FOUNDATION OF HIGH-RISE BUILDINGS BY MINIMAL THRESHOLD SETTLEMENT MICROPILES

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ABSTRACT

In the context of a high-rise building job site, deep foundations had to be designed with a minimal threshold settlement, in order to protect the superstructure from differential settlement issues. Therefore, a composite foundation system was successfully designed and built, mixing a group of micropiles and a laminated elastomeric bearing pad. This article aims to detail the innovative technical solution, to expose the method used to estimate the micropiles settlement, as well as to propose a comparison between the theoretical settlements and the settlements measured during load tests.

Keywords: foundation, micropile, settlement, high-rise building, bearing pad

INTRODUCTION

The ALTO project, started in 2016 in La Défense business center by BOUYGUES, includes the construction of a 150-meter-high tower and its external structure, known as the North exostructure, connected to each other.

It turned out to be essential to limit the differential settlement between the tower, very heavily loaded and based on a diaphragm wall, and its lightly loaded exostructure based on three concrete blocks.

In order to achieve this, the three blocks have been based on an original set made up of a group of micropiles and an elastomeric bearing pad, allowing to ensure a minimum settlement of the exostructure and consequently respect the criterion of differential settlement with the tower.

This article aims to detail the chosen innovative technical solution, to expose the method for estimating the settlement of micropiles, as well as to propose a comparison between the theoretical settlements and the settlements measured during the load tests.

PROJECT CONTEXT

Geology and location

The project is based in La Défense, the business district of Paris, near the Seine river. The geological context and the location of the three blocks of the North Exostructure in relation to the tower are as follows:

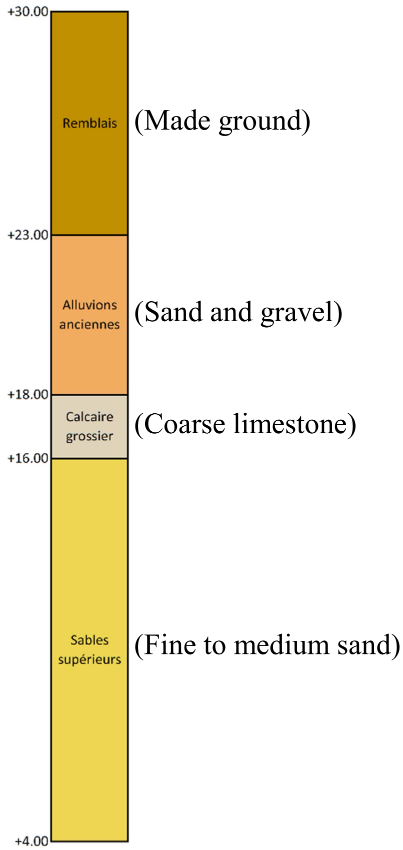

Fig. 1 - Stratigraphy

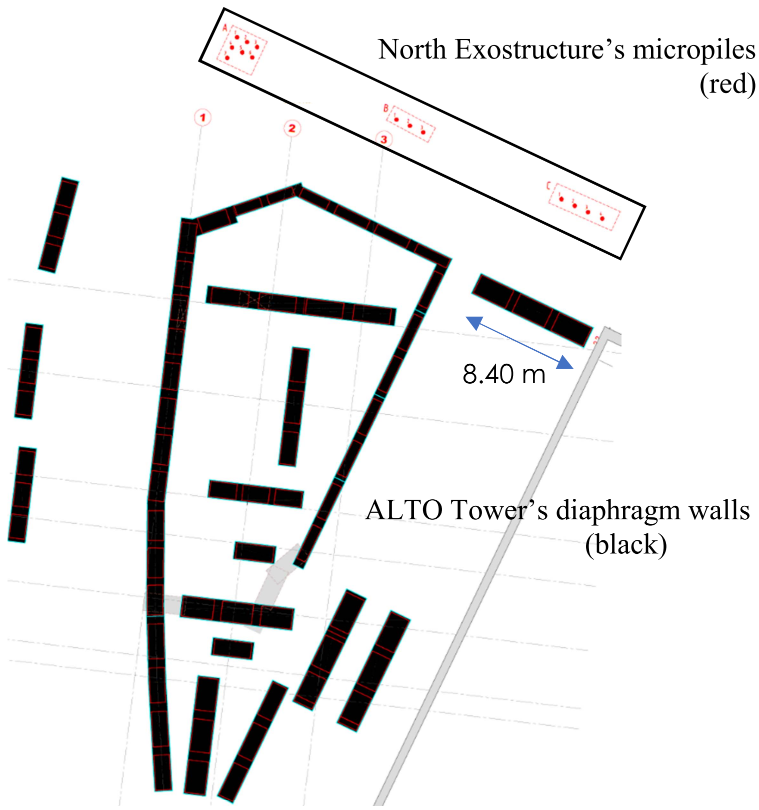

Fig. 2 – Foundations lay-out

Initial solution

The client solution consisted in ensuring the minimum settlement of the Tower's external structures by basing them on micropiles with a multi-metric free length (in the range of 3 to 5 m depending on the blocks) to make them settle. The issues inherent to this solution were as follows :

- The minimum settlement to be obtained, between 12 and 16 mm depending on the blocks, represented a very high value compared to the diameter of the deep foundations envisaged (200 mm);
- The high values of sought settlement led to choose small section tubes with a very high elastic limit (at least V110, f_y = 760 MPa or even 960 MPa) which, in addition to the disadvantage of being more fragile, are generally not in stock and suffer from very long delivery time ;
- It was not possible to increase the free length without reducing the bond length of the micropiles. In fact, given the presence of diaphragm wall nearby, the micropiles should not protrude from their base in order to avoid any load transfer;
- The creation of a "real" free length always proves to be a difficult task on micropiles, including when implementing an HDPE coating or an epoxy pitch, given the fact that there is always residual friction (which can reach 20 to 30 kPa). Furthermore, resort to over-drilling in order to ensure the

free length would have generated buckling constraints that were hardly compatible with the intensity of the vertical loads applied;

- Deep foundations settlement is generally estimated using the semi-empirical formulations proposed by Frank & Zhao (1982), established for piles with a diameter of approximately 0.80 to 1.20 m. In addition, even by readjusting the Menard modulus E_M and the lateral friction q_s from the load tests carried out on the micropiles of the adjacent project (Parking ALTO), it nevertheless remains difficult to precisely guarantee the settlement of a micropile grout bonded to the soil.

After considering the above obstacles, an instrumented compression load test on micropiles was planned. As this test is in no way a guarantee of success, it seemed essential, in a context of risk management, to foresee the case where the tests would not be satisfactory in order to show that the generated settlement would not reach the minimum threshold and would therefore not be sufficient.

Adopted technical solution

Considering the analysis presented above, it was decided to dissociate the guarantee of settlement – mainly provided by an elastomeric bearing pad – from the vertical load withstand ensured by micropiles.
Hence the composite foundation used, consisting of two reinforced concrete blocks enclosing a single pad, the whole being based on a group of micropiles as shown schematically in the following figure:

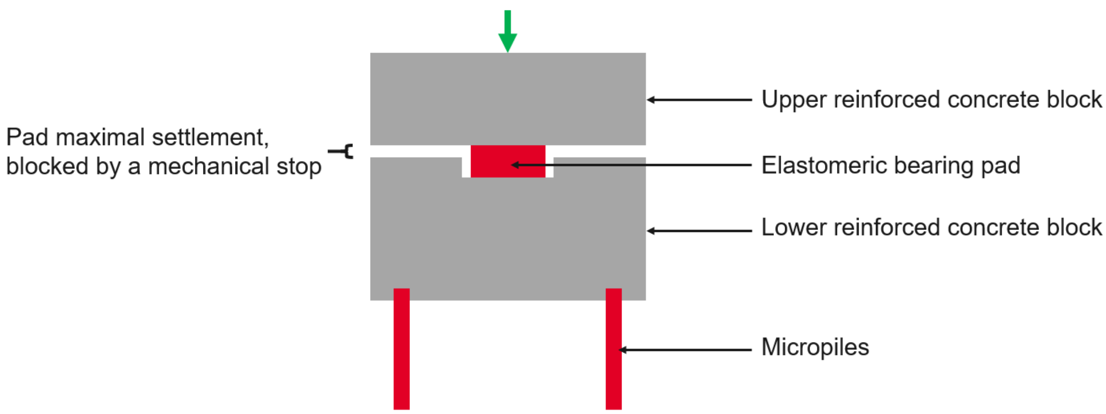

Fig. 3 – Composite foundation principle

In this way:

- the uncertainty about the overall settlement is greatly reduced since the actual settlement of the elastomeric bearing can easily be checked on a hydraulic press test, before its delivery to the working site;
- the installation of a mechanical stop between the two reinforced concrete blocks makes impossible for the pad to settle more than the desired value;
- it is possible to make micropiles with common elastic limit (type N80, f_y = 560 MPa) and dimensions (drill diameter of 200 mm), bonded over their entire length, with a post grouting single stage method.

In this variant design, the settlement of each block is therefore the sum of the proper settlement of the micropiles and the elastomeric bearing pad, according to the following schematic operating principle :

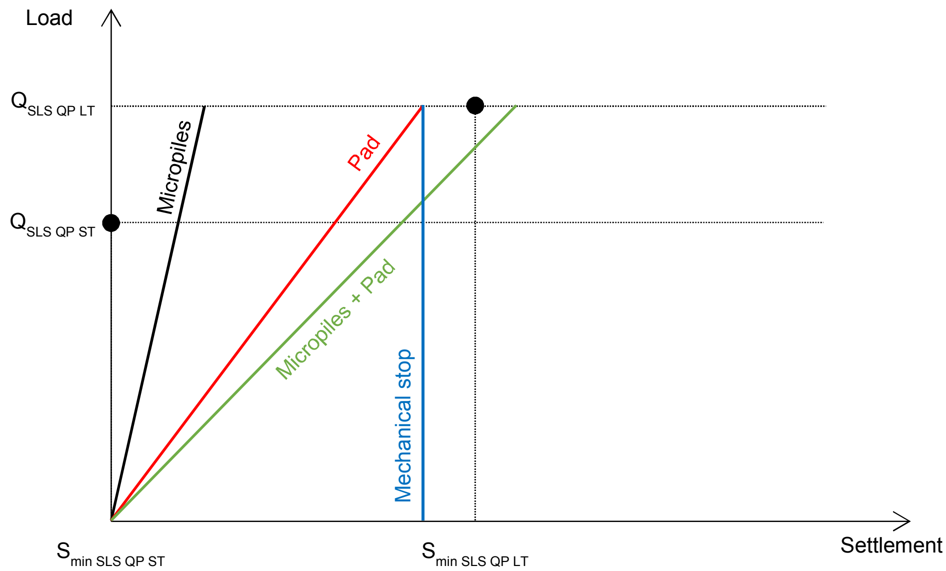

Fig. 4 - Composite foundation operating principle

It therefore remains only to ensure that the total obtained settlement is equal or greater than the targeted minimum settlement.

TARGETED MINIMUM SETTLEMENT AND SETTLEMENT ESTIMATION METHOD

Targeted minimum settlement

The targeted minimum settlements of the three blocks of the North Exostructure were defined from a 3D finite element model, considering the common criterion of maximum differential settlement of L/500 between the Tower and its external structures.
The only limit state justifying the control of settlements turned out to be the Quasi Permanent Serviceability Limit State in the long term, corresponding to the loads 30 years after the delivery of the Tower structure.
The targeted minimum settlements and the associated loads for each block are summarized below :

Block	s_{min} (mm)	$N_{SLS\ QP\ LT}$ (MN)
A	12	15,62
B	13	2,94
C	16	6,82

Table 1 – Targeted settlements for each block and associated vertical loads

Given the presence of external bending moments carried by the two horizontal axes, the barycenter of the foundations of each block was located so as to coincide with the point of application of the vertical force taking into account the eccentricity. In this way, all micropiles are subjected to the same vertical load under the limit state considered for the study of settlement.

Settlement estimation method

The micropiles settlement calculations were made via the Frank & Zhao (1982)'s method, based on two datasets allowing to carry out calculations in a high and low range as presented below:

- The high range of settlements is obtained using a first dataset, consisting of pressiometric modulus adopted by the geotechnician and lateral friction values q_s from the abacus of the NF P 94-262 standard.
- The low range of settlements is obtained using a second dataset, consisting of pressiometric modulus and lateral friction values q_s recalibrated from the load tests previously carried out under identical soil conditions in close proximity (ALTO Parking project).

In addition, all settlement calculations are carried out i) neglecting the tip resistance of micropiles, ii) neglecting the corrosion of metal tubes, iii) considering the current section of metal tubes.

	High range	Low range
Made ground	E_M = 5 MPa q_s = 90 kPa	E_M = 10 MPa q_s = 200 kPa
Sand and gravel	E_M = 40 MPa q_s = 270 kPa	E_M = 40 MPa q_s = 640 kPa
Coarse limestone	E_M = 30 MPa q_s = 250 kPa	E_M = 40 MPa q_s = 860 kPa
Fine to medium sand	E_M = 90 MPa q_s = 350 kPa	E_M = 90 MPa q_s = 585 kPa

Table 2. Soil data for calculating micropile settlement

The range calculations made it possible to overcome the uncertainties on the input data but not on the used method, so it was decided to take into account a flat-rate safety margin of 2 mm on the micropiles settlement, to be compensated by an elastomeric bearing pad settlement increased by the same quantity.

The results of these calculations for the own micropiles settlement under QP SLS by the Frank and Zhao's method are summarized below :

Block	$S_{theoretical}$ (mm) High range	$S_{theoretical}$ (mm) Low range	Margin (mm)	Targeted own micropile minimum settlement (mm) = Low range - margin
A	10	8	2	6
B	9	6	2	4
C	9	6	2	4

Table 3. Estimation of micropiles settlement

It should be noted that this project being a specific case, the unit used for the micropiles settlement calculations is the millimeter, and not the centimeter as in the general case in geotechnics.

Elastomeric bearing pad settlement estimation

The design and supply of the elastomeric bearing pads were carried out by FREYSSINET, as were the compression load tests at the factory, on the basis of the following vertical forces and targeted minimum settlements:

Block	Vertical force (kN)	Targeted minimum settlement (mm)	Calculated settlement (mm)
A	15620	7	8,4
B	2940	8	8,4
C	6820	11	11,1

Table 4. Elastomeric bearing pad settlement estimation

COMPARISON OF THEORETICAL AND MEASURED SETTLEMENTS

Compression control load tests on micropiles

The compression control load tests on micropiles were carried out at 1.0 * SLS QP LT to ensure the representativeness of the tests compared to the future actual loads. In figures 5 and 6 below, the evolution of the theoretical and measured settlements is compared to the applied load, for the two micropiles tested (one on block A and one on block C):

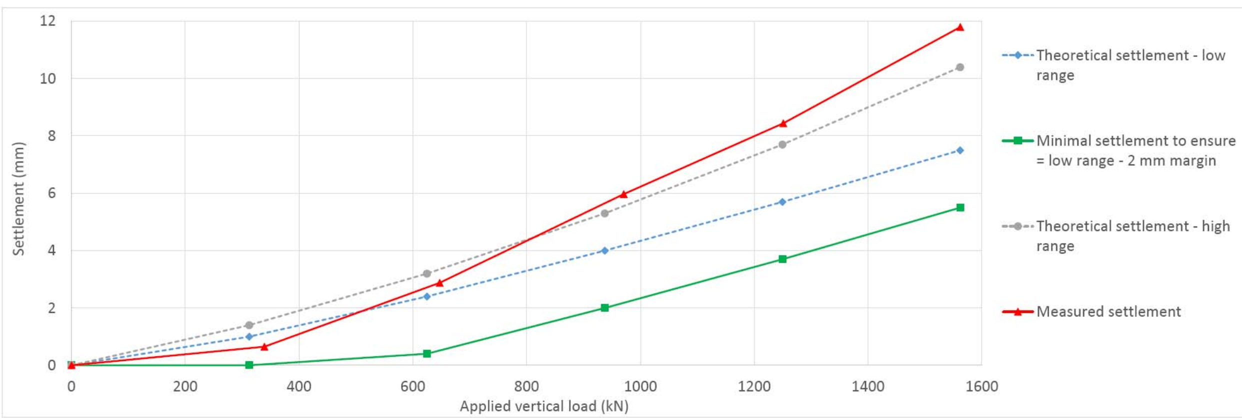

Fig. 5 – Micropile own measured settlement evolution – Block A

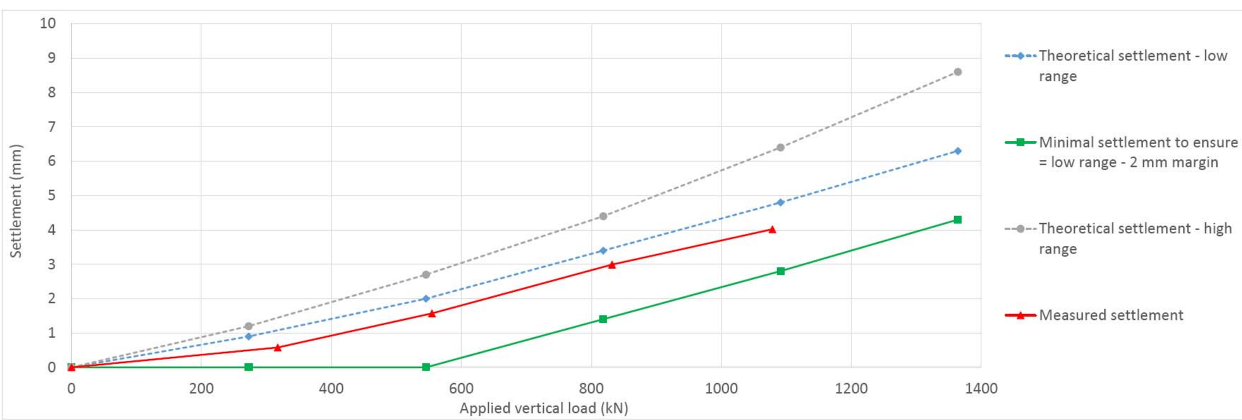

Fig. 6 – Micropile own measured settlement evolution – Block C

In both cases, the measured micropile settlement is greater than the targeted minimum settlement, making our solution functional.
It is also noted that the micropiles behavior was generally well approximated by the range analysis via the Frank & Zhao (1982)'s method, although the measured settlements were alternately above the high range (block A) and below the low range (block C), since the differences of settlement with the theoretical values were about a millimeter only, an unusual unit in the field of deep foundations.
These micropiles settlement measurements have therefore once again demonstrated the robustness of Frank and Zhao's method, which, here combined with soil characteristics from previous tests, has proved itself on the project without using numerical models (type finite element modelling).

Compression load tests on elastomeric bearing pad

Each elastomeric bearing pad underwent a compression load test before delivery to the working site. The obtained results are as follows :

Block	Targeted settlement (mm)	Measured settlement (mm)
A	7	7
B	8	6,5
C	11	13

Table 5. Results of compression load tests on pads

On both blocks A and C, the measured settlement is equal or greater than the targeted settlement.
On block B, although the measured settlement is 1.5 mm below the targeted value, it was decided in close collaboration with BOUYGUES and the project manager, that this slight lack of pad settlement did not justify its redesign.

Fig. 7 – Block C pad during compression load test

CONCLUSION

The singularity of this project was mainly in the obligation to increase the settlement of the deep foundations and not to limit it as it is usually done.

This particular request required a specific response from the SOLETANCHE BACHY Design Office, leading to rethink the client design to propose this innovative composite foundation solution, combining two techniques still used separately until now: micropiles and elastomeric bearing pads.

The implemented solution made it possible to solve the issues of differential settlements of a High-Rise Building with a high foundation load and a lighter loaded foundation of an external structure, while greatly reducing the associated risks.

Fig. 8 – Elastomeric bearing pad on top of lower concrete block (Block B)

REFERENCES

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