Verifying the capacity of deep foundations is an important part of the construction phase of a project. Various pile load test methods can be used to verify capacity; two different test methods were used for such purposes at a project in Barcelona, Spain.

The construction of an important project in Barcelona began in 2017. Given the size of the large diameter (1.5 m [5 ft]) cast in-situ piles, specified service loads (between 6 and 8 MN [1,350 and 1,800 kip]) and results of the geotechnical site characterization, it was decided to perform full-scale load tests to ensure that the piles provided the necessary axial resistance. Axial compression load testing using the bi-directional method was selected for this project. With this type of load test, an embedded jack assembly is attached to the steel reinforcement and positioned and cast within the shaft. Once the concrete has obtained sufficient strength, hydraulic pressure is applied to the jack assembly, which then pushes the two parts of the shaft (above and below the jack assembly) in opposite directions. The pressure increases gradually until one of the sections reaches geotechnical failure or until the assembly's thrust limit (i.e., stroke) is reached. At that time, the test ends and the axial capacity of the pile is determined to be at least twice the load that caused the failure.

An essential part of this test is determining the correct location of the jack assembly such that the resistance above the assembly equals the resistance below it. Otherwise, this test may underestimate the axial resistance of the foundation element, as the capacity of the most resistant section may not be mobilized. Unfortunately, this is exactly what happened with the first bi-directional test performed on the project. It was then decided to perform the other load tests using a different method with the understanding that the tests had to be performed in such a way to not delay the project.

**Pile Load Test Methods**

Of the foundation load test methods available, top-down static load tests are considered the most reliable. These tests apply a static load to the pile, either through weights (i.e., dead load) placed on a reaction structure on the pile head or, more generally, by anchoring the test beam to anchor piles adjacent to the pile being tested. A hydraulic cylinder then applies the loading gradually to the pile head, while both the applied load and resulting movement of the pile head are monitored and recorded. Performing a top-down static load test is a long and cumbersome process, both for the construction of the reaction system and for the test itself. This
means that top-down static load tests have an associated high cost and, in addition to mobilizing the large reaction elements, often interferes with the site logistics.

In the 1960s, an alternative to top-down static load tests was developed, the high strain dynamic test (HSDT), more commonly referred to as a dynamic load test (DLT). The main characteristic of a DLT is the productivity with this method and the elimination of a reaction system. To perform a DLT, a single blow on the pile head is required with an impact ram that is equivalent to approximately 2% of required mobilized static capacity. This impact generates pressure waves that are monitored by accelerometers and strain gauges mounted near the top of the pile, and the recorded data is then analyzed using signal matching techniques to estimate the pile's axial resistance.

However, the advantages of cost savings and short test duration are offset by a reduction in the accuracy of the test results. In addition, DLTs include viscous and inertial resistances that dissipate energy; therefore, greater impact energy must be applied to mobilize the test load, which can damage a concrete pile. To avoid these drawbacks, it was decided to perform a rapid load test using the Allnamics StatRapid equipment.

In 1991, just a few years after it was developed, the first Statnamic test was performed in Japan. Intrigued by the reliability of this new testing method, the Tokyo Institute of Technology, led by Prof. Osamu Kusakabe, grouped a research team to perform comparisons of this new pile load test method with top-down static load tests. The results of that investigation clearly demonstrated that results from both methods were equivalent; the results of the comparison were presented at the 1st and 2nd International Statnamic Seminars in 1995 and 1998, held in Vancouver and Tokyo, respectively, which led to the incorporation and implementation of this new testing method in the Japanese standards in 2002 (Japanese Geotechnical Society, 2002), being the first country in doing so. In the U.S., ASTM released a standard for the Statnamic test method in 2008 (ASTM D7383, Standard Test Methods for Axial Rapid Load (Compressive Force Pulse) Testing of Deep Foundations), which was recently updated and released as a 2019 standard. In 2001, the Dutch introduced their own standard for this method (CUR-H410, Rapid Pile Load Test). In 2016, the European Committee for Standardization, CEN, approved the rapid loading tests as Standard EN-ISO-22470-10:2016 (Geotechnical investigation and testing – Testing of geotechnical structures - Part 10: Testing of piles: rapid load testing), which was applicable to the project in Spain.

Given the environmental and safety regulations in many countries around the world, the fuel and transport thereof for a Statnamic test can be problematic. As a result, alternate rapid load testing devices were developed that do not involve combustion, such as Jibanshikenjo’s Hybridnamic and Matsumoto’s Spring Hammer Test, both developed in 2004, and, more recently, Allnamics’ StatRapid in 2012. These devices, which follow Procedure B in ASTM D7383, generate a load on the pile by releasing a drop mass equivalent to 5% to 10% of the test load in free fall. By varying the drop mass and drop height, a wide range of test loads can be applied with a particular device. A specially developed (relative soft) spring system is then placed on top of the pile to extend the load duration. Finally, to prevent any rebound, a catching mechanism is provided that is activated after the drop mass impacts the pile head.

Apart from extending the load duration, the specially-developed spring system also greatly reduces the stresses in the pile head. Therefore, it is a particularly convenient test method for cast in-situ piles, which generally use lower strength concrete than prefabricated piles. For the project in Barcelona, it was determined that a dynamic load test producing the required test load would have likely damaged the piles, which was one of the reasons why dynamic load testing was not selected. During a rapid load test, the test load is applied fast and yet slow enough to minimize dynamic effects (i.e., 100 to 200 msec for a rapid load test compared to 5 to 15 msec for a dynamic load test). As the load duration increases, the dynamic effects are reduced thereby avoiding the need to estimate complex dynamic soil

### Specifics of dynamic and rapid load testing

**Rapid Load Testing**

During a rapid load test, a load is applied to the foundation element under quasi-static conditions. One of the first applications was the Statnamic™ device, an amalgamation of STAtic and dynNAMIC, which was developed in Canada and the Netherlands in 1985. The Statnamic device consists of a reaction mass on top of a combustion chamber. Once solid fuel is ignited in the combustion chamber, the pressure gradually increases, lifting the reaction mass while, during the process, generating an opposite downward reaction force onto the pile head. Once the fuel has burned, the lifted reaction mass drops down within the container, where a bottom gravel layer acts as a catching system.
Of course, the test results resemble more closely those of a static load test. To ensure this is the case, both the ISO and ASTM standards specify a minimum load duration of 10 L/c where L is the pile length and c is the speed at which the stress wave propagates through the pile.

Rapid Load Test Analysis

When a pile is subjected to a load test, the total pile resistance can be split into three components: static, dynamic and inertial. As shown in [Eq. 1], the static resistance is represented by the term \( k \cdot u \) where \( k \) is the soil stiffness and \( u \) is the pile displacement. The dynamic resistance is represented by \( C \cdot v \) where \( C \) is the soil damping constant and \( v \) is the pile velocity. The inertial resistance is represented by \( m \cdot a \) where \( m \) is the pile mass and \( a \) is the pile acceleration.

\[ \text{[Eq. 1]} \quad F_{\text{total}} = F_{\text{static}} + F_{\text{dynamic}} + F_{\text{inertia}} = (k \cdot u) + (C \cdot v) + (m \cdot a) \]

Given the extended load duration during rapid load testing, the pile can be assumed to behave as a rigid body, where the velocity and acceleration are the same along the length of the entire pile. On that basis, in the late 1980s, 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, and centers around the point on the measured load-displacement curve where the displacement of the pile is maximal and the velocity of the pile equals zero, at which point the pile is assumed to behave quasi-statically. Therefore, from [Eq. 1], only the static and inertia terms remain (\( F_{\text{dynamic}} = 0 \)). Furthermore, given the equilibrium of forces, the measured force from the rapid load test (\( F_{\text{RLT}} \)) can be expressed as shown in [Eq. 2].

\[ \text{[Eq. 2]} \quad F_{\text{RLT}} = F_{\text{static}} + F_{\text{inertia}} = (k \cdot u) + (m \cdot a) \]

Rearranging [Eq. 2], the static resistance \( F_{\text{static}} \) can be computed using [Eq. 3].

\[ \text{[Eq. 3]} \quad F_{\text{static}} = F_{\text{RLT}} - F_{\text{inertia}} = F_{\text{RLT}} - (m \cdot a) \]

Measuring acceleration (using accelerometers), displacement (using an optical sensor) and \( F_{\text{RLT}} \) (using load cells), the unloading point can be defined. Using the load and acceleration at the instant the unloading point occurs \( (u_{\text{upm}}) \), the static resistance \( F_{\text{static}} \) can be determined. As an additional check, the measured displacement can be compared with the computed displacement determined from double-integrating the acceleration signal.

By comparing the results determined using the UPM with results from top-down static load testing, it became clear that the effect of the induced pore water pressures cause the mobilized resistance of a pile to be overestimated. Therefore, the value of \( F_{\text{static}} \) determined using [Eq. 3] must be corrected to take these effects (i.e., loading rate effects) into account, as shown in [Eq. 4] where \( \eta \) represents the loading rate effects based on soil type. Typical values for \( \eta \) are 1 for rock, 0.94 for sand and 0.66 for clay.

\[ \text{[Eq. 4]} \quad F_{\text{static, corrected}} = \eta \cdot F_{\text{static}} \]

Test Device

The StatRapid test device used on the Barcelona project consisted of a main frame, a modular hammer and a system of specially-designed springs, and was capable of generating a test load up to 12 MN (2,700 kip). The entire system was transported to the site on three trucks. Once the trucks arrived on site, the test device was assembled in about three hours due to its modular design.
The footprint of the test device used for this particular test was about 4 m by 4 m (13 ft by 13 ft), small enough to cause minimal, if any, interference with other ongoing site activities. Only when the device had to be moved using the crane was site work interrupted for about 15 minutes, which achieved the minimal interference requirement mentioned previously and was appreciated by the project developer and the construction contractor.

Test Preparation and Execution
For this project, 4 different types of piles for a total of 25 piles had to be tested. The required test loads varied between 6 and 8 MN (1,350 and 1,800 kips), which was easily accommodated by the selected testing equipment. The pile lengths ranged from about 28 to 35 m (92 to 115 ft); therefore, a specific load duration was required for each pile type since the minimum required load duration was a
function of pile length. To configure the device, including the drop mass and, especially, the spring system, computer simulations were performed in advance for each pile type to optimize the device configuration and to ensure that the rapid load test requirements would be met.

Rapid load tests using a cushioned drop mass are performed in accordance with a standard test protocol, usually consisting of two to five cycles with a gradually increasing test load, from which the load-displacement diagram is derived. For this particular project, five loading cycles were used for the initial tests to establish a good understanding of the soil response. Given the small plot size and limited site variability, subsequent tests could then be optimized to limit the load cycles to just two: the first one to confirm the soil stiffness and the second to mobilize the desired resistance. In those cases where the soil stiffness differed from the anticipated value, additional load cycles were performed to precisely define the load-displacement curve for that particular pile.

**Conclusion**

Using the testing procedure described, 25 load tests of 10 MN each were performed within 9 working days, with an average of 3 tested piles per day. In general, the mobilized resistance was about 20% higher on average than the required value, with the range of mobilized resistance ranging between 10% and 50% greater than the required resistance. Excellent coordination between the general contractor and the testing contractor was key to the successful completion of this testing work with minimal interference to the ongoing site activities and without any impact to the overall project schedule. Thus, after an inconclusive bi-directional load test at the beginning of the testing campaign, rapid load testing was successfully applied to confirm the axial resistance of the 25 test piles, which, in doing so, achieved the objective of the testing program.

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