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Experimental study on the dynamic behavior of laterally loaded single pile

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ABSTRACT

To improve the understanding of soil–pile interaction under horizontal dynamic loads and seismic events, a parametric centrifugal study was undertaken. Flexible piles with pile caps of different masses and instrumented with 20 strain gauges on the length of the pile were used for this purpose. The piles were impacted by a new horizontal impact device and the resulting displacement and acceleration for different levels of force were measured. The inherent basic parameters of soil–pile-interaction have been evaluated. An analysis of the damping in relation with depth and during vibration of pile is carried out. The equation of the movement of a beam equivalent to the pile under dynamic loading has been established and all the terms of this equation was determined using the experimental results. It shows that the value of internal damping of pile compared to other terms in the equation is insignificant. The term of inertia was divided into two parts, one related to the mass of the pile and the other related to the mass of the associated soil. The contribution of each term to the equation at different periods (or time of) of vibration was illustrated. Distribution versus time of the displacements and the reactions of the soil at any depth were deduced from the profiles of the bending moments by a double integration and a double derivation respectively. Then the dynamic *P*–*y* curves or loops were constructed based on these results. A static test has been performed with the same pile installed in the same conditions so that to obtain the static *P*–*y* curves. The procedures of experimental tests and *P*–*y* curves construction are explained and a comparison between static and dynamic *P*–*y* curves is also indicated.

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1. Introduction

Lateral loads on piles are developed both by the superstructure and by the wave propagation through the soil. The dynamic loads due to the horizontal movement of the superstructures are mainly generated by wind effects, machine vibrations, impact of vehicles or boats; the loads due to the wave propagation is primarily because of earthquakes. Therefore, the total forces are the result of two types of interaction: an inertial one from the movement of the superstructure and a kinematical one from the soil motion.

The high degree of the coupling between the modes and the components of the interaction explains the complexity of the dynamic soil–pile–structure interaction. Common methods to solve the problem of this type of interaction are considered independently for the two aspects. The kinematic effect of ground and the inertial interaction effect are evaluated separately, and are combined by superimposition to obtain the solution. A fundamental step towards understanding the behavior of pile–soil–structure interaction is believed to be the study of the free vibration response of piles.

Apart from the FEM and BEM methods which often require extensive computing resources, the use of the Winkler model for nonlinear support of a beam is considered a practical method for the design of laterally loaded piles. From the early developments, the modeling has consisted in taking into account the different aspects of pile–soil interaction such as the nonlinear behavior of the soil, the strain rate effects, the phenomena of compaction, damping, gapping and slippage. All these features have been accounted by *P*–*y* relationships between the pile and the soil. The consideration of the dynamic aspects in the Winkler model has been made in complementing the *P*–*y* curves by rheological elements such as masses and dashpots. The results given by the recent literature clearly show the difficulty in extending the static *P*–*y* curves to dynamic *P*–*y* curves (loops). The major objective of this research work is to study the inertial interaction of soil–pile systems and to derive static and dynamic *P*–*y* curves from experimental data.

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Considering the state of research on the topic, experimental approaches are considered most suitable for developing adequate the rheological elements for the soil–pile interaction response. Some investigators have used impact and ring-down full-scale pile tests to determine the dynamic and static parameters of soil–pile interaction (e.g. [9,1,3]). These full-scale tests are very expensive and limited to the specific field conditions. The horizontal Statnamic test is one of the more recently developed full-scale experimental approaches for studying the behavior of piles. From these types of tests, parameters are used for the modeling of dynamic loads caused by earthquakes, ship impacts and wind effects on structures and foundations. In any case, full-scale testing methods do not extensively respond to the lack of knowledge of the physical effects involved in soil–pile behavior. Centrifuge modeling is a less expensive tool and a more flexible alternative experimental technique to field tests. With the similitude laws, the behavior of piles and soils can be correctly modeled in the centrifuge and parametric studies can be performed. The modeling of models approach has proven that the scale effects are negligible and the recorded pile responses are reproducible [8].

2. Experimental test set-up

Fontainebleau sand which is a uniform silica sand that consists of fine and rounded particles was used in the experiments. Some physical properties of this sand are shown in Table 1.

The ratio of the diameter of the model pile (18 mm) to the grain size is 90, which is higher than the value of 30 above which there is no important scale effect on the bearing capacities of foundations [10]. Monotonic and cyclic behavior of this sand is presented in [5]. The method applied for the sand reconstitution was sand pluviation. The average density achieved in this way was 16.05 kN/m^3 which gives a relative density of 85%.

The pile model is 1/40 of prototype and all the tests were carried out in 40 g acceleration. The model piles are made with AU4G aluminum hollow pipes. The outside diameter is 18 mm (720 mm in prototype scale) and the thickness is 1.5 mm. They have a total length of 380 mm (15.2 m in prototype scale) for an embedded length of 300 mm i.e. 12 m in prototype scale. The stiffness EI converted to prototype scale is equal to 505.4 N m^2. The free height H above the soil surface where the impact was applied is equal to 2.2 m. A photo of test setup is shown in Fig. 1.

A method to characterize the relative stiffness of the pile is to calculate its transfer length l_0, namely

$$l_0 = \sqrt[4]{\frac{4E_pI_p}{E_S}} \tag{1}$$

E_pI_p is the stiffness of pile in bending and E_S is the module of reaction of the soil. The pile is regarded as flexible if $L/l_0 > 3$ (L is the embedded length of the pile) and as rigid if $L/l_0 < 1$ according to [4]. The difficulty of evaluation of l_0 lies in the choice of module of soil reaction which varies with the depth and the magnitude of loading. Remaud [11] conducted a study by interpolation and correlations from a Cone penetrometer test in centrifuge (40 g), allowing to estimate the module of reaction E_S. He estimated the module of reaction equal to 30 MPa at the depth of 4 m (the level of the first upper third of the pile). This level corresponds to an area where stress and strains are the most significant. The length of transfer l_0 is therefore of 2.8 m and the ratio L/l_0 is equal to 4.3. The modeled pile is therefore considered as flexible.

Table 1
Some physical properties of the Fontainebleau sand.

D_{50}(mm)	γ_s (kN/m^3)	γ_d min (kN/m^3)	γ_d max (kN/m^3)	e_{min}	e_{max}	φ	ν
0.2	26.44	13.64	16.83	0.616	0.940	35°	0.2

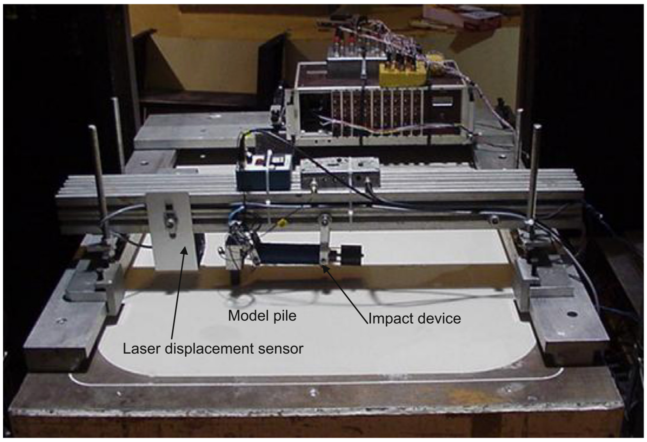

Fig. 1. Experimental set-up for dynamic test.

Table 2
Characteristical masses of the pile caps.

Pile cap number	M$_1$	M$_2$	M$_3$	M$_4$
Prototype (kg)	6554	13,360	32,019	54,502

In this study the inertial effect on top of the pile was reproduced by adding different pile caps. The pile caps were designed with a small thickness in the direction of the impact in order to decrease the effect of the rocking mode. Four pile caps were manufactured for the parametric studies relating to the mass of the superstructure.

The total masses of the pile caps including the instrumentation i.e. force sensor and accelerometer, are given in Table 2.

To measure the pile deformations and to compute the bending moments from them, the model piles were instrumented with 20 strain gauges assembled in half-bridge. The gauges were pasted on the outer surface of the piles. The strain gauges were protected by a layer of special material. Without protection, they are likely to deteriorate; particularly, when the pile is driven. The drawback is that the nominal diameter of pile, i.e. 18 mm, had increased. The increase in diameter can reach 1.5 mm. This protection did not have any significant effect on pile flexural stiffness because the coating material is very soft and its Young's modulus is very low compared to that of aluminum. Another effect would be on friction difference between aluminum with soil and coating material with soil. Two static tests were performed using two piles, one with coating and another without coating and strain guages. The head force–displacement curve did not show any noticeable differences [6].

In the static tests, 20 pairs (or couples) of gauges were used, whereas in the dynamic tests only 7 pairs of these gauges were utilized because of channel limitation for transferring and data acquisition. To evaluate the applied force, a piezoelectric sensor was mounted on the pile cap. To determine the displacement, two methods were employed: a direct measurement by an analog laser sensor with integrated amplifier and a piezoelectric accelerometer fixed on the pile cap which allows determination of the displacement by integration,

The impact force was generated by an innovative device shooting a steel ball against the pile. This device consists of a tubular guide wound by a coil. The coil is fed by a short high driving current pulse from the in-flight capacitors and triggered by a signal generator from the command room. The exit is just near

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