Dynamic Plate Load Tests

Luciene S. de Moraes, José Carlos A. Cintra, Nelson Aoki

Abstract. Dynamic load test is often used for bearing capacity evaluation of driven pile foundation. It is also reported the successful use of this test in bored piles and caissons. This research is mainly concerned with the adaptation, performance and interpretation of the dynamic load test in circular steel plate aiming at the verification of the bearing capacity of shallow foundations. The dynamic increasing energy test (DIET) was used. The tests were performed at the USP/São Carlos experimental foundation site, which soil profile consists of superficial unsaturated, porous and collapsible soil, and for that reason matric suction's measurements were made, since it has strong influence on the bearing capacity. It could be verified that it is possible to make use of the dynamic load test to plates, associated with analysis methods based on the stress propagation in bars (wave equation), to infer the plate-soil system bearing capacity. Good adjustments were found from dynamic and static load tests performed in a plate tested in this research field. It was also verified that the plate penetration into the soil caused an important increase in the plate-soil system bearing capacity.

Key words: plate static load test, plate dynamic load test, collapsible soil.

1. Introduction

An alternative method of loading testing for shallow foundations is presented: the dynamic plate load test. The dynamic load test is often used in the determination of bearing capacity for driven pile foundation. The monitoring during pile driving is an important tool extensively used in current practice in Brazil and also abroad. This system provides a quick answer in the determination of mobilized resistance, during pile's installation, when the dynamic increasing energy test (DIET) approach is used (Aoki, 2000). For some years, the monitoring has also been extended to bored piles, to evaluate the static mobilized resistance in a faster and less expensive way when compared with static load tests. Researches have already proved the applicability of the technique also in caissons.

This research is mainly concerned with the adaptation, performance and interpretation of the dynamic load test in a 25 mm thickness circular steel plate with 0.80 m diameter. The objective of the research program was to verify the possible use of the proposed analysis based on the stress propagation in bars (wave equation), to infer the plate-soil system bearing capacity.

The results obtained from dynamic and static load tests performed at the Experimental Foundation Site of USP/ São Carlos are compared. The soil profile typically presents a very porous superficial layer, unsaturated and collapsible, due to the weathering action under typical tropical conditions, common in the region. For this reason, the tests were performed with matric suction monitoring by means of tensiometers. This monitoring is of great importance, as the matric suction strongly influences the bearing capacity (Costa, 1999).

In that porous soil, the load-settlement curves obtained from several plate, footing and caisson tests showed that almost all settlement results from plastic (irreversible) deformation and the soil presents strain hardening, not clearly indicating the failure condition. The penetration of the plate then causes a major increase in the bearing capacity, by increasing the stiffness of the soil underneath it.

2. Site Characterization

The plate load tests were carried out at the Experimental Foundation Site of the University of São Paulo, in the city of São Carlos, Brazil.

The city of São Carlos is located 800 m above sea level, on top of rocks from the São Bento Group, which are composed by sandstone from the Botucatu and Pirambóia formations and basalt from the Serra Geral formation (Bortolucci, 1983).

The Experimental Foundation Site is at the extreme south portion of the University campus, in an area with a geological-geotechnical profile considered representative of the center-western region of São Paulo state (Cintra *et al.*, 1991). Figure 1 shows the geological profile from part of the city of São Carlos and the location of the University campus.

The typical soil profile at the test site includes a superficial lateritic clayey sand layer (brown colluvium) and the soil is very porous, unsaturated and collapsible, with low bearing capacity parameters and N_{SPT} ranging from 1 to 5 blows. A 0.3 m thick layer of pebbles, located at a depth of approximately 6 m, separates the superficial layer from a residual soil layer, which is composed of reddish clayey sand (saprolite). Both layers are classified as clayey sand (SC) according to the Unified Classification System. A

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clayey silt layer with fragmented and altered basaltic rock is reached at a depth of 24 m. The water table varies seasonally from 7 to 10 m below ground surface. The area of the experimental site was geotechnically characterized by laboratory and *in situ* tests and Fig. 2 summarizes the results obtained.

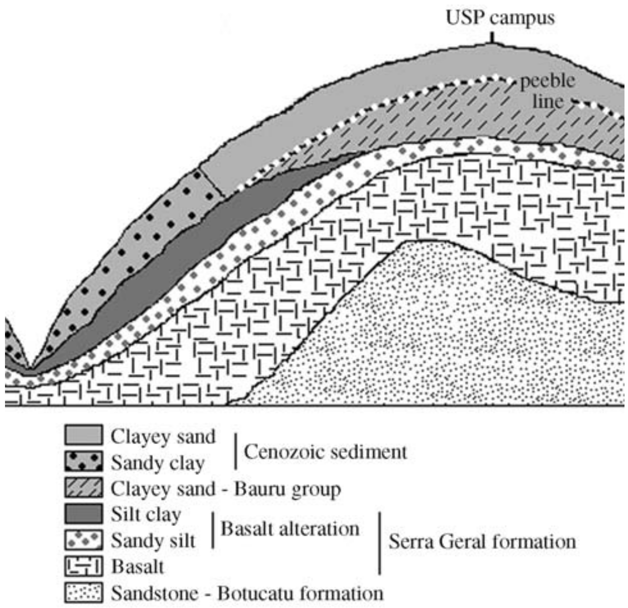

Figure 1 - São Carlos' shallow depth geology schematic section (Bortolucci, 1983).

Many researches have been previously carried out at the same site. These researches included the performance of dynamic load tests in caissons and static compression load tests in caissons, in pile groups and in many kinds of isolated piles with different geometries, including also uplift and horizontal static load tests in some types of piles and static load tests in footings and plates of several diameters and depths.

The results from plate, footing and caisson static load tests carried out at the site show that the load x settlement curves do not clearly indicate failure. The final portion of the curves presents a continuous, almost linear, resistance increase with settlement. A typical plate load test result is presented in Fig. 3. The test was performed at the foundation experimental site in an 80 cm steel plate.

Benvenutti (2001), testing caissons with successive static load tests in this same experimental site, showed that besides the non-definition of failure there is an increase of the caisson-soil system's bearing capacity, as the caisson penetrates the soil. Figure 4 presents the results of three static load tests performed sequentially in the same caisson. It can be seen that the final parts of the load x settlement curves constitute one almost straight line.

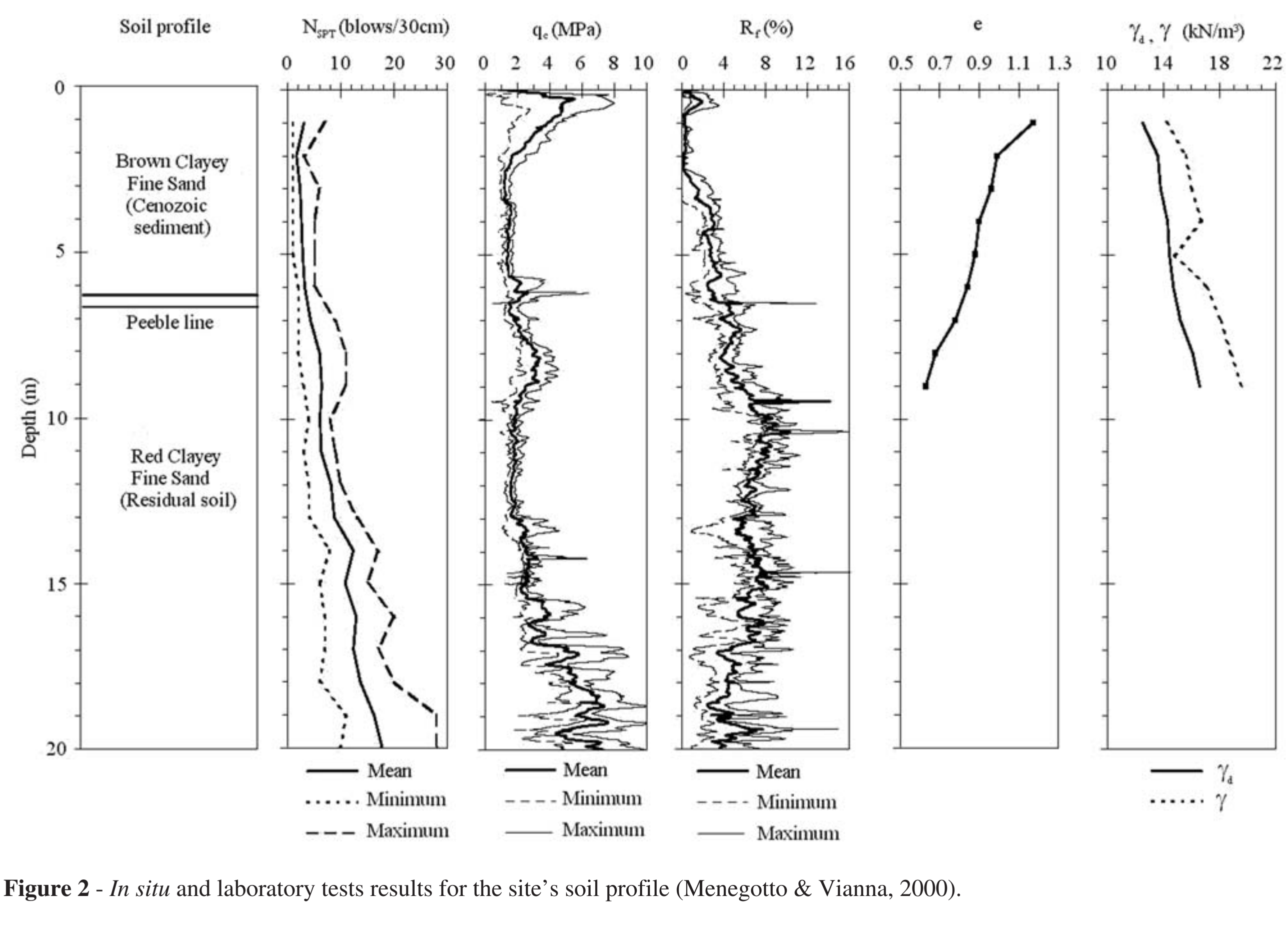

Figure 2 - *In situ* and laboratory tests results for the site's soil profile (Menegotto & Vianna, 2000).

In order to interpret the results with due account of the caissons penetration, Benvenutti (2001) considered that the final portion of each of the three successive curves almost align as a single straight line, disregarding subsequent unloading and reloading sequences up to reaching the maximum testing load from the previous test. A conventional failure criterion was chosen to determine the bearing capacity for some penetration levels. The bearing capacity was established as the load corresponding to a 25 mm settlement. Since the final portions of the curves constitute one straight line, it is possible to determine the bearing capacity for any desired penetration levels, which would correspond to an additional 25 mm settlement.

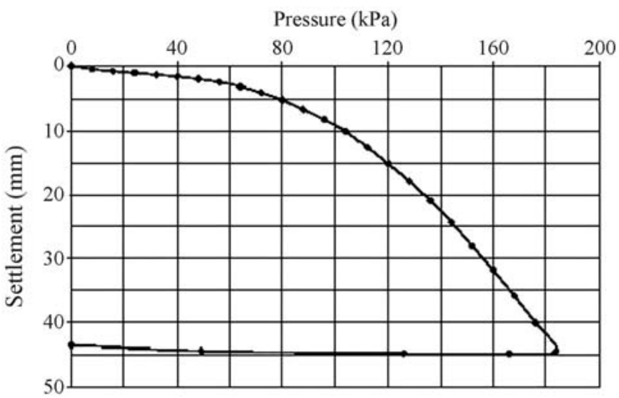

Figure 3 - Plate static load test at the experimental foundation site (Macacari, 2001).

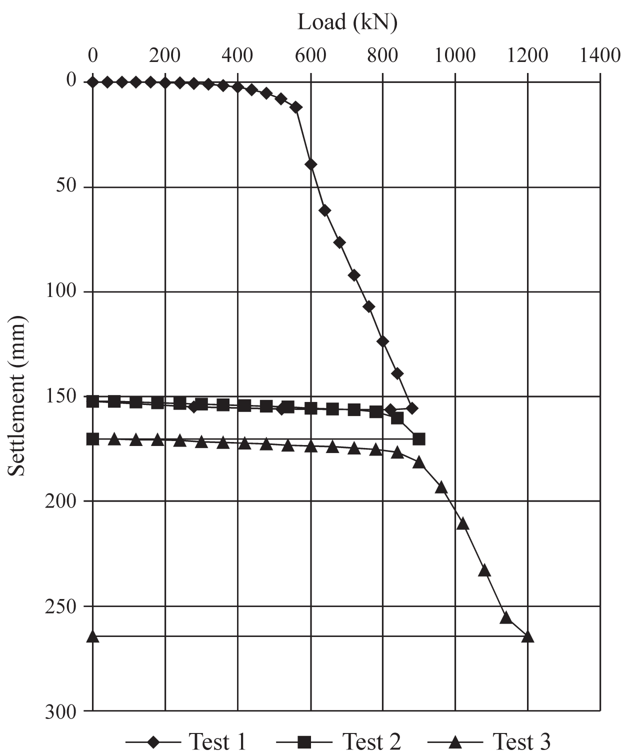

Figure 4 - Load x settlement curves for three tests performed on the same caisson (Benvenutti, 2001).

Besides, since the site presents a thick layer of unsaturated soil, the matric suction has to be taken into account. At the experimental site, an important influence of the matric suction on the bearing capacity has been observed (Costa, 1999). By means of static plate load tests in 1.5 m deep pits it has been verified that a small increase in the matric suction causes a major increase in the bearing capacity, as it can be seen in Fig. 5, where Ψ_m represents the mean soil matric suction measured by four tensiometers. The almost zero matric suction condition was obtained by flooding the pit for 24 h prior to the test.

3. Materials and Methods

Two dynamic load tests and four static load tests were performed on a 25 mm thickness circular steel rigid plate, 80 cm in diameter. The tests were performed in three pits (A, B and C) 0.90 to 1.00 m diameter and 1.5 m deep. Figure 6 presents the plan view of the site.

3.1. Dynamic load tests

Each increasing energy hammer blow was monitored with a scheme used in pre-cast pile tests, with the application of the PDA (Pile Driving Analyzer). The instrumentation consisted of two accelerometers, two strain transducers and a driving analyzer.

Additionally to the dynamic monitoring, settlement was measured using paper sheet and pencil. The measurements were performed by taping a sheet of paper in the tube connected to the plate as shown in Fig. 7.

3.2. Adaptation for dynamic plate load tests

The circular steel plate tested is 25 mm thick with 0.80 m diameter, resulting in a 0.50 m^2 soil contact area. To increase the stiffness, the plate is 25 mm thicker from its center up to 30 cm diameter (a 30 cm plate is welded to the center of the 80 cm plate, creating a projection that enhances the plate's stiffness).

The use of common dynamic test instrumentation, according to the Brazilian Standard NBR 13208/94 (ABNT

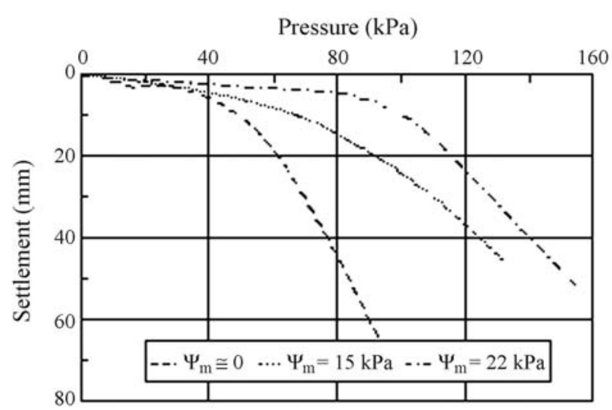

Figure 5 - Pressure *vs.* settlement static load test curves on 0.80 m diameter plate with different matric suction levels (Costa, 1999).

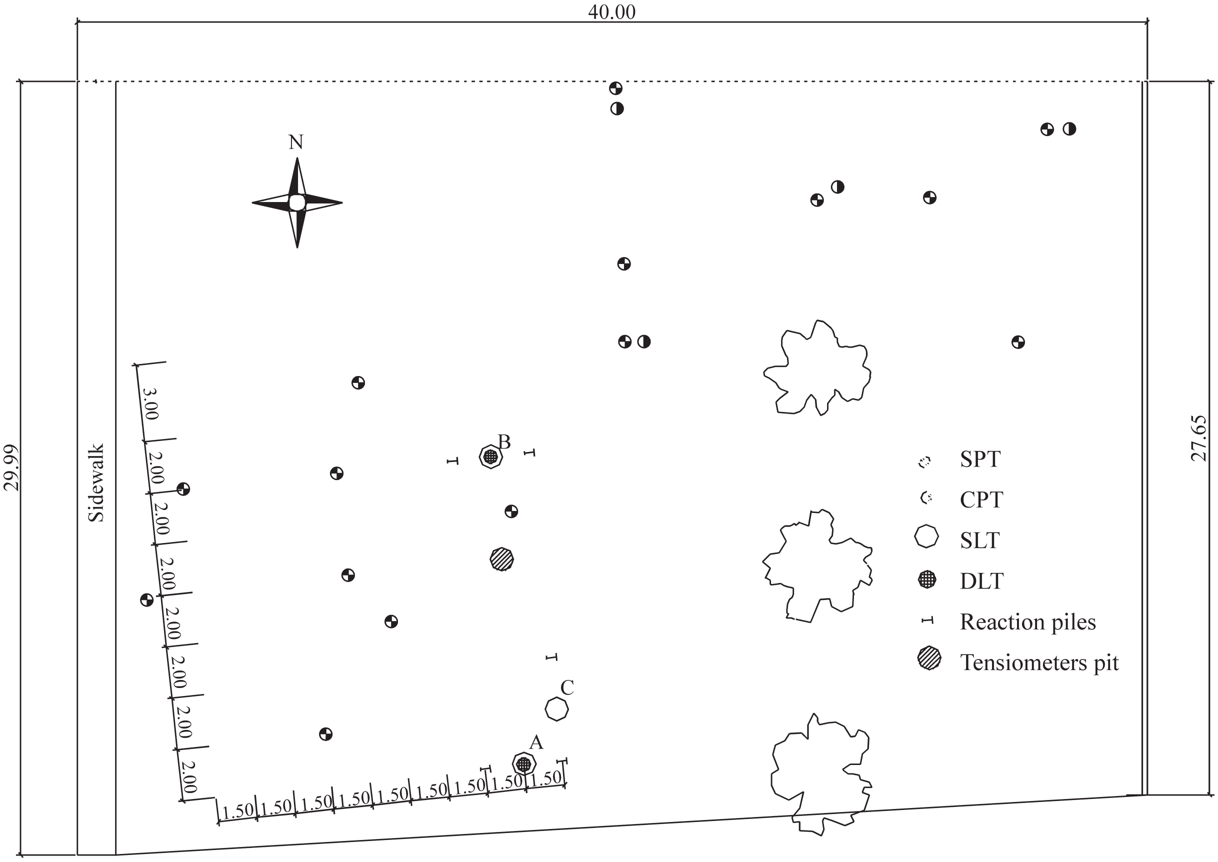

Figure 6 - Site plan view (dimensions in meters).

Figure 7 - Settlement measurements using paper sheet and pencil.

1994), was made possible by connecting the plate to a 7 m long steel tube, with external diameter of 0.22 m and 8 mm thick wall. The height of the tube was chosen based on numerical simulations of a stress wave running downwards and upwards a steel tube. It was simulated that the tube was 3, 4, 5 and 6 m long and the latter value provided good results. Thus, a 7 m long tube was then chosen, because the instrumentation can not be placed near the tube head, due to interference from the blows and possible damage of instruments. In addition, if the tube is not long enough the electric signals registered by the instrumentation are difficult to analyze, because of wave reflections. These numerical simulations were made using a wave equation application computer code developed by Aoki (1989).

A ring shaped frame was welded to the base of the tube described above. This frame was bolted to the plate as shown in Fig. 8.

A free fall 15 kN hammer mounted on a pile driver was used to perform the tests with increasing fall heights (2.5; 5.0; 7.5; 10.0; 12.5; 15.0; 20.0; 25.0 and 30.0 cm). Figure 9 shows the equipment being placed inside the pit (Fig. 9a) and the general setup of the dynamic testing assembly (Fig. 9b).

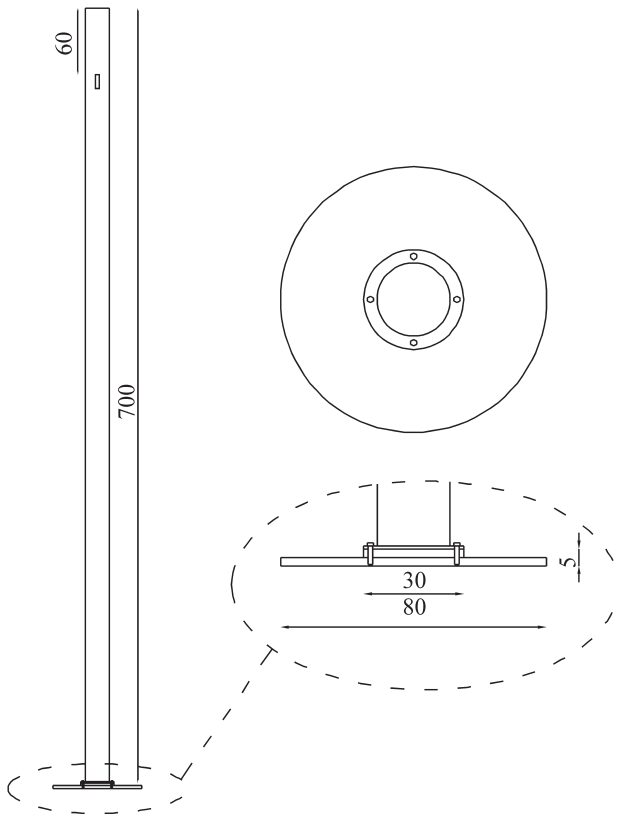

Figure 8 - Tube-plate arrangement used in the tests (dimensions in cm).

3.3. Static load tests

Two static load tests were performed after the dynamic tests at the same pits. The static load tests were performed with QML - Quick Maintained Load, according to Brazilian Standard NBR 12131/91 (ABNT, 1991), except for the time intervals that were altered to 15 min, according to Fellenius (1975) proposition. During each time interval the load was maintained and settlements readings were made at 0, 1, 2, 3, 6, 9, 12 and 15 min; unloading was made in two 15 min stages.

Costa (1999) performed other tests in nearby pits, excavated in the same condition as the ones described in this paper. One of them was a quick maintained load test with matric suction value close to the ones measured in the present work and therefore represents a similar situation. These results were used in the present paper for comparison purposes.

Figure 10 presents a schematic view of the static testing reaction assembly.

3.4. Matric suction measurements

During the time while the tests were performed, periodic matric suction measurements were made by means of tensiometers installed in a control pit. This pit was not used for testing and was excavated under the same condition and close to the other pits. Four tensiometers were installed

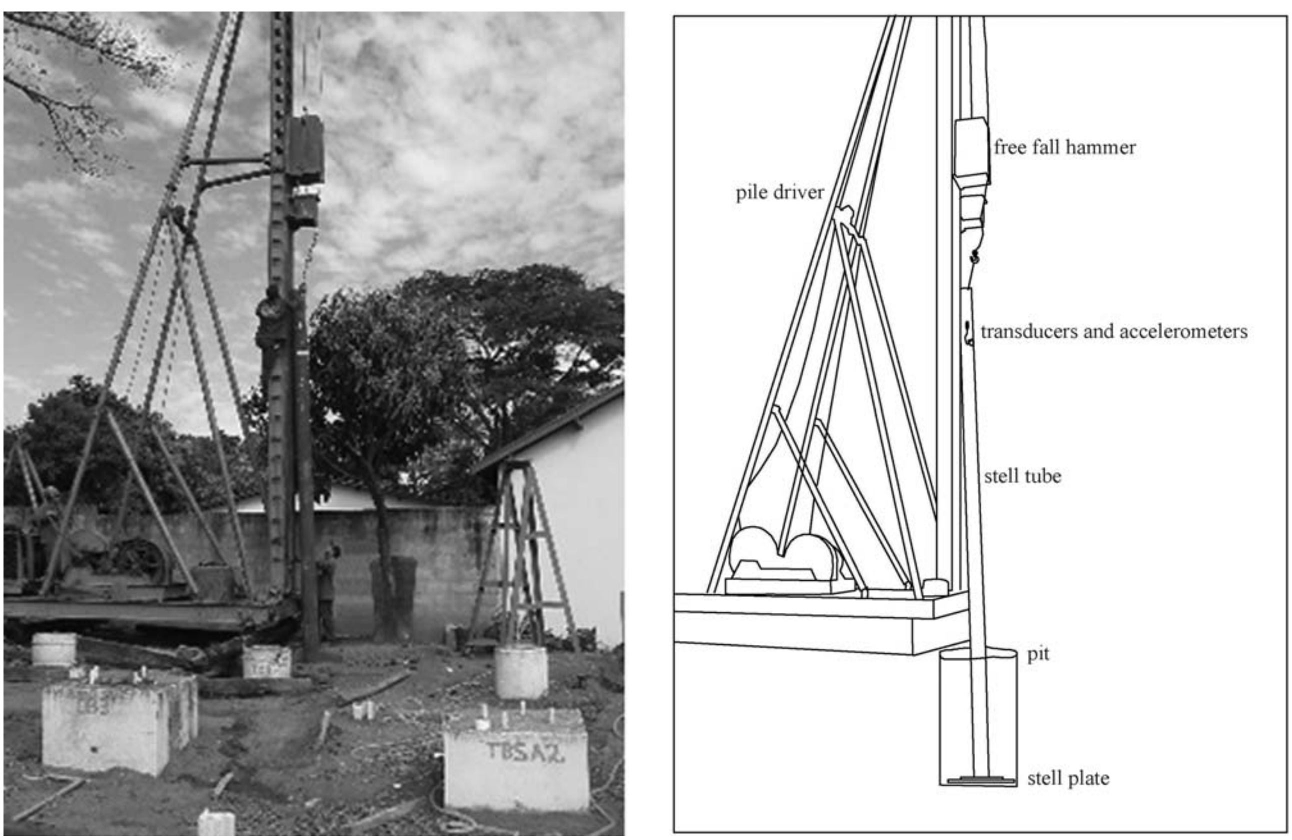

Figure 9 - (a) Plate-tube arrangement being placed inside the pit and (b) Test general assembly.

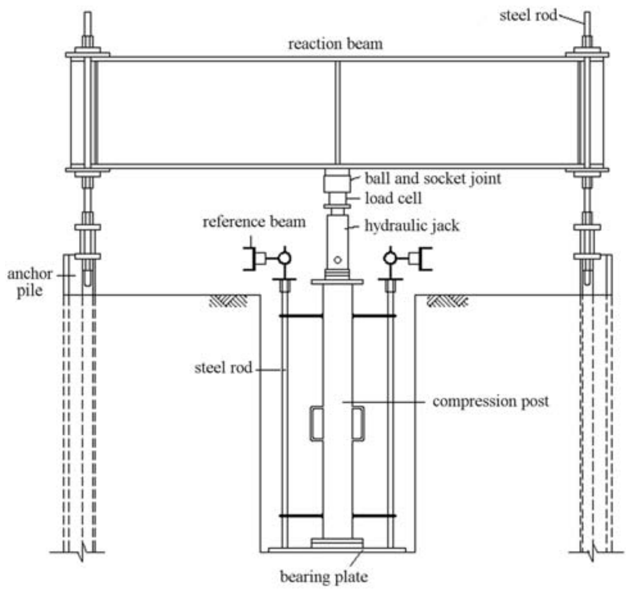

Figure 10 - General scheme of the static testing assembly.

Figure 11 - Tensiometers positions in the control pit.

0.20 m deep, connected to four vacuum meters. A portable vacuum pump was used to remove persistent air bubbles from the system. Figure 11 shows the positions of the tensiometers in the control pit.

The static and dynamic tests designations and brief descriptions are summarized in Table 1.

4. Results

The pressure x settlement curves obtained for the three static plate load tests are shown in Fig. 12. Figure 13 shows the results from the two dynamic plate load tests in terms of static reaction force obtained through CAPWAP® analysis and the maximum displacement measured by the (PDA). CAPWAP (Case Pile Wave Analysis Program) is a software based on the wave equation theory and signal matching procedure that predicts total bearing capacity of a pile or shaft, as well as resistance sharing between pile shaft and tip. The program takes as input the force and velocity data obtained from the PDA. Figure 14 presents the same results in terms of pressure x settlement. The static reaction forces were divided by the plate area and plotted against the maximum displacements measured by the PDA.

Table 1 - Testing program.

Test designation	Test type	Pit
SLT1	Static load test	C
SLT2	Static load test	A
SLT3	Static load test	B
DLT1	Dynamic load test	A
DLT2	Dynamic load test	B

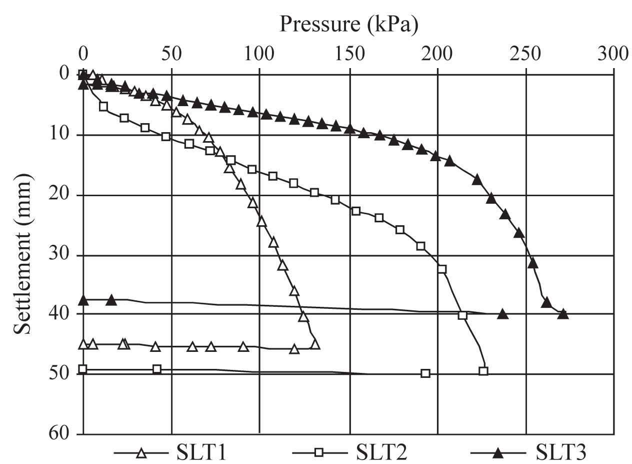

Figure 12 - Results of static load tests.

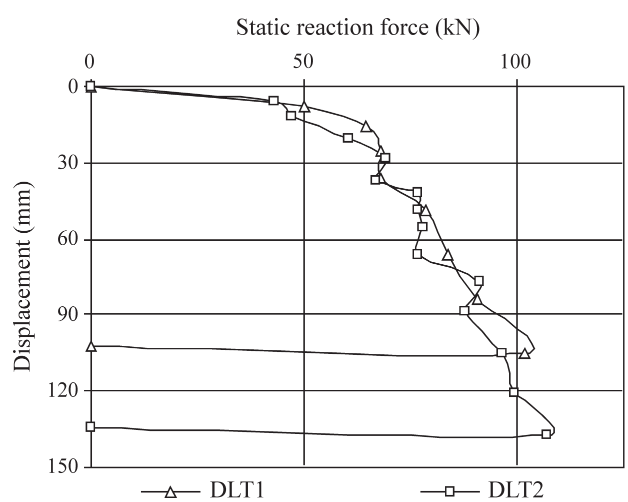

Figure 13 - Results of dynamic load tests.

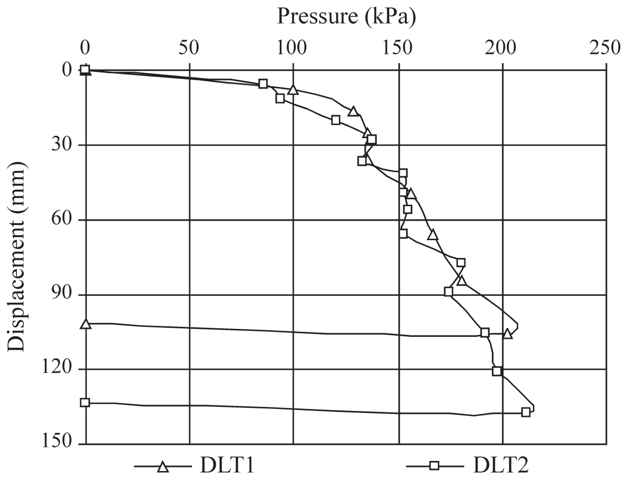

Figure 14 - Results of dynamic load tests.

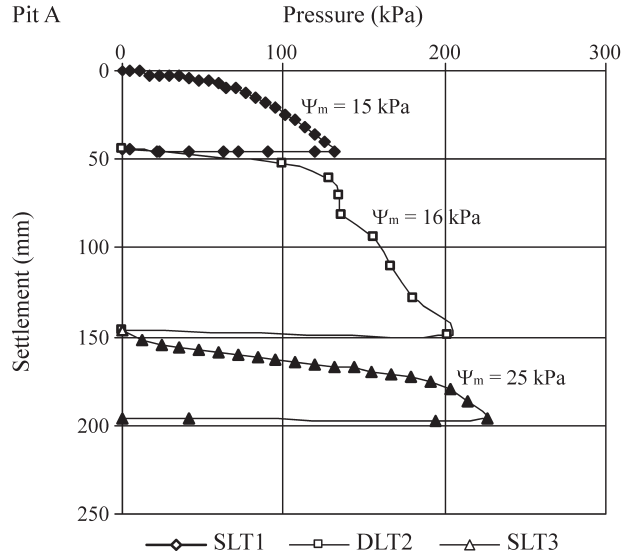

Figure 15 - Static, dynamic and static load tests pressure x settlement curves for tests in pit A.

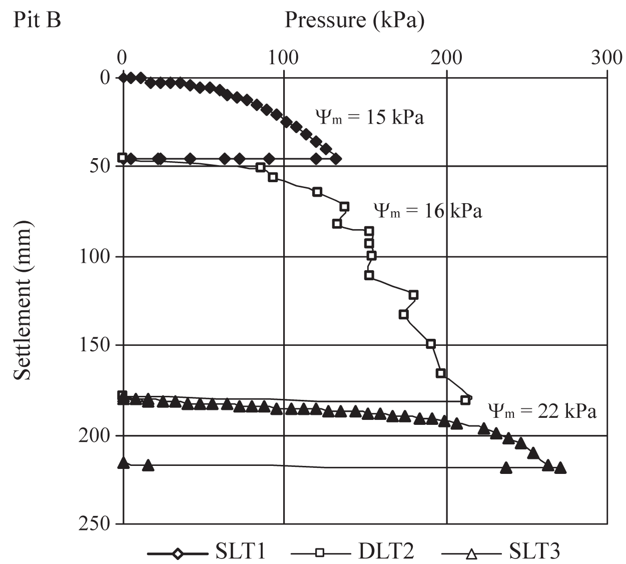

Figure 16 - Static, dynamic and static load tests pressure x settlement curves for tests in pit B.

5. Discussions

5.1. Comparison between static and dynamic plate load tests

Figures 15 and 16 show the pressure x settlement curves obtained from load tests performed in three pits: 1) Costa's (1999) static load test (SLT 1) in pit C; 2) Dynamic plate load tests (DLT 1 in pit A and DLT 2 in pit B) and 3) Static plate load tests performed after the dynamic tests (SLT 2 in pit A and SLT 3 in pit B). The three graphics show the accumulated settlement, according to the tests execution sequence. For the dynamic tests, the static reactive forces obtained through CAPWAP® analysis divided by the plate area are also shown in the figures. The settlement corresponds to the maximum displacement given by the PDA.

The three pressure x settlement curves of each Fig. (15 and 16) show an almost linear relationship between settlement and corresponding applied stress for the plastic strain phase, and almost horizontal unloading line. This kind of curve can also be observed in other load tests at the same location, performed in plates and caissons.

It can be seen in Figs. 15 and 16 that the final part of each pressure x settlement curve from the successive tests in the same pit consists of an almost straight line, as observed by Benvenutti (2001). Disregarding the subsequent unloading and reloading up to the maximum resistance reached at the previous test, a continuous consistent curve can be obtained with reasonable approximation. This continuous curve is formed by linking the three load test curves (static, dynamic and static again) performed on each pit, obtaining a single curve, that has typical shape, found in all plate load tests results at the experimental foundation site.

The dynamic load tests' curves fit reasonably well the two curves obtained from static loading tests. This consistent behavior observed in the static and dynamic tests indicates the viability of the execution the dynamic test with plates, similarly to those already in use for piles.

5.2. Dynamic load test validation through energy approach analysis

Another way found to validate the plate dynamic load test is to compare the energy given by the PDA with the one calculated from the test results. The energy given by the PDA is the total kinetic energy of the system. Figures 17 and 18 show the accumulated maximum applied energy given by the PDA against the calculated accumulated maximum energy, which is the area under the force x settlement curve (Fig. 13). According to Aoki & Cintra (1997), the calculated energy is the total kinetic energy of the system minus the work done and it is typically 70-90% of the total kinetic energy given by the PDA. The average ratio between calculated energy and PDA given energy was equal to 79% for pit A and 87% for pit B, which is consistent with the results reported by Aoki & Cintra (1997).

5.3. Influence of plate penetration on the bearing capacity

For the analyses of the influence of plate penetration on the plate-soil system bearing capacity, the single line formed by the three pressure x settlement curves of each pit was employed.

Since an open curve does not define failure because any stress increment causes soil stiffness to increase, it was necessary to use a conventional failure criterion in order to analyze the successive tests performed on the same plate.

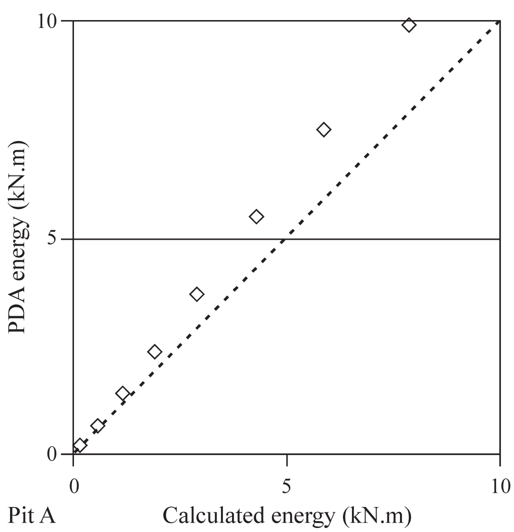

Figure 17 - Energy given by PDA against calculated energy (pit A).

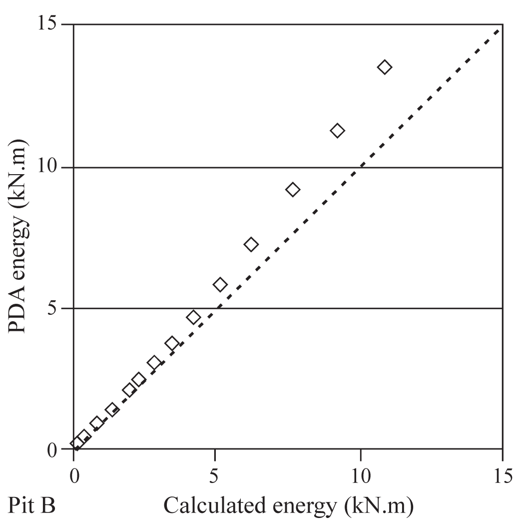

Figure 18 - Energy given by PDA against calculated energy (pit B).

The chosen criterion establishes that the bearing capacity corresponds to a 25 mm settlement. This is a total displacement limit criterion, where the bearing capacity is a function of a pre-determined displacement, based on the Boston construction code. The code establishes that the allowable stress is the smallest between two values: the stress corresponding to 10 mm settlement and the stress corresponding to 25 mm settlement divided by two. Teixeira & Godoy (1998) consider the value two as a safety factor, and therefore the bearing capacity is the stress corresponding to a 25 mm settlement itself. The value 10 mm would be an allowable settlement.

The solution used by Benvenutti (2001) to interpret successive static load tests in two caissons in the same experimental site was used to verify the bearing capacity increase with plate penetration. The failure criterion adopted assumed the bearing capacity as equal to the stress corresponding to an additional 25 mm settlement of the plate from its previous position.

The penetration depths chosen for the beginning of the loading phase were 0, 50, 100 e 150 mm. The value zero means no penetration prior to test. In other words the plate is at the surface in the beginning of the test. The bearing capacity values were considered as the pressures corresponding to 25, 75, 125 and 175 mm settlement, respectively.

Tables 2 and 3 present the bearing capacity values for each pit and the matric suction at the time the test was performed.

Comparing the stresses obtained for a 150 mm penetration with those for zero penetration, there were bearing capacity increases of 105% for pit A (Table 2) and 168% for pit B (Table 3). It can be seen in Fig. 19 that the bearing capacity increases linearly with the plate penetration .

Table 2 - Penetration and bearing capacity for pit A.

Penetration (mm)	Test	σ_r (kPa)
0	SLT1	102
50	DLT1	135
100	DLT1	185
150	SLT2	209

Note: σ_r = bearing capacity.

Table 3 - Penetration and bearing capacity for pit B.

Penetration (mm)	Test	σ_r (kPa)
0	SLT1	102
50	DLT2	153
100	DLT2	202
150	SLT3	273

Note: σ_r = bearing capacity.

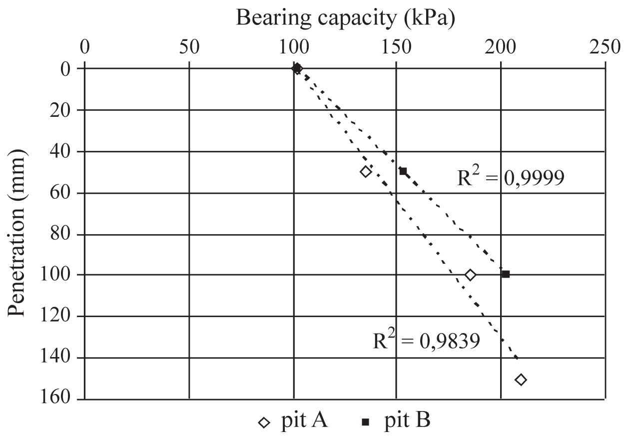

Figure 19 - Relationship between plate penetration and bearing capacity.

6. Conclusions

This paper presented the interpretation of the performance of dynamic load test on rigid circular 0.80 m diameter steel plate. A new dynamic load test approach was validated by the comparison between dynamic and static plate load tests and by dynamic load test analysis using the energy approach.

Because the tests were performed using the increasing energy approach, it was possible to obtain static pressure x displacement curves, similar to the pressure x settlement curves from static load tests.

Comparing the results from CAPWAP® analysis for blows with increasing energy with those obtained from static load tests, performed before and after the dynamic tests, an approximate continuous curve was observed, indicating the viability of the application of dynamic test to plates.

The average ratios between calculated energy from CAPWAP® analysis and the total kinetic energy given by the PDA were 0.79 for pit A and 0.87 for pit B, which are consistent with the results obtained by Aoki & Cintra (1997), validating the dynamic load tests with plates as well as the analysis and models used.

In the two pits described in the paper, four static load tests were performed (two per pit). Two dynamic load tests were performed during the time interval between static load tests. The three individual pressure x settlement curves from each pit were interpreted as a single curve, with reasonable coherence, not considering the unloading and subsequent reloading up to the maximum pressure from the previous loading stage. The final parts of the curves from the successive tests were nearly a straight line. It was observed that the bearing capacity increases with plate penetration. Without considering the penetration, the bearing capacity value obtained was 102 kPa. Considering a plate penetration of 150 mm, an average increase on bearing capacity of 137% was observed. So, another conclusion that could be detached from the studies is the penetration influence on the bearing capacity.

This research contributes to foundation engineering by validating the adaptation of the dynamic load test to a 0.80 m diameter steel plate. The dynamic test can be an alternative to the static load tests.

Acknowledgments

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Symbols

DLT: Dynamic load test
e: Void ratio
N_{SPT}: Standard penetration resistance
PDA: Pile driving analyzer
q_c: Cone tip resistance
R_f: Friction ratio
SLT: Static load test
γ: Specific weight
γ_d: Dry specific weight
Ψ_m: Matric suction
σ_r: bearing capacity