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RAPID LOAD TESTING OF FOUNDATION PILES IN BARCELONA

Introduction

For a project in the old port of Barcelona large diameter (1.5 m) cast in-situ piles with design service loads 6 - 8 MN were constructed. The piles installed 28-35 m in a soil profile that mostly consisted of (silty) sand. On 2 of the first constructed piles full-scale bi-directional load tests were planned to check pile capacity. With this type of load test, an embedded jack assembly is embedded in the pile shaft, pushing the upper part (shaft) up and the lower part (toe) down, with parts using each other for reaction. An essential limitation of the method is that the maximum test load is limited to the ultimate capacity of either shaft or toe, so ultimate capacity of the other will remain unknown. Unfortunately, this is what happened with the bi-directional tests performed on the project: the pile toe failed before required capacity was reached, while the behavior of the shaft suggested that only a portion of its capacity was mobilized when the test had to be terminated. However, this could not be concluded from the available test results, so additional load tests were needed to be able to accept the pile design. These tests had to be performed on already constructed piles (50 pcs), which ruled out bi-directional testing. A different test method was needed, with the understanding that execution of the tests should take as little time as possible, in order to minimize the delay of the – already suspended – project.

Figure 1 – Rapid Load Testing on site.

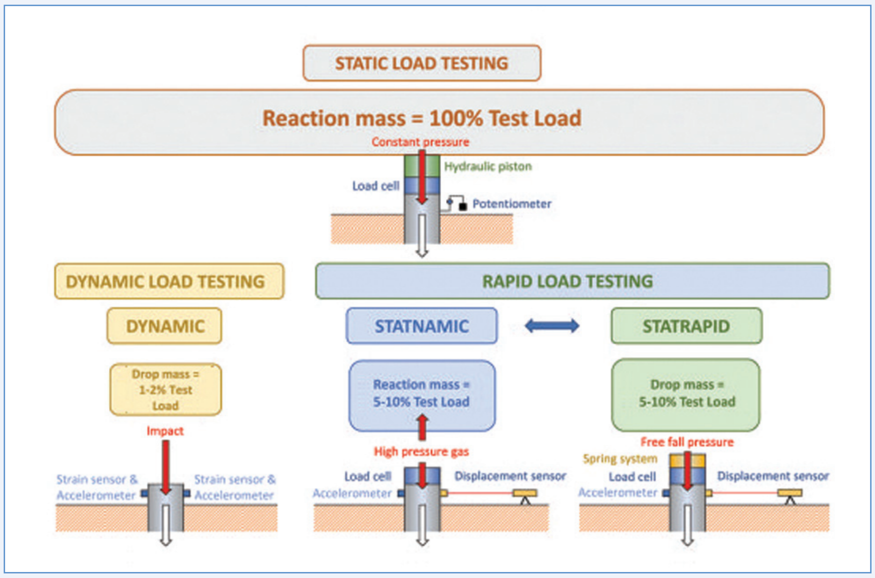

Figure 2 – Specifics of dynamic and rapid load testing.

Possible Pile Load Test Methods

Traditional static load tests (SLT) are considered the most reliable. However, performing takes a lot of transport and time, both for the construction of the reaction system and for the test itself. This results in high costs and a long execution time, especially in case of high test loads and multiple test piles, like in this case. This made SLT not viable.

An alternative method is a dynamic load test (DLT), which offers high test productivity and eliminates the need for a reaction system. To perform a DLT, a single blow is applied to the pile head with an impact ram with a mass of 1%-2% of the required mobilized static capacity. The impact (5-15 msec) generates stress waves that are monitored by accelerometers and strain gauges mounted near the top of the pile. To estimate the mobilized static resistance, the recorded data is analyzed using signal matching techniques based on simulation of the stress wave propagation through the pile. However, the advantages of cost savings and short test duration are offset by a reduction in the accuracy of the test results as well as the relatively wide spread in results related to the user dependency of signal matching, especially for concrete piles. In addition, DLT involves peak loads on the pile that are much higher than the mobilized static capacity. So much higher, that DLT can damage a concrete pile. Simulations made for this project revealed that the required DLT was likely to damage the piles.

SUMMARY

After the planned bi-directional load tests for a construction project in the port of Barcelona showed inconclusive results, execution of a large number of additional pile load tests was required, at short notice and with heavy test loads. This was possible by performing Rapid Load Tests (RLT), using a StatRapid device. In total 25 tests up to 12 MN were executed within 9 working days, putting the project back on track.

To avoid these drawbacks of DLT, it was decided to use another alternative method: Rapid Load Testing (RLT) using a StatRapid device. The devices generates a load with increased duration (100-200 msec) by free fall of a drop mass of 5% to 10% of the required test load on a specially developed spring cushioning placed on the pile head. To prevent any rebound, a catching mechanism is activated after the drop mass impacts the pile head. For each load cycle, the applied force, displacement and acceleration at pile head level are directly measured. By varying the drop mass and drop height multiple, increasing load cycles can be applied. Apart from extending the load duration, the spring system also greatly reduces the stresses in the pile head. Therefore, it is a particularly convenient test method for concrete piles.

Unloading Point Method (UPM)

Due to the increased load duration during RLT the pile can be assumed to behave as a rigid body, where velocity and acceleration are the same along the entire length of the pile. To ensure this is the case, international standards specify a minimum load duration T_{load} > 10 L/c where L is the pile length and c is the stress wave velocity through the pile.

On that basis Middendorp developed the Unloading Point Method (UPM), which is the commonly used method to analyze data obtained from a Rapid Load Test. The UPM is straightforward and, more importantly, is independent of the person performing the analysis. Rapid Load Testing and UPM are implemented in various international standards, among which ASTM D7383 in USA and Eurocode EN-ISO-22470-10:2016, which was applicable to the project in Barcelona.

The UPM centers around the point where the velocity of the pile equals zero (v_{upm} = 0). At this point (t_{upm}), that can be easily identified in the monitoring results (see picture), the displacement of the pile is maximal and the pile can be assumed to behave quasi-statically.

The total pile resistance during a load test can be split into three components: static, dynamic and inertial. See [Eq. 1]:

$$F_{soil} = F_{static} + F_{dynamic} + F_{inertia} = (k \cdot u) + (C \cdot v) + (m \cdot a)$$

With k the static soil stiffness, C the soil damping, m the pile mass and with u, v and a respectively displacement velocity and acceleration of the pile.

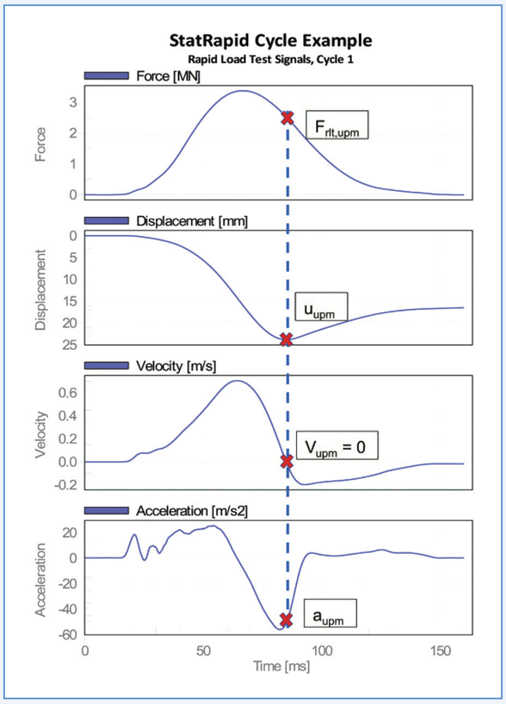

Figure 3 – Measurements needed to determine static resistance using the Unloading Point Method (UPM).

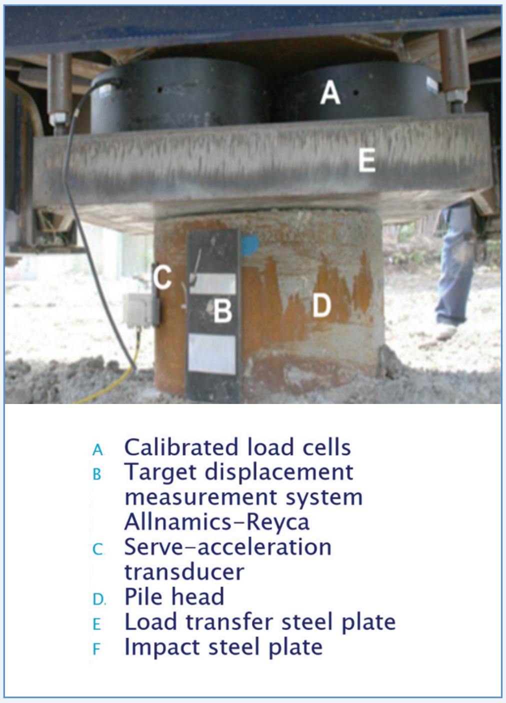

Figure 4 – Direct monitoring of force, displacement & acceleration.

The fact that v = 0 at t_{upm} implies that $F_{dynamic}$ = 0 at t_{upm} in [Eq. 1]. Furthermore, given the equilibrium of forces, the measured force from the Rapid Load Test (F_{RLT}) can be expressed as shown in [Eq. 2].

$$F_{RLT} = F_{soil} = F_{static} + 0 + F_{inertia} = (k \cdot u) + 0 + (m \cdot a)$$

Rearranging [Eq. 2], the mobilized static resistance (Fstatic) can be computed using [Eq. 3].

$$F_{static} = F_{RLT} - F_{inertia} = F_{RLT} - (m \cdot a)$$

In this equation, the pile mass (m) is known and all other factors at tupm are measured directly; using load cells (F_{RLT}), accelerometers (a) and optical sensor (displacement). With all factors at t_{UPM} known, the mobilized static resistance F_{static} can be determined.

Despite the quasi-static behavior, RLT is still a quick test, that does not capture time-dependent phenomena like creep or pore pressure dissipation. Therefore, the value of F_{static} determined using [Eq. 3] needs some correction to take these so-called loading rate effects into account. See [Eq. 4], where η represents the loading rate effects factor on soil type. Typical values for η are 1.00 for rock, 0.94 for sand and 0.66 for clay. [Eq. 4]

$$F_{static,corrected} = \eta \cdot F_{static}$$

Test strategy and safety philosophy

For load testing it is common to require a factor of safety (FoS) of 2.0 for the test piles. With design working loads 6-8MN that implied required test loads of 12-16 MN. The only StatRapid device that was available within the required time frame had a 40 ton drop weight with 10 MN nominal test capacity. Higher loads are also possible, but with shorter load duration, which can only be accepted as long as the criterion T_{load} > 10 L/c remains fulfilled.

Computer simulations performed in advance to establish the maximum possible test load that still fulfilled this criterion, revealed that loads up to 12-13MN could be achieved in this case.

It should be noted that in foundation works, increasing safety is about reducing uncertainty. Uncertainty is better reduced by testing more piles with lower FoS than by testing less piles with a higher individual FoS. The client and local authorities acknowledged this and accepted the proposal to test 50% of the already installed piles (25 pcs)

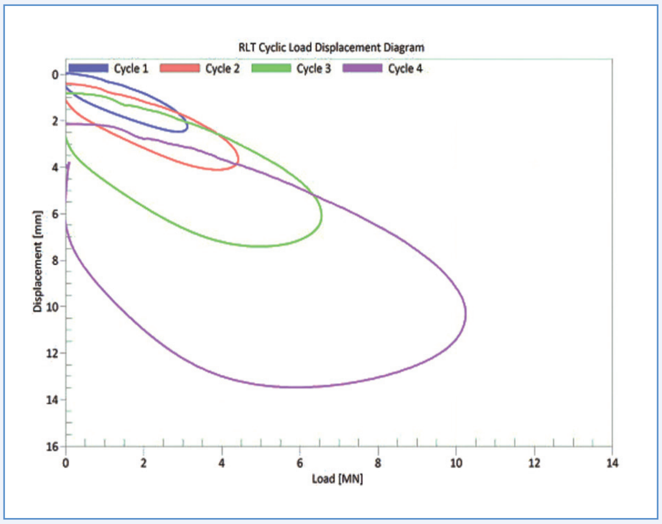

Figure 5 – Cyclic load-displacement diagram from a Rapid Load Test.

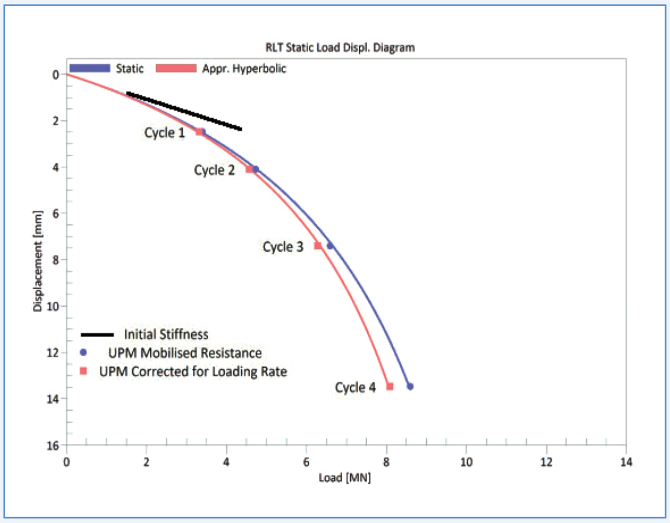

Figure 6 – Corresponding static load-displacement diagram derived from the Rapid Load Test.

Figure 7 – Moving the fully assembled and loaded test device.

Pile class [-]	nr of piles tested [-]	nr of cycles [-]	max. drop height [m]	required minimum load duration [ms]	actual load duration [ms]	max displacement (cum.) [mm]	permanent displacement (cum.) [mm]	Design load [MN]	Mobilized capacity [MN]	corresponding minimum factor of safety [-]
T1	12	2	2-2.5	82	83.6 (82 - 85.2)	9.8	3.2	7.9	9.8 (8.8 – 11.7)	1.25 (1.12 - 1.48)
T2	6	2	2.0	75	84.5 (82.5 - 85.4)	10.8	3.9	6.8	9.1 (8.7 - 9.4)	1.34 (1.29 - 1.38)
T3	4	2	2.0	70	83.8 (82.8 – 84.6)	11.6	4.6	6.2	8.0 (7.6 - 8.3)	1.29 (1.23 - 1.35)
T4c	2	2	2-2.5	87	87.6 (87.2 - 88)	6.7	0.4	7.8	9.5 (8.7 - 10.3)	1.2 (1.1 – 1.3)
T2 – O-Cell	1	4	2.0	75	85.0	13.5	3.9	6.8	8.1	1.19
T4c – 96	1	5	3.5	87	82.7	11.4	0.9	7.8	15.3	1.94

Figure 8 – Cyclic load-displacement diagram from a Rapid Load Test.

with test loads corresponding to a FoS of at least 1.20 – 1.30. Among the test piles were the piles that had also been subjected to the inconclusive bi-directional tests.

Test execution

The 25 test piles were divided over 4 different load classes, with required minimum test loads varying between 8 and 11 MN. Rapid Load Tests were performed in accordance with a dedicated test protocol. The first test piles were tested in 5 load cycles with a gradually increasing test load, in order to establish a good understanding of the soil response. Given the small plot size and limited site variability, subsequent tests could then be optimized by applying only 2 load cycles: the first one to confirm the soil stiffness and the second to mobilize the required capacity. In cases where test results seemed different from average, additional load cycles were performed to obtain extra data for the load- displacement curve for that particular pile.

Each load cycle took approximately 10 to 15 minutes to perform. For this project, a 400-ton crane was chosen, which was able to move the fully assembled device (63 ton) from one pile location to the next. Using this procedure the 25 load tests were performed within 9 working days, with an average of 3 tested piles per day. The last test pile was used for a small experiment, applying the maximum drop height of the device (4,0 m) and monitor load duration and maximum test load.

Test results

An overview of the main results is shown in the table. On average, the mobilized static resistance corresponded to FoS = 1.19 – 1.34. It should be noted that mobilized capacity is a safe lower bound value of ultimate capacity, because none of the piles failed during the tests.

Conclusion

After an inconclusive bi-directional load test at the start of the project, Rapid Load Testing was successfully applied to confirm the axial resistance of 50% of the already installed piles. By testing 25 piles in 9 working days, with test loads 8-12 MN and positive test results, the confidence in the pile design was restored and installation of the remaining 368 piles could be resumed. An open mind regarding safety philosophy on the side of client and authorities, as well as excellent coordination between general contractor and testing contractor were key to the successful completion of this testing work, without any further impact to the overall project schedule.

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