

Axial compression and pull-out tests on instrumented cast-in-place shafts of Viaducto Bicentenario, México

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ABSTRACT

The overpass on Periférico named Viaducto Bicentenario is being built in the northwestern metropolitan area of Mexico City. This 23.5 km long overpass will connect Cuatro Caminos and Cuautitlán Izcalli, in Estado de México. The superstructure is of the Gerber type. The support beam rests on two isolated and prefabricated columns; each of them is monolithically cast to its footing. The footing in turn has the corresponding holes and preparations to be received by four cast-in-place shafts. Subsoil founding conditions vary from stratified clays and soft volcanic rocks to harder rocks. Considering the magnitude of this overpass, as well as the variety of geomaterials along its trace, it was considered of great importance to carry out compression and pull-out load tests in different sites. Experimental test results of one site (A-72) and bearing capacity theoretical design are presented and compared in this paper.

RESUMEN

Al Noroeste de la zona metropolitana de la ciudad de México se construye el Viaducto Bicentenario que comunicará Cuatro Caminos y Cuautitlán Izcalli, en el Estado de México mediante una vialidad elevada de 23.5 km de longitud. El cuerpo de la superestructura es del tipo Gerber. La trabe de apoyo está soportada por dos columnas prefabricadas; cada una de ellas llega con su zapata monolíticamente colada y con sus preparaciones para ser recibida por cuatro pilas de cimentación coladas *in situ* que se desplantan en una diversidad de formaciones, abarcando desde las arcillosas estratificadas hasta las tobas y otras rocas. Dada la magnitud de la obra y la variedad de geomateriales donde se desplantaron los apoyos, se consideró muy importante verificar experimentalmente en campo las estimaciones teóricas de capacidad de carga de pilas, por lo que se ejecutaron pruebas de carga axial a compresión y a extracción en pilas instrumentadas en varios sitios de la obra. En este artículo se presentan los resultados de pruebas en uno de esos sitios, el A-72, y se comparan con las previsiones de diseño.

1 INTRODUCTION

1.1 Description of the overpass

The overpass has the main objective of providing efficient vehicular circulation on Periférico Norte, from Cuatro Caminos to Cuautitlán Izcalli, in Estado de México, in the metropolitan area of Mexico City. The overpass crosses the municipalities of Naucalpan de Juárez, Tlalnepantla, Tultitlán and Cuautitlán Izcalli. It has a total length of 23.5 km and benefits more than nine million persons.

1.2 Structural system in the overpass

The body of the superstructure is of Gerber type, in which the ends of each support beam rest on central isostatic beams. The support beam is supported by two isolated prefabricated columns; each one arrives to the site with its monolithically precast footing and with its preparations to be received by four cast-in-place shafts.

The column-footing weighs around 1200 kN. The footing measures 4.60 m by 3.60 m and 1.7 m height. The shafts have 0.80 m in diameter and variable lengths. The test shaft near support A-72 had 0.70 m in diameter and 21 m long.

2 GEOTECHNICAL CONDITIONS

2.1 Location

Figure 1 shows the position of Viaducto Bicentenario (thick line at Northwest) and the test location, in the geotechnical Zone I (Hills zone) defined in the local Building Code, RCDF (GDF, 2004). It can be observed that the trace of the overpass runs mainly on the Hills Zone, except a portion to the North, which crosses the border between the Transition Zone and the Hills Zone. The first series of tests, named A-72 given the nearby support nomenclature, was carried out on Section 1, which is located, from the geological point of view, within the Tarango formation, formed mostly of volcanic tuff, breccias, pumice dust and pyroclastic materials, layered with sands and alluvial gravel with reaching depths down to 50 m.

2.2 Stratigraphy of A-72 site

According to the sounding by means of the standard penetration test named SPT-A72 (Fig. 2), granular materials were detected at the site, mainly.

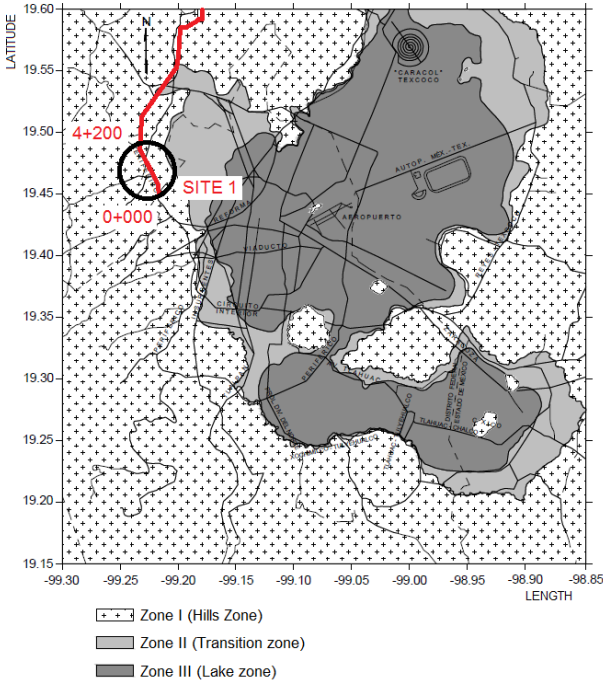


Figure 1. Geotechnical zoning of Mexico City and A-72 test location

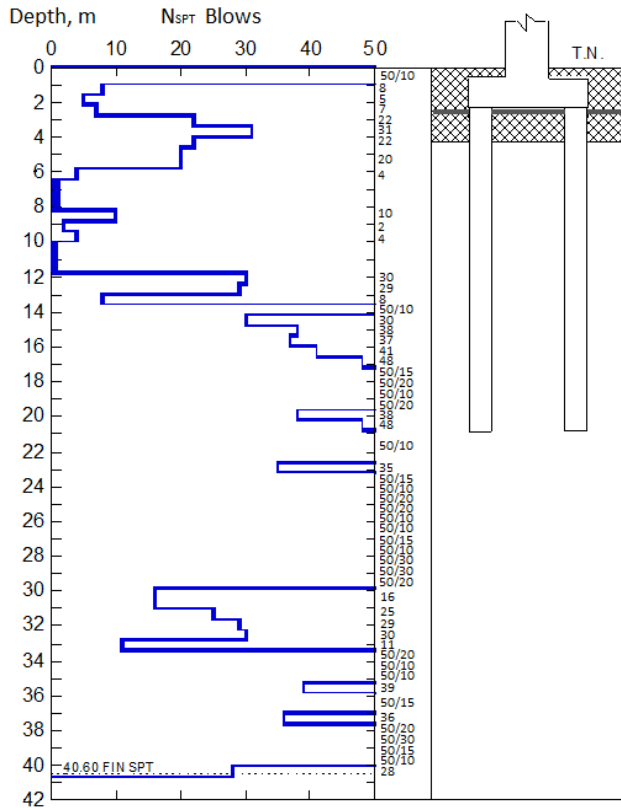


Figure 2. Soil profile at A-72 site

On the top, a heterogeneous fill 0.60 m thick was distinguished, composed mainly of dark brown clayey sand. Underneath, is a sequence of dark brown soft to medium clay extending up to 2.50 m depth, with 8 blows from the SPT. Up to 5.80 m depth a gravel layer was detected in a matrix of fine to medium sand, brown to gray in color, of medium relative density. Underling this stratum there is a silty soft clay of dark brown color with some layers of fine to medium sand, extending up to 11.80 m depth. Finally, gravel packed in a matrix of fine to medium sand was detected, of dark gray color and very high relative density; this stratum extends up to 40 m depth with more than 50 blows from the standard penetration test, having a lens of clayey sand between 30 m and 33.50 m depth, with 11 to 30 blows from the SPT.

3 DESCRIPTION OF THE INSTRUMENTATION

The objective of the load tests was to distinguish and quantify with precision the contributions to bearing capacity by shaft friction and tip of the shaft. To achieve this objective the shaft was instrumented internally with electric and mechanic transducers or sensors (Hanna 1985). The actions and reactions on several sections of the shaft were determined from the measurements obtained with strain gages embedded in the concrete. These sensors were integrated to the steel reinforcement of the shaft (Fig. 3).

In addition, several tell-tales or mechanical devices to measure displacements between two sections were installed; in this case, between two sections of the shaft and its head. Also, retrievable vibrating wire extensometers were used, which have similar functions to that of the tell-tales. For that, a PVC pipe was used to place them in, fixed to the main steel by means of plastic straps. Finally, the estimation of the loads acting on the tip of the shaft was obtained through the recordings of a pressure cell at the tip. The depths at which the sensors were placed are shown in Fig. 4.

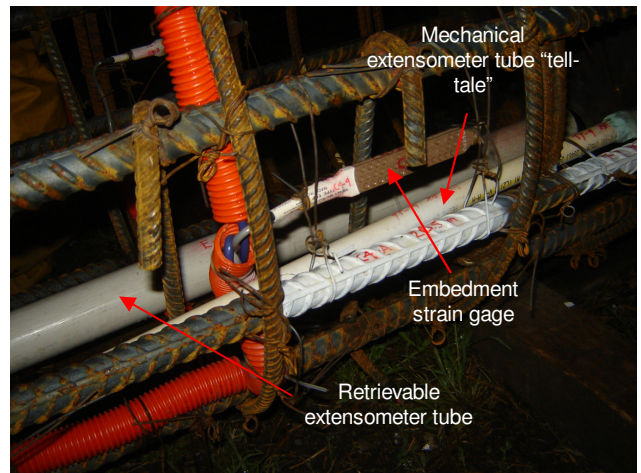


Figure 3. Instrumented shaft section

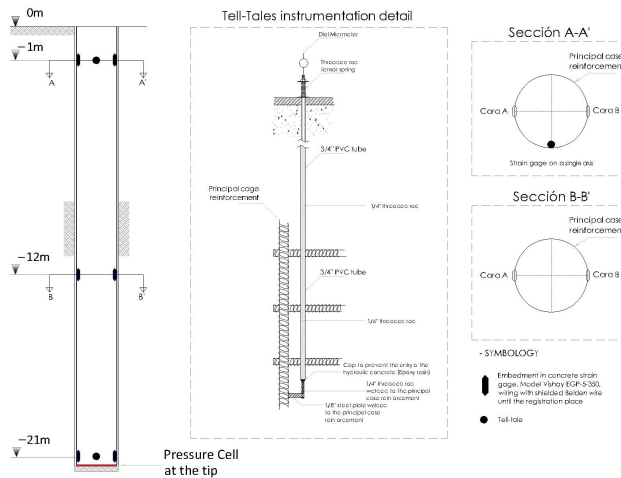


Figure 4. Shaft Instrumentation at A-72 site

The monitoring of the strain gages obliged to recur to an automated data acquisition system (DAS), which makes a scan at intervals of up to one second, keeping all its recordings for later analysis. Despite this digital system, precaution was taken of also including dial indicators to measure head displacements directly (Fig. 5).



Figure 5. General view of head instrumentation for a compression test

4 REACTION SYSTEM AND LOAD APPLICATION

At the central shaft named “test shaft” of a group of five, as shown in Fig. 6, an axial compression test, a pull-out test and a lateral load test were carried out. For the axial compression test, the reaction system forms an H shape in plant, with a main beam that reacts directly with the head of the test shaft, and transfers the load to two secondary beams, and those to four external reaction shafts that work at pull-out. The assembly of each of the

reaction shafts ends when casting its heads in their corresponding reaction block. Such blocks are already attached to the steel reaction beams by means of high resistance steel rods.

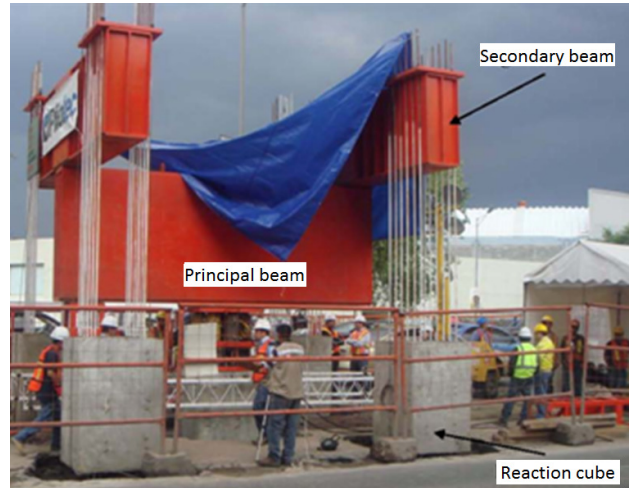


Figure 6. Arrangement for the compression test (A-72 site)

Afterward, a pull-out test was carried out to that same test shaft. Obviously, the reaction system was modified with respect to the arrangement of the compression tests. The secondary beams now rested on the blocks, and the main beam on the secondary beams. The hydraulic jacks now placed on the main beam pull the head through the high resistance rods.

5 TEST PROGRAM

The execution of axial load compression and pull-out tests followed the general guidelines established by the ASTM (1981) standardized procedure, under the section referring to tests with constant load increments applied at constant time intervals, although adjustments were made to meet the objectives of the investigation and to satisfy the very limited time restrictions imposed by this work under construction.

The sequence of the axial load compression and pull-out tests on site A-72 was as follows: the compression test in its phase I began on June 25th, 2009 and concluded the next day. Then, the pull-out test was carried out, starting on June 30th, 2009 and concluding the next day. In the meanwhile, the results of the compression test phase I were analyzed, concluding that the tip had practically not been requested, so the convenience of doing an additional load compression test was considered, here recognized as phase II, with the objective of displacing the shaft tip sufficiently to work. Thus, phase II of the compression test began on July 7th, 2009 and ended the next day. The loading stages of the

compression tests in their phases I and II are described in Table 1. The loads indicated are nominal.

Table 1. Compression loads applied for A-72 test

Stage	Load			Unload	
	Number of load increments or cycles	Increasing magnitude or cycle (kN)	Maximum load kN	Number of load decrements	Decreasing magnitude kN
PHASE I					
1 Preload	3	400	1200	3	400
2 Sustained load	6	350	2100	-	-
3 Cycling	50	300	2400/1800	6	350
4 Failure	11	800	9000	5	1800
PHASE II					
1 Preload	5	1000	5000	5	1000
2 Failure	13	800	10000	6	1666

6 COMPRESSION TEST RESULTS

6.1 Load-displacement response at the shaft head

The load-displacement response at the shaft head for all the phase I load stages is shown in Fig. 7. The results correspond to those recorded automatically by the load cells and the displacement transducers on the head.

In a first stage, a maximum load of 1147 kN was imposed on the shaft, showing a deformation of 1.3 mm; upon arrival at this load, the shaft was controlled unloaded, recording a permanent displacement of 0.2 mm. For the second loading stage, a sustained load of 1962 kN was reached, associated to a head displacement of 2.5 mm; with this sustained load, cyclic loads were applied on the third stage, identified as cycles A and B, with maximum and minimum loads of 2335 kN and 1649 kN, with cycle B concluding with a sustained load of 1961 kN. At the end of the cyclic stage the accumulated displacement was 2.8 mm. After this stage, the shaft was completely unloaded, with an elastic recovery of 2.1 mm, meaning that up to these load levels, the shaft-soil system behavior is shown mainly at the elastic interval. At the fourth stage, a maximum load of 8650 kN was reached, associated to an accumulated deformation of 39.9 mm; the elastic recovery at that stage was of 12 mm, meaning that the shaft-soil system showed an important permanent deformation.

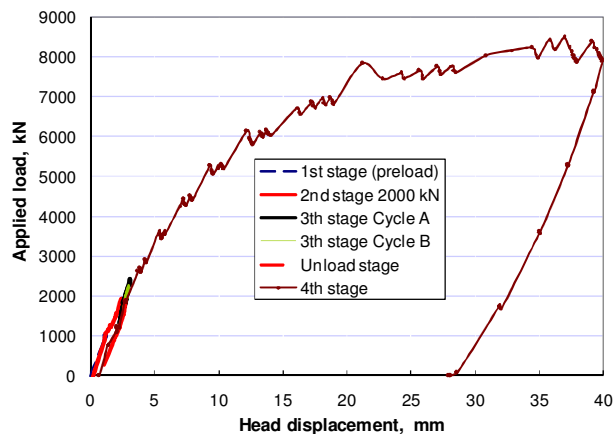


Figure 7. Load-displacement curves. Compression test, phase I

Figures 8 and 9 compare the load and displacement measurements for the fourth stage recorded with displacement cells and transducers, against those obtained from manometer readings associated to the jack area and three dial gages placed at the head. It is observed that the resulting curves are entirely similar, showing slightly smaller deformations to those recorded with dial gages, particularly for the initial stage of the loading branch and for the unloading branch.

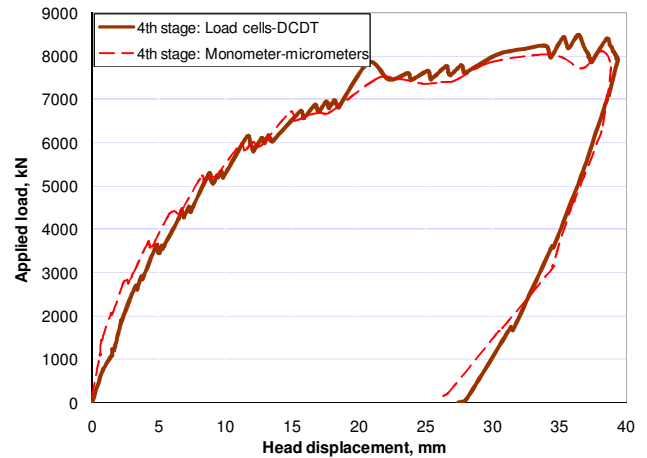
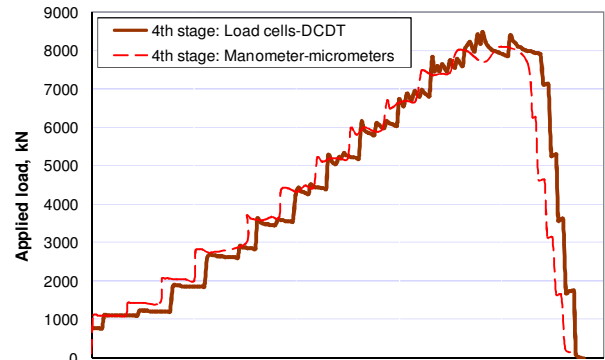


Figure 8. Load-displacement at head for fourth stage. Compression test phase I



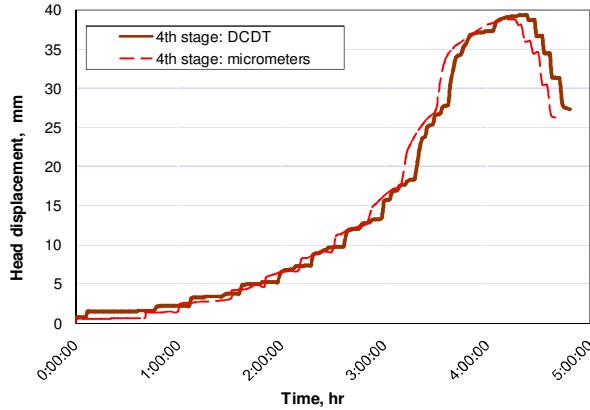


Figure 9. Measurements at head versus time for fourth stage of phase I

The above figures show, on one hand, data fidelity by obtaining practically the same results with two different measuring systems, and on the other, make evident the goodness of having redundant measuring systems to ensure having records in case of lost information or damage of one of them (Dunnicliff, 1988).

Similarly, results obtained from the test in phase II have been recorded. The compression test for phase II was preceded by a pull-out test, so that in a first stage of this phase the shaft was subjected to a compression pre-load of magnitude equal to the applied pull-out load, and at a second stage the shaft was taken to geotechnical failure. The results of both stages of phase II are shown in Figure 10, where the load applied to the head and the deformations measured by DCDT have been put into a graph. We point out that the unloading branch slope of stage one is very similar to the loading branch slope of stage two; in this stage a maximum load close to 10,000 kN was reached.

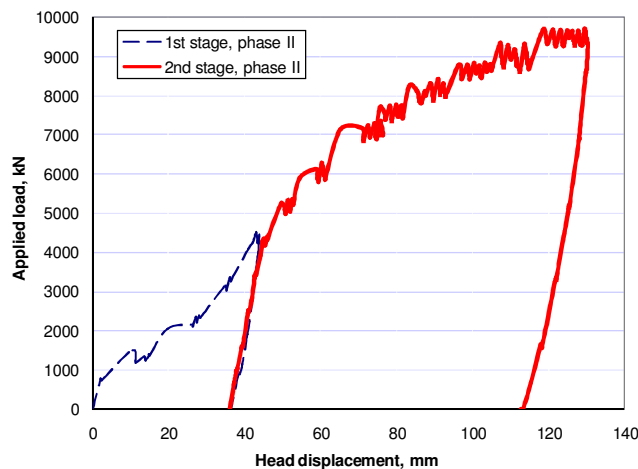


Figure 10. Load-displacement curves, Compression test, phase II

6.2 Load at different depths

Microstrains (unitary deformation values times 10^{-6}) recorded in the concrete, against time for the fourth stage of phase I, are depicted in Figure 11. Records have been arranged by section according to their location at the shaft's depth. At 1 m section depth, maximum values of 600×10^{-6} were recorded, whereas at the section near the tip at 21 m depth, microstrains are barely in the order of 30×10^{-6} , indicating that the tip was not requested.

The load at which the shaft was requested in the instrumented sections was inferred with microstrains data, the concrete elasticity module and the area of the shaft cross section (Fig. 11). The deformability properties of the concrete were obtained by compression test in the lab, making use of direct sampling of the shaft concrete. We point out that the load recorded at the tip is barely in the order of 300 kN against the nearly 9000 kN applied to the head, as shown in Figure 12.

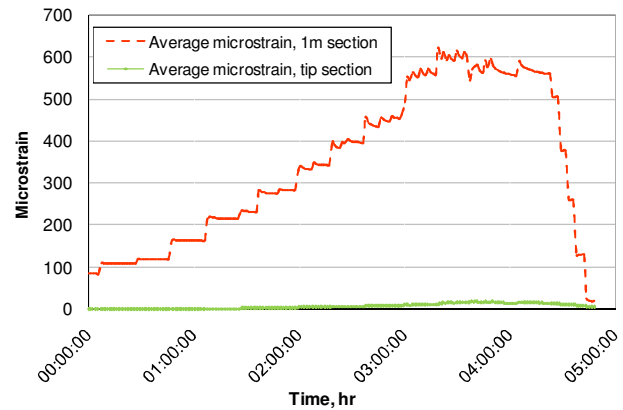


Figure 11. Measured microstrains versus time, fourth stage, phase I.

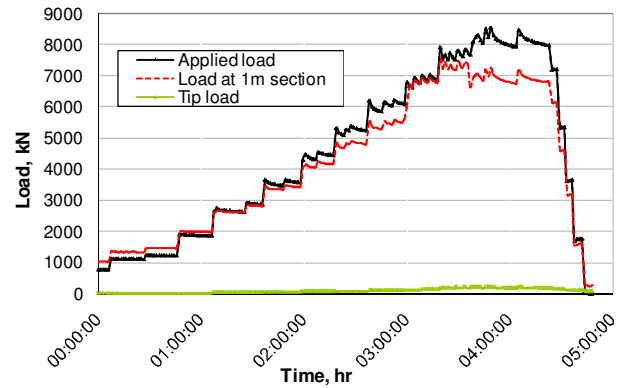


Figure 12. Load variation at head, section at 1 m and at tip (21 m) against time, fourth stage, phase I

Figure 13 shows the loads recorded at different depths for phase II. In this phase, the maximum load applied to the shaft was around 10,000 kN. The tip showed a load of 4,800 kN for the maximum load at the

head, indicating that the tip was indeed requested in phase II.

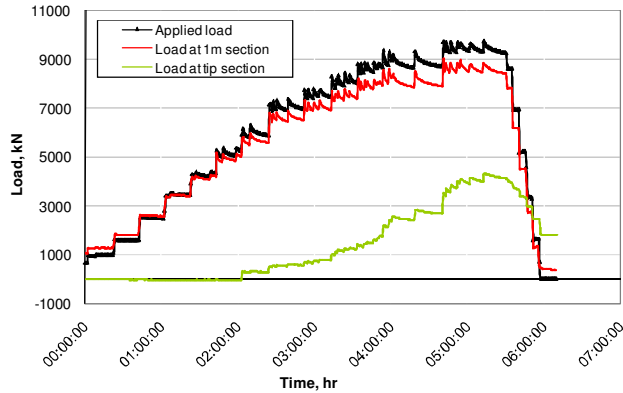


Figure 13. Load variation at head, section at 1 m and at tip (21 m) against time, second stage of phase II

7 PULL-OUT TEST RESULTS

7.1 Head Load-displacement response at the shaft head

The head load-displacement response for the pull-out test is shown in Figure 14. Results correspond to those recorded automatically by the load cells and displacement transducers at the head, DCDT.

Note that for the load of 4,000 kN measured at the head, deformation was almost of 60 mm.

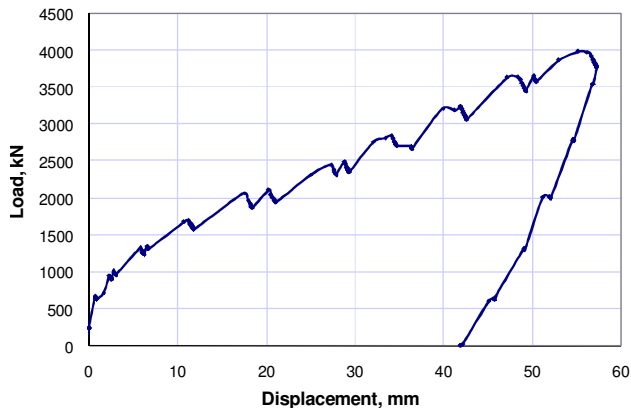


Figure 14. Load-displacement at head. Pull-out test

7.2 Load at different depths

Microstrains (unitary deformation values times 10^{-6}) recorded in the concrete, put in a graph against time for the pull out test are shown in Figure 15. Records have been arranged by section according to their location at the shaft's depth. At the section of 1 m depth, maximum values of $-350 (x10^{-6})$ were recorded, the minus sign indicating that the section worked under tension stress, whereas at the section near the tip at 21 m depth,

microstrains are very low, in the order of -10 , indicating that the tip was not mobilized with the pull-out.

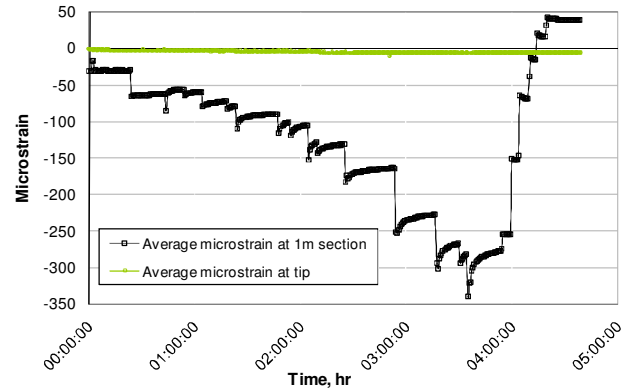


Figure 15. Microstrain measured against time, second stage of pull-out test

8 COMPRESSION AND PULL-OUT THEORETICAL LOAD CAPACITY ESTIMATIONS

The theoretical estimations of the shaft axial load under compression and pull-out, were reviewed (Romo *et al.*, 2009) with different criteria (O'Neill & Reese, 1999; Reese & Wright, 1977 taken from McGregor & Duncan, 1998; Poulos & Davis, 1980; Wysocky, 1999; Decourt, 1995) according to the geotechnical conditions of the site. Firm soils and alluvial formations predominated. Results of an exploratory campaign based on SPT borings were available in this stage.

Figure 2 shows the stratigraphic profile at A-72 site, including the footing and foundation shafts arrangement. Figures 16 and 17 show the theoretical estimations with different criteria for compression and pull-out bearing capacity, respectively, for site A-72. We point out that these results correspond to definitive foundation shafts of 80 cm diameter, whereas the load tests described here were made on shafts of 70 cm diameter. In both cases, the base depth was the same.

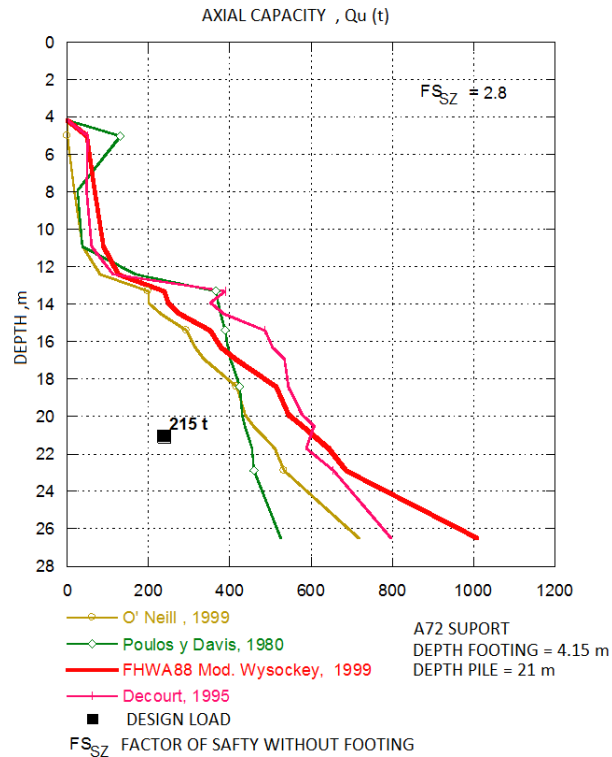


Figure 16. Theoretical estimations of the compression load capacity. A-72 site (in tons).

From the review of the theoretical procedures, we concluded that the Wysockey method (1999) was the most adequate and practical to establish the load bearing capacity at the different sites of this overpass, including the A-72 support. Figure 16 shows that a 80 cm diameter shaft would have a top load capacity of 605 t (5,935 kN), which compared to the maximum load close to 10,000 kN (Figure10) applied at phase II, results in a theoretical estimation on the safe side, more so when considering that the test shaft diameter was 70 cm.

The top theoretical pull-out capacity of 490 t (4,807 kN) for a 80 cm shaft diameter, is slightly superior than that obtained in the pull-out test for the 70 cm test shaft diameter of 4,100 kN. In this respect, it must be considered that, besides the smaller diameter of the shaft, the pull-out test was carried out only five days after the shaft had been subjected to geotechnical failure by compression, as well as being loaded cyclically with considerable cyclic deviatoric loads, just as described in section 6.1.

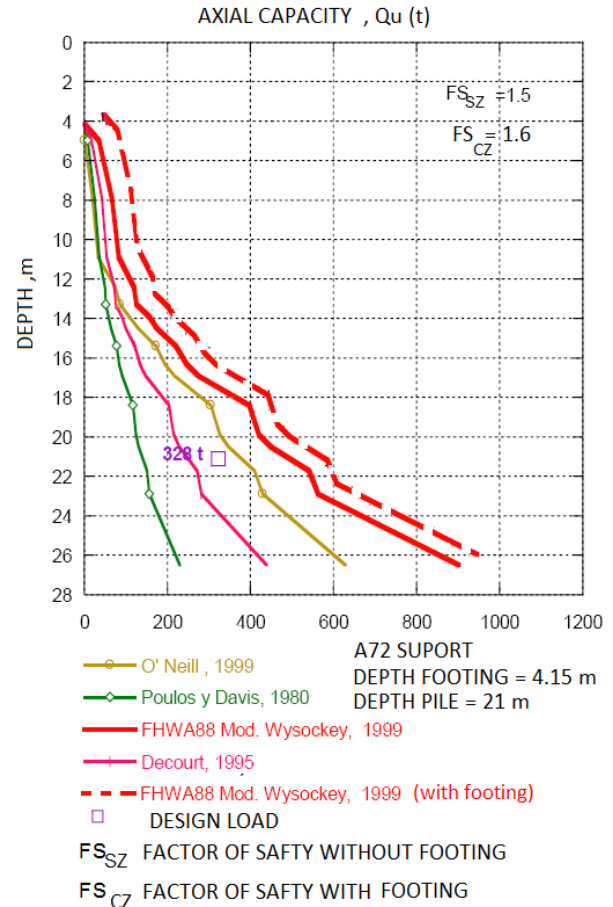


Figure 17. Theoretical estimations of pull-out capacity. A-72 site (in tons).

9 CONCLUSIONS

- a) Upon being subjected to axial vertical load equivalent to the design or permanent loads (2110 kN), which includes the structure own weight and that of the vehicles circulating on it, the test shaft barely suffered displacement of slightly less than 3 mm –see Figure 8. The implication of this result is that in the case of supports such as A-72, the settling occurs during their construction, with no prejudice to the operation of the bypass.
- b) At a final stage of compressive load (phase II), and after having executed a pull-out test, the geotechnical failure of the shaft was practically reached with a maximum load of 9700 kN, causing a penetration of 94 mm. With this maximum load, the shaft's body suffered 11 mm of compression, defining a relative displacement between the tip and the surrounding soil of 83 mm; this is slightly less than 12% of the shaft's nominal diameter.

- c) From the microstrains measured in the test shaft's concrete (Figures 11 to 13) it is observed that the point bearing contribution begins with loads above the design load (permanent actions), so we can affirm that the work of the shafts of the Viaducto Bicentenario at sites such as the one tested, for operating conditions, is basically by shaft friction.
- d) We must emphasize then that this foundation system shows very convenient behavior, because the provision of resistance by friction on the lateral area of the shafts is sufficient to support the sustained loads imposed by the operation of the overpass, and more. Inasmuch as accidental loads that could be imposed by earthquakes, wind or any other exceptional perturbation, are covered by the potential load capacity offered by the tip of the shafts, this is so with additional settlement.
- e) The above conclusions are supported by three independent measuring systems whose results are coincidental; these are: i) direct measuring of the load at the tip of the shaft by means of a calibrated electric pressure cell; ii) measurements of unitary micro-deformations with strain gages embedded in the concrete; and iii) measurements of compression suffered by the shaft, between its head and different depths along the shaft.
- f) In reference to the pull-out load capacity, it reached a value of 410 tons. This amount is comparable to that imposed in extreme condition by an exceptional earthquake, so there is no reason to worry, also because there are other elements that reduce actions on the shafts, such as the depth at which their head connects to the footing.
- g) We were able to verify that the geotechnical criteria adopted for the design of the foundation shafts for the Viaducto Bicentenario, in particular the Wysockey solution, are justified and pertinent, judging by this first load test near support A-72, where difficult stratigraphic conditions were recognized.

ACKNOWLEDGEMENTS

The authors wish to express their thanks to the Sistema de Autopistas, Aeropuertos, Servicios Conexos y Auxiliares del Estado de México (SAASCAEM), which propitiated the participation of the Instituto de Ingeniería,

UNAM, in this project. Also, we are grateful to Viaducto Bicentenario, S.A. de C.V. of the Grupo OHL México (concessionaire) for their acceptance and interest in carrying out these tests.

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