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Analyzing Unidirectional and Bidirectional Load Tests on Barrettes and Piles in Mexico City: Construction, Execution, and Interpretation

Análisis de pruebas de carga unidireccionales y bidireccionales en Barrettes y Pilas en la Ciudad de México: Construcción, Ejecución e Interpretación

Luis Fernando García Espinoza
Design Engineer, CIMESA, Soletanche-Bachy México, garcia.fernando@cimesa.net
Guillermo Clavellina Miller
Design Office Manager, CIMESA, Soletanche-Bachy México, clavellina.guillermo@cimesa.net
Nallely Flores Parra
Design Engineer, CIMESA, Soletanche-Bachy México, flores.nallely@cimesa.net

ABSTRACT: In a construction located in the Lacustrine Zone of Mexico City, the installation of foundation elements, specifically piles at a depth of 54 meters and barrettes (rectangular shape piles) at a depth of 80 meters, is necessary. To assess the load-bearing capacity of these elements, static load tests were conducted. Unidirectional load testing was employed for the piles, while bidirectional load testing using two levels of Osterberg Cells was utilized for the barrettes. This paper relates the construction process of the foundation elements, involving the positioning of the Osterberg cells and the instrumentation, for the implementation of both types of tests along with the interpretation of their respective results.

KEYWORDS: load testing, foundation elements, barrettes, piles

1 INTRODUCTION.

For the construction, in the Lacustrine Zone of the Mexico Valley, of buildings reaching heights of up to 300 m and six parking basements to a depth of 30 m, the project demands the use of deep foundation elements, specifically piles at a depth of 54 m and barrettes positioned at a depth of 80 m.

To verify the load capacity of the barrettes and piles, two static load tests were carried out on barrettes with a section of 2.70x1.20 m, founded at a depth of 80 m. The load was applied using Osterberg Cells (O-Cell), which had a maximum load capacity of 10,888 t. Additionally, two static load tests were carried out on circular piles with a diameter of 1.20 m, founded at a depth of 54 m, with a maximum test load of 2000 t, which was applied using a steel frame attached to reaction piles.

This document outlines the construction procedure of the foundation elements, including the placement of Osterberg cells and instrumentation, as well as the execution of the two types of load tests performed and the interpretation of the results.

1.1 *Geotechnical zoning and stratigraphy*

According to the geotechnical survey carried out at the project site, the soil stratigraphy corresponds to the lacustrine zone. This area is characterized by highly compressible clay deposits, separated by sandy layers with silt or clay content, moderately compact to very compact and with variable thicknesses, Table 1.

Table 1. Project stratigraphy

Geotechnical unit	Deepness		γ	*c*	*φ*
	De (m)	A (m)	(t/m³)	(t/m²)	(°)
U1	0.0	-5.0	1.5	5.0	25
U2	-5.0	-20.0	1.2	3.0	0
U3	-20.0	-29.5	1.2	7.0	0
U4	-29.5	-33.0	1.6	0.0	30
U5	-33.0	-39.0	1.3	15.0	0
U6	-39.0	-59.5	1.7	8.0	32
U7	-59.5	-74.5	1.5	30.0	0
U8	-74.5	-89.5	1.8	10.0	34

where:

U1	Surface crust
U2	Clay formation 1
U3	Clay formation 2
U4	Hard Layer
U5	Lower clay formation
U6	Upper stratified series
U7	Deep clay formation
U8	Lower stratified series
γ	Volumetric weight
c	Soil cohesion
φ	Friction angle

1.2 *Static load tests on foundation elements*

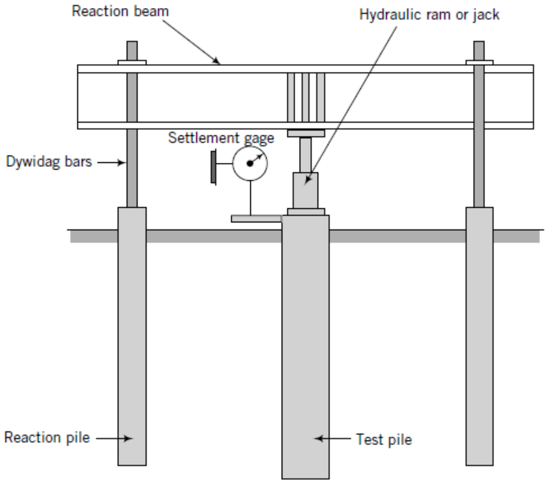
Load testing involves applying a simulated load to a structural element to assess its performance under specific conditions, such as axial compression, tension, or lateral forces. This helps engineers understand how the element will behave in real-world scenarios.

For foundation elements, axial compression load tests allow obtaining the friction stress and load capacity at the tip with its corresponding deformation. In the same way, it allows evaluating the construction process and whether this procedure could generate any decrease in the load capacity of the element.

In general, there are two methods for applying axial load to a foundation element, which are indicated in the following subchapters.

1.2.1 *Unidirectional*

The application of the load on the head of the foundation element is carried out by means of hydraulic jacks which will be joined to a reaction mechanism, Figure 1. The application of the load can also be carried out by means of elements that generate a counterweight. In this way, stresses are generated at the tip and the shaft of the foundation element that oppose the applied load. This type of tests has a procedure indicated in the ASTM-D1143 standard, where there are 7 ways to carry out the test.



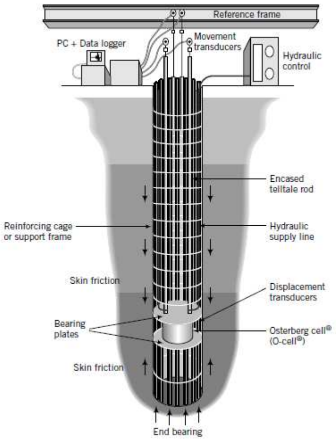


Figure 1. Unidirectional load test scheme, with reaction frame (Budhu, 2001).

1.2.2 *Bidirectional*

The load is applied at specific points, or multiple levels, through load cells embedded within the foundation element, Figure 2. The cells can be pressurized for the application of loads from the surface level, and with these loads, the foundation element may experience upward or downward movements. The procedures for applying the load are standardized by ASTM-D8169, which indicates 2 types of tests: rapid and extended.

Figure 2. Bidirectional load test scheme using Osterberg cell.

2 DESCRIPTIONS OF THE LOAD TESTS OF THE PROJECT

2.1 *Unidirectional axial load test*

Axial load tests were performed on two piles with a diameter of 1.20 m, which were installed to a depth of 54.0 m. To replicate the existence of the basements in the project, a double steel casing was placed around each test pile, extending to a depth of 33.3 m. This casing prevents the generation of frictional forces between the pile and the soil.

The reaction system consisted of steel beams and six piles with a diameter of 1.0 m, also installed at the same depth (54.0 m), and spaced 3 m apart, as shown in Figure 3.

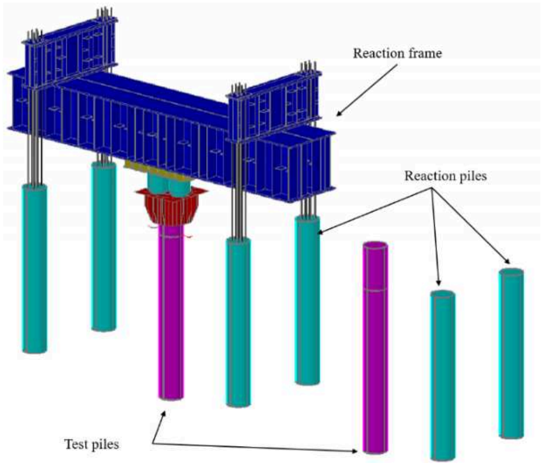


Figure 3. Scheme of test piles, reaction, and steel frame.

The reaction frame is made up of two secondary metal beams supported on a main reaction beam. The connection between the reaction piles and the frame was made by means of high resistance steel bars of 5.1 cm in diameter, Figure 4.

Figure 4. Reaction frame for unidirectional load test.

The load application was carried out using 3 hydraulic jacks with a capacity of 1000 t each. The load was transferred to the pile through a steel bed of plates placed on a steel head of the pile.

The load measurement was carried out with pressure gauges connected to the hydraulic jacks and, additionally, vibrating wire cells were installed that automatically measured the applied load.

To measure the vertical displacements of the pile head, a system of ruler and tensioned wires was used, in addition to topographic measurements.

To measure the displacements and load along the element, pairs of strain gauges were installed.

The load application was contemplated to be carried out through load increments of the order of 100 t (5% of the maximum test load) in an interval of 30 minutes until reaching the maximum load or a certain failure criterion.

Once the maximum charge is reached, the battery would be discharged by applying decrements of the order of 10% of the maximum applied charge.

2.2 *Bidirectional axial load test*

Two load tests were carried out on barrettes with dimensions of 2.7x1.2 m deployed at 80 m depth.

Four Osterberg cells were placed, which were in pairs at 2 depth levels, the first at 57 m and the second at 75 m. Each Osterberg cell array had a load capacity of 2722 t, which could develop a maximum load of 5444 t, Figure 5.

Figure 5. Osterberg load cells.

For each level of Cells, 6 vibrating wire displacement transducers were placed, which were fixed to the bottom plate of each cell. These transducers have the function of directly measuring the opening of the cells.

Four Tell-Tales were placed located at the top plate level of each pair of cells. These Tell-Talles will allow the upward displacement generated by each cell to be recorded.

In addition, there were 4 Tell-Tales type ECT (Embedded Compression Tell-Tale) placed from the level of the lower plate of the pair of cells at 75 m depth, which will allow measuring the compression between this level of cells and the tip of the barrette.

Likewise, it was required to place 2 ventilation tubes placed from the bottom plate level of each cell array to the platform level. These tubes will allow ventilation of the annular space between the Osterberg Cells and the clear cover of the barrette.

Finally, four extensometers (“Sister Bars”) were used at different depth levels within the barrette. The levels at which they were located coincide with the boundaries of the strata of the geotechnical model.

Loading was applied using the extended loading procedure, which is done in increments of no more than 5% of the estimated maximum test load. The load would remain constant at each increment for at least 30 minutes. In this way, the load tests were planned to be carried out in three stages, Figure 6:

Stage 1: The first cell array located at 75 m depth is pressurized where the tip load capacity and friction between the 75 to 80 m deep section are evaluated. In this stage, the lateral friction of the 75 m of barrette is used as a reaction medium.

Stage 2: The upper array of cells located at 57m depth is pressurized to evaluate the friction resistance between the two levels of cells. In this stage, the lateral friction of the 57 m of barrette is used as a reaction medium.

Stage 3: The upper arrangement is further pressurized to evaluate the frictional resistance of the upper section of the pile. In this stage, lateral friction below the upper arrangement of cells is used as a reaction medium, that is, from 57 to 80 m deep.

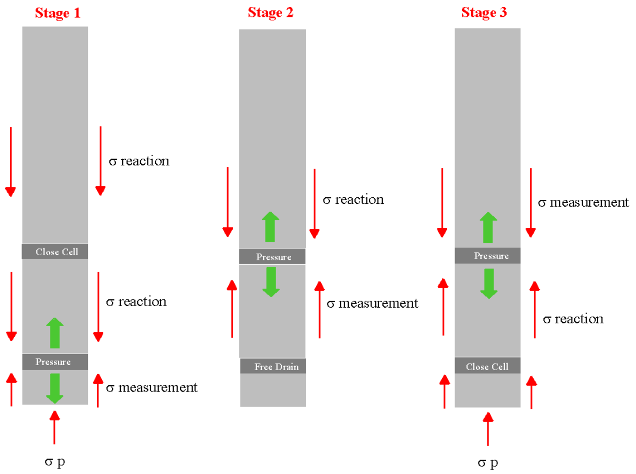


Figure 6. Scheme with load stages for bidirectional tests.

3 CONSTRUCTION OF TEST PILES AND BARRETTES

3.1 *Pre-injections, verticality and post-injection in piles and barrettes*

Proper construction methods for barrettes and piles in the Valley of Mexico's lacustrine zone is crucial for ensuring the successful execution of foundation elements. To achieve this, preliminary injections of mortar were performed to depths of 54 and 80 meters, corresponding to the offset levels of the test foundation elements.

The main objective of these preinjections is the sealing of possible sand lenses found randomly in the clay formations, as well as possible cracks that exist in the subsoil clay formations. Sealing these cracks or sand lenses prevents sudden drilling mud loss during the construction of the piles or barrettes, which can destabilize the excavation.

During the drilling of the barrettes and piles, the verticality was verified by means of the cables and, in addition, by means of a drilling equipment program, which allows the operator to observe the percentages of deviation and twist. Additionally, once the excavation has been carried out, a survey is carried out using a sonar called “Koden” which descends along the entire depth of the drilling and can graph the profile of the excavation.

Two 10 cm diameter tubes were placed on the test piles and barrettes to perform post-injection at the tip of these test elements. The post-injection was carried out 72 hours after casting the element and was carried out under the following sequence: drilling through the reservation to a depth of 0.20 m below the planting level, cleaning the inner tube by circulating clean water, filling the tube with grout injection and placement of the plug and, finally, pressure grout injection up to a maximum volume or reaching a maximum pressure of 5 kg/cm^2.

3.2 *Construction of test and reaction piles*

The two 1.2 m diameter test piles were constructed using concrete with compressive strength of f´c= 450 kg/cm^2.

Drilling was carried out using Bauer BG-30 type drilling rig and bentonite mud was used as drilling fluid. Upon reaching the bottom, bottom cleaning was carried out and the drilling bentonite mud was replaced with clean bentonite mud.

The instrumentation was placed in the assembly of the piles and during the descent of the pile reinforcement to the drilling, the cables that would come to the surface were placed.

Four 4.8 cm diameter sonic tubes were placed in each stack to carry out “Crosshole Sonic Logging” integrity tests.

Additionally, 6 circular piles of 1.0 m diameter were built, founded at a depth of 54 m. Six high-strength bars of 5.4 cm diameter were placed in each of the piles, which were connected to the reaction frame.

A concrete slab on the tests area was constructed to provide a flat surface for the placement of the concrete blocks that resist the weight of the secondary beams when a load is not being applied and, additionally, a suitable surface for placement of the instrumentation frame, where the strain readings will be recorded, Figure 7.

Figure 7. Reaction frame assembly.

3.3 *Construction of test barrettes*

The two test barrettes measuring 2.7x1.2 m in size were constructed using concrete with compressive strength f'c= 450 kg/cm^2. Bentonite mud was used as drilling fluid.

Due to the 80 m length of reinforcement, the reinforcement was lowered to the drilling in 5 lifting sections, Figure 8, where the load cells were in 2 of them. In the sections with the load cells, the lifting maneuver was carried out using two cranes, where one of them loaded the lifting handles and the other crane punctually loaded the Osterberg cells.

Figure 8. Lifting of reinforcement section with Osterberg Cells.

At the location of the cells, steel plates were placed above and below each of them, additionally, IR-type profiles were placed above these plates which could help transfer the load to the barrette, Figure 9.

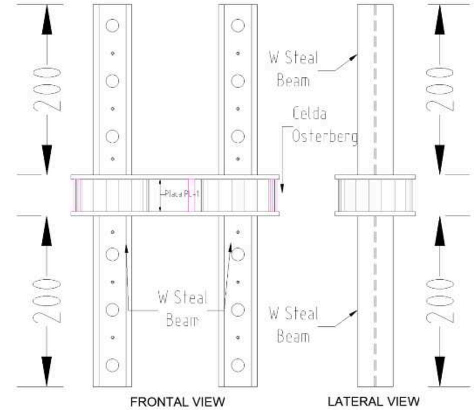


Figure 9. Schematic detail of Osterberg Cell arrangement assembly.

Additionally, the longitudinal reinforcement of the barrette had to be cut during the lowering of the assembly, to prevent the reinforcement from resisting tension forces due to the load of the cells themselves. To cut the reinforcement, welded plates had to be placed between the reinforcing rod and the cell plates, Figure 10.

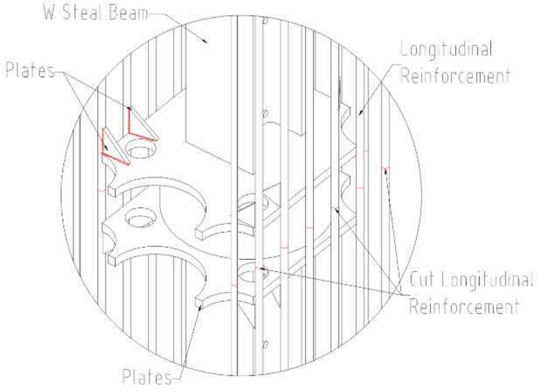


Figure 10. Schematic detail of plates for cutting longitudinal reinforcement.

Additionally, grease was placed above and below each cell plate to prevent the concrete from bonding to these plates.

Figure 11. Reinforcement descent to drilling in the Osterberg cell area.

Placement of the reinforcement cages into the drilling shaft of the test barrettes lasted up to 12 hours, because of: the instrumentation had to be installed, execution of 4 overlaps of reinforcement cages due to the 5 lifting sections and the cutting of longitudinal reinforcement at the cells zone, Figure 11.

4 EXECUTION OF LOAD TESTS

4.1 *Unidirectional static axial load test*

The test was carried out as initially planned, that is, 20 load increments of 5% of the planned test load (2,000 t) lasting 30 minutes. Each increase was applied by activating the pump that injects pressure into the hydraulic jacks. The magnitude of the applied load was verified by load cells and maintaining the pressure of the 3 hydraulic jacks constantly.

Load and displacement readings were taken at 0, 5, 10, 20 and 30 minutes after application of each load increment.

Once the maximum load was reached, it was held for 2 hours and readings were taken at 0, 5, 10, 20, 30 minutes, and subsequently every 15 minutes until completing the two hours of sustained loading.

Once this stage of sustained loading was completed, the load was removed in ten decrements of approximately 10% of the maximum test load, lasting one hour each.

Once the test was completed, a final reading of the threads and rules was carried out 12 hours after having completely unloaded, to measure the residual settlement.

It should be noted that in both test piles the maximum load of 2000 t was achieved.

4.2 *Bidirectional static axial load test*

Initially, the cells were pressurized to break the weld that kept the cells closed, and these readings were taken as "zero reading".

During the execution of the test, the test procedure was slightly adjusted according to what was initially established. This adjustment was made because in Test Stage 1, the tip deformed a little more than estimated, thus, to illustrate, the loading stages of the first test barrette are described:

Stage 1. In the first stage, the two cells located at a depth of 75 m were applied 8 increments of bidirectional load, with a maximum load of 1968 t descending and 1620 t ascending. The loading stages stopped at this eighth increment because there were 14.3 cm of deformation (14 descending and 0.3 cm ascending). Subsequently, 5 load decrements were applied.

Stage 2A. The cells located at 57 m depth were pressurized, when the sixth load increase was carried out, a sudden deformation of 7.5 cm occurred. The maximum load was 1,359 t descending and 1,092 t ascending, for which the geotechnical failure of the section from 57 to 75 m deep was achieved. At this stage it was also possible to mechanically close the cells located at 75 m depth, leaving them with a stroke of 3 cm.

Stage 2B. Following the closure of the cells at 75 meters depth, the behavior of the barrette from 57 to 80 meters indicated a return to a rigid body state. In this way, in this stage 9 additional increases were applied to those of the previous stage. In this way, a final load of 3,670 t was achieved in downward and 3,403 t in upward. These loads produced deformations of 6 cm upwards and 14 cm downwards. In this way, the geotechnical failure of the section from 0 to 57 m was achieved.

Stage 3. In this last stage, the cells located at 57 m depth were blocked. In this way, the load began in the cells located 75 m from which 8 load increments were initially applied to reach the load of Stage 1, subsequently 4 additional increments were applied where a maximum descending load of 2952 was reached. t and ascending of 2604 t for a maximum displacement of 1.3 cm ascending and 16 cm descending.

Figure 12 shows a barrette during the test execution.

Figure 12. Bidirectional load test execution.

Schematically in Figure 13, the adjustment of the loading procedure is indicated, according to the behavior of the test barrette.

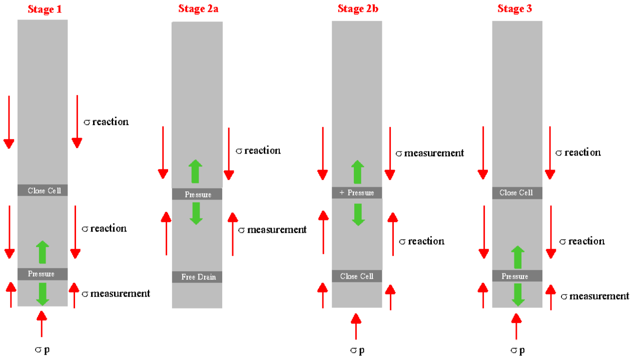


Figure 13. Test procedure adjustment scheme.

The second test barrette had similar behavior, therefore, a summary of the results for each test stage for both barrettes is shown in Table 2.

Table 2. Maximum loads and deformations for each loading stage in test barrettes.

ID	-	Maximum load (t)	Displacement (cm)
BT1-E1	Upward	1620	0.3
	Downward	1968	14
BT1-2A	Upward	1092	1.4
	Downward	1359	7.5
BT1-2B	Upward	3404	6
	Downward	3670	14
BT1-E3	Upward	2604	1.3
	Downward	2952	16
BT2-E1	Upward	2132	4.3
	Downward	2481	14.5
BT2-2A	Upward	1203	1.8
	Downward	1471	8.1
BT2-2B	Upward	2625	6.1
	Downward	2892	8.5
BT2-E3	Upward	3094	1.5
	Downward	3444	15.8

In this way, the maximum possible load was achieved in each of the test barrettes.

5 RESULTS ANALYSIS

5.1 *Unidirectional static axial load test*

5.1.1 *Test pile 1*

Test pile 1 reached a maximum load of 2056 t for a vertical deformation of 11.4 cm.

The load-deformation curve shows a linear behavior up to 1300 t, but from that load it is observed that there are larger displacements with load increases like the previous ones, Figure 14.

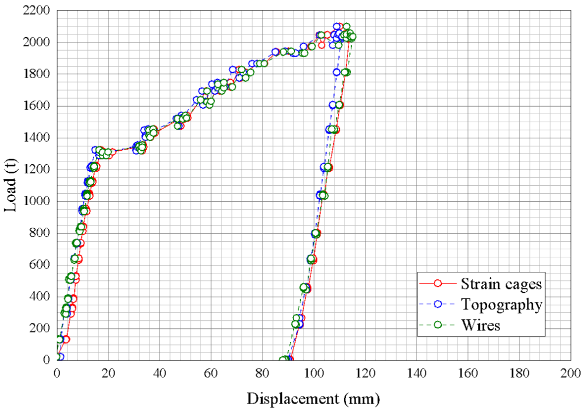


Figure 14. Load-Settlement Chart for Test Pile 1.

Figure 15 illustrates the axial load distribution with depth. The graph indicates minimal load loss due to friction within the casing pipe. Below this zone, the load transfers proportionally between the shaft and the tip of the barrette.

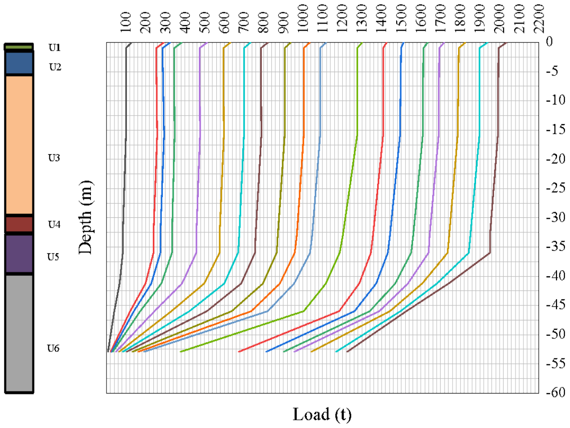


Figure 15. Axial load distribution with respect to depth for test pile 1.

Using Sister Bars placed along the test pile, stress-displacement graphs are constructed by instrumentation level. For its construction, the theoretical perimeter of the section and the difference in strength between each level of Sister Bars are considered.

In this way, if we consider that the pile has a maximum displacement of 2.5 cm, average friction stress values of 10.2 t/m^2 are obtained, while at the tip it can develop a stress of approximately 460 t/m^2.

Finally, after removing the load completely, there was a recovery of 2.5 cm, maintaining a residual settlement of 8.9 cm.

5.1.2 *Test pile 2*

Test pile 2 achieved a maximum load of 2075 t for a vertical deformation of 10.4 cm.

The load-deformation curve shows a linear behavior up to 1480 tons. Beyond this load, there was an increase in the slope, due to the increase in deformations with the increase in loads like the previous ones, Figure 16.

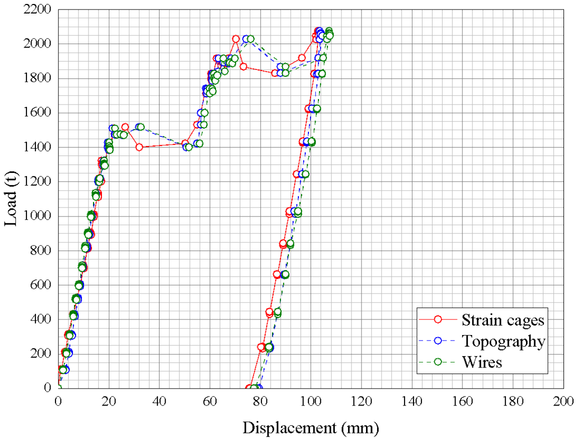
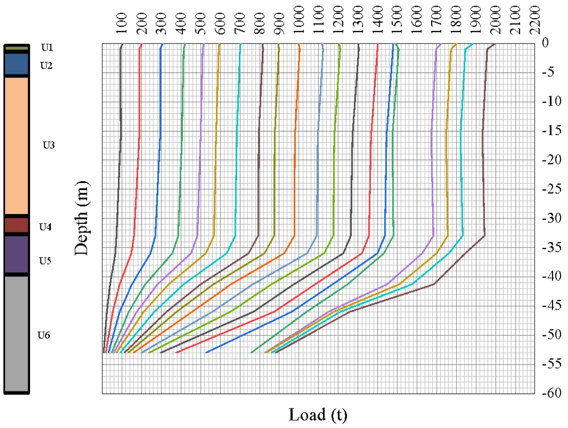


Figure 16. Load-Settlement graph for test pile 2.

In Figure 17, the load distribution with respect to depth is shown, where it can be observed that the load is transmitted without friction loss in the casing pipe, and after that, the load is distributed in the shaft and tip of the pile.

The stress-displacement graphs by level show stress values like those of pile 1, that is, if we consider that the pile has a maximum displacement of 2.5 cm, average friction stress values of 11.5 t/m^2 are obtained, while at the tip it can develop a stress of approximately 470 t/m^2.

Figure 17. Axial load distribution with respect to depth for test pile 2.



5.2 *Bidirectional static axial load test*

5.2.1 *Test barrette 1*

From the bidirectional load test, axial load and displacement curves were obtained for each cell level. During the load increases in each of the stages, readings were taken at each Sister Bar level of the load, to know its distribution according to depth.

Figure 18 shows the axial load and displacement curve for the 3 loading stages in the cells located at 75.0 m depth, while Figure 19 shows the same results, but for the cells located at 57 m depth.

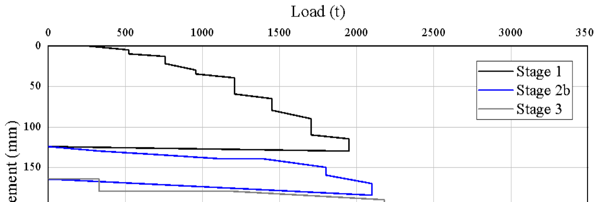


Figure 18. Load-Displacement graph for load cells at 75 m, test barrette 1.

Based on the test results, average friction stresses were obtained in the barrette shaft indicated in Table 3. These stresses correspond to deformations of approximately 2.5 cm. Additionally, for the same deformation at the tip of the barrette, an admissible stress of 230 t/m^2 was reached, Figure 20.

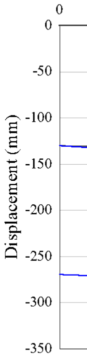


Table 3. Average stresses for barrette test 1.

Depth (m)	$\sigma_{skin\ friction}$ (t/m^2)
From 30 to 57	9.0
57 to 75	8.9
From 75 to 80	6.6

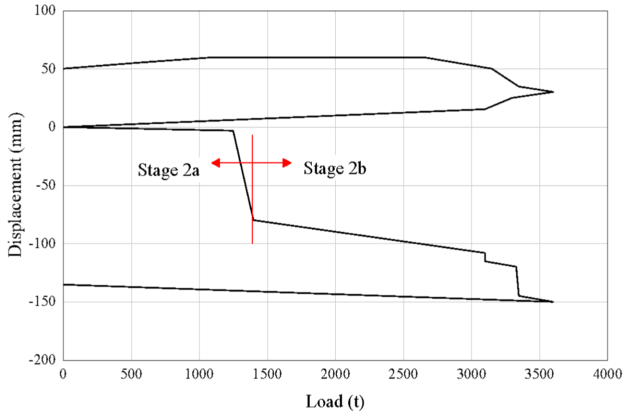
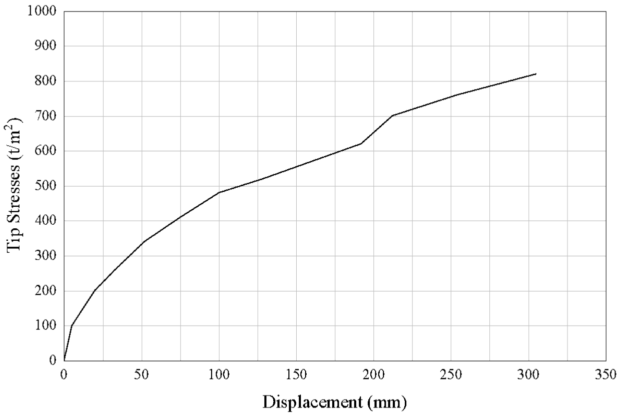


Figure 19. Load-Displacement graph for load cells at 57 m, test barrette 1.

Figure 20. Load-Displacement graph at the tip of test barrette 1.



5.2.2 *Test barrette 2*

In the same way as test barrette 1, axial load and displacement curves were obtained for each level of cells. Thus, Figure 21 shows the axial load and displacement curve for the 2 loading stages in the cells located at 75.0 m depth, while Figure 22 shows the same results, but for the cells located at 57 m depth.

Figure 21. Load-Displacement graph for load cells at 75 m, test barrette 2.

Based on the test results, average friction stresses were obtained in the barrette shaft indicated in Table 4. These stresses correspond to deformations of approximately 2.5 cm. Additionally, for the same deformation at the tip of the barrette, an admissible stress of 280 t/m² was reached, Figure 22.

Figure 22. Load-Displacement graph for load cells at 57 m, test barrette 2.

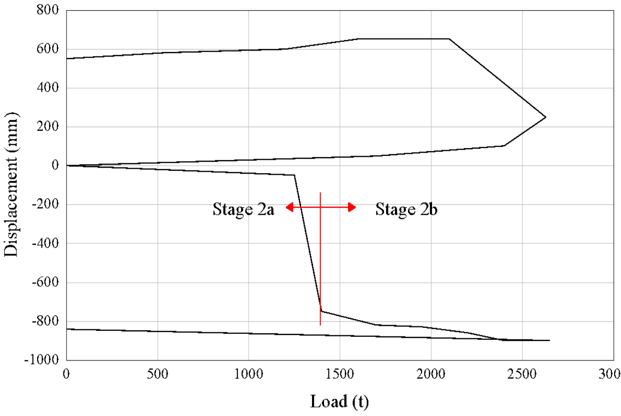


Table 4. Average stresses for barrette test 1.

Depth (m)	$\sigma_{\text{skin frction}}$ (t/m²)
De 30 a 57	7.3
57 a 75	9.4
De 75 a 80	4.9

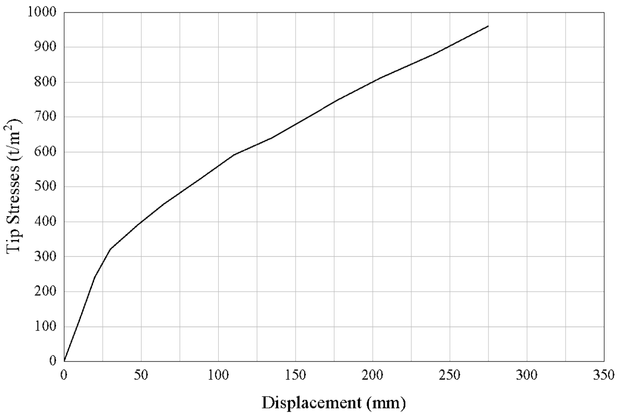


Figure 23. Load-Displacement graph at the tip of test barrette 2.

5.2.3 *Equivalent curve for test barrettes*

The method for constructing an equivalent curve consists of choosing an arbitrary point on the ascending and descending curve, where the sum of the loads that generate this same displacement is the load that is graphed on the equivalent curve.

The shortening caused by the compression of the element must be considered in the analyses, so the curve already constructed is adjusted with this criterion.

$$\delta_{\uparrow} = c\,\frac{Q_{\uparrow} * I}{AE}$$

$$\delta_{\downarrow} = c\,\frac{Q_{\downarrow} * I}{AE}$$

where:
Q: upward or downward load applied
L: compression barrette length
A: barrette cross section
E: modulus of elasticity of barrette

The weight of the element during upward or downward movement is also considered in the adjustment of the equivalent curve.

$$Q_{\uparrow} = Q_{\uparrow} - w_P$$
$$Q_{\downarrow} = Q_{\downarrow} + w_P$$

Where:
Q: upward or downward load applied
w_P: weight of the barrette providing or subtracting load from the cells by gravity.

With the previously established considerations, the equivalent curves were obtained for both barrettes.

For the BT-1 barrette, considering maximum displacements of 2.5 cm, a load of 4400 t was obtained corresponding to an average friction stress of 8.1 t/m², Figure 24. This average value is like the average values indicated in Table 3.

For the BT-2 barrette, considering a displacement of 2.5 cm, a load of 4000 t was obtained which corresponds to an average friction stress of 7.3 t/m², Figure 25. This average value is like the average values indicated in Table 4.

Figure 24. Equivalent curve for test barrette 1

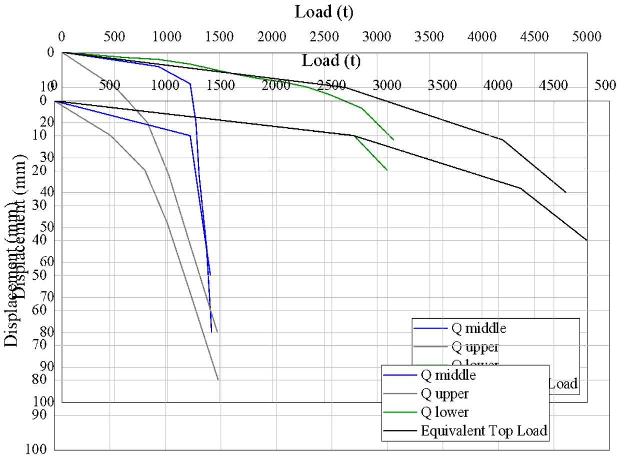


Figure 25. Equivalent curve for test barrette 2

It should be noted that the friction stress between the foundation element and the ground was estimated using the normal section of the barrette, but for the test barrettes, once the 3 loading stages were completed, it became evident on the surface that friction was developed between ground-ground at an average distance of 1.5 m from the dimensions of the barrette, Figure 26.

Figure 26. Superficial cracks at the end of loading stages in test barrette.

6 CONCLUSIONS

Load testing of deep foundation elements is crucial for understanding their behavior under real conditions. These tests measure the relationship between applied load and resulting deformation, allowing engineers to design foundations that can withstand the expected stress range during service.

Compression load tests with reaction frames are primarily used with circular foundation elements because the applied loads can reach the ultimate load capacity of the element.

Compression load tests using Osterberg cells allow significant higher magnitudes of loads to be applied to the foundation test elements.

In both kinds of load tests, it is important to consider all the construction details to successfully achieve their execution, for example, in the Lake Zone of the Mexico City Valley, the use of pre-injections is essential to prevent the excavation from destabilizing during drilling.

Particularly in the load tests with Osterberg cells, there are construction particularities to be considered to achieve their correct execution, that is, from the lifting maneuver of the cell reinforcement to the consideration of cutting the reinforcement at the cell level, as well as the placing of grease in that same area to prevent the concrete from adhering to the plates.

In the test piles considering a deformation of 2.4 cm, average friction stress of 10.8 t/m^2 was obtained, while, at the tip for that same level of deformation, an average stress of 465 t/m^2 was obtained.

In the test barrettes, if the deformation is restricted to the same 2.4 cm, an average friction stress of 7.7 t/m^2 was obtained, and a stress of approximately 255 t/m^2 can be developed at the tip.

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