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The high-rise building foundation with developed stylobate part design features using piles tests data

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The paper presents two structural solutions for the high-rise building pile foundation where stylobate and high-altitude parts are not separated by a contraction joint studying results. The main difference between these structural solutions is in the use of piles of different lengths: in the first version all piles have the same length (implemented in practice) and the second version (perspective) is use of different lengths of piles and their support various engineering-geological elements (EGE): the longer piles support by stronger EGE under the altitude part and the shorter piles support by weaker EGE under the stylobate part. In calculations of the adopted versions piles tests results and geodetic observations have been considered for the used calculation methods verification.

Keywords: bored pile, «base – foundation – above-foundation building part» system calculation, static jacking load test, stylobate

Особливості проектування фундаментів висотної будівлі з розвиненою стилобатною частиною з використанням даних випробувань паль

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Подано результати дослідження двох конструктивних рішень пальового фундаменту для висотної будівлі, в якої стилобат та висотна частина не розділені деформаційним швом. З’ясовано, що основна відмінність конструктивних рішень полягає у використанні різних довжин паль: перший варіант – усі палі однакової довжини (реалізований у натурі); другий варіант (перспективний) – використання різної довжини паль і їх обпирання на різні інженерно-геологічні елементи: під висотну частину – довші палі з обпиранням на міцніший ІГЕ, стилобатна частина – коротші палі з обпиранням на слабший ІГЕ. При розрахунку прийнятих варіантів ураховано результати випробування паль та дані геодезичних спостережень для верифікації використаних розрахункових методів. Результати розрахунку показали, що більш економічним та раціональним з точки зору роботи конструкцій виявився другий варіант. У середньому матеріалоємкість фундаментів та технологічних процесів зменшилася на 10%, а величина осадок і їх нерівномірність у 2,5 раза порівняно з першим варіантом фундаментів. Крім того, підтверджено можливість використання розробленої методики з визначення осадок будівлі з використанням даних випробувань паль. Розходження виміряних осадок будівлі та прогнозних розрахункових у середньому складало не більше 10%, що є цілком прийнятним для прогнозування осадок будівель на стадії проектування.

Ключові слова: буронабивна паля, розрахунок системи «основа – фундамент – надфундаментна частина будівлі», випробування статичним вдавлювальним навантаженням, стилобат.

Introduction. The high-rise buildings construction requires the stylobate part ensuring the comfortable stay of people and meeting their needs developed. As a rule, parking lots, engineering, social facilities and amenities etc. are arranged in stylobates. The situation is rather common when the architectural requirements to the internal space organization in the building stylobate and high-altitude parts cause the organizing impossibility a complete contraction joint for separating building altitudinal and stylobate parts. It is because the contraction joint arrangement requires paired columns installing, which leads building internal space deviation from the original version envisaged by an architect.

Therefore, a complicated task of the pile foundation designing for two building spaces high-altitude part including (with significant loads on the columns) and low-rise stylobate part (with light loads on the columns) arises before the designer. For this reason, to avoid significant internal forces due to nonuniform deformations in building structures occurrence it is necessary to construct a foundation where deformations non-uniformity between the stylobate and high-altitude parts do not limit value exceed.

Thus, high-rise buildings with a developed stylobate part foundations various structural solutions studying is relevant with regard to obtain the optimal economic and structural design.

Review of the latest research sources and publications. Different lengths piles using supported by various engineering-geological elements, that is, under the altitude part the longer piles supported by harder EGE are arranged and under the stylobate part the shorter piles supported by weaker EGE are arranged.

Such approaches implementation to the foundations design proved to be effective.

For example, in time of the underground parking arranging under the Goethe Square in Frankfurt/Main, piles of different lengths were used for the central column and the columns along the perimeter. The piles lengths under the central part were larger in twice as under the peripheral part and deformations non-uniformity was within the permissible limits [1].

Moreover, the same approach was used in tall buildings construction in Berlin, e.g. SONY-CENTER and Treptowers [2].

The authors justifying calculations carried out of such foundations considering computer modeling and design parameters monitoring during the construction process.

Definition of unsolved aspects of the problem. However, the settlements and their irregularities were forecasted without consideration the «load – settlement» dependence of the pile deformation during its testing by a static jacking load that enabled to approximate maximally the settlements value theoretical calculations to the received ones at the construction site.

The main difference between the static jacking loads tests carried out in Ukraine [3] and foreign countries [4 – 5] is in compliance with Ukrainian regulatory documents; according to them each load increment is held to the chosen level of settlements stabilization depending on the soil type at the base. Thus, the settlements values prognosis with action of one pile on another one considering (cluster effect) is more accurate when the test data carried out by the procedure used in Ukraine applying.

Problem statement. The versions of the building pile foundations structural solutions should be considered for not to exceed the recommended limit value of deformations non-uniformity in the building stylobate and high-altitude parts in order to avoid the occurrence of significant internal forces in their structural elements that enables to make economic decisions for the building structures.

Basic material and results. To solve the tasks set forth in the paper, by way of illustration, it is reasonable to take a multistory building (26 floors) with a stylobate part (4 floors) where the high-altitude and stylobate parts are not separated by a contraction joint. The building computer model is presented on Fig. 1.

As the building foundation, a pile foundation is considered. The bored piles were of an 820-mm diameter. Two types of pile foundation were adopted: 1) in the first type of a foundation the lengths of piles were the same (22.0 m) for the high-altitude and stylobate parts with their resting on the same engineering-geological element (EGE) (this type of foundations was implemented at the construction site); 2) in the second type the lengths of the piles were different (22.0 m and 34.50 m) and the shorter piles were arranged under the stylobate part and longer ones – under the multistory part. The piles were supported by the different EGEs. Such piles lengths were chosen by the EGEs with different deformation characteristics presence. At the same time these piles were tested. The «load – settlement» dependence for two piles is shown on Fig. 2. The experimental piles seating on the engineering-geological section is presented on Fig. 3.

Fig. 3 approves that Kiev Marl EGE-6 (which has general deformation module E=50 MPa) forms the base for the 22.0-m long piles, and the fine sand EGE-7 (E=69 MPa) is the base for piles of 34.5 m length.

The pile field plan (the first type) with the same piles lengths is shown at Fig. 4. The pile field consists of 449 piles and the piles concrete volume is 5235 m^3.

The pile field plan (the second type) with different lengths of piles is shown in Fig. 5. The pile field consists of 177 piles by 34.50 m length with the piles concrete volume 3236 m^3 and of 155 piles of 22.0 m length with the piles concrete volume 1807 m^3. Total piles concrete amount is 5043 m^3.

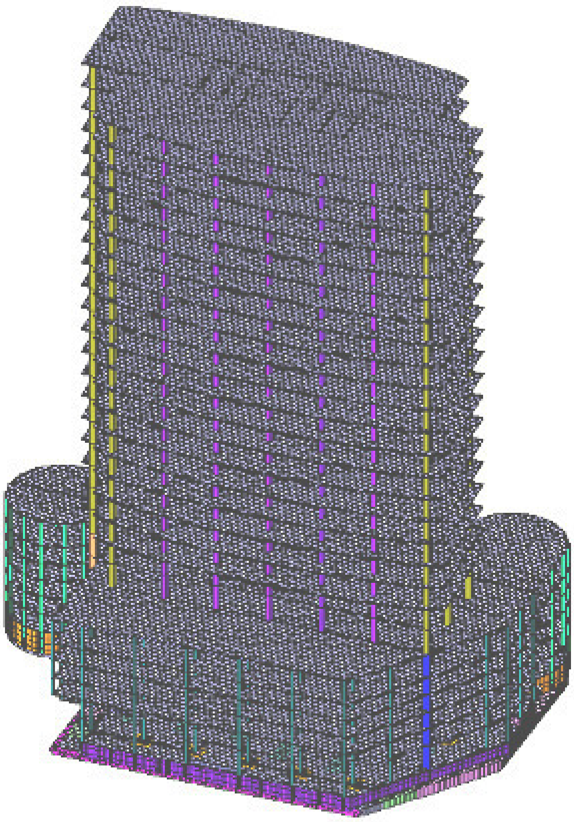

Figure 1 – Considered building computer model (piles are not shown)

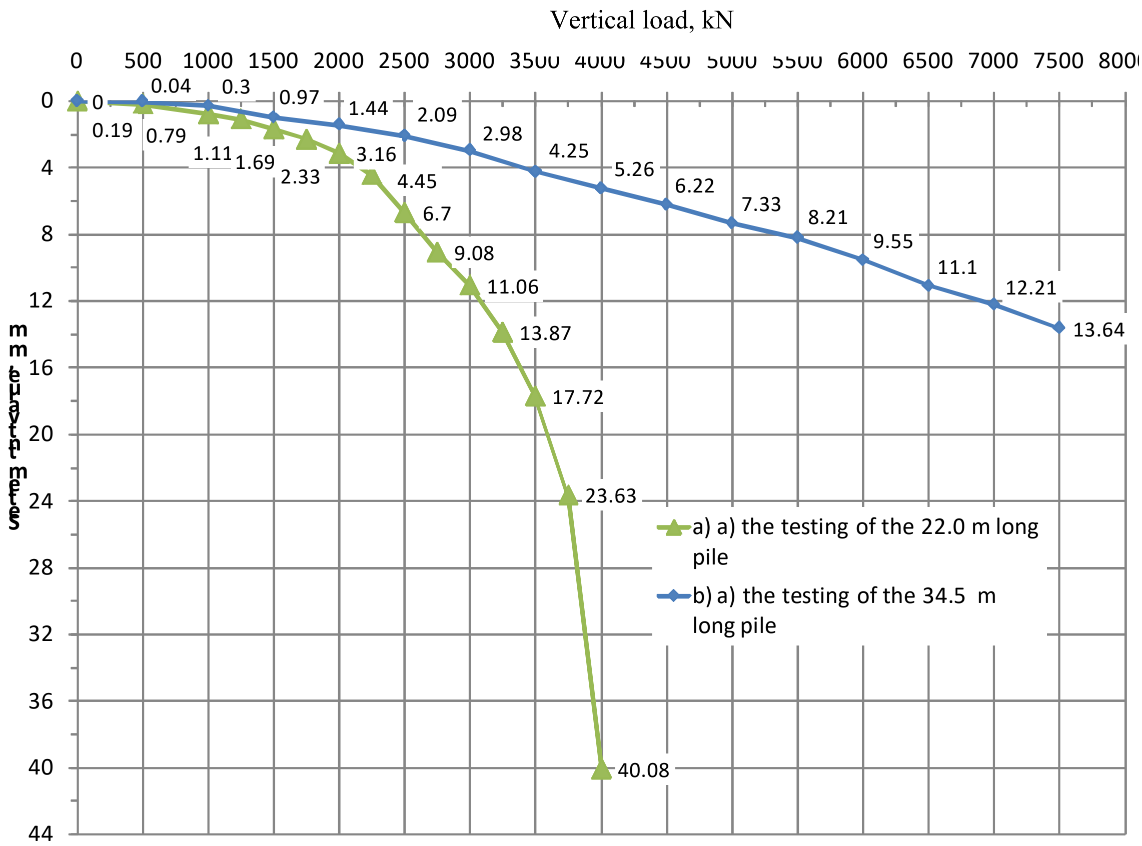

Figure 2 – Test of a pile with a diameter of 820 mm:
a) length of 22.0 m; b) length of 34.5 m

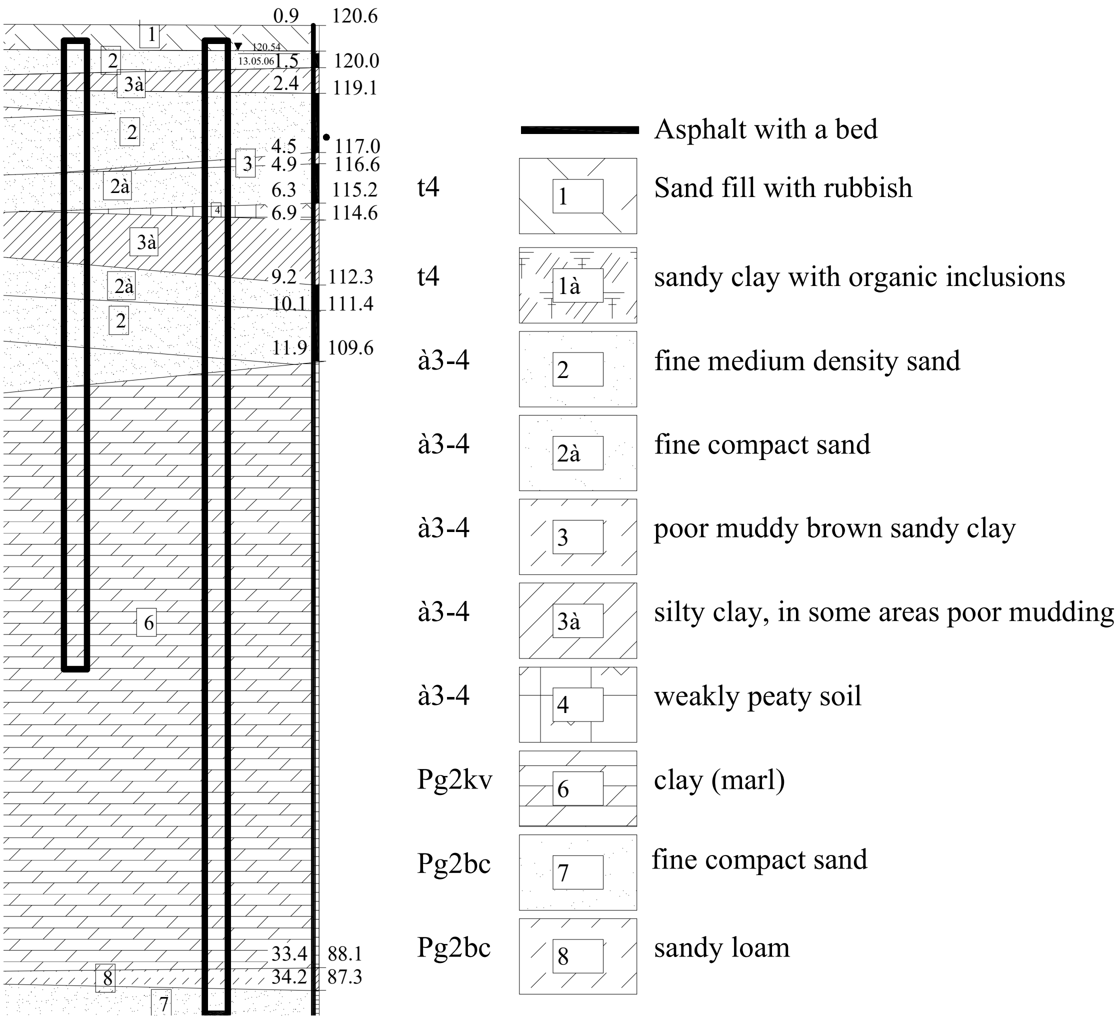

Figure 3 – Experimental pile spacing in the engineering-geological section

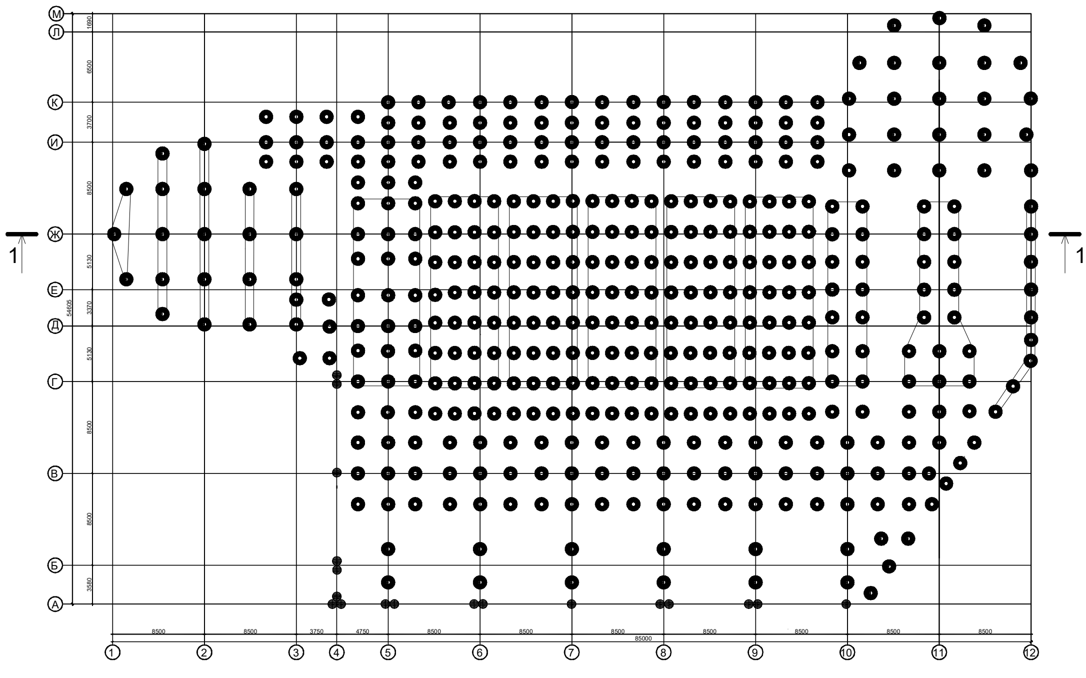

Figure 4 – Plan of the pile field with equal pile lengths – Type 1

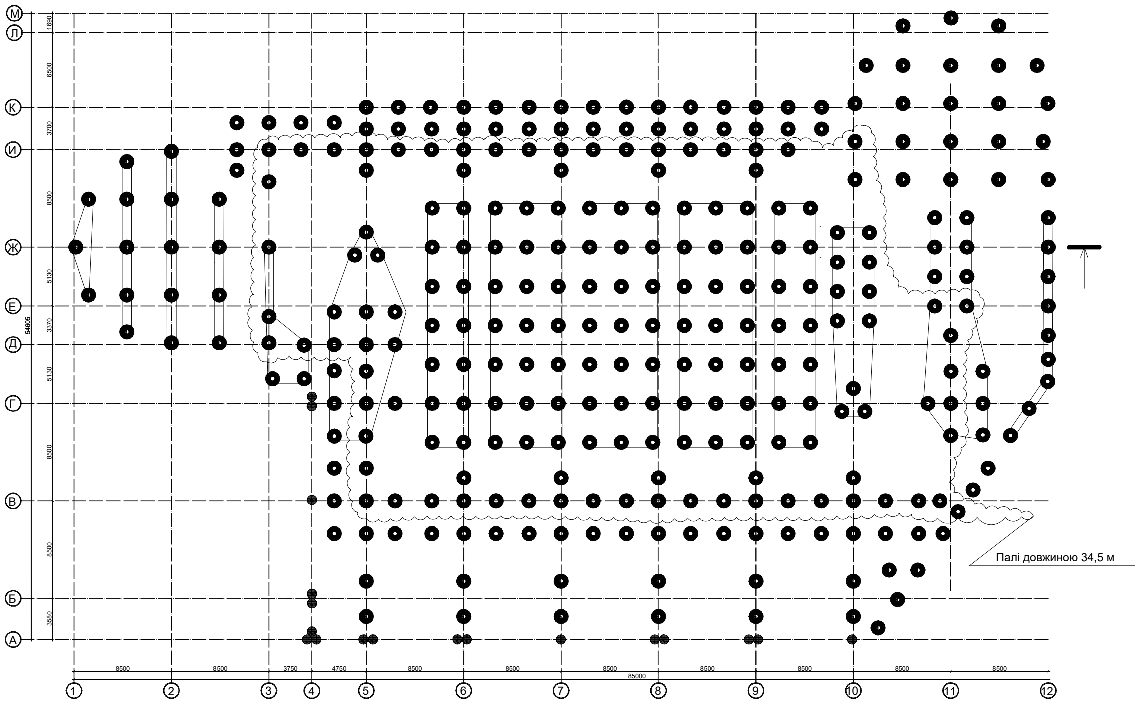

Figure 5 – Plan of the pile field with various pile lengths – Type 2

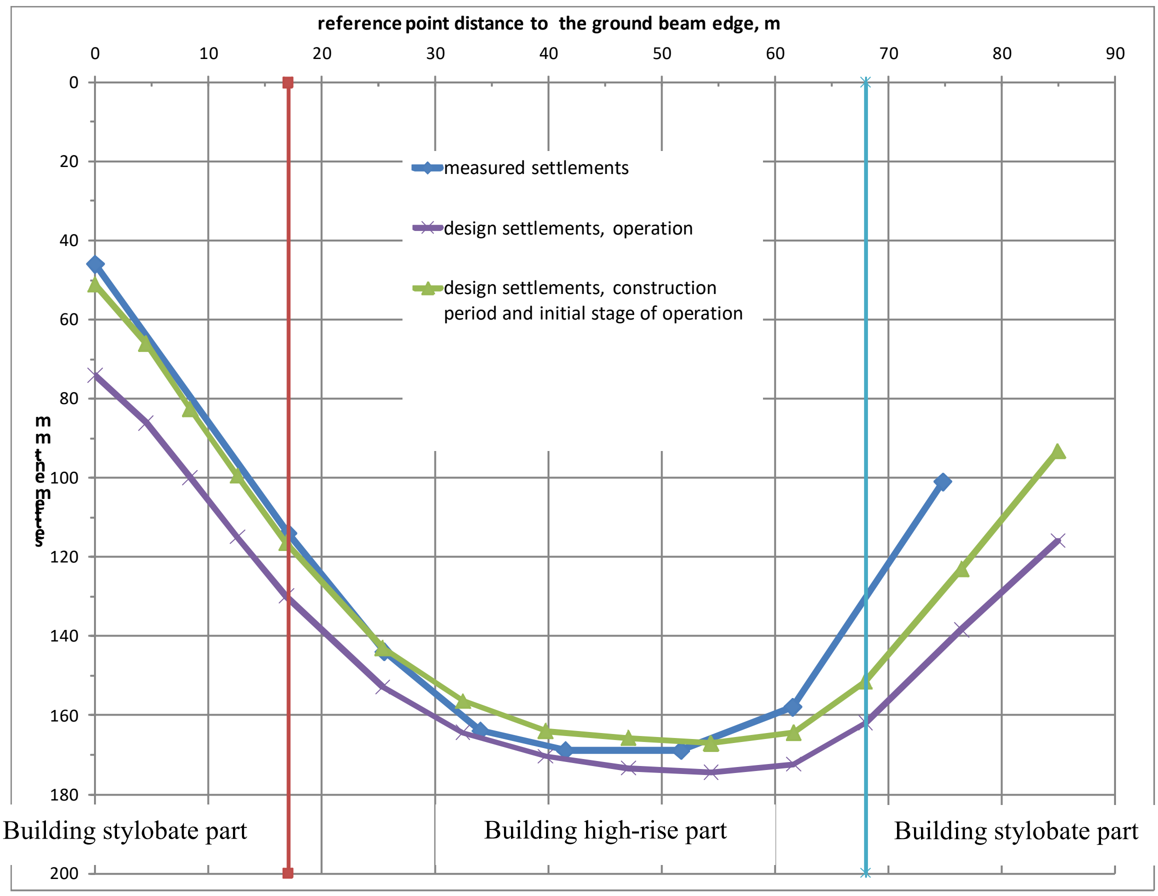

Figure 6 – Measured and calculated building settlement for foundation of type 1 implemented at the construction site

The pile foundations with piles of different lengths calculation using the methods presented in the regulatory document [6] is complicated by the fact that the «load – settlement» diagrams for the different lengths piles differ significantly (Fig. 2), and when presenting the surveys results of the total deformation modules values, as a rule, can be substantially underestimated. Therefore, for the calculation of the "base – foundation – above-foundation building part" system, the modified calculation procedure presented in works [7 and 8] is used. The calculation procedure details can be found in paper [6]. The procedure summary is as follows:

1) the carrying out of the «base – pile foundation – above-foundation building part» system first calculation (according to requirements [5]) considering the conditional foundation dimensions for each pile, which, according to the test data, are determined by the static jacking loading. The first calculation is performed with the same significant value of stiffness at the pile base where the extra forces from nonuniform deformations do not occur in the above-foundation structures. This calculation gives the loads on the piles $N_{II,i}$ and their settlements s_{ij}, with piles actions on each other being considered, which results in the bedding value C_{zi}^{K} for each pile, where index «K» means that the pile settlements are obtained with an allowance for the cluster effect. In addition, the result of the calculation is the correlation between the bedding values of each pile and other ones;

2) the building piles settlements determination without considering loads mutual influence received in the previous paragraph. As a result of this calculation, the bedding value C_{zi} is obtained for each pile;

3) the determination of the cluster effect value as the ratio $K=C_{zi}^{K}/C_{zi}$ for each foundation pile. In this case, for the deformations non-uniformity assessment it is possible to determine each pile settlement value by means of multiplying the settlement value received by the pile during load tests in accordance with paragraph 1 by the individual pile cluster effect value not considering the building stiffness (figures 7 and 8);

4) the cluster effect average value determination for all piles

$$K_m = \sum_{i=1}^{n} K_i \qquad (1)$$

where n is a number of piles, pieces;

5) the determination is based on the experimental pile "load - settlement" curve, the experimental pile settlement $s_{i,e}$ due to the loads received in accordance with para. 1 of this procedure;

6) the determination of the piles settlements average value $s_{m,e}$ obtained in accordance with para. 5 of the procedure,

7) the determination of the «base – pile foundation average value iteratively recalculated above-foundation building part» system settlement by means of the individual pile settlement average value $s_{m,e}$ multiplication according to para. 6 by the cluster effect value K_m obtained according to para. 4, that is

$$s_m^{k}=s_m \times K_m \qquad (2)$$

8) the iterative recalculation of the bedding values for the "base – pile foundation – above-foundation building part" system considering the average settlement value obtained according to para. 7 and the bedding values ratio obtained according to para. 1. As a result, the non-uniform settlements of the «base – pile foundation – above-foundation building part» system are obtained considering the stiffness of the above-foundation building part and the piles test with a static jacking load results.

An advantage of discussed procedure is that the cluster effect load and coefficient are known for each foundation pile, thus, it is possible to get the each pile settlement value that it receives without consideration the above-foundation structures stiffness, using the "load – settlement" dependence for the experimental pile. It enables to assess the deformations non-uniformity value.

The verification of the proposed procedure is performed on the first type foundation by comparing the measured and design settlements. At Fig. 6 the settlements values measured at the construction site (observation lasts over 10 years) and settlements design values calculated for two cases (the first case refers to the period of construction completion and the operation initial stage, the second case includes the operation period) are shown. The data are given for the section 1-1 (Fig. 4). Fig. 6 shows that on the average, the relative difference between measured and designed settlements values does not exceed 10% that indicates acceptable accuracy with regard to the prognosis of the settlement value using the proposed method. It should be noted that the better fit of the design settlement values was found in the calculations for the construction period and the operation initial period, rather than for the operation period. It is caused by the fact that the load between the piles of the stylobate and high-altitude parts was redistributed due to the cracks formation in the slab ground beam, but not because of the overloaded periphery piles settlement, provided that the ground beam operated without cracks.

Now the calculation results of two foundations types should be considered in more detail. At Fig. 7 the cluster effect values distributions in section 1-1 (figures 4 and 5) for foundations both types are shown. Fig. 7 shows that within the stylobate parts of two foundations types the cluster effect values differ not substantially and vary from 1.3 up to 8 with increase from the periphery to the center, which is quite logically explained by the piles interaction with decrease in the distances between them. At the same time, there is a difference in the building high-altitude part for two foundation types: the cluster effect is 10 ... 11.3 (mean value is 10.7) for the foundation of type 1 and 8 ... 9.9 (8.9) for the foundation of type 2. It also corresponds to the process physics, since the cluster effect decreases with the distance increase between piles.

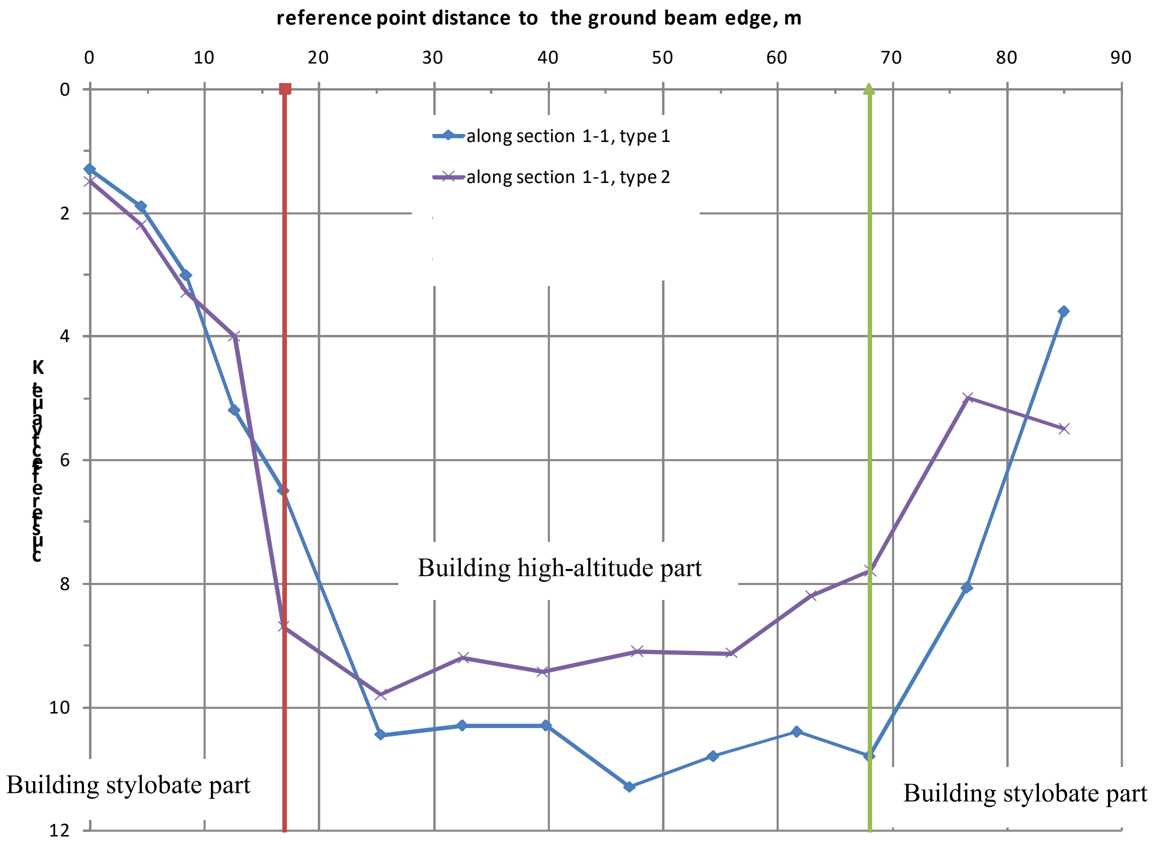

Figure 7 – Distribution of the cluster effect value along the larger side of the ground beam (in section 1-1, figures 4 and 5) for two types of foundations

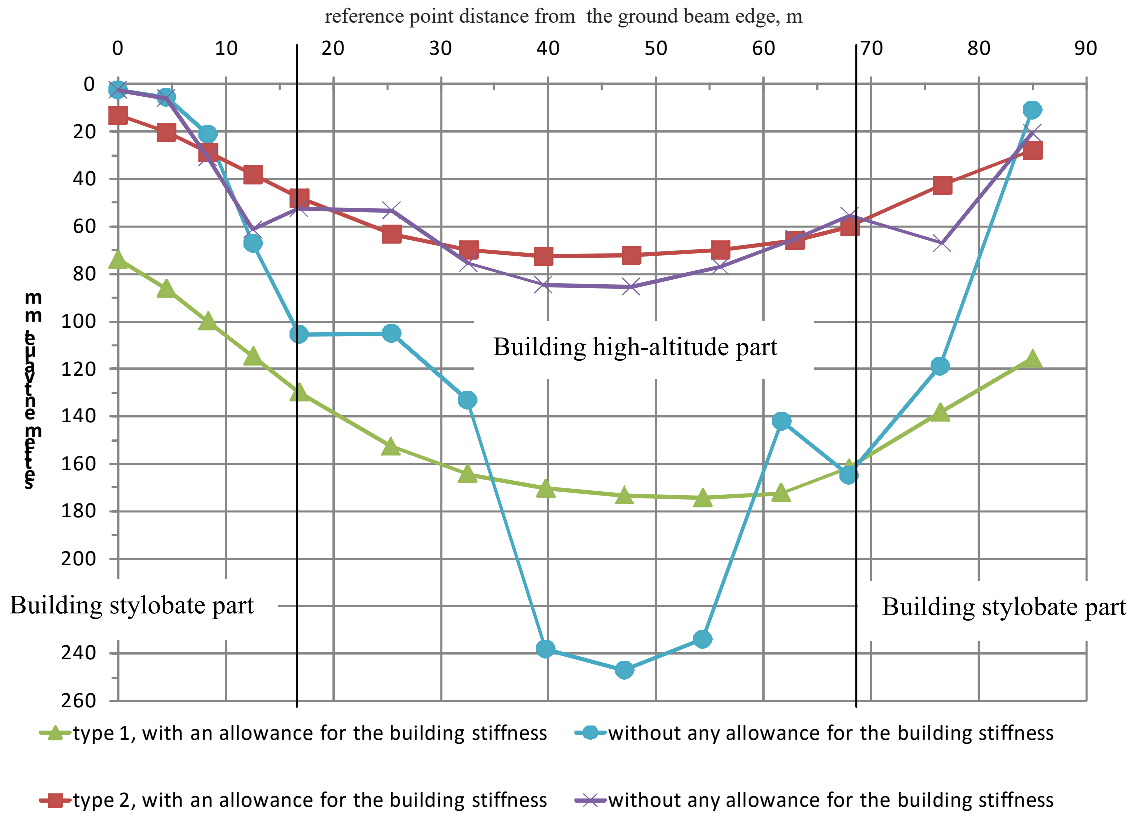

Figure 8 – Slab ground beam settlements for two types of foundations considering the above-foundation structures stiffness and without its consideration (in section 1-1, figures 4 and 5)

However, the data presented in Fig. 8 are more interesting. It is evident from Fig. 8 that the first type of foundation (all piles are the same) features the foundations significant irregularity between the stylobate and the high-altitude parts. Thus, according to the diagram without consideration the building stiffness, the stylobate part settlement varies within the range of 1.5 ... 100 mm, while the central part settlements are in the range of 140 ... 245 mm. This irregularity is caused by the fact that the loads on the central part piles were on average 3450 kN, but according to the test diagram (Fig. 2), in this range the pile works in a zone of nonlinear deformations. At the same time, within the stylobate part, where the pile works in the conditionally linear dependence of "load – settlement", the average load on the piles is 2500 kN (Fig. 2). With such a significant non-uniformity the significant force occur in the building part above the foundation. These forces redistribution can be carried out in two ways as follows:

1) if the building part reinforcement above the foundation is chosen considering the internal forces due to nonuniform deformations, the building redistributes the loads between piles without the cracks occurrence, which ensures its further normal operation. At the same time, more loaded piles are unloaded, but less loaded ones get more loading;

2) if the building part reinforcement above the foundation is selected without consideration the internal forces due to nonuniform deformations, then the building redistributes the loads between the piles with the cracks appearance (in fact, building is divided into separate blocks), and its further normal operation does not be ensured within the period of operation prescribed by the standards. The most dangerous in that case is that if the load on the piles (usually within the stair-lift block) exceeds pile based on the soil basis properties bearing capacity, then an emergency situation arises as the building subjects to the deformations of significant values.

A completely different picture is observed for the second foundations type (Fig. 8). Since the pile works in a conditionally linear phase throughout the entire load range (Fig. 3), the building does not undergo significant nonuniform deformations (Fig. 8), even considering the difference between the cluster effects in the stylobate and high-altitude parts (Fig. 7). So, it can be stated that the second type of foundations is more rational with regard to the structures above the foundation work and is more economical foundation. The comparison of two foundations types is presented in Table 1.

Table 1 – Comparison of two foundations types under the building with high-altitude and stylobate parts without a contraction joint

Parameter	Foundation of type 1	Foundation of type 2	Note
Average settlement of the high-altitude part, mm	150,0	70,0	
Average settlement of the stylobate part, mm	110,0	50,0	
Maximum non-uniformity of deformations	0,006	0,002	For the second type of a foundation the nonuniformity does not exceed the recommended value of 0.002
Values of bending moments in slab ground beam, kN x m	-4530…16600 ()	-2760…11000	The reduced range of force variation. For the second type of a foundation the enforcement necessity is 1.5 times less than for the first type of a foundation
Quantity of piles with a length of 22.0 m, pieces with a length of 34.5 m, pieces	449	155 177	
Piles concrete volume	5235	5043	For the second type of a foundation the pile concrete saving is 192 m^3
Total length of a pile borehole, r.m.	9878	9516	For the second type of a foundation the pile saving of a pile borehole drilling is 362 r.m.

Conclusions

The results of executed research enable to make the following conclusions:

1) the piles testing results use by the static jacking loading in accordance with the proposed procedure for the pile foundation settlements determination have showed a high convergence of the measured settlements values with the design ones. On average, the design settlements exceeded the measured ones by 10%, which proves a sufficient accuracy of calculations;

2) for high-rise buildings with a developed stylobate part, when the absence of a contraction joint between the stylobate and high-altitude parts is necessary, the use of foundation where under the high-altitude part the longer piles resting on the harder EGE and under the stylobate part the shorter piles being supported by the weaker EGE are arranged, is more rational with regard to the design and the structures performance. On average, there was the material consumption decrease for foundations and technological processes by 10%, and settlements values and their irregularity by 2.5 times compared with the first version of the foundations.

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