

## **EFFECT OF INCLINED PILES ON THE DYNAMIC PERFORMANCES OF AN END-BEARING PILE GROUP**

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### **ABSTRACT**

Inclined piles are prohibited by many codes in seismic area. Nevertheless the battered effect has not yet been clarified because very few data are available. In this paper, we focus on the influence of inclined piles on the inertial response of a group of two piles as an introduction to the more complex analysis of the performance of such groups under seismic loads. The present work is a comparison at reduced scale in the centrifuge of the response of two simplified end-bearing pile groups: a group composed of two vertical piles and group composed of a vertical pile and a pile inclined at 25° to the vertical. Each pair of piles is linked by a massive pile cap rigidly fixed on the piles. Repeated horizontal impacts were applied on the pile cap. The effect of the pile inclination on the response has been evaluated in terms of frequency analysis, cap acceleration, bending moment profiles and axial load at each pile. Results highlight that the inclined pile increases the pile group stiffness, decreases the maximum bending moment below the soil surface and increase axial load in each pile of the group.

Keywords: inclined pile, impact test, centrifuge modeling, pile group

### **INTRODUCTION**

In seismic area the behavior of inclined pile is considered as detrimental. Seismic regulations such as the French one PS92 (1992), prohibit the use of inclined piles to resist to seismic load. Other regulations, such as the European one (Eurocode 8 chapter 5) are less restrictive and indicate that "it is recommended that no inclined pile be used for transmitting lateral loads to the soils. If in any case such piles are used they must be designed to carry safely axial as well as bending loading".

The main drawbacks most often mentioned by engineers were summarized by Gazetas (2003). He mentioned the effect of the possible soil densification that follows an earthquake which induces bending stress in the inclined piles and the reduction of bending capacity of the inclined pile induced by the development of large tensile force during an earthquake. Another main factor is the large forces induced onto the pile cap connection during the earthquake: he indicates the possible tensile or compressive failure at the connection with the cap when the pile is embedded or the extraction of the pile because of cyclic axial distress in case of floating piles.

However recent studies have pointed out that in several configurations, battered piles may have a beneficial behavior. During Kobe (1995) earthquake, the only one quay in Maya Wharf that suffered limited displacement was that built with inclined piles, while the two other types, without inclined

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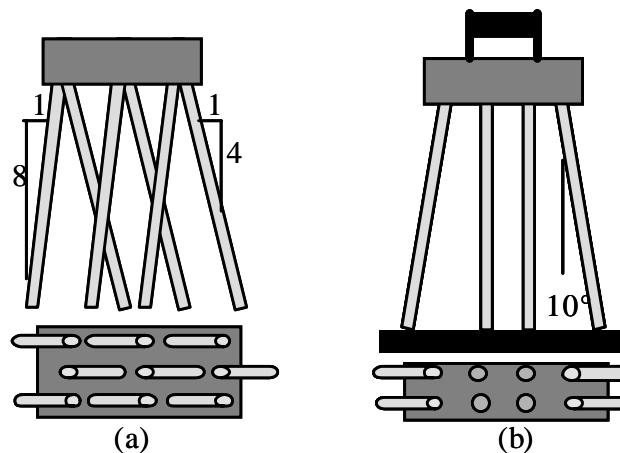
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piles were severely damaged (Kastranta et al., 1998). Numerical analysis pointed out that the presence of inclined piles was one of the reasons why the quay wall managed to withstand the severe seismic motion and experienced only small displacements. In addition, Lam et al. cited by Gazetas (2003) showed that both, the pile cap displacement and the bending moment profile, may be drastically reduced in liquefied soil due to the stiffening effect of the battered piles.

Until today very few case-histories or experimental data have been well documented on this topic. The influence (beneficial or detrimental) of battered piles on the seismic response of pile groups has not yet been clearly established. In the static and cyclic domain, Zhang et al. (1999) have performed centrifuge tests to study the effect of the pile inclination and soil density by submitting a single in-flight battered pile to horizontal static loading. From measurements of the pile head displacement, they concluded that the batter effect was minor in very loose and loose sand, and significant in medium-dense and dense sand. The increase of the horizontal resistance as regard to vertical piles was respectively 24 and 50% in medium-dense and dense sand for piles loaded against the batter. In the case of piles battered in the loading direction, the resistance decreased was respectively 15 and 35% for medium-dense and dense sand. McVay et al. (1996) have studied the effect of battered piles in fixed-head 3x3 pile group which layout is typical in California (Fig. 1a). They compared the pile cap displacement of the battered pile group with that of a vertical pile group.



**Figure 1. Pile group configuration (a) McVay et al. (1999) (b) Okawa et al. (2002)**

As previously, the battered effect was negligible in medium-loose sand. The authors justify these results by the limited axial capacity of the pile in the loose sand. In medium-dense sand the lateral resistance increased was 20 to 50% as regard to that of a fixed-head vertical pile group.

In the seismic domain few experimental studies have been devoted to the effect of inclined pile on the pile group response. Okawa et al. (2002) performed centrifuge seismic tests at 45g in a laminar box on two end-bearing and fixed-head pile groups. Each pile group was composed of 8 aluminum pipes (4x2). The first one was only composed of vertical piles and the second one battered piles (Fig. 1b). They pointed out that the use of inclined pile decreases the acceleration amplitude on the footing and on the superstructure and the bending moment at the pile-cap interface. In addition comparing the time histories of the bending moment and the axial load in the pile, they highlighted that the presence of inclined pile changes the overall deformation pattern of the pile group. Finally by coupling their experimental results to numerical modeling, they indicated that the behavior of the vertical pile group seemed largely influenced by the inertial effect. On the opposite the inclined pile group response highlighted the kinematics interaction. In the framework of the French research program FOREVER (2002) the influence of inclination of micropile on the seismic behavior of micropile group was studied. Seismic centrifuge tests were performed in a laminar box on several micropile group

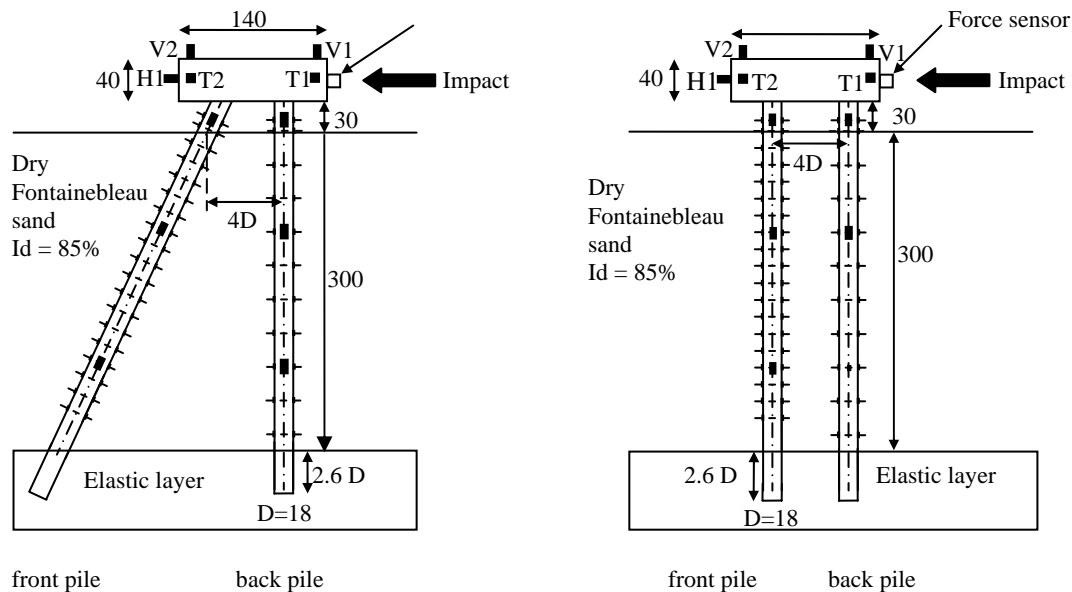
configurations among which 1x2 vertical and inclined pile group. It was showed that inclined micropiles induce a decrease of the pile cap displacement. Contrary to the results of Okawa, the bending moment is increased at the pile cap interface in inclined micropiles. In addition the maximum bending moment is reduced below the soil surface in inclined micropile group.

In the framework of the European Research Program Quaker, an experimental study of the effect of inclined pile on the seismic response of pile group has been initiated based on centrifuge modeling. The final objective is to provide an experimental database to calibrate and validate the available analytical and numerical methods developed for the seismic soil-pile interaction. The response of two groups will be compared: one composed of two vertical piles, one composed of one vertical and one inclined pile. As the soil-pile interaction is generally analyzed in terms of the inertial and the kinematic interaction, impact tests were performed first in order to analyze the inertial component of the seismic response. These tests intend to highlight the main differences between those pile groups through the frequency response, the accelerations at the cap, the bending moment profiles and the axial load in each pile.

## EXPERIMENTAL SET UP AND PROGRAM

### Experimental set up

Figure 2 represents the design of the two models of end-bearing pile group. In the first configuration both piles are vertical contrary to the second configuration where one pile remains vertical and the second is inclined at  $25^\circ$  to the vertical.



**Figure 2. Pile group layouts (in mm).**

The flexible model piles at a reduced scale of 1/40 which characteristics are given in table 1 are aluminium tubular piles. The correspondent prototypes characteristics are also given in table 1. Each pile is instrumented with strain gages for the evaluation of the bending moment at different depth and the axial load. The bending moment at the pile cap connexion is estimated from the measurement of the bending moments above the soil surface and at the soil surface.

In both configurations the piles are capped with a rigid beam which provides a moment restraint at the pile heads. The rigid cap is made up of two parts assembled around the pile heads with six bolts. As the frequency response is sensitive to the assembly conditions the bolt tightening is performed with a dynamometric key. In addition, a massive geometry has been chosen to avoid additional vibration modes. The movement of the pile cap during impact tests is recorded through five accelerometers (H1 : horizontal direction, V1 and V2 vertical direction, T1 and T2 transversal direction).

**Table 1. Characteristics of the pile groups**

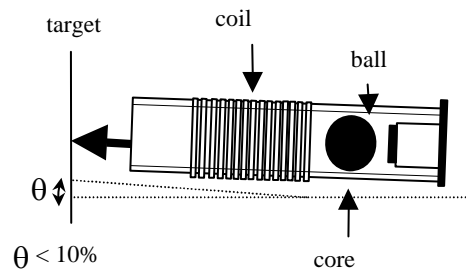
Characteristics	Model scale	Prototype scale 40g
<i>Piles</i>		
Embedded depth of pile	300 mm (sand) 47 mm (elastic layer)	12 m (sand) 1.88 m (elastic layer)
External diameter	18 mm	0.72 m
Internal diameter	15 mm	0.60 m
Young modulus	$7.4 \cdot 10^{10}$ Pa	
<i>Bending stiffness</i>	197 N.m <sup>2</sup>	505 MN.m <sup>2</sup>
<i>Cap</i>		
Dimensions (LxlxH)	140mmx40mmx40mm	5.6m*1.6m*1.6m
Weight	560 g	33.8 T

Soil specimens with two layers were used to simulate the end-bearing pile conditions. The first layer, representing the bed-rock, is a supposed elastic layer made of cast resin moulded around the pile tips previously correctly positioned. Its mechanical characteristics are given in table 2. The piles are embedded on a length of 2.6 diameters of the pile. The top layer is a layer of an homogeneous dry Fontainebleau sand which has been reconstituted by air pluviation at a density of 84%. The Young modulus of the elastic layer is 2.5 higher than that of at the sand/elastic layer interface at 40g and can be considered as a stiff layer in the test configuration.

**Table 2. Characteristics of soil layers**

<i>Fontainebleau sand</i>	
$I_D$	84%
$\gamma_d$	16.2 kN.m <sup>3</sup>
$K_0$	0.32
<i>Elastic layer</i>	
E	480 MPa

The dynamic loads are generated by an electromagnetic coil accelerating a steel ball (Bonad et al., 2002). A schematic representation is given in figure 3. This device generates Dirac-like force impulses with a typically duration of 0.25 ms in the case of the test performed on both pile groups (model scale). The amplitude of the impact is measured with a load cell glued on the pile cap.

**Figure 3. Dynamic loading device**

### Experimental program

Four dynamic tests were performed on each pile group for repeatability tests and comparison of the responses of both pile groups. Previous studies performed on the inertial response of a single floating pile (Chenaf et al., 2006 ; Bonab, 2002) highlighted that the inertial response was stabilized after a series of 10 to 15 impacts at the same level of maximum force. Considering these observations, each group was submitted to a minimum of 20 identical impacts.

As the duration of impacts was always the same, in the following we consider the maximal force instead of the total momentum received by the pile group from the ball. Table 3 summarizes the 8 tests performed. It indicates the total number of impacts and the corresponding range of amplitude. The number indicated in bracket is the number of relevant impacts (the others are largely weaker) and the corresponding level of amplitude. The difference between the total number of shocks and the number of relevant shocks comes from a problem with the capacitor that feed the electromagnetic coil of the dynamic loading device.

**Table 3. Impact tests performed on both pile groups.**

Box	Type of pile group	Number of impacts	Amplitude of the impact (kN)
Q14	Vertical	-	-
	Inclined	19 ( <b>17</b> )	2630 – 3624 ( <b>3540</b> )
Q15	Vertical	35 ( <b>19</b> )	221 - 4746 ( <b>4640</b> )
	Inclined	23 ( <b>18</b> )	415 - 5309 ( <b>3700</b> )
Q17	Vertical	27 ( <b>16</b> )	627 – 3074 ( <b>2980</b> )
	Inclined	30 ( <b>21</b> )	982 – 2789 ( <b>2570</b> )
Q18	Vertical	29 ( <b>20</b> )	1239 – 3278 ( <b>3060</b> )
	Inclined	26 ( <b>13</b> )	1060 – 3653 ( <b>3513</b> )

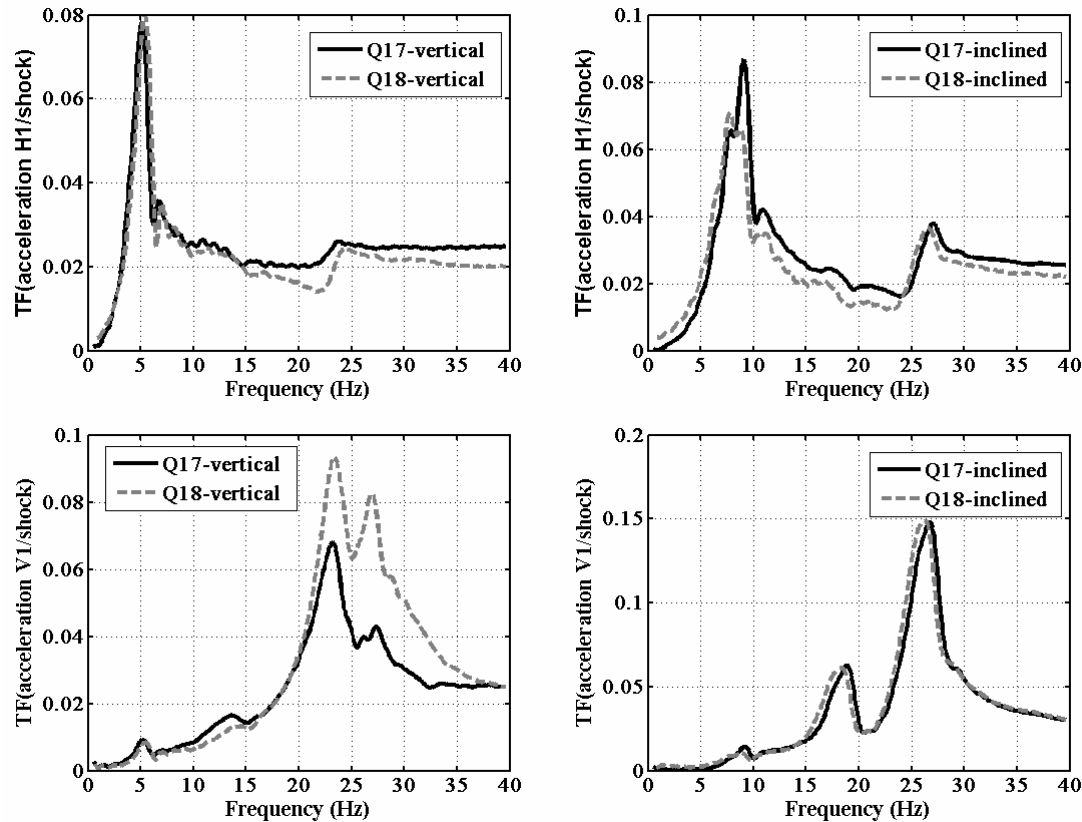
In the following analysis the repeatability of the tests and the comparison of pile groups responses is achieved considering the stabilized responses. Only results obtained from the tests performed in boxes Q17 and Q18 are presented in this paper.

## ANALYSIS AND DISCUSSION

### Frequency response

The frequency analysis has been performed through transfer functions between the bending moment or the axial load or acceleration and the impact applied at the pile cap. The resonance frequencies have been determined taking into account the amplitude ratio and the phase difference. In addition the repeatability of the frequency response during the successive impacts has been verified through the coherence function calculated from the last five relevant impacts performed on each pile group. Figure 4 represents the amplitude of the transfer function of the horizontal and vertical acceleration (H1 and V1). In terms of frequency response a good repeatability is obtained for the tests performed on vertical pile group (figures on the left). In the case of the inclined pile group, despite the difference of the impact amplitude (box Q17: 2570 kN and box Q18: 3513 kN), the frequency response are almost the same. It indicates that, for this range of impact amplitude, if the behavior of the soil-inclined pile group system is non-linear, the effect of non-linearities is negligible on the modal frequencies.

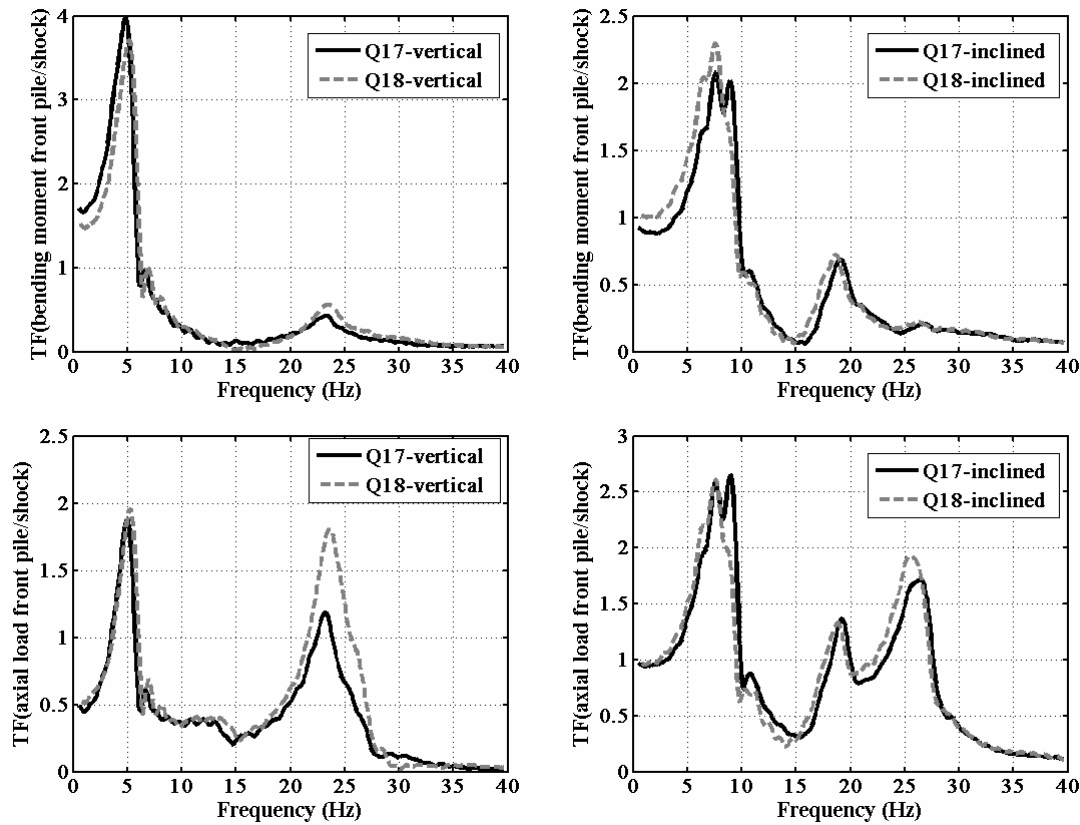
In horizontal acceleration H1, the principal resonance frequency is 5.1 Hz for the vertical pile group. For the inclined pile group there is a double peak of amplitude (7,5 and 9 Hz). Contrary to the vertical pile group, a second less powerful resonance frequency is identified on the inclined pile group response at 26 Hz. This resonance frequency corresponds to the most energetic frequency in the case of the vertical acceleration V1 on which two other frequencies are identified around 19 and 8Hz. In the case of the vertical pile group only two resonance frequencies can be identified from the amplitude ratio and the phase difference: the first one around 23 Hz and the second one around 5.1 Hz.



**Figure 4. Amplitude of the transfer functions – Horizontal (H1) and vertical (V1) accelerations measured at the pile cap**

Figure 5 represents the front pile bending moment calculated at the pile-cap connection and the front pile axial load above the soil surface in the cases of the tests performed in the boxes Q17 and Q18. In both cases, the most powerful resonance frequency for the bending moment calculated at the pile cap interface is the same as the most powerful resonance frequency of the horizontal acceleration. It suggests that the corresponding mode of vibration is a kind of translation-rocking motion of the pile cap which induces bending moment in the piles. Despite that the principal resonance frequency of the inclined pile group cannot be clearly identified, this group has a stiffer behavior than the vertical one for this mode of vibration. In the case of the front pile axial load measured above the soil surface, two peaks can be pointed for the vertical group and three for the inclined one. They correspond to the resonance frequencies identified on the transfer function of the vertical acceleration V1 but the amplitude ratio between the resonances frequencies are not the same.

The measurement of the vertical acceleration is more sensitive to the rotation of the pile cap than to a movement of translation-rocking. It can be assumed that the resonance frequencies around 23 Hz for the vertical pile group and around 18 Hz and 26 Hz for the inclined pile group correspond to modes involving principally a rotation of the pile caps (with such 2 modes in the case of the inclined pile group). Under this assumption, the axial load in the piles is induced by the rotation modes and the translation-rocking modes. In both groups, the axial load induced by each kind of mode of vibration is far from negligible. In addition, in the case of the inclined pile group, the mode corresponding to a frequency around 18 Hz has a coupled action in axial load and bending moment in the piles.



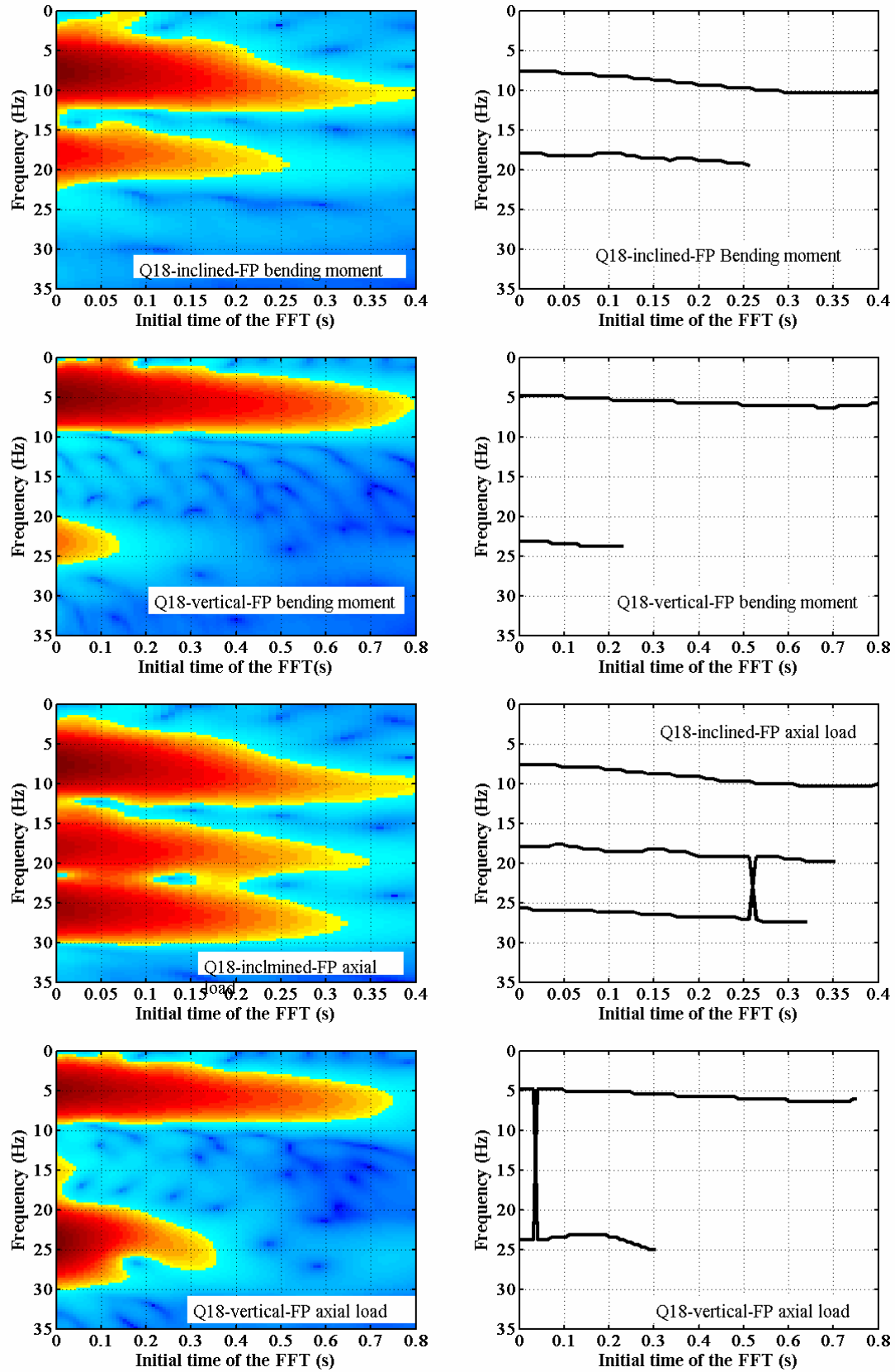
**Figure 5. Amplitude of the transfer functions in the front piles:  
Top: bending moment at the pile-cap interface, bottom: axial load above the soil**

### Time frequency analysis

The time frequency analysis enables to visualize the evolution the frequency response versus time. The evolutions are similar for the accelerations, the bending moments and the axial loads along each group. Consequently figure 6 is limited to the presentation of the time frequency response of the bending moment at the pile-cap interface and of the axial load above the soil surface, measured in the front pile. The time frequency analysis has been performed with a moving 0.4 s Hanning windowing. Left hand side figures are the time-frequency contour maps. Right hand side figures present an extraction of the frequency peaks along time.

The resonance frequencies appear not to be constant versus time for both pile groups. The evolution of the resonance frequencies is higher in the case of the inclined pile group. For the inclined pile group the frequency corresponding to the translation-rocking movement seems either to increase from 7.6 to 10.1 Hz or be a combined mode vibration with narrow frequencies. For the vertical pile group it increases from 4.9 to 5.5 Hz. In the case of the frequencies of the modes of rotation they increase from 18 to 19,7Hz and from 25.6 to 27.2 Hz for the inclined pile group. The increase of the frequency for the vertical pile group is lower: from 23.2 to 23.8 Hz.

The time-frequency analysis also highlights that, regarding the translation-rocking mode, the response duration of the inclined pile group is shorter than that of vertical pile group. For equivalent applied forces, the responses vanish respectively after 0.8 s and 1.2 second.

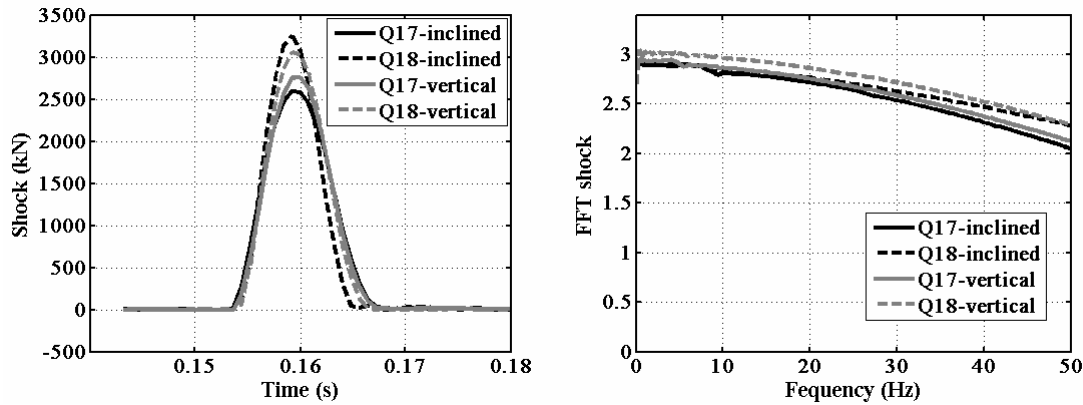


**Figure 6. Time-frequency analysis - bending moment and axial load above the soil surface in the front pile.**



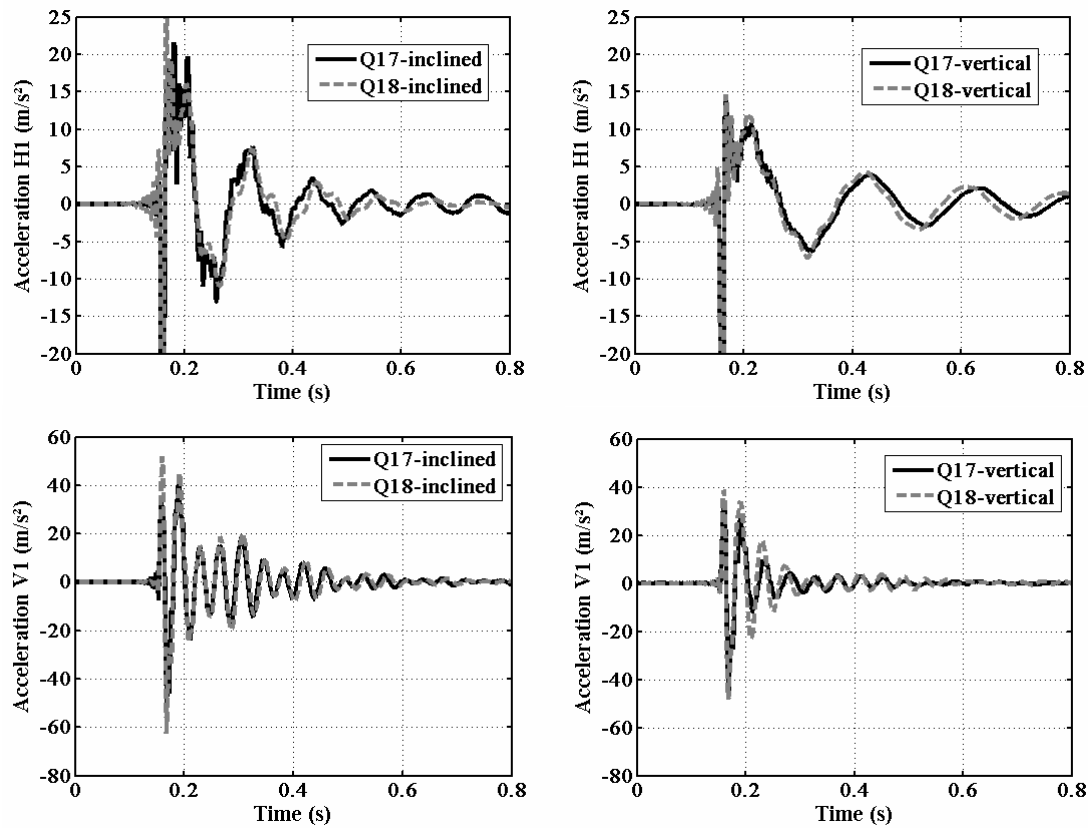
### Pile cap movement

In both pile groups the frequencies of the principal modes of vibration are below 30 Hz. Consequently instead of taking into account impacts with the same amplitude, impacts which frequency contents below 50 Hz are almost the same have been considered for the following analysis. Figure 7 represents the considered impacts and their frequency content below 50 Hz for the tests performed in boxes Q17 and Q18.



**Figure 7. Amplitude and frequency content of the impacts on pile cap**

Figure 8 represents the horizontal acceleration H1 and the vertical acceleration V1 for each pile group. In both cases a good repeatability is obtained.

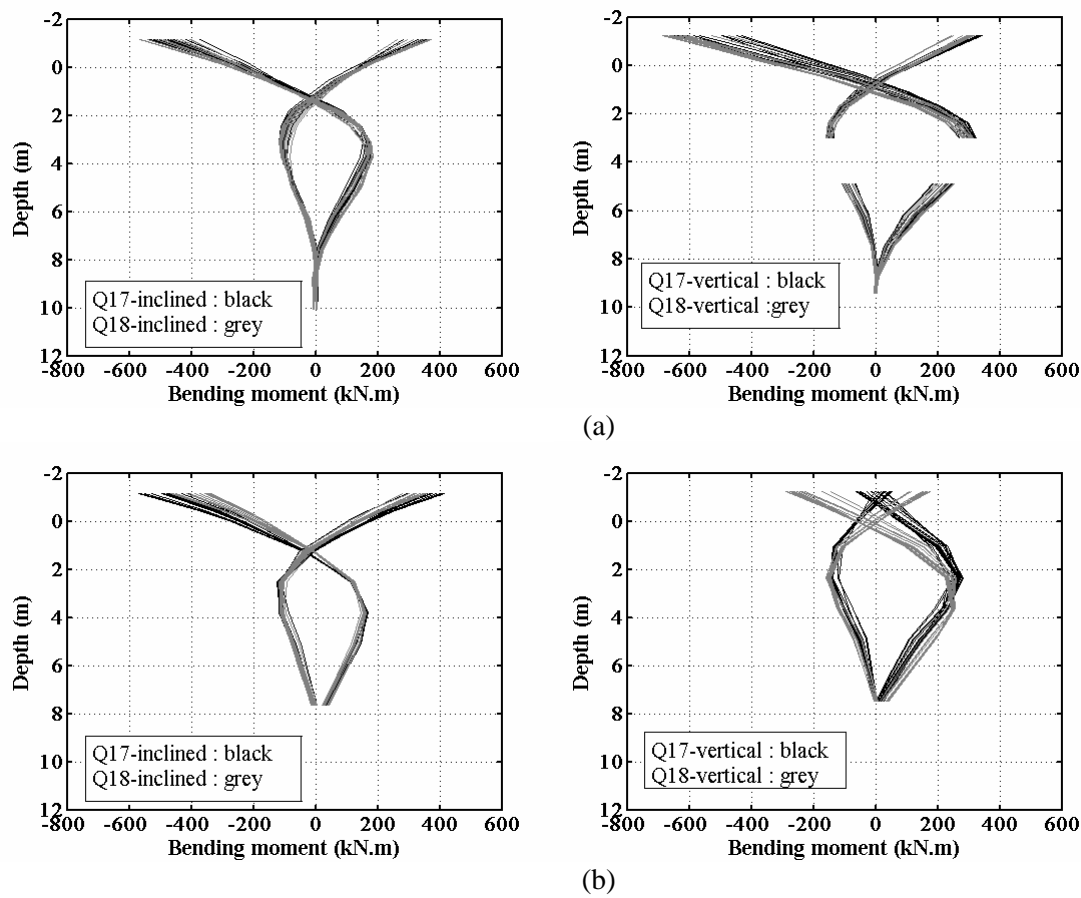


**Figure 8. Time response : horizontal acceleration H1 and vertical acceleration V1 measured at the pile cap of the inclined pile group (left) and the vertical pile group (right)**

For the horizontal acceleration, high frequencies appear at the beginning of the signal. They can be due to electrical perturbations or high modes of vibration which induce very small displacements. Taking into account the acceleration induced by the translation-rocking mode of the cap, the maximum accelerations of the inclined and vertical pile groups are respectively around 12 and 10 m/s. As the corresponding frequency is 5.1Hz for the vertical pile group and approximately, between 7.6 Hz and 10.1Hz for the inclined one, the horizontal displacement is between 2 of 3 times higher for the vertical pile group. In the vertical direction, the acceleration V2 (figure 2) is negligible (less than 1 m/s). Then the center of rotation of the corresponding rocking mode can be assumed to be at the vertical of the accelerometer V2. The maximum accelerations V1 measured on the inclined pile group is slightly higher than that of the vertical pile group. The greatest difference between these two types of groups is finally that in the case of the inclined pile group the duration of high amplitudes is longer.

### Bending moment profiles

Figure 9 presents the maximum bending moment profiles measured on both piles of each pile group.



**Figure 9. Bending moment profile (a) in the front pile and (b) in the back pile of the vertical and inclined pile groups**

Tests performed on inclined pile group are repeatable whereas the results obtained on the back pile of the vertical pile group highlight a difference of the bending moment at the pile/cap interface. It can be significant of different boundary conditions at the back pile head between tests, despite the use of a dynamometric key for the cap assembly.

In both piles, the maximum bending moment measured below the soil surface is higher for the vertical pile group. In the front pile, the maximum bending moment is about 120 kN.m for the inclined pile whereas it is higher than 320 kN.m for the vertical pile group. In the back pile the maximum bending moments, for the inclined and the vertical pile groups, are respectively 170 kN.m at a depth of 3.8 m and between 260 and 280 kN.m at a depth of 2.3 m (box Q17) or 3.6 m (box Q18).

The maximum values of the bending moment near the cap are approximately the same in the front and the back pile of the inclined pile group. For instance for the test performed in the box Q17 the maximum bending moment in the front pile and back pile are respectively - 535kN.m / 365 kN.m and -570 kN.m / 410 kN.m. In the vertical pile group, despite the problem of repeatability for the back pile, the front pile maximum bending moment seems higher than the back pile one. In addition the compared responses highlight that the difference of the front pile maximum bending moment is not significant between the inclined and the vertical pile groups. In the case of the back pile, it can be concluded that the inclined pile group should sustain higher bending moments.

### Axial load in the piles

Figure 10 represents the axial load measured in the front and the back pile of each pile group. A good repeatability is obtained for the tests performed in the boxes Q17 and Q18. In both piles the maximum axial load is higher in the case of the inclined pile group. The maximum compressive load is around 980 kN in the front pile and the maximum extension load is around 1370 kN in the back pile. In the case of the vertical pile group the correspondent values are respectively 570 kN and 680 kN. The compared responses highlight that the presence of the inclined pile increases the axial load both in the front and the back piles. The ratio between the inclined pile group and the vertical pile group in term of maximum axial load is around 1.7 for the front pile and around 2 for the back pile.

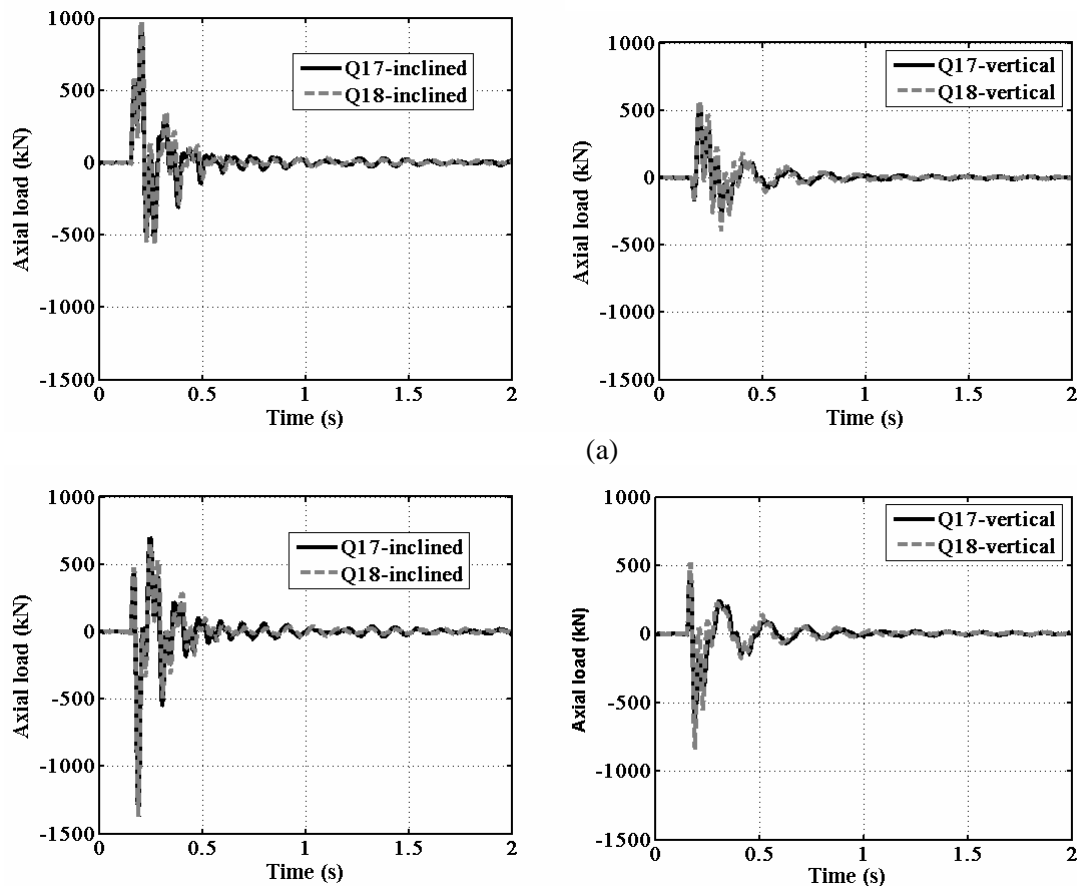


Figure 10. Time response of the axial load in (a) the front and (b) back pile in the inclined pile group (left) and the vertical pile group (right)

### CONCLUSIONS

Centrifuge tests were performed on groups of end-bearing piles in order to analyse the influence of inclined piles. The responses of two groups are compared under horizontal impact loading: one with two vertical piles and the other with a vertical pile and an inclined pile.

The frequency analysis highlights a mode of translation-rocking of the cap, for which the inclined group is stiffer than the vertical one, and a mode involving principally a rotation of the cap (with two such modes for the inclined pile group). Furthermore, the frequencies of the modes of vibration increase versus time. This increase is higher for the inclined pile group than for the other one.

Concerning the pile cap movement, the inclined pile induces a decrease of the translation movement and an increase of the duration of a significant vertical acceleration. In addition in both pile groups the center of the rotation movement of the cap can be assumed to be near to the vertical of the end of the pile cap on the front pile side.

In term of bending moment profile, the presence of the inclined pile induces a decrease of the maximum bending moment below the soil surface in both piles. In addition, from these tests results, the influence of the inclined pile on the maximum bending moment at the pile cap interface seems to be negligible in the front pile whereas it induces an increase of the maximum bending moment in the back pile.

The axial load is increased in the front and the back pile of the inclined pile group by respectively a factor of 1.7 and 2.

### **AKNOWLEDGEMENTS**

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