Skyscrapers of «Moskva-City» Business Center - Tests of Bored Piles

Gratte-ciel du centre d'affaires « Moskva-City » – Essais de pieux forés

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ABSTRACT: The Moscow International Business Center (MIBC) "Moskva-CITY" is a complex of 19 sky-scraper buildings. The buildings are supported by 20-30 m long 1.2-1.5 m dia piles, spaced at 3-5 m. Behavior of a pile within such a group differs from that of a standalone single pile. Therefore, analysis of such a footing requires prior determination of pile side and tip resistance. The paper describes a known test technique, based on application of a jacking system, and specially developed for «Moskva-CITY» system, with the test load applied downward with the help of a measuring system and jacks that act separately on the pile tip and on its side surface. The obtained test data was used for the project design analysis to verify the applied analytical model and the respective soil parameters.

RÉSUMÉ : Le Centre d'Affaires International de Moscou "Moskva-CITY est un complexe de 19 gratte-ciels. Les bâtiments sont fondés sur des pieux de 20 à 30m de long, de 1,2 à 1,5 m de diamètre, espacés de 3 à 5 m. Le comportement d'un pieu dans un groupe est différent du comportement du pieu seul. L'analyse de telles fondations demande d'abord la détermination du frottement latéral et de la résistance de pointe. La communication décrit un essai technique, basé sur l'application d'un système de vérins, élaboré spécialement pour le projet «Moskva-CITY», avec la charge appliquée vers le bas grâce à un système de mesure et des vérins qui agissent séparément sur la pointe du pieu et sur sa surface latérale. Les résultats obtenus ont été utilisés pour l'analyse de la conception du projet, afin de vérifier la modèle analytique et les paramètres du sol adoptés.

1 INTRODUCTION

MBIC is located on the Krasnopresnenskaya embankment and consists of a group of unique high-rise buildings (Figure 1) in one architectural complex. The terrain, divided into 20 sites, will include a central transport hub yet to be erected (with 2 conventional subway lines and a mini-subway line), a complex of intricate underground structures, transport intersections, etc.

Figure 1. MIBC photo (August 2012).

The downtown location of MIBC gives easy access to the complex. The 15 sky-scrapers are designed up to 150 to 400 m high with different numbers of stories. Most of them feature a frame-shaft design i.e., the staircase-elevator core is fixed together with ventilation shafts and other service premises, to which the building framework columns are fixed by floor discs.

CITY Geology of the terrain is characterized by Carbon deposits (C3, Figure 2). The soils top down from the surface are represented by an upper fill (1), underlain by limestone alluvium (2), alternating limestone, marl and hard clay layers (3-8). Such soil conditions dictated application of raft footings, pile footings and piled raft footings (Petrukhin et al, 2008). The pile footings under the high-rise buildings, bearing more than 0,4MPa mean pressure, consist of 1,0-1,5 m dia bored piles, spaced at 3 – 5 m. The piles are long so that they penetrate through softer clays, marls and fissured limestone to rest on medium-hard and hard Suvorovsky bed (Figure. 2, geotechnical element 7) and Podolsky-Myachikovsky bed (Figure 2, geotechnical element 8), having Rc=20 – 40MPa.The footing under the tower on the site is an exception in that the supporting piles rest on Ratmirovsky medium strength limestone (geotechnical element 5).

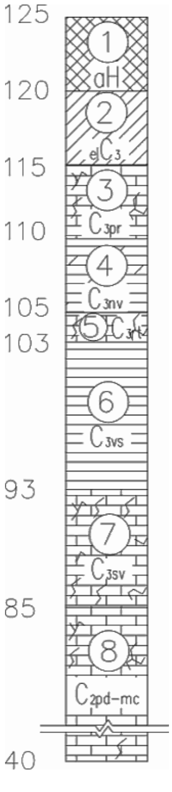


Figure 2. Geotechnical section

Pile footing analysis showed that the piles are loaded non-uniformly both in plan and along their length. The peripheral piles bear times 1,5-2,5 greater loads then the internal ones (Petrukhin et al, 2008; Kharichkin A. et al, 2009), and this was taken into account in the project design, therefore, some corner piles (site 4) have larger diameter (1,5 m) than that of internal ones (1,2 m). Distribution of forces along the pile length is different for different piles and is essentially different for a single pile. Therefore, such footing design requires 3D numeric analysis. In order to perform such analysis it is necessary to determine pile side and tip resistances on the basis of pile test data.

The paper presents data of pile tests, conducted by different methods, this data was compared and the application in design practice was analyzed.

2 RESULTS OF PILE TESTS

As has already been discussed above, it was necessary to erect cast piles of high bearing capacity (2000-3000 ton) within the bounds of the Moskva-CITY area. These pile tests, conducted by standard technique (load applied from the top), encountered technical difficulties and costs, as it was necessary to install anchor piles, to assemble a load transferring frame and a system of jacks. Worldwide such pile tests, Moskva-CITY skyscrapers inclusive, are done as per the Osterberg method, using-submersible jacks. The jacks were installed in the pile body, the tested pile (its upper part) serving as their stop.

Within the Moskva-CITY area in order to determine side and tip resistances in particular soil layers there were installed gauges in the piles to measure relative deformations of the pile shaft and forces in reinforcement. Stresses were determined, using the elastic modulus values of concrete

Figure 3 shows the 1,2 m diam. 22,6 m long test pile TP1 longitudinal section on site 11 with jacks locations shown (elevation 84,93) and gauges at three elevations (1…3) bottom-up: 84,43 m (1.5 m below jacks); 89,0 and 92,0 m (4 and 7 m above jacks).

The test showed that for maximum load 20,1MN, the jack upper plate displacement was 1,7 mm, that of the lower one 2,3 mm, the forces at level 1 were 12,5 MN (elevation 84,43 m); at level 2 – 3,4 MN (elevation 89,0 m) and at level 3 – 0,8 MN (elevation 92,0 m).

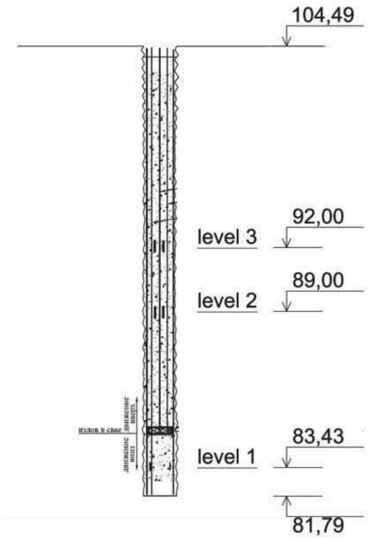


Figure 3. Cross section schematic of TP1 test pile (site 11)

Evidently, internal forces in the pile decrease fast to less than 5% at 7 m distance from the jacks (Figure 4). This shows high values of strength and deformation parameters of the soil.

The obtained distribution of forces in the pile body yielded the pile design side resistance F_i:

$$F_i = (N_0 - N_i)/A_i, \qquad (1),$$

with F_i as pile design side resistance over area A_i between two levels of sensors i and jacks 0;

N_0 and N_i as forces in jacks and in piles at the level of sensor i respectively.

The analysis, based on equation 1, yielded design side resistance for 1…3 to be F1= 1,34МПа; F2= 1,1МПа; F3=0,73МПа. The difference of the analytical values is due to difference of design resistances mobilization rates at different levels, depending on pile versus soil displacements, as well as to certain peculiarities of the surrounding soil properties.

Similarly equation 1 gave measured values of side resistance over other segments, that were obtained on other sites. The values were within 12-20 MN (Table 1), mainly 18 – 20MN. The causes of this scatter are similar to those mentioned above for test pile TP1.

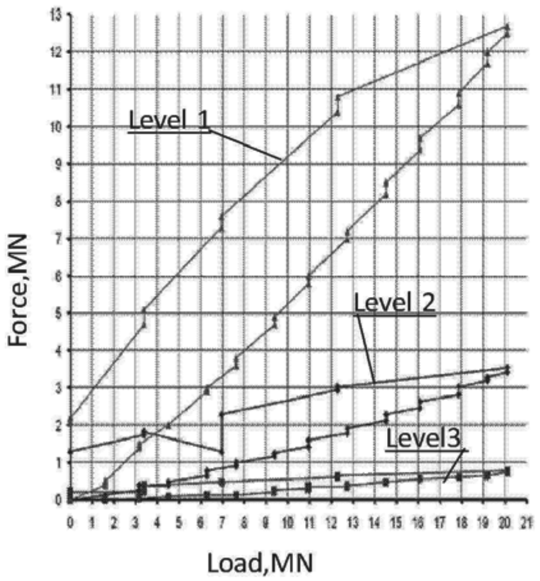


Figure 4. The distribution of forces in the body of the pile.

Force

At sites 12 and 13 there were staged special tests to establish pile side resistances. A 10,5 m long 1,2 m diam. pile fragment was tested at site 12 with the help of jacks, installed at 4 m distance from the pile fragment top (elevation 81,6 m).For maximum 33,30 MN load the fragment settlement was 3,2 mm. The calculated pile side resistance was F = 2,55 MN/m^2.

Similar tests of two 1.5 m diam. pile fragments 6 m long (item 2,3, Figure 5a) and3 m long (item 2,3, Figure 5b) were done at site 13 (Zaretsky Yu.K., Karabajev M.I. 2006; Duzceer R. et al, 2009).

The fragments were cast at 14,6 m and 23,3 m depths from the ground surface (Figure 4). The boreholes above the fragments were filled with rubble. The test side resistances of the pile fragments were F = 2,00 – 2,20 MN/m2. Therein, the 3 m long fragment 2 (Table 1, pile 13c, Figure 5b) displaced 17 mm (i.e. ultimate side resistance was mobilized) F = 2,20 MN/м2.The 6 m long fragment 2 (Table 1, pile 13a, Fig.5a) – 2,00 MN/m2. Other results are given in Table 1.

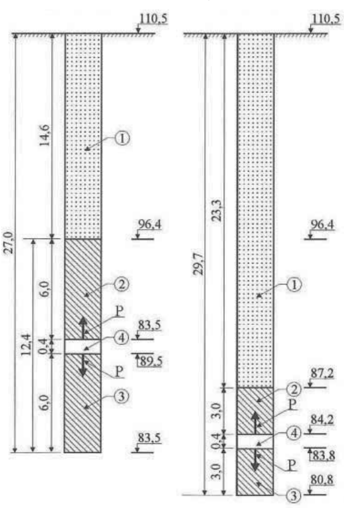

a) b)

Figure 5. Pile cross section and test set-up on site 13

Pile test data yielded high ultimate side resistance F = 2,20 – 2,55 MN/m2.

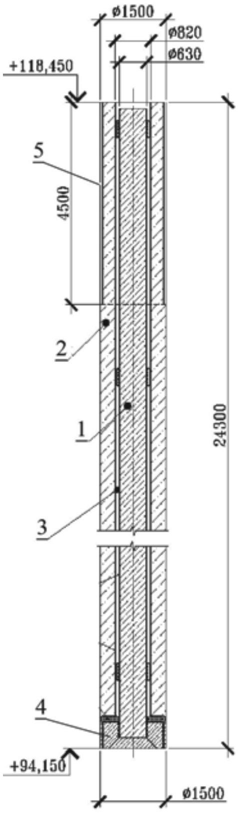
To prove that the above design solutions are valid and safe there was developed a special set-up on site 16 (Figure 6) and a procedure for cast piles static tests by 36 MN vertical static load.

Table 1. Result of pile test.

Site (Pile)	Pile parameters				Max load, MN	Max displacement head/tip, mm	Side resistance determination method	Pile side resistance MN/m^2
	Ø, m	L, m	Head level, m	Jack level, m				
3(1)	1,2	28	113	86,1	20	3,1/1,5	D	1,20
3(2)	1,2	28	113	86,1	20	1,8/2,5	D	1,20
4(1)	1,2	28,6	110,4	87,4	26,5	4,1/1,7	D	-
4(2)	1,2	28,0	110,4	84,4	24,5	3,4/1,4	D	-
11(1)	1,2	22,6	104,5	85	20,00	1,8/2,1	D	1,30
11(2)	1,2	22,6	104,5	85	16,50	1,0/1,5	D	1,80
12	1,5	10,5	85,1	81,6	33,30	3,2/7,5	D,F(4)	2,55 (1,55)*
13A	1,2	27	109	89	33,3	6,1/3	F(6)	2,00
13Б	1,2	29,7	109	83,7	25,13	17/6	F(3)	2,20
14 (1)	1,5	19,2	103,2	88,4	33,33	8/65	D	2,00
14 (2)	1,5	19,2	103,2	92,6	33,33	16/4	D	1,90
15 (1)	1,5	20,4	103,8	93,4	1350	4/150	D	200
15 (2)	1,5	19,4	103,8	86,4	3333	10/10	D	200
16(1)	1,5	24,3	118,5	114	3000	8,3**	F(19)	33
16(2)	1,5	24,3	118,5	114	3200	7,2**	F(19)	36

*2,55(1,55) – values with no brackets were determined from tensometer data analysis , in brackets from fragment test data;** top-down fragments tests ; D, F – side resistance was determined as per equation 1 and from pile fragment test data ; F(4) – fragment length m.

In order to separate side and tip resistances the pile consisted of two parts: inside part 1 (630 mm external diam.) and outer part 2 (1500 and 820 mm ring diam.). The hollow space between the pile segments (3) was filled with elastic material to let the parts to freely slide against each other. The interior part (1) was connected with a stiff plate (4). In order to isolate the pile exterior top (2) from the soil mass an external casing tube was installed on the top (5). The loaded system included two steel box cross beams (Figure 7), connected with service piles, used as anchors.



The tests were started by load application to the interior part of the pile (1) and through it to the plate (4) (pile tip test).

Then the set-up was adjusted to step wise load application to the exterior part of the pile (2), and pile side resistance was determined.

The initial plate test and elastic spacers between pile parts prevent data distortion in the pile exterior side test.

The test results (Figure 8,9) show that the central part of the plate displacement largely exceeds that of the pile-shell.

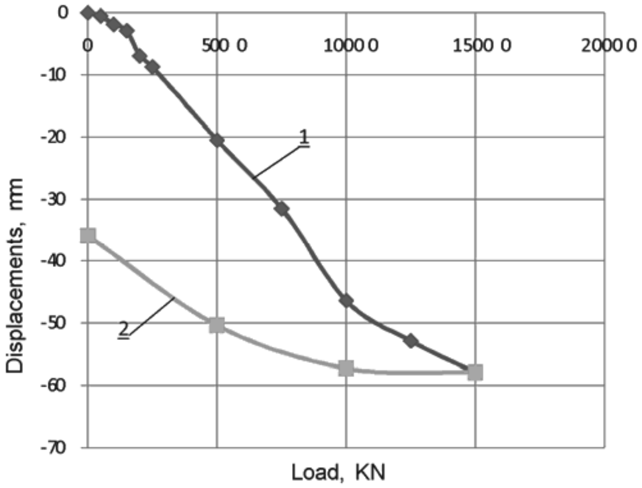
Figure 6. Loading set-up

The pile tip resistance for equal displacements was one order of magnitude less than that of the side resistance and several orders of magnitudes less than the analytical value. This fact shows presence of mud on the borehole bottom, which could not be removed during drilling operations.

Soil resistance below pile tip at other sites demonstrated its strong dependence on the quality of the bottom face and on the quality of special operations (soil grouting), e.g. on site 4 grouting was done to 5 m below the pile tip.

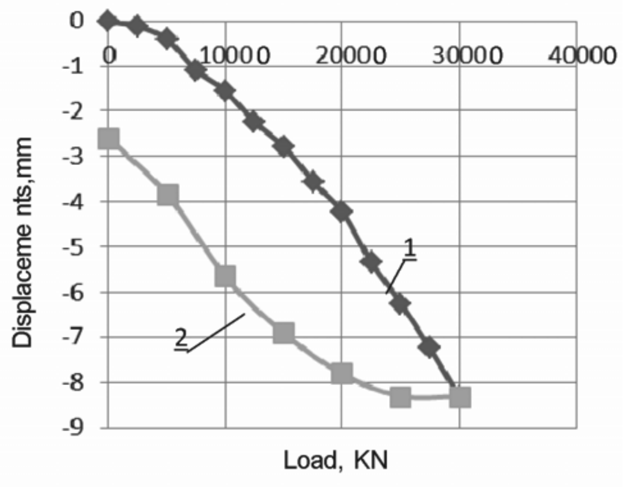
This shows the necessity for extra operations to clean and to compact the bottom, e.g. by grouting the soil under pile tip, by compacting the bottom, e.g. by ramming broken stone or stiff concrete into the bottom, etc. (Petrukhin et al, 2011).

Figure 7. Loading set-up



1 – loading, 2 - unloading

Figure. 8. Pile tip test diagram



1 – loading, 2 - unloading

Figure. 9. Pile 5 side test diagram

3 PRACTICAL APPLICATION OF PILE TEST RESULTS

As was mentioned above, analysis of pile footings of MIBC Moskva-CITY sky-scrapes mainly consists in determination of pile side and tip resistances (maximum values and their dependence on displacements). Analysis of such piles can be done numerically with the help of 3D software.

The analytical soil model, developed for such analysis, shall be verified by solutions of test problems. The test problems in this case are single pile tests. In the process of test solutions design parameters are specified (side resistance as well as soil strength and deformation parameters).

Figure 10 gives analytical and test data of pile tests, obtained by submersible jacks at site 11.The numerical simulation was done with the help of PLAXIS 2D 8.2 software. The analytical model was the ideal elasto-plastic model with Mohr-Coulomb strength criterion.

The following assumptions and prerequisites were adopted for the analysis:

- the input values of physico-mechanical parameters of geotechnical elements were adopted as for the 2nd limit state analysis;
- static loads alone were adopted for the analysis. Shock, dynamic, vibration and other technological loads and actions due to construction operations were not taken into consideration;
- pile material was considered elastic.

In order to harmonize the results of tests and analyses there were used improved parameters of surrounding soil. 3 interlinked parameters: E, φ and c were selected. There were done several analyses, in which soil parameters were chosen as approximation of experimental data by analytical data, which were upper and lower jacks plates displacements and variation of forces and deformations in the pile at different levels along the pile length.

Final results are presented on Figure 10. Their comparison with experimental data showed their sufficient proximity: the scatter does not exceed 10%. The analyses showed that with practically identical soil strength parameters the soil stiffness modulus values, obtained from the analyses is times greater than the one, obtained from geotechnical investigations, that was further accounted for in soil analysis.

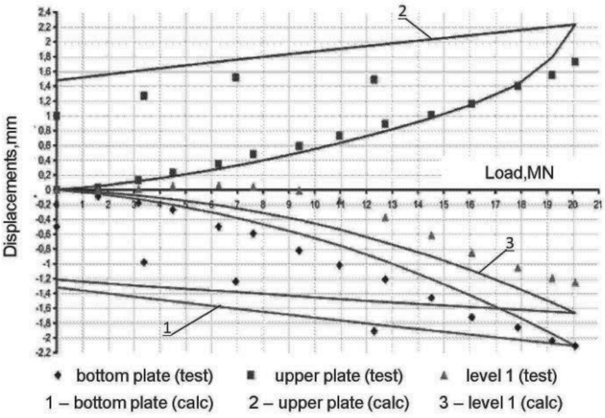


Figure 10. Data from pile tests by Osterberg method, compared with numerical simulation data.

4 CONCLUSIONS AND RECOMMENDATIONS

Pile side and tip resistance rather than a single pile bearing capacity are important for designing MIBC «Moskva-CITY» footings.

Side and tip resistance can be determined by tests of pile fragments, separate side and tip tests by means of a specially developed method, described in the paper, or by means of pile tests with gauges, installed in the pile body, to measure distribution of forces along pile length.

It is recommended to verify pile footing interaction with soil and to verify the analytical model, using single piles test data.

It is recommended to verify the values of design mechanical soil properties, obtained from geotechnical survey, by back analysis, using single pile tests.

It is admissible to adopt cast pile side surface resistance equal to 1,8MPa (180t/m2) for Suvorovsky and Podolsk-Myachikovsky medium-strength and strong limestones.

In order to activate cast pile tips it is necessary to apply special measures to clean and to compact borehole bottom face, e.g. to grout pile tip – soil interface, to compact the bottom face by filling rubble or by stiff concrete ramming, etc.

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