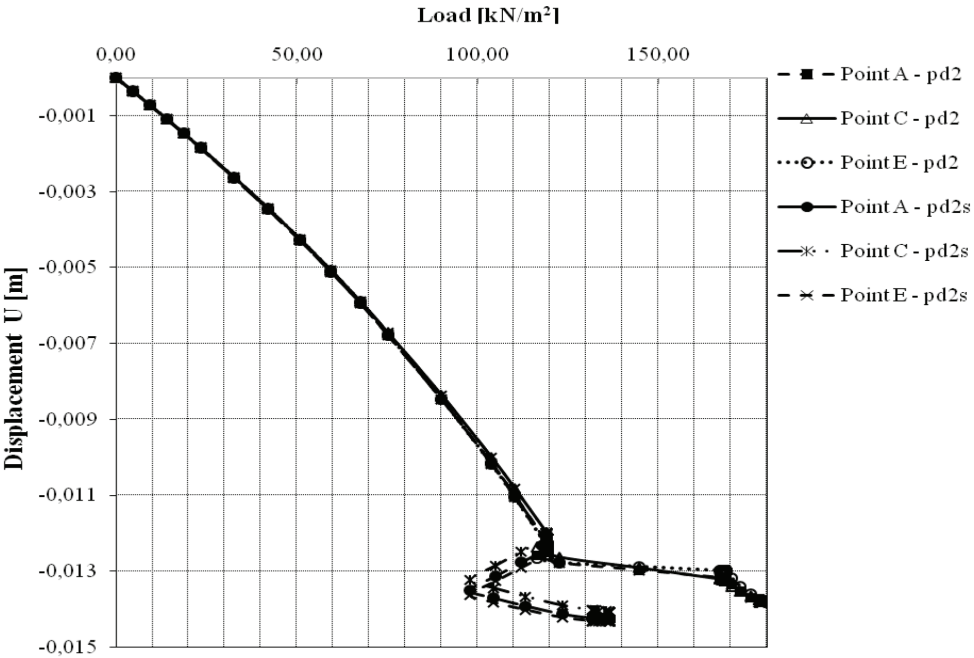

Fig. 12. The theoretical settlement curves of jet grouting column: symmetric and asymmetric technologies of jet grouting column formation – pd2, pd2s

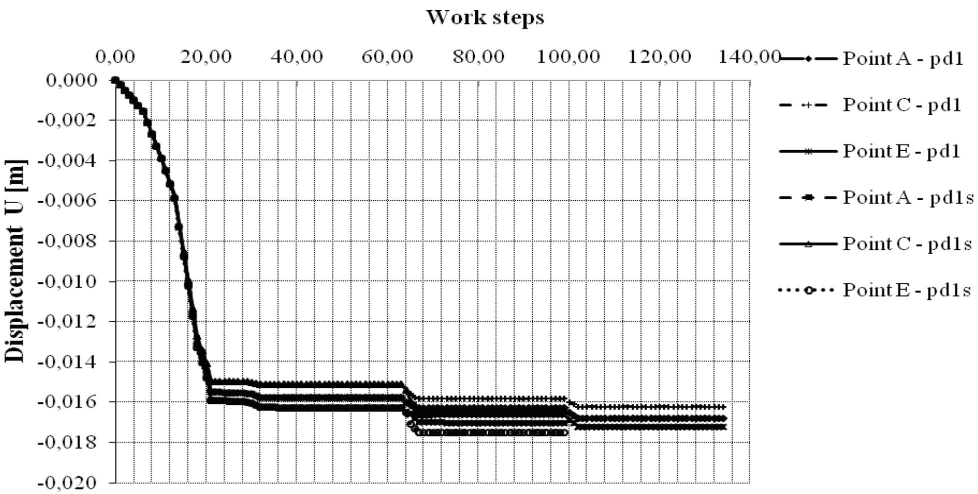

Fig. 13. The graphs of jet grouting column settlement: asymmetric and symmetric technologies of jet grouting column formation due to work stages – pd1, pd1s

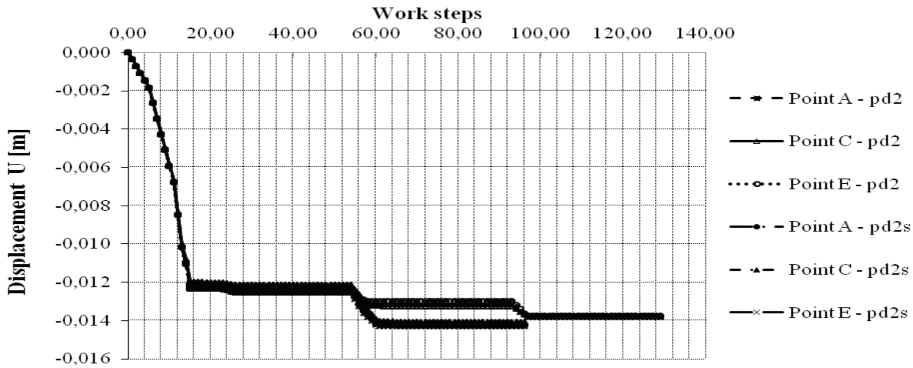

Fig. 14. The graphs of jet grouting column settlement: asymmetric and symmetric technologies of jet grouting column formation due to work stages – pd2, pd2s

Table 5

Results of spread footing settlement depending on the footing formation technology and diameter of the central column

Footing technology	Final settlement of the points in the spread footing in selected stage of calculation			The settlement of the points in relation to the maximum settlement			Inclination of spread footing
	The left edge C	The middle A	The right edge E	The left edge C	The middle A	The right edge E	
	[m]	[m]	[m]	[%]	[%]	[%]	[°]
1	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Stage 1							
Settlement curves pd1 or pd1s							
Asymmetric	–0.015	–0.015	–0.016	53.57	53.57	57.14	0
Symmetric	–0.015	–0.015	–0.016	53.57	53.57	57.14	0
Settlement curves pd2 or pd2s							
Asymmetric	–0.012	–0.012	–0.012	42.86	42.86	42.86	0
Symmetric	–0.012	–0.012	–0.012	42.86	42.86	42.86	0
Settlement curves pd3 or pd3s							
Asymmetric	–0.027	–0.026	–0.024	96.43	92.86	85.71	0.05730
Symmetric	–0.027	–0.026	–0.024	96.43	92.86	85.71	0.05730
Stage 17							
Settlement curves pd1 or pd1s							
Asymmetric	–0.015	–0.016	–0.016	53.57	57.14	57.14	0.01910
Symmetric	–0.015	–0.016	–0.016	53.57	57.14	57.14	0.01910
Settlement curves pd2 or pd2s							
Asymmetric	–0.012	–0.012	–0.013	42.86	42.86	46.43	0.01910
Symmetric	–0.012	–0.012	–0.013	42.86	42.86	46.43	0.01910
Settlement curves pd3 or pd3s							
Asymmetric	–0.028	–0.026	–0.024	100	92.86	85.71	0.07639

1	2	3	4	5	6	7	8
Symmetric	–0.028	–0.026	–0.024	100	92.86	85.71	0.07639
Stage 18							
Settlement curves pd1 or pd1s							
Asymmetric	–0.016	–0.016	–0.017	57.14	57.14	60.71	0.01910
Symmetric	–0.016	–0.017	–0.018	57.14	60.71	64.29	0.03820
Settlement curves pd2 or pd2s							
Asymmetric	–0.013	–0.013	–0.013	46.43	46.43	46.43	0
Symmetric	–0.014	–0.014	–0.014	50.00	50.00	50.00	0
Settlement curves pd3 or pd3s							
Asymmetric	–0.028	–0.026	–0.024	100	92.86	85.71	0.07639
Symmetric	–0.028	–0.026	–0.024	100	92.86	85.71	0.07639
Stage 34 (Final settlement of spread footing with symmetric technology of jet grouting column formation)							
Settlement curves pd1 or pd1s							
Asymmetric	–0.016	–0.016	–0.017	57.14	57.14	60.71	0.01910
Symmetric	–0.016	–0.017	–0.018	57.14	60.71	64.29	0.03820
Settlement curves pd2 or pd2s							
Asymmetric	–0.013	–0.013	–0.013	46.43	46.43	46.43	0
Symmetric	–0.014	–0.014	–0.014	50.00	50.00	50.00	0
Settlement curves pd3 or pd3s							
Asymmetric	–0.028	–0.026	–0.024	100	92.86	85.71	0.07639
Symmetric	–0.028	–0.026	–0.024	100	92.86	85.71	0.07639
Stage 35							
Settlement curves pd1							
Asymmetric	–0.016	–0.017	–0.017	57.14	60.71	60.71	0.01910
Settlement curves pd2							
Asymmetric	–0.014	–0.014	–0.014	50.00	50.00	50.00	0
Settlement curves pd3							
Asymmetric	–0.028	–0.026	–0.024	100	92.86	85.71	0.07639
Stage 51 (Final settlement of spread footing with asymmetric technology of jet grouting column formation)							
Settlement curves pd1							
Asymmetric	–0.016	–0.017	–0.017	57.14	60.71	60.71	0.01910
Settlement curves pd2							
Asymmetric	–0.014	–0.014	–0.014	50.00	50.00	50.00	0
Settlement curves pd3							
Asymmetric	–0.028	–0.026	–0.024	100	92.86	85.71	0.07639

5. CONCLUSIONS

Based on the results of numerical calculations (Table 5) and the graphs in Figs. 8 through 14 illustrating the settlement of footing, the following conclusions can be drawn.

There is a significant influence of the technology used in forming jet grouting columns on the magnitude of foundation settlement. Maximum values of settlement, equal 2.8 cm, were obtained in numerical simulation performed for the central column the diameter of which was the largest and equalled 2.0 m. Definitely the lowest settlement has been obtained for the central jet grouting column of 0.5 m in diameter, which compared to maximum settlement values amounts to 53.57% for symmetric technology and 50% for asymmetric jet grouting technology. If the diameter of the central column is 1.0 m, its settlement amounts to 57.14% of the maximum one, regardless of the technology used. Therefore, a contractor concerned with injection works should take into account the settlement of the foundations depending on the way they are to be constructed and to model any displacements that might affect the effort of superstructure.

The results that are identical for both symmetric and asymmetric technologies show that there are some diameters of the columns above which the mode of forming columns is not important (in our example, considering insignificant number of cases, it is the diameter of the central column = 1.0 m).

Columns of minimum diameter (in this article = 0.5 m) behave in the subsoil as concrete piles or concrete micro-piles, which stabilize settlement and contribute to obtaining the lowest displacements of foundations.

Based on the graphs from Fig. 14, one can state that at symmetrical technology of making grouting columns larger and practically final settlement in shorter time, it is obviously as a result of the implementation of extreme columns at the same time. Settlement is bigger than carried out at the same time, settlement for asymmetric technology, despite the fact that final displacement are close in the value to each other.

Another problem, however not considered in this paper, may also be the proper analysis of soil–jet grouting column interaction, in case of strongly stratified or overconsolidated subsoil. A need of more precise evaluation of soil compressibility in adverse geotechnical conditions was discussed, among others, by Młynarek et al. (2013).

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