STATIC BEHAVIOR OF STEEL H-PILES UNDER AXIAL LOAD USING SCALE MODELS IN VERY SOFT CLAYS

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ABSTRACT

The Complementary Technical Standards of Mexico's City Building Code do not mention the criteria to compute the bearing capacity of Steel H-piles. It is necessary to increase knowledge in using steel H-piles as foundation elements in very soft soils of Mexico City. Considering their applicability to reinforce structures as well as new foundations in confined spaces, this research is proposed to obtain the axial load capacity of piles at scale in laboratory. This paper describes the construction and testing of scale models in laboratory of steel H-piles to measure their axial compression and tension load capacity in the soft soils of Mexico City. Three types of piles were fabricated at scale. Tests were performed on individual piles and pile groups. Based on the axial load tests, the load-displacement curves are presented both in compression and tension. The analysis of the results is shown, and comments are given regarding the ultimate bearing capacity of piles. Recommendations are presented regarding the determination of the bearing capacity of these piles in the very soft soils of Mexico City.

Keywords: steel H-piles, "scale" models, axial load tests

SCALE MODELS

Very few load tests in steel H-piles have been conducted in Mexico. The use of scale models in geotechnical engineering offers the advantage of simulating complex systems under controlled conditions and the opportunity to gain of insight into the fundamental mechanism operating in these systems (Meymand, 1998). Under many circumstances (e.g. axial and lateral load tests in piles) scale models give more economic alternatives than those from real scale models. Taking as scale models those that are tested in the laboratory under certain scaling laws. Real-scale models are those that are carried out in site with real dimensions and under real field conditions, without using any scaling law, being this type of model what we name prototype. For other investigations (e.g. soil-pile-structure interaction or pile group effect) scale models allow the simulation of phenomena that cannot be achieve "on purpose" in the prototype. Besides the qualitative interpretation, scale test results are often used as reference points to calibrate analytic or numerical methods or to conduct quantitative predictions of the real scale pile response. For these applications it is necessary to have a collection of ratios or laws of scale that relates with the observed model and the prototype expected behavior.

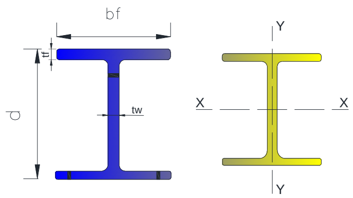
Physical scale models have been applied in order to assess those different factors that the load capacity of a material involves. In Mexico, scale models of piles cast *in situ* have been made (e.g. Ibarra E. 2013) and steel tubular piles (e.g. Luna O., 2002; Cruz E. 2003), and in other parts of the world, pile scale models have been used to evaluate the efficiency of group piles (Bilal et al., 2019).

The objectives of this work include the manufacture and execution in the laboratory of scale models of steel H-piles to measure their axial compression and tension load capacity. Scale models can meet similarity requirements at different degrees. A suitable model correctly takes into account the main characteristics of the problem, allowing the secondary characteristics not to take a main role, therefore the predictive equations are not significantly affected. An approach, considering a viable model to be applicable, consists of identifying and modeling the primary forces and processes while eliminating secondary effects, thus obtaining an "adequate" scale model. This approach is the one used in the present research.

Pile design for the scale models

The piles used in this research correspond to IR type steel profiles. According to our experience in the use of these piles as foundation elements for office buildings and apartments of 3 to 7 levels in the clay of Mexico City, Table 1 shows three types of profiles. In all cases for the piles a volumetric weight γ_m of 7850 kg / m3, an elasticity modulus of 2.1x106 kg / cm2 and a yield stress fy of 3515 kg / cm2 were considered.

Table 1. Characteristics of steel piles used as prototype

Symbology	ID	M [kg/m]	d [mm]	tw [mm]	b_f [mm]	tf [mm]	Pp [mm]	Ap [cm^2]	Ix [cm^4]	Iy [cm^4]
	W10x17	25.30	257	6.1	102	8.4	909.8	32.2	3,409	148
	W18x35	52.20	450	7.6	152	10.8	1492.8	66.5	21,228	637
	W24x55	82.00	599	10	178	12.8	1890	104.5	56,191	1,211

M: Mass per unit length, d: depth of section, tw: web thickness, bf: flange width, tf: flange thickness, Pp: pile perimeter, Ap: pile area, Ix and Iy: moment of inertia around the X and Y axes, respectively.

Knowing the scale factors used with the models allows to extrapolate, in an approximate manner, the results to the prototypes. In this work an analysis was conducted in order to obtain the dimensions and mases of scale piles of the three pile prototypes shown in Table 1 according to the similarity equations of the Buckingham Pi Theorem (Meymand, 1998). Table 2 presents the pile dimensions and scale factors used for the three steel profile prototypes. For the W10x17 and W18x35 profiles, the height scale factors, d, and the flange width, bf, are 8; for the W24x55 profile the scale factors are 7, for the same parameters. Mass per longitude unit factors M, are 14.50, 4.27 and 13.00kg/m for the steel profiles W10x17, W18x35 y W24x55, respectively. Table 2 presents data and dimensions of the different parameters used to manufacture the scale piles. The height-length ratios of the steel piles, both the prototype and the scale models are 19, 11 y 8 for the profiles W10x17, W18x35 and W24x55, respectively. Through the use of different scale factors, and to verify that the similarity between prototype and model is met, Table 3 presents the similitude ratios computed for the three studied steel profiles of the prototypes and scale models. Figure 1 presents the diagrams with the dimensions of the profiles for the prototypes (blue color) and scale models (red color) that will be manufacture. The values indicated in Figure 1 are in millimeters.

DEVELOPMENT OF THE PHYSICAL SYSTEM FOR LOAD TESTS

This section presents the manufacture of the piles, the design and construction of the load frame, the load application and measurements systems, as well as the containers to place the soil and accessories for the execution of tests in groups of piles.

Manufacture of piles to scale

Steel plates of different widths and thicknesses were used to manufacture the piles. To comply with the required measures, cuts and joints were made between the plates. Figure 2 shows the manufacturing process which includes cuts, adjustments and welding of the pieces that make up the piles corresponding to the three types. Pieces of each scale pile were manufactured according to the dimensions of table 2. Once the pieces were welded, in order to avoid the early corrosion of the piles, anticorrosive paint was applied on them and they were marked every 1 cm to be able to keep track of the number of blows during the driving process. In the head of the piles, a slot was made to pass through screws in order to tie them to the system and to carry out the tension tests.

Table 2. Scale factors and characteristics of the steel piles used in the scale models

Pile ID		W10x17			W18x35			W24x55		
Variable	Unit	Prototype	Model	Scale factor	Prototype	Model	Scale factor	Prototype	Model	Scale factor
d	[mm]	257	32.13	8	450	56.25	8	599	85.57	7
bf	[mm]	102	12.75	8	148	18.50	8	178	25.43	7
Mc	[kg]	232.648	2	116.324	195.597	2	97.7985	181.36	2	90.68
M	[kg/m]	25.3	1.74	14.5	52.2	4.27	12.2	82	6.33	13.0
Ep	[kN/m^2]	2.10E+08	2.10E+08	1	2.10E+08	2.10E+08	1	2.10E+08	2.10E+08	1
Ix	[cm^4]	3,409	2.822	1208.0	21,228	17.133	1239.0	56,191	62.901	893.3
Iy	[cm^4]	148	0.196	755.1	637	0.610	3250.0	1,211	1.506	804.1
L	[mm]	5000	625	8	5000	625	8	5000	714.3	7
d/L	-	19	19	1	11	11	1	8	8	1

Table 3. Similitude relationships between prototype and scale model of the piles used

Pile ID	W10x17		W18x35		W24x55	
Similitude $\pi_p = \pi_m$	Prototype	Model	Prototype	Model	Prototype	Model
$(Mc/DM)_p=(Mc/DM)_m$	0.035780	0.035780	0.00832682	0.00832683	0.003692	0.003692

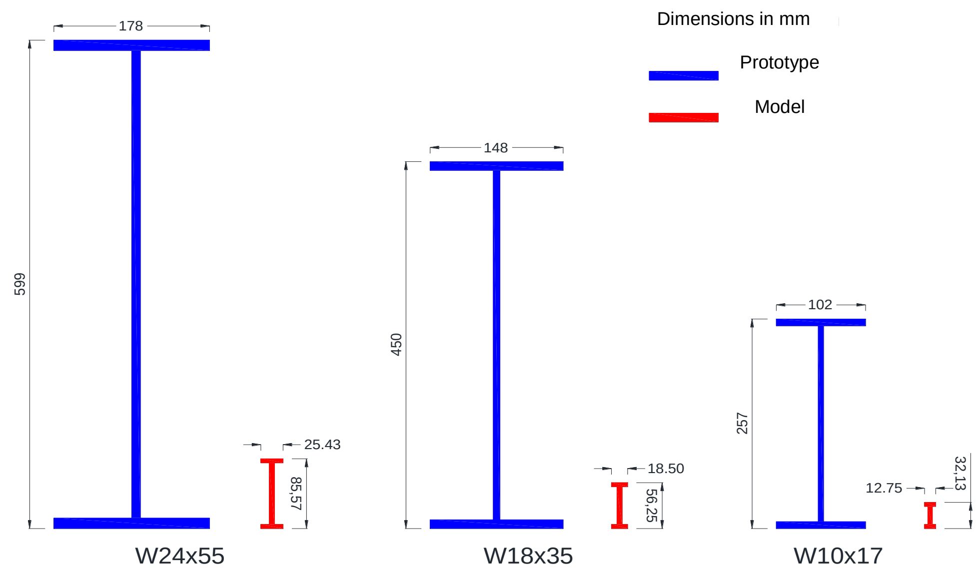


Fig. 1. Prototype and scaled steel H-pile considered in the analyzes

Fig. 2. Manufacture of piles to scale

Soil containers

The dimensions of the soil container must be such that the walls and base do not influence the results of the load tests. For this, an arrangement of 4 piles separated 3 times the depth of section (d), center to center of each pile, was considered. The separation between these piles and the container walls is also a minimum of 3 times the depth of section (d). The diagrams of the containers for each type of pile are shown in Figure 3. The containers were made of 3 mm thick steel sheet for the walls and a 95 mm thick steel plate. Internally, 9.5 mm-thick square rods were placed, every 10 cm in order to be reference guides and to tie the material as it is placed. Once the plates were cut to the dimensions mentioned, they were welded to the base plate.

Load frame and load measurement and displacement reading system

The load frame was constructed with 4-inch height structural steel (H-beams) and was manufactured in such a way that it can be bolted together so that it can be increased or decreased in size according to requirements. It has two columns and a beam where the hollow plunger cylinder is placed to apply the axial load. At the base, extensions were placed to rest the containers and serve as a counterweight during the tests. The height is 1.8 m, and extensions can be removed and mounted on the columns to have sufficient height to drive the piles. The system to apply compression and tension loads consists of a hydraulic pump, a 30-ton hollow piston cylinder and a 2-inch stroke. It has a load cell with a capacity of 5 tons and two dial micrometers to measure pile displacements. The assembled system is shown in Figure 4a.

EXECUTION OF THE AXIAL COMPRESSION AND TENSION LOAD TESTS

To fill the three containers, an open pit was drilled at a site in Mexico City Lake Zone, which exhibits high compressibility and low shear strength. The typical soil profile sequence in the lacustrine zone of Mexico City subsoil includes a thin superficial dry crust, a first clay layer, several tens of meters thick, a first hard layer, a second clay layer and the so-called deep deposits. The material was placed in 0.10 m layers. Index and mechanical tests were carried out to the material placed in the containers, including tests for water content, plasticity index, hydrometer test, miniature vane shear test, pocket vane shear test and pocket penetrometer tests. The fines percentage varies between 85-95%. The water content (w) of the clays ranges between 80% and 120%. Solid densities (Gs) vary between 2.13 and 2.53. The plasticity indexes vary between 50 and 100%.

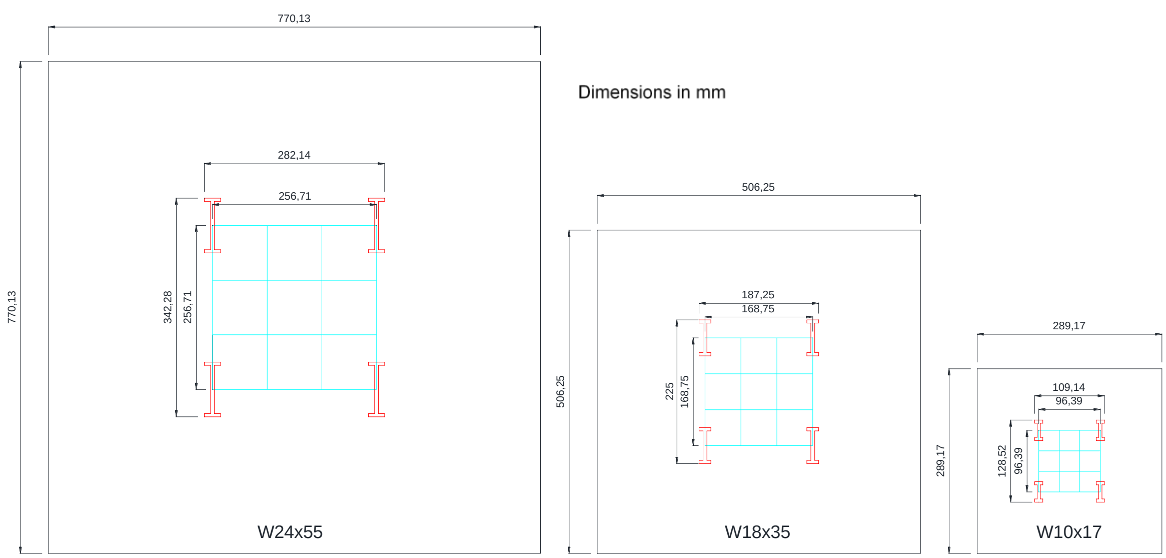


Fig. 3. Distribution of pile groups in the scale models with spacing 3 times the width d. The values indicated are in millimeters.

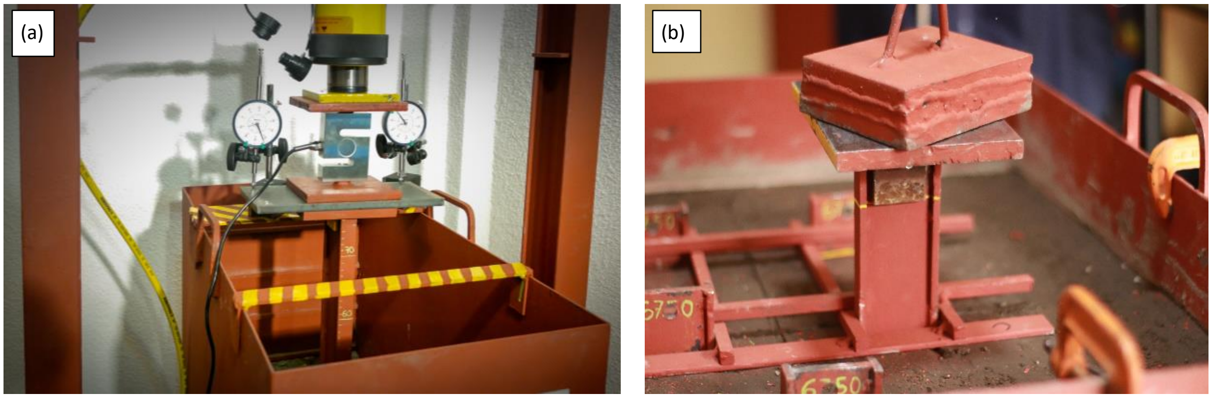


Fig. 4. (a) Load measurement system and displacement reading system and (b) pile driving

Driving the piles

On soft ground (soft clay and very soft clay) it is common for the installation to be carried out using impact hammers or vibrohammers. In this work, the driving of the piles was simulated using an impact hammer, dropping a steel mass of 3.82 kg and falling heights between 0.15 and 0.45 m (See Figure 4b). 15 piles were driven, 5 in each container, one corresponds to the individual pile and the remaining four correspond to the group of four piles (2X2 arrangement). The results presented in this work correspond only to the W24X55 and W18X35 piles. During the driving process, a record of the number of blows every 0.05 m of penetration was kept (see Figure 5). Due to space issues, as can be noted, the larger piles required a larger number of blows (20 to 80 blows / 0.05m) and a higher drop height (0.10 to 0.4 m), and the driving of the first two piles required a larger number of blows due to a misalignment of the axis and the hitting mass, which was corrected for the other driving processes. Regarding the driving of the W18X35 piles, there was a similar behavior for each container, where the number of blows and height of fall increased with depth. The W10X17 piles presented a considerable decrease in the number of blows required for driving with measured values of 6 to 8 blows per 0.05 m and fall heights of 0.3 m.

Axial Compression load tests

Once the piles have been driven, they are kept in the humid storage room of the laboratory to carry out compression tests initially. The analyzes began at 7 days with the W24X55 Piles for the individual pile as well as for the group of 4 piles (see Figure 6). The pile group supported a compression load of 815.3 kg and a maximum displacement of 11.56 mm. During the discharge, the pile was maintained with a permanent displacement of 8.77 mm. The individual pile supported a load of 187.6 kg and presented a displacement of 6.00 mm. Comparing the behavior of the individual pile with a group pile assuming that the transmitted load in each pile is a quarter of the total load, Figure 6b was graphed. The behavior of the group pile and the individual pile is similar, although the group pile presents a greater displacement and a slightly higher maximum load than that of the individual pile. In the elastic branch both in loading and unloading, the group pile presents a greater displacement than the individual pile. The pile spacing is 3 times the height, d, of the pile. For the W24X55 pile group, a second loading stage was carried out 30 days after installation, reaching a load of 893.6 kg and a cumulative displacement of 15.67 mm (See Figure 7a). Figure 7b compares the curves at 7 and 30 days, where a hardening effect of the clay is observed at 30 days (more pronounced initial branch).

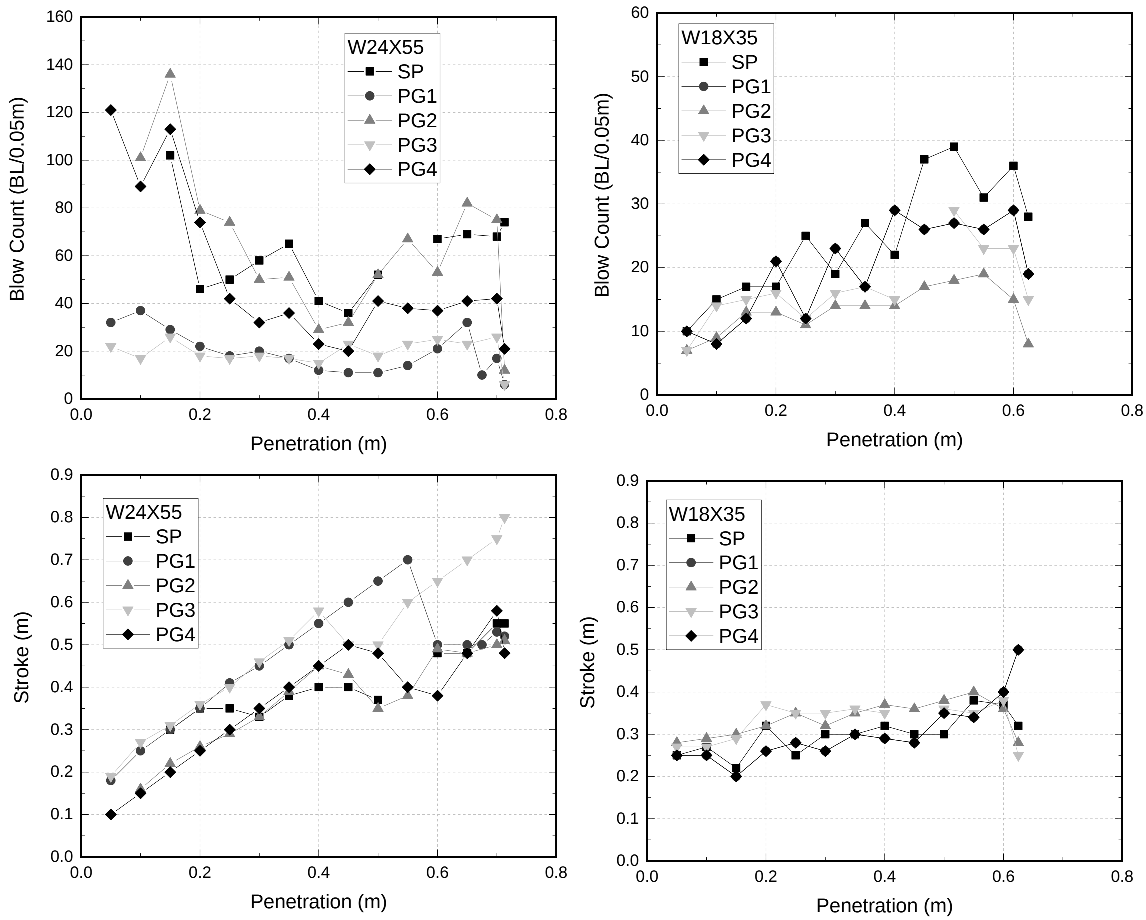


Fig. 5. Number of blows and y ram drop height during pile driving.

Likewise, the W18X35 piles were tested. The W18X35 single pile supported a load of 142.0 kg and presented a displacement of 5.13 mm. Figure 8 shows a comparison of the compression curves for the W18X35 and W24X55 piles 7 days after installation. A similar general trend is observed in the shape of the curves, however, the W18X35 individual pile shows a more pronounced nonlinear behavior.

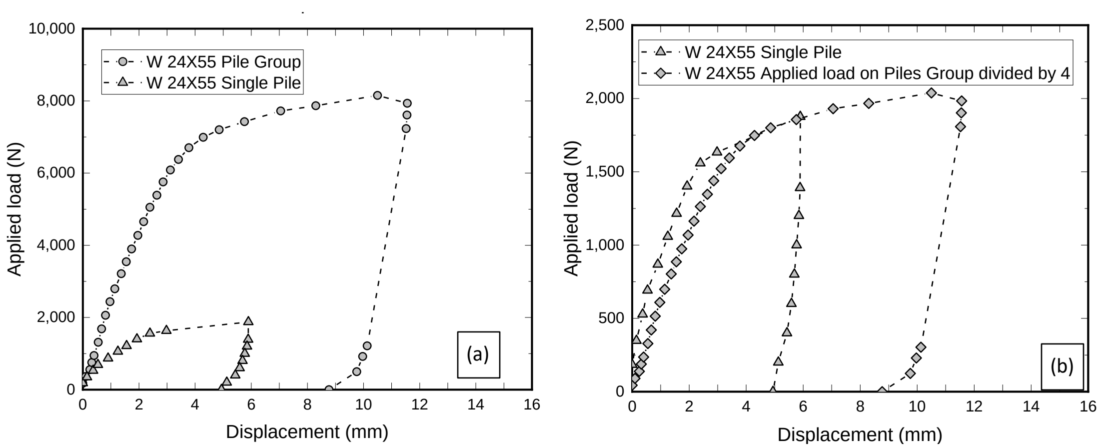


Fig. 6. Load-displacement measured curves of the compression tests for the pile group and single pile, W24X55

Pull-out test

10 days after the compression load test for the W24X55 pile was performed, the pile tension load test was carried out. The pile supported a maximum tensile load of 85.9 kg and a displacement of 14.54 mm. The nonlinear behavior is more noticeable, having an elastic branch in less than 1 mm. Furthermore, the displacement obtained for the maximum tensile load is much greater than the displacement obtained in the compression load test. An important point to highlight is that, once the stress test was completed, the pile was removed and the soil adhered to the pile formed an envelope on the periphery of the H-pile (see Figure 9). On the ground surface, cracks were formed around the pile area, likewise, in the soil with depth, a rectangular shape corresponding to the soil envelope and the pile could be seen.

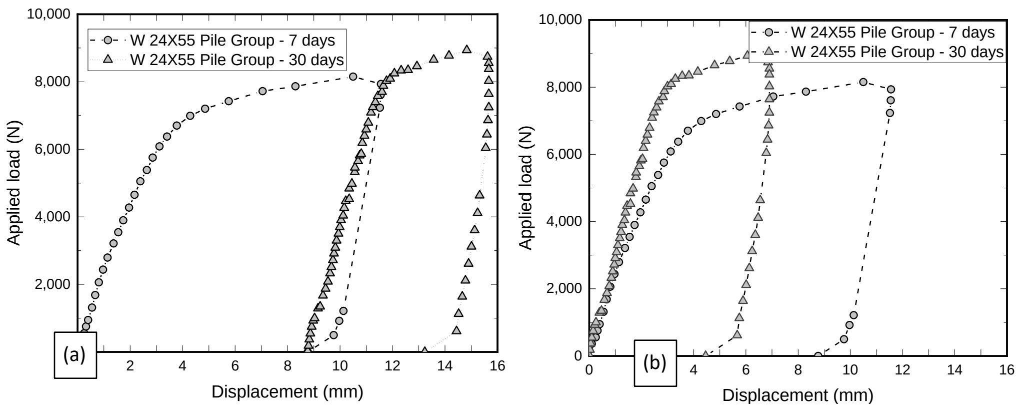


Fig. 7. Comparison of load-displacement measured curves of the compression tests to the pile groups at different times.

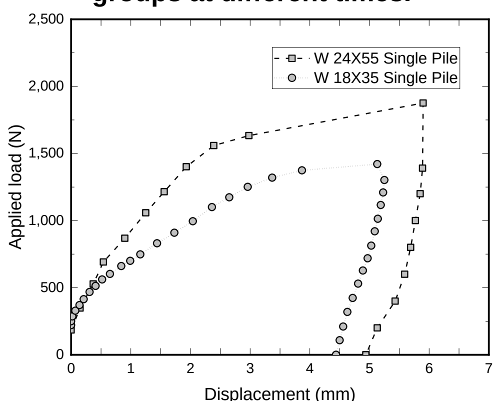


Fig. 8. Comparison of load-displacement measured curves of compression tests of single piles

SUMMARY AND CONCLUSIONS

The manufacturing of the scale steel H-piles and the construction of the loading system allowed us to conduct out axial compression and tension load laboratory tests in soft clays of Mexico City. The driving of the piles was simulated using a striking mass as is done in the field with impact hammers. By registering the number of blows with depth during driving, it was possible to identify but not quantify the increase in soil resistance to driving. Through the use of pile driveability analysis with the wave equation, it is possible to do a back analysis to obtain the soil resistance by comparing the results with the driving records. From the compression test to the W24X55 piles, it was seen that the behavior of the group pile and the individual pile is similar for the analyzed separation between piles, although the group pile presents a greater displacement and a slightly higher maximum load than the ones of the individual pile. In the elastic branch both in loading and unloading, the group pile presents a greater displacement than the individual pile.

Comparing the compression curves of the group of piles at different times, a hardening behavior of the clay was observed, having a more pronounced elastic branch and a more marked area when passing to the inelastic branch for the test after 30 days of having installed the pile. The curves for the individual W18X35 and W24X55 compression piles showed a similar general trend in the shape of the curves, however, the W18X35 individual pile showed a more pronounced nonlinear behavior.

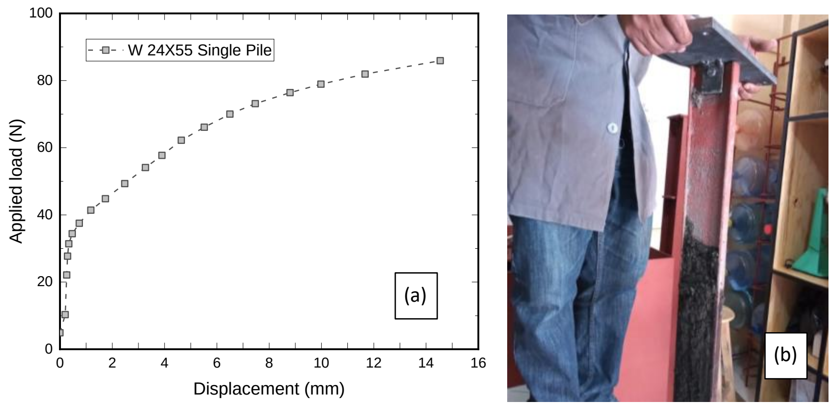


Fig. 9. (a) Load-displacement curves of the W24X55 individual pile tension load test and (b) soil adhered to the pile after the tension load test.

In regard to the tension test, the measured displacement for the maximum tension load is greater than the displacement measured during the compression load test. When the pile was removed, the soil adhered to the pile forming an envelope on the periphery of H-pile. In practice it is usual to consider a percentage of the envelope area of the H-pile to determine the soil bearing capacity. It must be noted that scale models are a low-cost alternative to real scale tests and they provide interesting results that allow us to have a better understanding of the behavior of the piles, especially on steel H-piles since there are fewer load tests compared to the static tests on concrete piles. Lastly, the use of steel H-piles in clayey soils such as those in Mexico City is more frequent and this investigation provides data that can be used to calibrate advance numerical models. Through numerical simulations that represent this loading tests, it is possible to calibrate different constitutive laws and evaluate their response against the results of this work.

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