An optimal pile foundation construction for skyscrapers

Une construction optimale pour les gratte-ciel

Stanislav Shulyatev
PhD, NIIOSP named after N.M. Gersevanov, Russia, shulyatevs@yandex.ru

ABSTRACT: The article considers the issues of using the maximum of pile length by achieving pile limited equilibrium to satisfy all the deformation criteria for the skyscrapers. In case the pile limited equilibrium is achieved while constructing, additional loads will transfer to the surrounding piles. The process can be stopped until the necessary number of piles get the limited equilibrium. To determine the real pile behavior in the condition of the limited equilibrium 45 static pile tests under the maximum load 120 000 kN applied when constructing skyscrapers in Russia were summarized. Tests analysis makes it possible to estimate the value of the limited and residual skin friction for different soil conditions. The results of FEM analysis show the soil and foundation behavior when a part of piles reaches the ultimate equilibrium. As the result of the researches the approach to the optimal pile foundation design is made. The sphere of its implementation and practical significance are also considered.

1 INTRODUCTION

In accordance with the classical theory the ultimate bearing capacity of a pile is divided by point and side resistance (Terzaghi and Peck 1948). The side resistance or skin fraction is usually calculated by using Mohr- Coulomb strength theory. As to the point or base resistance it is calculated by using the limit equilibrium theory. Consequently, if to make calculations for a single pile 2m with 20 m length in stiff clays theoretical bearing capacity has to be 72180 kN with the same distribution between point 37340 kN and side 34840 kN resistance. However, according to pile tests results, the real base resistance doesn't exceed 6 MN and the side resistance isn't reached when applying 60 MN (the test was made by using O-cell method).

2 PILE TESTS ANALYSYS

To make it clear why it can take place 45 single pile test data were analyzed which were made in various soil conditions around Russia with different length and pile diameter with tests loads up to 120 MN. The tests were conducted by using both a traditional up-down method and the Osterbergs method mostly made by Fugro Loadtest. The part of a single pile test results is described in Shulyatiev et all 2013. In the figure 1 the results of a pile test are shown where on y-axis settlement (S,m) is reduced relatively to a pile diameter (Ø,m). From the fig. 1 it follows that in most cases the pile bearing capacity wasn't commonly reached (less than 50% according Russian codes SP 22.13330.2011 and less than 5% according to Eurocode 7). Apart from that, for more than 50% of tests the relative pile settlement (S/Ø) didn't exceed 0,02. For the rest piles with S/Ø>0.02 75% of tests revealed sharp settlements increase with flattening of load- settlement graph afterwards. These changes took place when the bottom part of piles were tested and they are possible only if there is a sludge layer under the pile toe.

In order to make sure of that, NIIOSP named after N.M. Gersevanov conducted the field work to measure the thickness of the sludge layer under the toes of over 200 piles. The results showed that that the regular cleaning method using a flat knife leaves a layer of sludge which varies from 5 to 20 cm.

The analysis tests data showed that in more than 60% of tests the theoretical skin friction calculated via Mohr-Coulomb theory of strength is twice as low as measured ones (Fig 2). Besides it should be noted that the reduction of the side resistance doesn't depend on settlements (Fig 2). Thus, theoretical or numerical calculations significantly underestimate the skin friction. As to a base resistance it is mostly overestimated due to a sludge layer. For the time being the most reliable method to define the bearing capacity of a pile is the direct pile test. The pile toe cleaning has to be made by using non standard ways to increase the base resistance. For this purpose beating the pile toe with amiesite can be used.

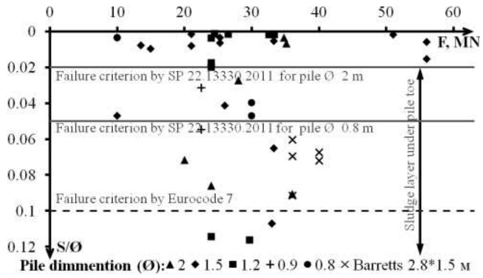

Figure 1. Static load tests for different piles length and diameter results. The relative value of settlement (S) is calculated depending on the pile diameter (Ø)

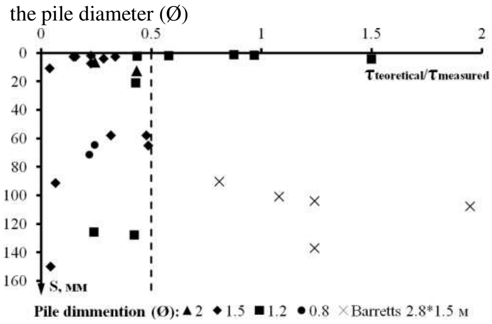

Figure 2. The ratio between theoretical and measured ultimate skin friction and pile settlements (S, mm)

3 FINAL ELEMENT ANALYSYS

Pile foundations are usually used if the soil immediately below its base does not have adequate bearing capacity or in cases when total or differential settlements of raft foundation exceed the required values. In the world practice the pile bearing capacity is usually determined via Mohr–Coulomb or other strength theories with its further pile load test confirmation. Analysis of skin friction to update the soil characteristics and design data after a pile test are usually ignored. Reserves of skin friction are usually compensated at the expense of peculiarities of piles performance in groups (Terzaghi and Peck 1948, Poulos 1968). The skin friction of inner piles is efficient for 1/3 of its lengths only while outer piles work along the full length. It leads to overloading the outer piles from 2 to 4 times. The pile toe can be involved in the working process only after deformations which is seldom possible in reality. Compression contact layer between soil and mat is also necessary to activate a raft. The measurements of pressure showed that pile raft get not more than 10-15% of the building total weight. All above results in significant reduce of economical and technical foundation characteristics.

With the purpose of developing more optimal foundation designs with maximum pile length work the series of numerical researches have been made. The main tasks of the researches were including pile toe and its maximum lengths in working process, decreasing the differential settlements and bending moments of foundation.

The analysis results obtained by using the uniformly distributed load on plane strain foundation with average stiffness showed that to achieve even force distribution in piles (fig.3) the pile length from the corner one should be calculated by using this approximate equation:

$$l_{(n+1)} = \frac{2 \cdot l_n}{3} + l_1 \quad (1)$$

Basing on equation (1) it is possible to choose a pile foundation rigidity by changing a pile length according to load distribution on foundation. It can be used to provide levelling of differential settlements and bending moments in foundation, stresses in superstructure.

According to the field investigations made with ultimate equilibrium piles the residual skin friction in hard clays can be up to 50% from the regular one and 70% for the limestones. Taking into account that the measured skin friction can be 20 times higher than the theoretical one the residual skin friction can achieve significant values and in compliance with monitoring data can be 157 kN/m^2 in clays and 1422 kN/m^2 in limestone. Nevertheless, the pile foundations are designed not to allow any pile reach the ultimate equilibrium. The potential of the residual friction has been ignored so far.

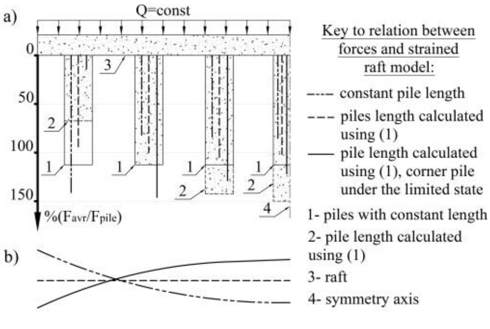

Figure 3. a) a principle numerical model with relation between forces on the top of a pile (F_{pile}) relatively to average force (F_{avr}), b) a strained raft model

The stiffness of buildings especially skyscrapers is constantly changed in the construction process from flexible (after raft arrangement) to rigid conditions with parabolic and saddle-shaped contact pressure distribution. According to the numerical researches when a pile is overloaded and reaches the limited equilibrium the additional loads are transferred to the neighboring piles (fig.3). In case a corner pile reaches the limited equilibrium the skin friction of the next pile will work for the 80% of its length. Thus, it is possible to control the foundation stiffness in the construction process. The result of modelling shows (fig.3) that it can also lead to redistribution of loading between a piles and a raft equally. If needs arise piles which reached ultimate equilibrium can be involved in working process at a definite period of time by compressing the sludge layer with the required thickness and including a pile toe in work. The combination of two approaches using a pile with different length and allowance of some or all piles operating after limited equilibrium is achieved it is possible to change the differential settlements and tilt to the opposite ones with reducing stresses in raft and structure (fig.3b).

4 CONCLUSION

It is very common to use very deep pile foundations when designing skyscrapers to avoid the excessive differential settlements and for soil bearing capacity guarantee. As a pile load test analysis show a theoretical skin friction can be 20 times lower than a real one. The base resistance as a result of a sludge layer, which can be 20 cm thick is usually overestimated. Numerical investigations show a possibility of matching piles stiffness to superstructure loads with some pile foundation disable parts at the required stage of constructing by arrangement piles with different length and bringing some piles to the limited equilibrium. To make it a pile test is needed with a mandatory requirement to bring a pile to the ultimate state with determination of the residual skin friction. According to a pile test analysis it is necessary to update the soil strength theory parameters as well as a pile design to detect the foundation stiffness to settle problems with differential settlements, tilt of the construction and bending moments. Considering absence of a pile theory after reaching the ultimate equilibrium the following development of a pile work theory is also needed to research the post equilibrium skin friction resistance. It can be done only via great mass analysis of real pile tests in different soil conditions measuring the changings of skin friction during the test before and after the ultimate equilibrium. For this reason it is necessary to develop the world wide platform where the pile test results from all over the world will be accumulated. Creation of such platforms with consolidation of scientists from all around the world to work at the fundamental problems of soil mechanics and foundation engineering has to be one of the main trends of the International Society of Soil Mechanics and Foundation Engineering.

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