Tomography: A New Technology for Quality Control of Deep Foundations

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Abstract

Drilled shafts are a frequently used solution in foundation engineering. Very often a small number of large sized elements are used to absorb the loads. Consequently, assuring the quality of the concrete becomes fundamental for the success of the project. The international tendency for evaluating the integrity of deep foundations has been of using indirect and non-destructive methods, based on the emission and reception of acoustic waves. This paper presents a short description of the *cross-hole* test on drilled shafts, and of the method of analysis called *tomography*. This technology, already available for general use, is an important tool for verifying the quality of deep foundations, and especially of drilled shafts. Its application is illustrated by a case study of the "Jacu-Pêssego" viaduct in the outskirts of São Paulo, Brazil[5].

Keywords: Integrity, Drilled shafts, Cross-hole, Tomography

INTRODUCTION

The verification of the quality of deep foundations is very often a challenge, as their elements are normally buried underground. In contrast to the elements that comprise the superstructure, usually only very limited extensions of the foundation elements are accessible. The evaluation of physical aspects of foundation elements – like the uniformity and continuity of their constituent material and their geometry (cross section and length) – is not an easy task.

A deep foundation may be inspected, for example, by simply excavating the surrounding terrain. This procedure has the advantage of allowing direct observation of the conditions of some piles on a job. However, the limited depth that can be reached by the excavations often means that only a partial investigation of the shafts will be carried out. Other techniques involve the use of core drilling for extracting samples of the concrete, or even static or dynamic load tests.

The international tendency for evaluating the structural integrity of deep foundations has been of using indirect and non-destructive methods, especially those based on the emission and reception of acoustic waves (Kormann, 2002). Examples of those techniques are the Low Strain Integrity Test and the Cross Hole Sonic Logging (CSL). This work presents a short description of the Cross Hole test, with emphasis on the technique of tomography for foundation piles. Its use is illustrated by presenting the use of those techniques in the "Jacu-Pêssego" viaduct in Sao Paulo, Brazil.

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THE *CROSS-HOLE* TEST AND PILE TOMOGRAPHY: EXECUTION AND BASIC PRINCIPLES

The cross-hole test on piles is intended to verify the quality of the concrete along the shaft (e.g. Brettmann and Frank, 1996; Paikowski, 2000). The technique involves generating electric pulses in a control and data acquisition unit. Those pulses are converted to ultra-sonic waves, which are captured by a receiving probe, where they are converted back to electric signals. The probe output is filtered around its resonant frequency, to minimize electronic noise.

The transmitter and the receptor probes operate inside water-filled tubes. To ensure a complete scan of the pile core, usually three or more tubes – normally one for each 0.25 or 0.30 m of pile diameter – are previously installed during casting. The tubes are arranged on a circle close to the pile edge, and should preferably be installed along the full pile length. Steel or PVC tubes may be used, and to ensure their verticality they should be attached to the reinforcement cage. To guarantee a good bonding of the tube with the concrete, it is recommended that the tubes be filled with water during the casting of the pile.

The test is performed by first positioning the transmitter and the receptor probes at the bottom of a pair of tubes. The two probes are next raised simultaneously along the pile shaft, while the depth, the time between the emission and the reception of the pulse and its energy are continuously recorded. The probes may be raised manually or by means of a motor driven device. The scans are repeated for all possible tube combinations. This allows the mapping of defect regions along the depth and also by cross section quadrant. On small diameter piles it is possible to place both transmitter and receptor probes in the same tube (single hole testing).

The data recorded in the field is analyzed using specific software (e.g. Pile Dynamics, 2004). The interpretation is done by measuring the travel time of the ultrasound pulse. The detection of defects is based on the fact that lower quality material along its path will slow down the ultrasound wave, or will even completely block the wave propagation in more severe cases. Many factors that may cause a delay in the arrival of the ultrasound pulse – such as soil or slurry intrusions, low quality material and voids – also lead to a reduction in the energy of the received signal. The analysis is therefore performed based on both arrival time and signal energy.

It is possible to combine the data obtained from different pairs of tubes, so that the results can be seen in two or three dimensions. This type of analysis is done by the tomography software (e.g. GeoTomo, 2003), which facilitates the identification of defects and confers an objective interpretation to the test.

CASE STUDY: THE JACU-PÊSSEGO VIADUCT

The technique of pile tomography was employed for the first time in Brazil on the Jacu-Pêssego Viaduct, built by the "Empresa Municipal de Urbanização (EMURB)" next to one of the major highways (Rodovia Ayrton Senna) leading to the city of São Paulo, Brazil. To avoid exceptional disturbance of local traffic, the viaduct was built parallel to the existing highway, on a single abutment. The final positioning was obtained by rotating the viaduct around its axis, after it was built.

The geologic-geotechnical profile of the soil at the central abutment is characterized by the presence of alluvia overlaying the typical soil of the Tertiary from the Sedimentary Basin of São Paulo. About 11 m thick medium compact to very compact sand layers are found below a superficial layer of organic material. Quite hard clayey layers are found next, with the occurrence of argillite/siltite at the base of the borings. The data from the cone test shows high tip resistance, compatible with the SPT N numbers. The water table is located about 8.0 m below the cut-off level of the piles.

The foundation of the central abutment – which will have to withstand the highest loads – consists of 30 drilled shafts executed with bentonite slurry, with 1.60 m diameter and lengths varying from 22.0 to 25.0 m. Four piles were specially prepared for cross-hole testing, by placing

50 mm nominal diameter tubes. The selection of the piles for the cross-hole tests was random. The integrity of all piles was verified with the Pile Integrity Tester (PIT), by the low strain method. In the present case the bottom of the PVC tubes coincided with the end of the reinforcement cage, a little above the tip of the pile. Table 1 presents the piles and tube data, utilizing the usual convention of identifying tube number 1 as the closest to the geographic north, with the numbers increasing clockwise. It should be noted that, although up to four tubes were used (like in the case of pile E9), a larger number of tubes would allow a more complete investigation.

Table 1. Data of the piles tested with *cross-hole*.

Pile	Total length (m)	Tube lengths (m)			
		1	2	3	4
E7	25.35	22.80	22.83	22.89	-
E9	24.85	22.65	22.62	22.65	22.71
E11	25.85	23.04	23.11	23.06	-
E15	25.20	22.98	23.04	22.98	-

Figure 1 shows details of the equipment and of the execution of the tests. Figure 2 illustrates the results of the cross-hole tests on pile E9. This figure indicates the ultrasound pulse energies and arrival times, with a schematic representation of the pile condition, based on the interpretation of the signals. The measurements reveal a small defect around 3.5 m below the pile top, which appears on tube pairs 1-4, 2-4 and 3-4. Also, a slight attenuation of the intensity of the ultrasound is perceptible very close to the pile top. This attenuation reduces further down the tube, where a better bond exists between the tube and the surrounding concrete.

The signals from pile E9 were also analyzed with the TomoSonic tomography program. The results are shown on Figure 3. For this analysis, wave speeds below 3000 m/s were considered indicative of low quality concrete. This lower limit was established based on the specified concrete strength of 18 MPa. The tomography analysis indicated that only 2% of the total cross section at 3.5 m below the top was below specifications. Generally speaking, the cross-hole and PIT tests indicated that all piles were acceptable as far as their structural integrity is concerned.

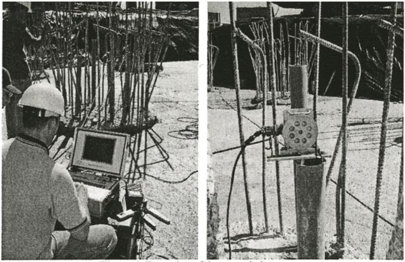
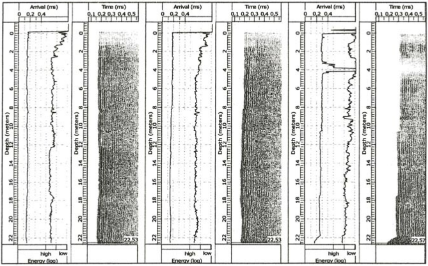
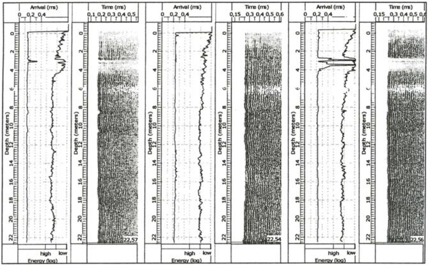


Figure 1. Execution of the *cross-hole* tests.

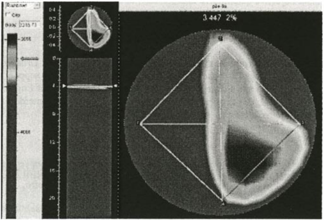


(a) Tubes 1-2 (b) Tubes 2-3 (c) Tubes 3-4

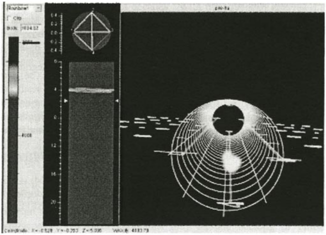


(d) Tubes 4-1 (e) Tubes 1-3 (f) Tubes 2-4

Figure 2. *Cross-hole* tests – arrival time and energy graphs – pile E9.



(a) Cross section 3.4 m below the top.



(b) 3-D view of the pile.

Figure 3. Results of the tomography analysis of pile E9 – *TomoSonic* progam (GeoTomo, 2003).

CONCLUSIONS

The cross-hole test and pile tomography are based on the emission and reception of ultrasound pulses, using probes that travel along the pile length inside previously installed tubes. Although those techniques are already in wide use around the world, they are only starting to be employed in Brazil. Its use proved satisfactory in the case of the Jacu-Pêssego viaduct project. Together with other alternatives available for the verification of the integrity of deep foundations – such as the PIT test – pile tomography is an important tool for the improvement of control quality processes. The more objective quantitative interpretation of the data is one of the main advantages of pile tomography.

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