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Deep Foundation with Driven Precast Concrete Piles and Monitoring with Pile Driving Analyzer PDA

Nicolás Tapia, Matías Cuitiño, Aldo Guzmán

Pilotes Terratest, Alonso de Córdova 5151, of. 1401, Las Condes, Metropolitan Region, Chile.

Abstract: A practical case of deep foundation for an industrial plant in Puerto Natales is presented, using precast reinforced concrete piles that are driven into soft clays (Nspt < 5 blows/ft). Equipment and methods were used for the evaluation of the pile structural integrity and their geotechnical capacity by means of PDA monitoring (Pile Driving Analyzer) during driving. With the results of the PDA test, together with the CAPWAP computational tool, the design hypotheses were verified. During the execution of the project, it was possible to achieve the optimization of the embedment depth and the variation of the required number of piles.

Key words: deep foundations; driven-precast-concrete pile; monitoring; pile driving analyzer

1. Introduction

Prefabricated reinforced concrete pile driving is a deep foundation technology, classified as part of the so-called full displacement pile group, because it is achieved by driving piles on the ground of prefabricated reinforced concrete components (usually square or circular sections) and applying controlled energy impact. Compared to piles that are pretreated by improving the surrounding soil through encryption, the lateral displacement caused by compression and infiltration of the pile tip into the ground generates resistance gains in the pile (e.g. Rhine River, 2018; Taiping and Huishan, 1988). The controlled impact used in HINCA comes from the use of high-tech hammers installed on specially designed cranes or piles. The most common hammers currently available include hydraulic hammers or diesel hammers, which can change energy by changing the mass or changing its falling height. This article discusses the use of precast reinforced concrete piles on the basis of an industrial ship and collection tank project in Natales Port, Magellan, Chile.

In the past 25 years, we have no records of using precast reinforced concrete piles in Chile. The equipment and technology used in this project comply with the current standards of the technology and have significant advantages in achieving higher pile loads and being able to measure their bearing capacity and integrity using instruments, which will be expanded later.

The geotechnical surveying and mapping related to pile driving projects is the work carried out immediately before the installation of project piles. Through this work, a certain number of high deformation dynamic tests were carried out to determine important aspects such as pile rejection definition, bearing capacity, and pile driving depth for each department of the project division.

This article introduces the main advantages of the prefabricated pile deep foundation system, considering the specific boundary conditions of the project, as well as the results of geotechnical surveying and the monitoring and control of the pile's expanded base through high deformation dynamic load tests. These piles are monitored and controlled through a PDA system (pile driven analyzer; Candela and Sainz, 1993; Arcos and de Juan, 2007), which consists of components that are responsible for processing sensor signals, storing, and visualizing data.

In general, the bearing capacity of driven piles can be estimated by means of empirical driving expressions that start from the rejection measurement, which is defined as the permanent drop that a pile suffers when receiving a certain number of blows of a certain energy. In the literature, there are numerous formulas proposed by different authors (e.g. FHWA, 2016), which depend on the hammer weight, pile weight, mass drop height and measured rejection. These formulations, which are based on the energy conservation principle, allow a quick estimation, although they require a prior calibration. With the advances of electronics and technology, the use of these formulas is being replaced by pile driving analysis with equipment such as the PDA that uses the principle of wave propagation.

The case presented in this article is based on the FHWA manual (2016) as the design criterion, which allows defining the geotechnical safety factor based on the minimum percentage of tests conducted on the total number of piles to be carried out for the entire project. Specifically, for this project, infrastructure construction is planned to be carried out on multiple ships and collection tanks, and 2% of the constructed piles were tested to determine a global safety factor equivalent to FS = 2.15 for pile soil engineering capacity.

2. Wave Propagation, Fundamentals and Methodology

Modern pile driving analysis methods are based on the propagation equation of compression or tensile waves traveling along the pile during the driving process (Smith, 1960; Candela and Sainz, 1993; FHWA, 2016).

The CASE method, developed in the mid-1960s at Case Western Reserve University (Cleveland OH, USA) is a method for predicting the bearing capacity of the pile based on measurements taken by electronic equipment such as PDA at the moment of driving. This model considers a hypothesis of a uniform, elastic pile and ideal plastic behavior of the soil, obtaining the general expression of theoretical and experimental considerations, which expresses the soil resistance RLT as a sum of two components, a static S and a dynamic D.

The CASE method expresses the static resistance S and dynamic resistance D as follows:

$$RLT = S + D \qquad (1)$$

$$RLT = \frac{1}{2}[F(\mathrm{t}_1) + F(\mathrm{t}_2)] + \frac{1}{2}[V(\mathrm{t}_1) - V(\mathrm{t}_2)](\frac{EA}{c}) \qquad (2)$$

where RLT is the total soil resistance during pile driving, F(t) is the force at the pile head as a function of time, V(t) is the velocity at the pile head as a function of time, t_1 is the chosen time during pile driving, usually the first peak, t_2 is the reflection time of the first peak, from the pile tip (t_1+2 L/c), L is the length of the pile below the measuring point, E is the elastic modulus of the pile material, A is the cross-sectional area of the pile and c is the velocity of the propagating wave in the pile. The pile driving analyzer (PDA) is a device that uses the CASE method to analyze the signals it receives from the strain (ε) and acceleration sensors installed in the piles, as shown in Figure 1. It is possible to determine, among other parameters, the mobilized resistance of the pile in the ground, energy transmitted to the pile, maximum compressive and tensile stresses generated inside the pile, velocity wave propagation velocity and strength and structural integrity.

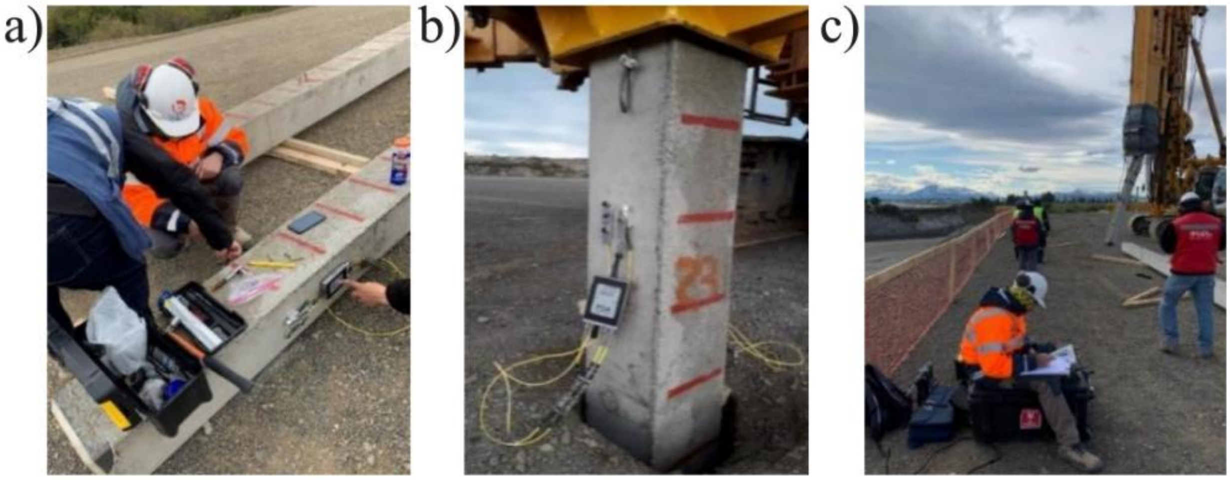

Figure 1. a) Sensor installation, b) pile installation and c) monitoring with PDA equipment.

In the early 1970s, a calculation program called CAPWAP (case pile wave analysis program) was developed (Goble and Rausche, 1970; Rausche et al., 1972). CAPWAP is a software that by means of an iterative process (signal matching) allows to simulate signals similar to those captured with the PDA during the recording. From this signal matching, the different static and dynamic parameters of the soil are obtained, as well as the pile resistance, among others.

CAPWAP (CW) is based on a mathematical model that discretizes the hammer-pile-soil system into continuous and uniform segments (finite elements), associating an elasto-plastic spring model and a damper with each segment. CAPWAP uses as input the measured downward wave (WD_m) to set the pile model in motion (see Figure 2), and calculates an upward wave WU_c and compares it with WU_m (measured by the PDA) at time 2 L/c . In this way the model parameters are iteratively adjusted until WU_c and WU_m are similar.

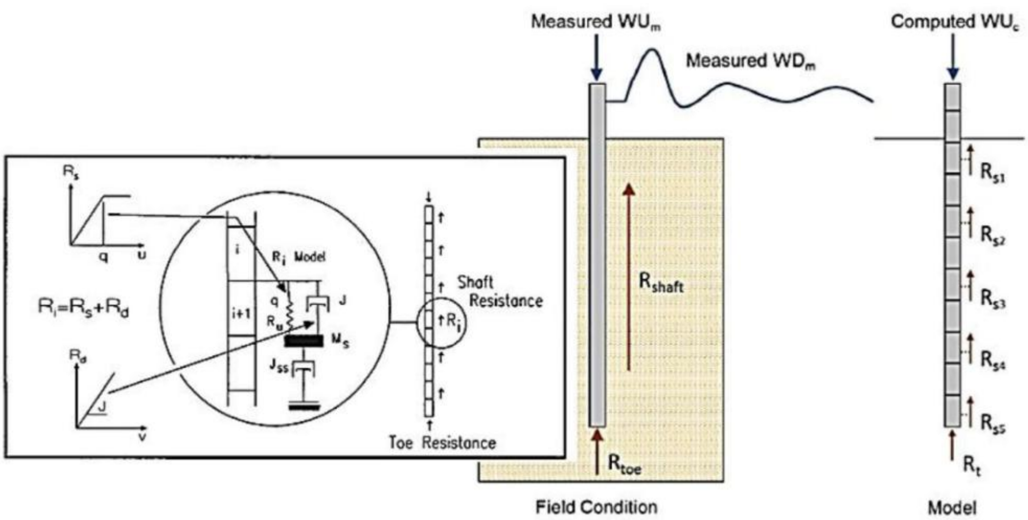

Figure 2. Hammering and Piling Models in CAPWAP Signal Equalization Method (FHWA, 2016).

3. Project

This case involves the deep foundation of an industrial factory in Natales Port, which is located a few meters offshore. According to the geotechnical study, the subsoil was formed in its upper stratum mostly by soft to very soft clay deposits called Mazacote, very characteristic in the Magallanes region (Donoso and Avalos, 2006), whose thickness reached a variable depth of up to 28 m from the working platform. The clay presented Nspt values of 0 to 7 blows/ft, with several points with 0 blows/ft, with γ = 1.8 ton/m^3 and s_u = 2 to 57 kN/m^2 (characterized on average with s_u = 20 kN/m^2) having even observed that the test bars descended by their own weight in some sections. Underlying the clay is a silty-clay gravel deposit with good geotechnical characteristics and suitable for embedding the pile tip, with values of Nspt > 60 blows/ft, γ = 2.1 ton/m^3, ϕ' = 40°.

The presence of highly deformable clay forces a solution to control or reduce the expected settlement of structures, especially project storage tanks. The alternative solution for gravel columns does not allow for a reduction in settlement to the required level for the project.

Given the geographical location of the project, the use of on-site prefabricated concrete piles is not a competitive solution due to the high cost of concrete supply. Therefore, it is recommended to use precast reinforced concrete piles with a cross-section of 27 × 27 cm, which eliminates many logistical issues.

The structural capacity of the piles in accordance with ACI318 (2019), using 50 MPa strength concrete, was calculated to be 234 tons, while the tensile capacity, using 420 MPa yield steel, was determined to be 41 tons. The piles are prefabricated in section lengths of up to 12 m, which facilitates their transport and handling on site, but makes it necessary to use special quick joints to join pile sections. These steel joints are formed by prefabricated metal pieces joined by a system of pins and dowels in accordance with EN 12794 (2005), as shown in Figure 4. The ultimate tensile strength is 98 tons (maximum allowable tensile load during driving is 88 tons). For the study project, a Junttan HHK7-9A hydraulic hammer with a mass of 7 tons was used, allowing to control and regulate its drop height up to 1.2 m and to control the frequency of blows. The hammer was mounted on a state-of-the-art Bauer BG28 tracked piling rig, facilitating its mobility on site and the guidance of the pile sections to be driven with the rig's mast.

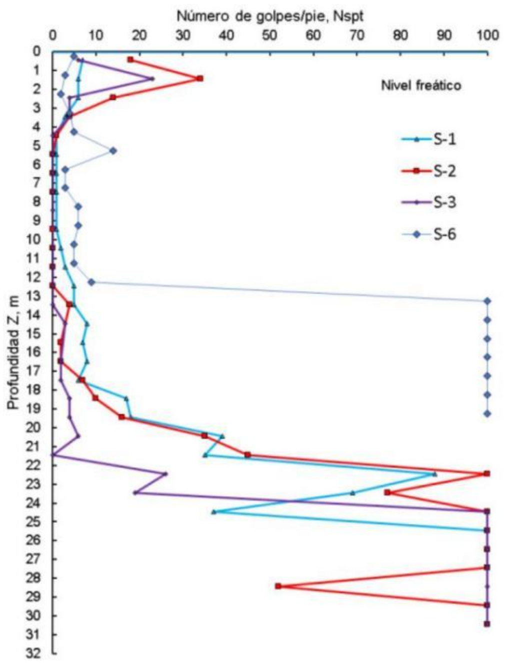

Figure 3. Variation of Nspt with depth.

Figure 4. Quick joint for prefabricated pile according to EN 12794 (2005).

4. Geotechnical Monitoring

In the previous surveying stage, PDA equipment was used to read the deformation and acceleration inside the pile using accelerometers and deformation gauges, thereby inferring the stress caused by hinge effects inside the pile. By using wave equations, the integrity and bearing capacity of piles are estimated on-site to determine rejection criteria, verify or validate project design assumptions, and determine the pile driving depth for each sub department of the project.

Figure 5 shows the surveying plan of an industrial ship under study. According to FHWA (2016) guidelines, high deformation dynamic load tests must be conducted on 2% of the piles (16 piles of the ship) executed in the project.

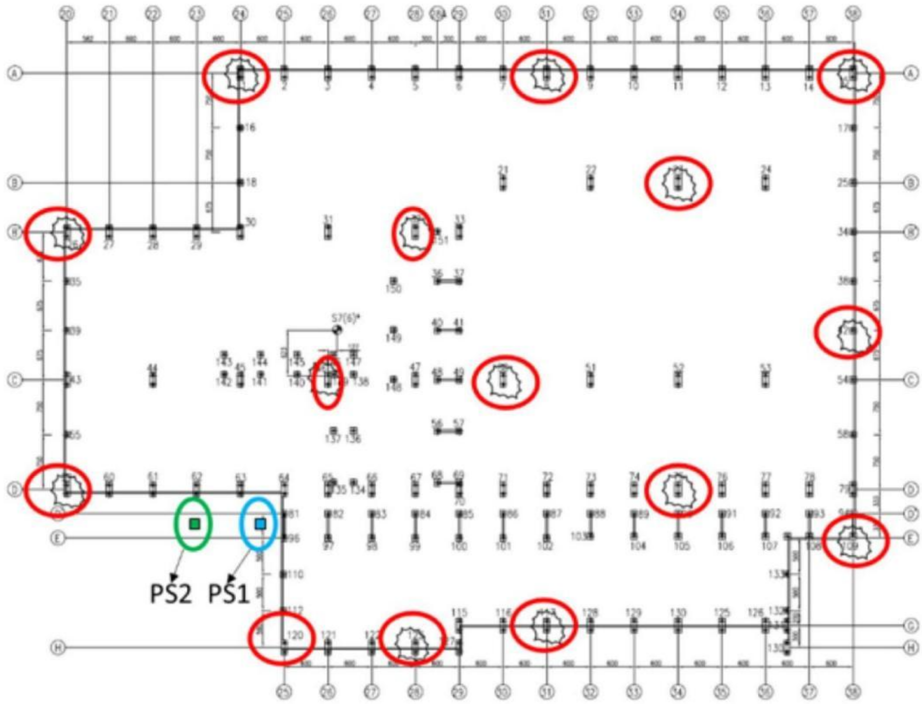

Figure 5. View in industrial building 01: circles indicate the piles instrumented with PDA in the mapping stage.

The main purpose of PDA monitoring is to verify the final bearing capacity of piles during direct pile driving without exceeding their structural capacity. On the other hand, monitoring helps determine the required pile length for each department, thereby optimizing the design. Then, by 3D modeling all the piles on the map, the expected depth of the remaining piles can be interpolated at each point, which brings important benefits in terms of the cost of using pile segments and the length loss of each pile.

Deformation and acceleration measurements were conducted 75 cm below the pile head. For this purpose, two deformation gauges and two piezoresistive accelerometers were fixed on the opposite side of the pile, as shown in Figure 6.

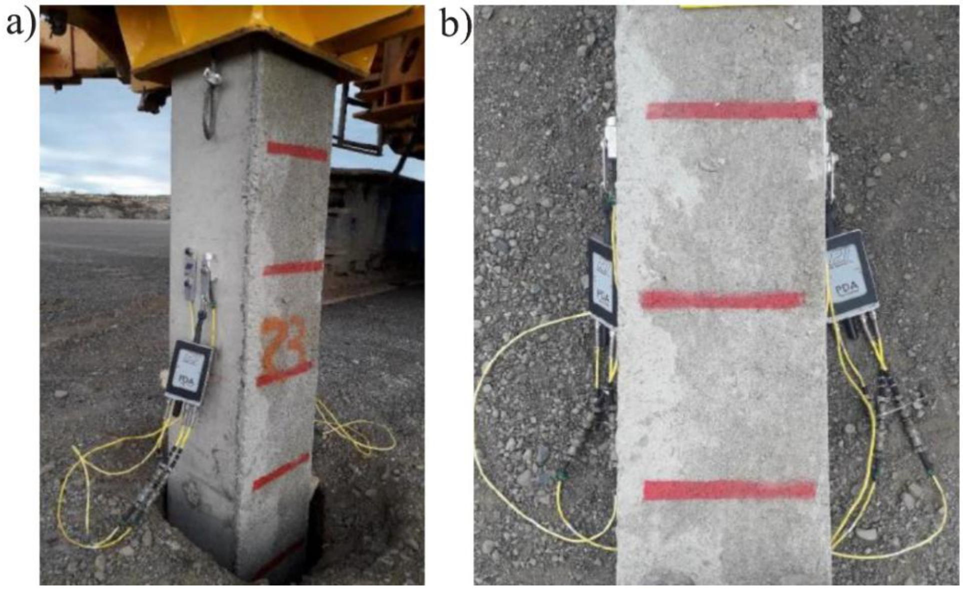

Figure 6. Instrumentation installed in the pile: a) side view and b) front view.

In addition, as part of the mapping process, seven piles were randomly selected and underwent instrumented rehydration in order to quantify the gain resulting from the rearrangement of the soil surrounding the pile (shaft gain). This was complemented by the tip resistance and also facilitated the optimization of the final length of the pile. These rehydration tests were conducted at 24 hours and 7 days (see Table 1).

Table 1. Soil strength recovery or gain (measured shaft loads)

Pile	Direct drive, kN	7-day rehydration, kN
32A	250	550
59B	350	480
62	200	310
64	315	520
109B	270	510
117B	360	480
120B	320	430

Soil recovery is evidenced by an average value of approximately 1.6 between days 1 and 7, which is referred to as SETUP, i.e. strength gain relative to the strength at the end of the initial pile driving. The average frictional resistance gained was 170 kN. The SETUP value obtained from the redriving process was somewhat lower than that used in the previous driveability simulation (SETUP = 2.0) (Thendean et al., 1996). However, the lower measured gain per shaft was compensated by the higher tip capacity achieved in the gravel.

For the case of Pile 117B, Figure 7 presents a comparison of the curves measured with PDA (CASE method) in direct driving (day 1) and redriving (day 7), under the same conditions of mass and height of mass drop. The continuous curve represents the force applied by the hammer to the pile, and the segmented line represents the velocity (integration of the acceleration) of the propagating wave. It can be seen that both curves represent an embedded pile condition, since both velocity and force remain equal until about time 2 L/c (L is the depth of the pile tip), separating abruptly shortly before this point, where the force increases due to the embedded condition and the velocity drops.

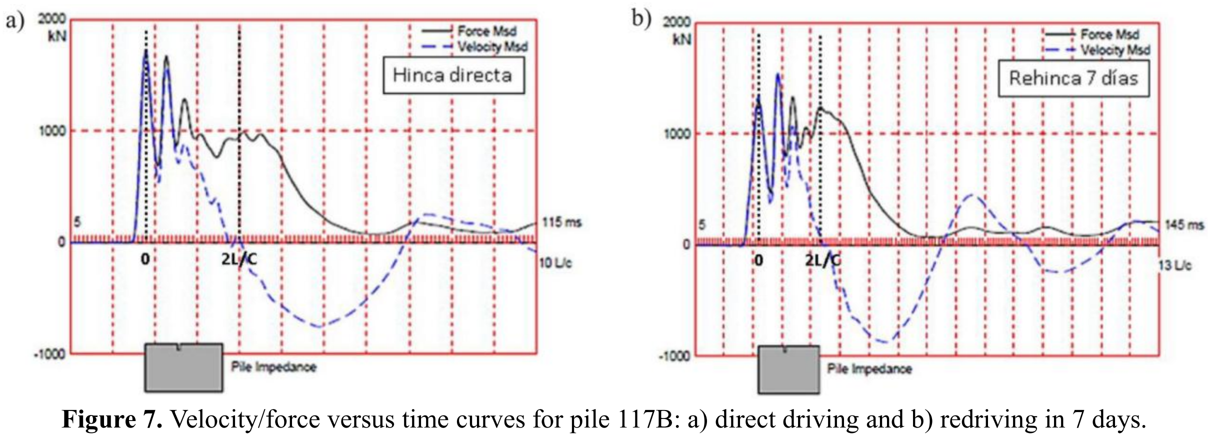

Figure 7. Velocity/force versus time curves for pile 117B: a) direct driving and b) redriving in 7 days.

The signals obtained with the sensors were analyzed with CAPWAP, showing that the iterative process had a good fit between the measured and simulated applied load curves, as shown in Figure 8. From the simulations with signal matching, the load versus pile deformation curve shown in Figure 9 is obtained, where 1,280 kN correspond to the pile tip capacity and 480 kN correspond to the pile shaft capacity, adding up to a final capacity of 1,760 kN.

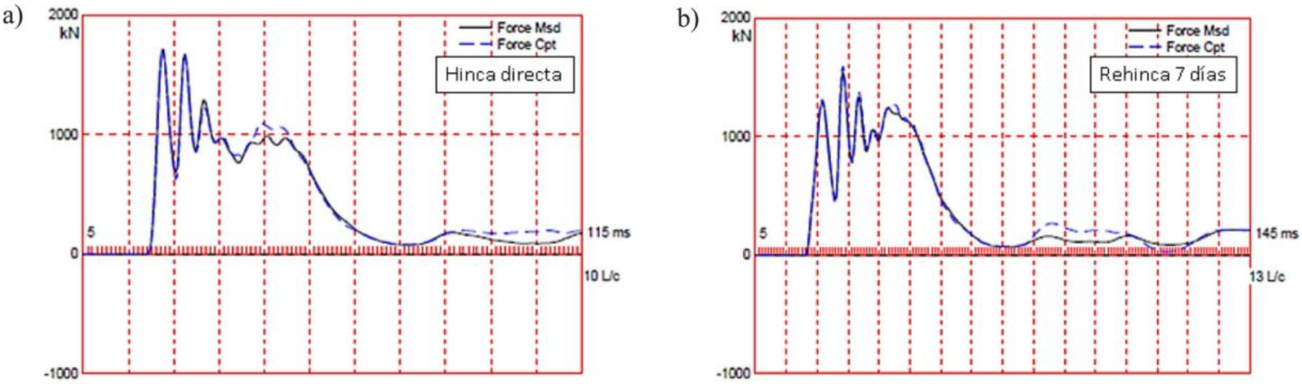

Figure 8. CAPWAP simulations for pile 117B: a) direct pile driving and b) redriving in 7 days.

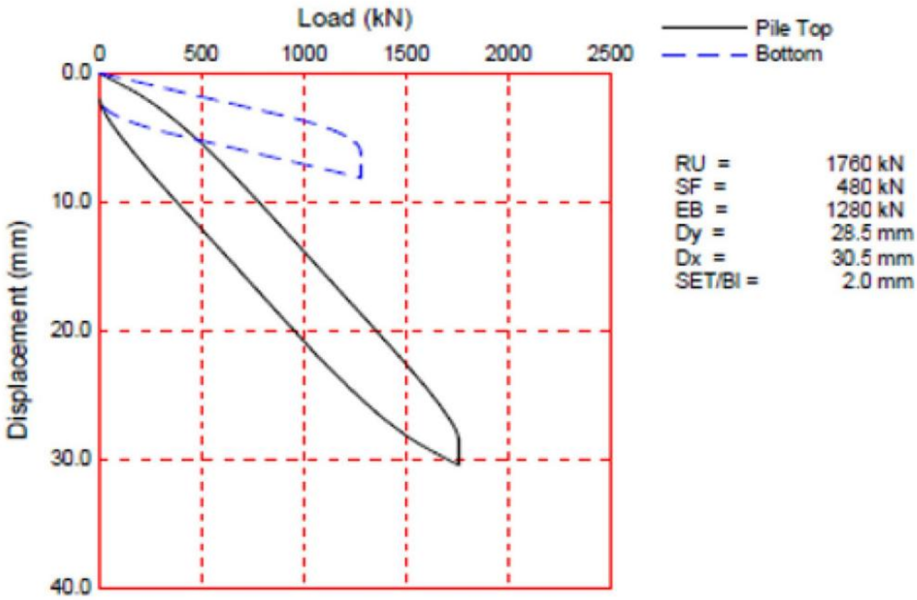

Figure 9. CAPWAP load-deformation simulation for pile 117B.

In 16 tests performed using PDA in one of the bays, the maximum stresses during pile driving at the top of the pile (CSX) measured by the PDA reached maximum values of 36 MPa. The maximum values recommended by the European standard EN12699 (2015) for reinforced concrete piles are 90% of f'c (40 MPa). Although the high compressive stresses during driving were close to the limit, no pile failure was evidenced. The maximum tensile stresses recommended by EN12699 (2015) according to the type of steel used are 7.3 MPa, indicating maximums in the tests in the order of 7.8 MPa, which were slightly above the limit of the recommended stresses. All of the above was monitored by the field engineer in order to bring all the test piles to the capacity limit, without jeopardizing the structural integrity of the piles.

5. Structuring of the Foundation with Driven Piles

The plant structure was designed in such a way that the piers were unloaded on reinforced concrete footings or heads supported on several piles. In the case of using less than three piles per footing, braces were used to control the moments in the direction perpendicular to the axis joining two piles.

In case of high horizontal forces, as for example in the tank area of the project, and given the low moment capacity of the driven piles due to their small cross section (27 × 27 cm), inclined piles were designed as shown in Figure 10 , allowing for an efficient design of the foundation.

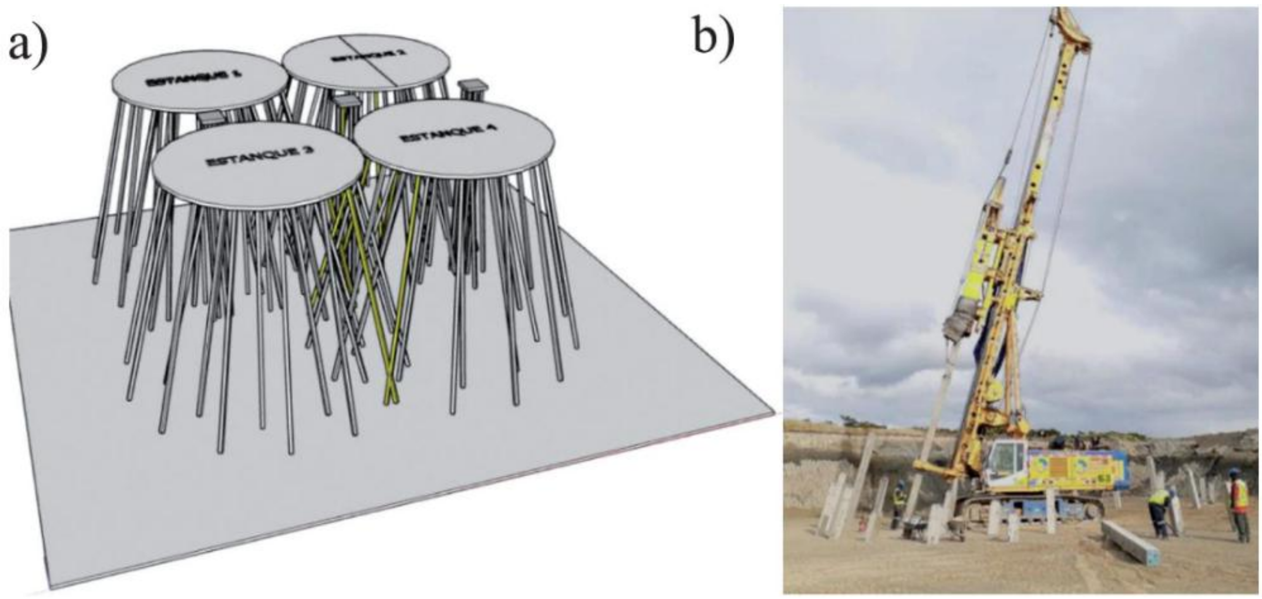

Figure 10. a) Inclined piles to absorb horizontal stresses and b) driving of inclined piles.

6. Conclusions

This article describes the first project executed with precast reinforced concrete driven piles after several decades, which is a milestone among the deep foundation solutions available in Chile. The use of precast reinforced concrete pile driving can effectively control the deep foundation problems of industrial plants in soils with very low strength and on land where geographical and edge conditions make another solution very expensive.

The structural integrity of the piles and their geotechnical capacity were monitored by means of PDA (Pile Driving Analyzer) equipment through high deformation dynamic tests, which allowed visualizing the structural integrity of the pile, load capacity, hammer performance and compressive and tensile stresses in the piles. The monitoring allows to check the depth of the competent soil, allowing in some cases to reduce the length of the sections to be prefabricated, which represents a considerable saving in concrete and joint costs. In addition, the monitoring made it possible to define a rejection condition that would allow shortening project deadlines and, above all, not running the risk of exceeding the structural capacity of the piles due to excessive compressive or tensile stresses resulting from driving.

The use of precast piles in the project generated an efficient solution in terms of cost, time and technical performance. The large number of large deformation dynamic tests (24 in total) that could be performed in the monitoring stage resulted in significant economic benefits both in raw materials and logistics, but also provided great security to the project given the large number of tests performed, limiting the uncertainties of other technologies that require static tests, which often represent a high cost and entail high logistics.

Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

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