Procedures Used for Dynamically Laterally Loaded Pile Tests in a Centrifuge

**ABSTRACT:** Most of the experimental work carried on pile behavior on centrifuge has been limited to monotonic or cyclic loading, or both. As dynamic loads generated by shocks and earthquakes are difficult to model in centrifuge, not much work has been reported in the literature on the impact mechanism to produce shock in-flight, though seismic loads can be well simulated by in-flight shakers. A complete experimental procedure, i.e., hammering system, measurements, and test procedures, has been developed to test on centrifuge lateral impact on piles. In the first part of the paper following the test procedure, the experimental set-up is detailed from the soil preparation and piles equipment to the horizontal hammering or impact system. Innovative parts of the system such as the impact system and its monitoring are described. The second part describes the feasibility and the practice of the impact device and the adopted procedure to test on centrifuge different types of piles (jacked, cast-in, and 1 g driven) in sand. The first series of tests are focused on the evaluation of possible errors and influences due to pile position, boundary effects, and repeatability of tests. Scale effects have been studied by carrying out a series of modeling of models tests at 40 and 60 g. In conclusion, all these preliminary centrifuge tests have demonstrated that the complete experimental set-up including the impact system and its use procedure is achieved and able to perform horizontal impacted pile tests on centrifuge.

**KEYWORDS:** centrifuge, pile testing, dynamically loading, soil-pile interaction

**Introduction**

Lateral loads on piles result from lateral movement of the superstructure or from the soil in which they are founded or from both. Dynamic horizontal loads on superstructure are due to wind, machine vibrations, truck or boat shocks, and nonuniform wave impacts. Soil dynamic loads are generated by ground motions such as earthquakes. Therefore, generally speaking, piles are subjected to two kinds of interactions, i.e., an inertial one from the movement of the superstructure and a kinematic one from the soil motion.

The use of the Winkler approach for modeling a pile as a beam on nonlinear support is the most commonly adopted method for designing laterally loaded piles. From the early development for static loading (Terzaghi 1951; Vesic 1961; Reese et al. 1974; Reese et al. 1975) to the most recent publications on dynamic loading, (El Naggar and Novak 1996; Boulanger et al. 1999), this type of analysis takes into account different aspects of interactions such as the nonlinear behavior of soils, soil frequency effect, soil plasticity, and the phenomena of compaction, damping, gapping, and slippage. All these interactions are distributed along the length of the pile and synthesized in \( P-y \) relationships between the soil displacement \( y \) and the soil reaction \( P \). This issue is still subject to research. Hajialilue-Bonab (2003) presented detailed results for establishing the \( P-y \) curves or loops from experimental tests.

In recent years, centrifuge modeling is increasingly seen as an alternative to field tests, mainly for two reasons. First, behavior of soils is correctly modeled since the stress-strain state corresponds to the full-scale field; second, centrifuge testing is an economic solution for undertaking parametric studies. Table 1 gives some of the scaling relationships used in converting from model units to prototype units.

In order to analyze the inertial part of the interaction, most of the loading must be applied or concentrated on the superstructure. But, considering the confined volume of a soil sample in the centrifuge may introduce harmonic loadings, which lead to important interactions with the walls of the centrifuge box (Coe et al. 1985; Bourdin 1987); these interactions must be accounted for. An impact loading radiates low energy and limits the risk of creating stationary waves in the soil (it corresponds to the Statnamic field test). At full scale, this type of impact is obtained by truck crashes on a bridge pier founded on piles, boat berths on harbor facilities or, even by wave impacts. Very few results have been published on tests with horizontal impacts (Grundhoff et al. 1998) in the centrifuge. One reason is probably due to the difficulty in reproducing these impacts. This difficulty has been overcome by the development of an electromagnetic driver that produces remote controlled repeatable im-

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<th>TABLE 1—Scale factors in centrifuge modeling.</th>
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pacts on the pile head. A complete experimental set-up, i.e., hammering system, measurements, and test procedures, has been developed to be able to perform horizontal impacted piles tests on centrifuge. This paper describes the techniques used for carrying out and analyzing horizontal impact tests on single piles at reduced scale in the centrifuge. This study has been carried out on the centrifuge facilities of the Laboratoire Central des Ponts et Chaussées (LCPC, France).

Soil Medium Preparation

The soil used in the present study is a dry Fontainebleau sand. It is white, clean, and homogeneous fine siliceous sand. The grain size distribution curve shows that the average diameter of the grains is 200 µm, and the part of grains which is smaller than 300 µm is equivalent to 90 % (the particle sizes must be small enough with respect to the model foundation in order to limit the grain size effect). For this study the ratio between the diameter B of model pile (18 mm) and the average grain size is 90. Ovesen (1979) has recommended a minimum value of 30 where no scale effect is observed in studying the pile-soil interaction in centrifuge.

A sandy sample was prepared using the pluviation technique. The density obtained is a function of the drop height, the horizontal speed of the hopper, and the width of the aperture. The remote-controlled operation of the pluviation system allows good repeatability of the process and a good soil homogeneity with a standard error of the density limited to less than 1 %. Reconstituted sand with an average density of 16.05 kN/m³, corresponding to \( \rho_D = 85.3 \% \) for a dense sand, was used in this study. The density for each container was checked using control boxes inserted in the homogeneous sand in the container (Garnier et al. 1993). These control boxes were located in the middle of the strong container (dimensions: 1200 by 800 by 360 mm) which is located far enough from the model pile and the box walls.

Pile Models

The prototype pile has a diameter \( B = 0.72 \) m, a stiffness \( EI_z = 505.4 \) N·m², and an embedded length \( L = 12 \) m. In the present research work, various inertial effects were produced by adding different pile caps on the top of the pile. The free part of the pile corresponds to the height \( h \) at which the impact was applied and equal to 2.20 m as shown in Fig. 1. The model piles were fabricated as a tubular pipe from aluminum alloy.

Modeling of the pile is a procedure in which the prototype pile is modeled at different scales. If the same behavior is observed at the three scales, it can be concluded that no scaling relation influences the results. In this study, the reference tests were carried out at the scale 1/40 and a comparison was done with tests run at scale of 1/60. The geometrical and mechanical characteristics of the piles are summarized in Table 2.

Pile Caps

The pile caps were designed with a minimal thickness in the direction of the impact, i.e., closer to the diameter of the pile so as to decrease the effect of the rocking mode around the clamped pile head.

Four pile caps were fabricated for the study in proportion to the mass of the superstructure (Fig. 2). The dimensions and the corresponding masses are shown in Table 3 and Fig. 2. The pile caps M1, M2, and m2 were made of aluminum (Al), whereas those referred to as M3, M4, and m3 were made of steel. The total mass of each pile cap includes the associated instruments (i.e., force sensor and accelerometer).

Pile Instrumentation

In order to measure the strains and determine the local bending moments along the pile as a function of depth, the model piles used for the 40 g tests were instrumented with 20 strain gages wired as half-bridges configuration as shown in Fig. 3. The spacing between the gages was 15 mm corresponding to 0.60 m in the prototype.

To record the applied force, a piezoelectric sensor (type PCB Piezotronics, model 200B05) was fixed on the pile cap. Its bandwidth frequency was 310–475 kHz, which enables a precise recording of the variation of the force during the whole period of the impact (typically 250 µs at model scale). In order to reduce the high frequency content of the shock between two metallic materials (the impacting ball and the force sensor surface), a nylon tip was pasted on the force sensor. Fixing the force sensor directly against the pile cap enables the recording of the actual force that is applied to the cap.

An optical laser sensor was set up for measuring the displacement of the pile head. This sensor with integrated amplifier (Type Wenglor, model YP06MGV-P24, resolution 20 µm, linearity 1 % maximum, sampling rate 40 kHz) was positioned facing the center of the pile cap. A piezoelectric accelerometer (Type Bruel & Kjaer, model 4393) was screwed in at the same level. The displacement

| TABLE 2—Geometric and mechanical characteristics of model and prototype piles. |
|---------------------------------|-------|--------|--------|
|                                | Model 1/40 | Scale | Model 1/60 | Scale |
| Length L \( [m] \)             | 15.2     | 0.380  | 0.254    |
| Embedded depth \( D \) \([m]\)   | 12       | 0.300  | 0.200    |
| Diameter \( B \) \([m]\)       | 0.72     | 0.018  | 0.012    |
| Impact load height \( h \) \([m]\) | 2.2      | 0.055  | 0.037    |
| Stiffness \( EI_z \) \([N·m²]\) | 505.4    | 197.4  | 39.0     |
information provided by these two sensors was compared after double integration of the acceleration and results was found to be consistent with a standard error of less than 5%.

All these data were recorded at a sample rate of 20 kHz in order not to miss any of the highest frequency modes of the pile system or the sand layer response.

Pile Set-up in the Centrifuge Box

Because of the pile movement during impact testing, some properties of the sand (e.g., density and stress) are probably modified from the pile to an unknown distance around the pile. Remaud (1999) summarized data from different research works and indicated that the disturbed zone can be considered as having a maximum radius not exceeding 10B, where B is the pile diameter. For a model pile width of 18 mm in the present study it is 180 mm; the distance between each two piles were kept at 300 mm to avoid any interaction in all the tests. Considering the sizes of the centrifuge box, i.e., length 1.2 m by width 0.8 m by depth 0.36 m, and the used zone in the box, only six tests per box were possible as schematically illustrated in Fig. 4.

Impact Device

The impact was generated with a driver consisting of an electromagnetic gun accelerating a 24 mm steel ball. This gun is a tubular guide wound externally by a coil. The coil is fed by a short high current driving pulse from in-flight capacitors and remotely triggered by a signal generator installed in the command room of the centrifuge. The gun exit was positioned just near the impact point (~1 cm) so that the ball is bounced back into the gun, enabling repetition of other similar shocks. The bounce of the ball on its target along with a slight back slope of the tube (<5 %) returns the ball to its initial position; a special mechanism for reloading the gun is unnecessary. For a perfectly horizontal impact, it would have been possible to bend the tube slightly, yet this option proved some-
what technically strenuous for limited benefit. The straight set-up used provides for a reasonably “horizontal” shock given that due to the back slope of the guiding tube, the vertical component is probably less than 5% of the horizontal component.

The electronic triggering system is composed of two sets:

- an onboard energy bank made of two 100 V – 47,000 µF capacitors (2.5 kg) directly feeding the coil when triggered;
- in the command room of the centrifuge, a rheostat charges the capacitors through the slip rings of the centrifuge automatically after each shot, while a signal generator enables remote triggering of the coil feeding through an electronic gate on the capacitors.

The ball velocity at the exit of the guiding tube (see Fig. 5), is controlled through the resistance and the duration of the trigger impulse.

The amplitude of the impact can be tuned in flight with a remote controller. Repetition of shocks is also remotely controlled, either to reproduce the same pulse one by one or to cumulate increasing amplitude of impacts. This gives the opportunity to study the progressive deterioration of the soil pile interaction after a series of impacts. The time duration of the impact is typically $t = 0.01$ s (prototype scale), which corresponds to a Dirac impulse as regard to the vibration period of the tested pile systems in this research work, namely from 0.2 to 0.5 s in prototype scale (scale factor for time or period in dynamic problem is $1/n$).

An optical diode has been placed at the end of the tube. The signal delivered by the diode shows the end of phase at $T_o$ for the direction leading to the shock and $T_b$, following the bounce. The difference in these times is used in evaluating the momentum. The velocity of the ball before impact $V_o$ and then after the rebound $V_b$, are both calculated according to the relations: $V_o = d/T_o$ and $V_b = d/T_b$ (where $d$ = ball diameter), and the momentum equation is as follows: $P = m.d(T_b - T_o)/(T_b - T_o)$. This optical device allows a comparison between the momentum value calculated from these diodes and the value derived by integrating the time history of the force from the force sensor fixed on the target. A full description of this device has been provided by Hajialilue-Bonab et al. (2004).

**Pile Installation**

The piles were installed in the centrifuge box using three different methods of installation.

**Cast-in Pile**—The box is first placed under the hopper. Sand pluviation is conducted until the reconstituted sand layer reaches a height corresponding to the tip of the model pile. The model pile is then suspended with a nylon cable. The sand pluviation procedure is then continued around the pile until the chosen final thickness of sand is obtained. This method of pile installation does not generate extra confining pressure on the pile. The pile may be considered similar to a drilled or cast-in-place pile (Fig. 6).

**1 g Driven Pile**—This mode of installation is done with a manual hammering system. A simple device designed at LCPC allows a good repeatability of the pile driving, regardless of the operator (Fig. 7). During the pile driving operation, the number of hammer blows per unit length of penetration is recorded in order to check the sand homogeneity. At the end of the driving, a small coni-
cal depression around the pile had been observed. It is approximately 10 mm deep, indicating a densification of the soil around pile.

1 g Jacked Pile—A hydraulic jack is used to drive the pile in the sand at 1 g level. This installation method is not representative of any full-scale pile driving because it is done at 1 g: spinning the centrifuge from 1 g to 40 g will generate vertical shear stresses along the pile, and this does not occur in the field.

Test Results

Two model piles, successively equipped with two pile caps, M2 and M3, were installed in place according to the three aforementioned methods. These piles were subjected to a series of eleven identical impacts. The objectives were to analyze the dynamic responses for these three cases of installation and the variation due to impact repetition.

The output from the first strain gage, located at the soil surface, was selected to compare the resonance frequency and the damping ratio. The damping ratio of the responses were evaluated using the half-power method.

The resonance frequency of the driven pile was found to be higher than the jacked and cast-in piles, with the cast-in pile giving the lowest resonance frequency. It is also observed that the rate of increase in the resonance frequency of driven piles is lower than that for both of the other cases (Fig. 8).

It can be observed that the highest damping is obtained for the jacked pile (whereas the same method produced intermediate levels of frequency) and the lowest damping is observed for the driven pile. Damping for the cast-in pile falls between the two.

Different types of pile installation methods can be characterized by two main disturbances of the soil around the pile, namely the development of a stress-strain field and changes in the local density.

Considering the cast-in model piles, the change of initial properties of the surrounding soil during the pile installation is less significant than for other cases. There is, however, a disturbance in this case inherent to the preparation of the soil medium. The presence of the pile before sand pluviation slightly disturbs the homogeneity of the soil density adjacent to the pile.

In the case of pile driving, the density of soil medium around the pile increases and the stress state is modified compared to initial stresses. This modification of the stress state is partly relaxed because of the dynamic movement between the grains induced by the shock of driving.

In the case of jacked piles, there is also a modification of the density and the stress state around the pile. It can be supposed that the modification of the state of stress is more significant than the density change because there is no dynamic effect in this case.

Considering these assumptions, the results can be interpreted as follows:

- The resonance frequency and the stiffness of the driven pile are higher than those of the jacked and the cast-in piles because the density of the soil around the pile is increased significantly.
- The resonance frequency of the jacked pile is higher than that of the cast-in piles because the confining stress and the density of soil around the pile are higher than cast-in piles.
The damping ratio is strongly dependent on soil density and the stress state of soil around the piles. Indeed, the damping ratio for the driven pile is smaller than for the jacked pile and the cast-in pile. It can be concluded that the damping decreases with the density, but increases with the stress state of the soil around the pile and with depth.

Sources of Error Related to Pile Positioning and Consequences

As the dimensions of the model are reduced, any small error can involve nonnegligible uncertainties at prototype scale. Therefore, different sources of error were identified and are evaluated below.

Irrespective of the method used among the three installation techniques presented above, the possible errors during installation are as follows (Fig. 9):

- eccentricity between the location at which the gages are positioned and the direction of the impact (uncertainties in the bending moment, $E_{u1}$); and
- difference between the obtained and the chosen depth of embedment of the pile, $E_z$.

To limit the error related to the direction of the axis of the gages, a mark of location was made on the head of the pile. If necessary, the direction was corrected by a manual rotation of the pile, before proceeding with the driving. The absolute uncertainty was evaluated at ±3 deg.

The error relative to the embedment depth of the pile after driving was compared to the chosen depth results from the conical hollow around the pile created during pile installation. This uncertainty was estimated to be equal to ±2 mm. For a test run with a scale of 1/40, i.e., at 40 g, this corresponds to an error of 8 cm at the prototype scale.

Repeatability Tests

Two tests were carried out using the same model pile, instrumentation, dynamic lateral loading, position of the pile in the container, and pile cap in two successive containers. The comparison of the obtained measurements is given in Fig. 10 for two identical impacts. It is observed that the maximum displacements at the pile head are very consistent until a time $t=2$ s. Beyond that there is a small change in frequency, which is also observed for the bending moments at various depths. These small differences can be linked to the various source of errors mentioned before.

The frequency content of the pile response in two cases are compared in Fig. 11 using the Fourier transform of one of the strain gage outputs. The frequency distribution is very similar in both cases as well as the resonance frequency which are 2.36 Hz and 2.43 Hz (prototype scale). The observed difference is 3 %, which is considered acceptable for this type of experimental work.
Boundary Influences

One of the most important effects in centrifuge dynamic tests is the boundary influence due to possible propagation of reflected waves. Two main boundary influences can be identified:

- the soil sample tends to vibrate at its main frequency whereas the rigid container imposes rigidity at the edges of the soil mass which blocks the free vibration of soil medium; and
- wave reflection generated by the vibrating structure in the soil from the walls of the container and superimposing themselves to the movement of the studied system.

The first effect does not relate to this study because the soil medium does not vibrate such as in an earthquake experiment. Therefore, we will only check the importance of the second effect.

As stated above, piles were installed at six locations in each box (Fig. 4). Considering these locations, four positions were identical (Cases A) with respect to the proximity from the box walls and two (Cases B) were different. It is assumed, that if the responses of the piles are identical along these two typical positions, it may be concluded that either there is no boundary effect in our tests or the boundary effects are similar for all the tests.

To verify these assumptions relative to the influence of the walls of the box during the dynamic tests, a comparison was carried out with two different pile caps, M1 and M4, respectively. A very light superstructure producing a “high” resonance frequency close to 4 Hz (M1), and a heavy superstructure giving a “low” resonance frequency of 1.55 Hz (M4). In the case of pile cap M4, comparison for two typical locations A and B is given in Fig. 12. To observe if any influence exists, the response of the piles under the first applied impact is discussed. The aim of this to eliminate the effect of cumulative impact.

A very good agreement is observed for the bending moment versus time along the pile for the measurements from the two depths as presented in Fig. 12; measurement from other depths confirm the same observation. The pile response in its various components is very coherent. The small difference in the resonance frequency is less than 4 %. It is not possible to distinguish errors coming from boundary effects and other errors mentioned above. This difference remains in the range of acceptable errors as usually observed in experimental studies.

This test was repeated for pile cap M1 and similar results were obtained. It appears that the pile responses have a similar shape for the two locations without any significant changes in the damping values and the frequency. A conclusion can be drawn in relation to the influence of reflections on the box wall: the waves generated by the pile and reflected by the sides of the box have no evident or quantifiable influence on the response of piles to impacts in the centrifuge for the arrangement studied.

FIG. 11—Normalized FFT of strain for two similar tests in two different containers.

FIG. 12—Comparison of pile responses in two locations A and B.
Scale Effect and Modeling of Models

By reducing the scale in experimental tests, it is not possible to reproduce with accuracy all the details of the prototype, and some approximations must be accepted. It is therefore important to understand that the model analysis is not perfect and hence it is necessary to identify the scale effects and evaluate them. The influence of nonuniformity of the artificial gravity in the box is an example of one of the scale effects. A reliable technique to assess the scale effect is "modeling of models" (Ovesen 1979). It is particularly useful when comparison to a prototype test is difficult. This method consists of comparing the response of the model at different scales. The models are expected to have the same behavior. If this is the case, the tested modeling procedure is generally considered to be valid.

As this research work was carried out at a reduced scale of 1/40, another reduced scale of 1/60 was selected to compare the results. These two scales are not very different because the instrumentation and limitations of the study procedure do not allow a larger scale ratio than 1/40. As it was both technically difficult and expensive to put strain gages on the 1/60 pile model, tests were run with size restriction and no gages were used for the two pile models scaled at 1/40 and 1/60. Tests were carried out with the two pile caps (M2, m2) and (M3, m3). The piles were installed by driving at 1 g. This procedure is not optimal in terms of comparison as the two piles are not driven in the same stress field condition of the soil. The ideal comparison would have been that the pile at the 1/40 scale pile be driven at 40 g and that the 1/60 scale pile be driven at 60 g.

The piles were subjected to cumulative impacts of increasing amplitude, starting from a very weak impact, until the 20th impact, which was relatively high.

Pile head displacement and acceleration, at the point of impact, and the applied force were measured for these tests. The results reported here are for the prototype scale. Figure 13 shows the Fourier transformation of the displacement at the pile head for the pile tested at 1/40 scale with the pile cap M2 and for the pile scaled to 1/60 with the pile cap m2 (same prototype mass as M2). The comparison is also presented for the cap M3 and m3 (Fig. 13).

A very good agreement is observed among the responses obtained at the two scales: the general shape of the fast Fourier transformation (FFT) and the resonance frequency of the soil-pile system are very similar. For the pile cap m2 or M2, the frequency resonance is approximately 3 Hz, and for the pile with pile cap m3 or M3, it is approximately 2.1 Hz, at prototype scale. It is observed that the resonance frequency decreases with the accumulation of impacts. Figure 14 shows more accurately the similarity of the response in terms of evolution of the resonance frequency along with cumulative impacts.

Another comparison was carried out between the maximum displacements obtained from similar tests at two scales: 1/40 and 1/60.
placements of the pile head at these two scales, related to the applied momentum. Figure 15 illustrates the good agreement between the two scales of tests.

Taking into account the number of tests carried out, it can be concluded that there is no scale effect for these two levels of acceleration and the chosen reduction scales.

**Conclusions**

The ability to carry out horizontal impact tests on piles in the centrifuge has been achieved by developing a new electromagnetic impact driver described here. Its versatility lies in the remote tuning of the amplitude of the impact and any program of repetition of impact driver described here. Its versatility lies in the remote tuning of the amplitude of the impact and any program of repetition of impacts.

The efficiency of sensors (laser displacement versus accelerometer, force sensor versus presence diodes at the exit of the canon) allows for an accurate recording of the time history of the force, the displacement and the acceleration of the pile head, all these data forming the boundary conditions in a numerical modeling of these types of experiments.

Main sources of uncertainties related to reconstitution of the soil medium and installation of the piles were investigated and evaluated. Repeatability of testing in different soil samples was proved on a wide range of frequencies and is verified with tests carried out on pile caps with different masses.

The two most important factors that were examined are the scale effect and the effect of reflection of waves from the box walls. A “modeling of models” approach has shown the scale effect on the frequency response of the soil-pile system to be negligible. Tests carried out at different locations in the box show that waves reflected from the box walls have no significant effect.

It was then possible to establish a comprehensive testing program in which different parametric studies were undertaken to study factors such as: effect of superstructure mass, effect of the impact amplitude, and finally, the evaluation of dynamic P-y loops (Hajialilue-Bonab 2003).

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**References**


