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## Centrifuge modelling of inclined pile foundations under seismic actions

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**ABSTRACT:** Although inclined pile foundations are sometimes used in civil engineering structures, their behavior under seismic loadings is not yet thoroughly understood. This paper presents an experimental work on inclined pile foundations under earthquake loadings. Dynamic centrifuge tests are performed to investigate the influence of inclined piles on the superstructures and to quantify the soil-structure interaction. Some key parameters are analyzed such as the residual bending moment, the total bending moment and the axial forces. It is found that in certain cases inclination plays a beneficial role to the seismic behavior of the pile foundation system and that the presence of inclined piles increases its natural frequency. Comparing to a vertical pile foundation, the residual bending moment envelope curve is different and larger values are observed. This novel experimental work provides significant data to understand the behavior of inclined pile foundations in seismic regions.

**KEY WORDS:** Centrifuge Modelling; Inclined Pile Foundation; Seismic response; Soil-structure interaction.

### 1 INTRODUCTION

Inclined piles, also called batter piles or raked piles are widely introduced in civil engineering constructions where a substantial lateral resistance is required. However nowadays, many building codes or standards like AFPS 1990 [1] and Eurocode-8 [2] do not recommend using inclined piles in seismic regions. To be less conservative, codes like ACI318-05 and ACI318-11, although they do not prohibit the use of inclined piles in earthquake-resistant structures, pay attention to the potential damages at the junction of the inclined piles and the buildings caused by important seismic forces. The main drawbacks of the inclined piles are generally identified as: large forces onto the pile cap, reduction of the bending capacity due to the induced tensile forces, unfavorable rotation on the cap and additional bending moment due to the settlement of the soil [3].

Different field observations, like the wharf failure in the port of Okland in 1989 (Loma Prieta earthquake), and in the port of Los Angeles in 1994 (Nothridge earthquake), reveal the unsatisfactory performance of inclined piles. However, recent studies put in evidence a possible positive performance of inclined piles. As reported by Gazetas and Mylonakis [4] inclined piles, if properly designed, can be beneficial rather than detrimental both for the structure they support and the piles themselves. Pender [5] and Berrill et al. [6] suggest also important beneficial effects regarding the use of inclined piles. However, the argument about whether the use of inclined piles is detrimental or beneficial is still unsettled. In 2004, Harn [7] pointed out that the poor performance of inclined piles in the past earthquakes might be due to the lack of knowledge and of analytical tools. The use of displacement based design and of carefully detailed inclined piles may result in a better behavior and significant project savings.

In addition, Giannakou et al. [8, 9] studied numerically, in the time domain, the performance of batter piles. In their study, linear constitutive laws were assumed for the soil and

the inclined pile groups and five different inclinations were considered. They found that, for seismic loadings and purely kinematic conditions, batter piles tended to confirm their negative reputation. However, when the total response is considered (kinematic and inertial interaction) their influence could be beneficial. The work of Giannakou et al. [8, 9] has shown that in order to understand the performance of inclined piles the influence of the superstructure and the inertial response of the upper structural system have to be taken into account.

In this paper, dynamic centrifuge tests are performed to investigate the influence of inclined piles on the response of some superstructures and on the soil-structure interaction. The effects of inclined pile are highlighted by comparing the behavior of a 1X2 symmetric configuration of 15° inclined piles supporting a SDOF (single degree of freedom) superstructure with that of a 1X2 vertical pile group that support the same SDOF superstructure. For both pile groups, short and tall superstructures are considered in order to study the influence of the inertial loading coming from different types of superstructures on the performance of inclined piles. The short superstructure represents a shear force dominated loading case and the tall building an overturning moment dominated loading case. For both configurations floating piles were considered and a stiff pile cap imposes a rigid connection at the pile head. The behavior of the different soil-pile-superstructure configurations under dynamic excitations is analyzed in terms of residual bending moment, total bending moment and axial force.

### 2 EXPERIMENTAL PROGRAM

#### 2.1 Introduction

All the dynamic centrifuge tests have been performed at 40 g level. In the following all the data were presented at the prototype scale otherwise mentioned.

The various model configurations tested are shown in Figure 1. In order to investigate the behavior induced by the inclined piles, each time the response is compared with the response of the corresponding vertical pile group configuration.

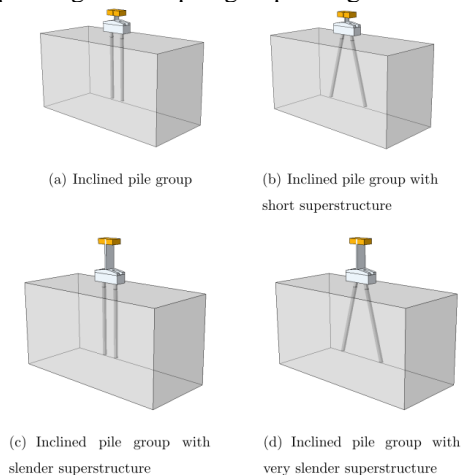


Figure 1: Model configurations used in the dynamic centrifuge tests

## 2.2 Base shaking signals

Three real earthquakes are selected. The first two signals, Martinique Jara and the Northridge records, are broad band frequency range earthquakes (Figure 2(a) and (b)). They have been selected to enable the determination of the frequency response of the soil column and of the soil-pile-superstructure system. In order to determine the natural frequency of the superstructure system, these signals are first attenuated to small intensities to avoid significant plasticity in the soil. The third signal is a recording of the Kobe earthquake. It has been selected because most of the energy comes from frequencies below 1.5 Hz, see Figure 2(c), that are lower than the response frequency of the soil column and the soil-pile-superstructure systems. To be in the capacity range of the IFSTAR shaker [10], the three earthquake signals have been filtered within the frequency range of 20~350 Hz at the model scale. Furthermore, when large intensity earthquakes are concerned, they should be attenuated to be in the acceleration range of the shaker (-9db and -4db for respectively the Northridge and the Kobe records)

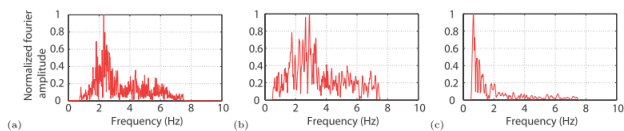


Figure 2: Fourier spectrum of the base shaking signals: (a) Martinique Jara, (b) Northridge earthquake and (c) Kobe earthquake.

## 2.3 Experimental set-up

All the test are performed in dry dense N34 Fontainebleau sand ( $D_r=80\%$ ). The properties of this sand reported in Table 1.

Soil	$e_{min}$	$e_{max}$	$e$	$\nu$	$D_r(\%)$	$\gamma_d(kN/m^3)$
Fontainebleau NE34	0.545	0.866	0.580	0.25	80%	16.155

Note:  $e$ : void ratio;  $\nu$ : poisson ratio;  $\gamma_d$ : weight of sand;  $D_r$ : relative density of sand

Table 1: Fontainebleau sand NE34: Material properties [11]

The piles are made of aluminum alloy and have a hollow section. They are instrumented with pairs of strain gauges that enable the determination of the bending moment profile and the axial stress at different depths. The connection between the piles and the pile cap is assumed rigid. The pile heads are thus rigidly inter-connected via a stiff cap that prohibits rotations between the pile heads and the cap [12]. Table 2 gives the characteristics of the piles and of the pile cap at the model and the prototype scales.

Item	Model scale 40 g	Prototype scale 1g
Pile-embedded depth	326.5 mm	13.06 m
Pile-external diameter	18 mm	0.72 m
Pile-Young's modulus	74000 MPa	74000 MPa
Pile-Bending stiffness	197 N·m <sup>2</sup>	505 MN·m <sup>2</sup>
Pile-Yield strength	245 MPa	4245 MPa
Pile cap-Dimensions	140 mm × 40 mm × 40 mm	5.6 m × 1.6 m × 1.6 m
Cap-weight	560 g	33.8 tonne

Table 2: Characteristics of piles and of pile cap

The possible soil-cap interaction and the lateral resistance of the pile cap are not considered hereafter. To limit the soil-cap interaction, piles are designed to stand at a certain distance above the ground surface, see Figure 3.

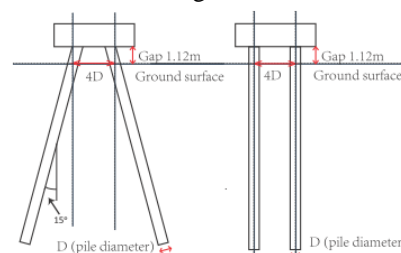


Figure 3: Spacing of piles in inclined pile and vertical pile groups (prototype scale).

Two types of SDOF superstructures with different heights of gravity center are considered i.e. a short and a tall building. Both buildings are designed such as they have:

- the same resonant frequency under fixed base conditions,
- the same top mass,
- the same total weight (foundation and superstructure system).

The frequencies of the short and tall building under fixed-base conditions are tuned at 2.0 Hz (prototype scale).

Instrumentation layout of the tests is presented in Fig. 4. The movement of soil column is followed by two vertical arrays of accelerometers (From CH03 to CH09 and from CH14 to CH19). In order to highlight potential boundary effects, these accelerations are compared with that recorded on the flexible container (Equivalent Shear Beam box). In addition to measurement of bending moment and axial load in both pile, the kinematic response of the cap and superstructure are followed through accelerometers and laser sensors. The double integration of the accelerometers, combined with the use of pass band filter, enables the determination of the dynamics displacement.

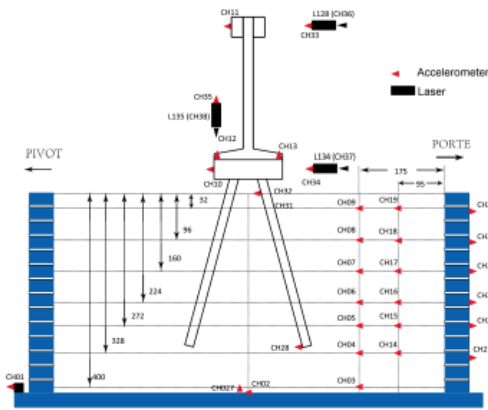


Figure 4: Distribution of sensors in the soil-pile-superstructure system for the centrifuge tests

The adopted shaking sequence of the earthquake signals and the corresponding variation of Arias intensity are listed in Table 3 and plotted in Figure 5. Table 3 also presents the series of seismic tests that has been performed.

NO.	Seismic signal	Arias Intensity (m/s <sup>2</sup> )
1, 2, 3	Martinique Jara -1 dB	0.2
4, 5, 6	Northridge -20 dB	0.2
7, 8, 9	Northridge -9 dB	2.43
10, 11, 12	Kobe -4 dB	3.51
13, 14, 15	Martinique Jara -1 dB	0.2
16, 17, 18	Northridge -20 dB	0.2

Table 3: Shaking sequence

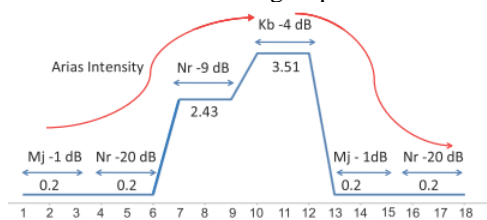


Figure 5: Variation of arias intensity

All the dynamic centrifuge tests that have been performed using real earthquake excitations are listed in Table 4.

NO.	Date	Description
01	2011-06-24	*Inclined pile group with short building (real earthquake)
02	2011-06-30	*Vertical pile group with short building (real earthquake)
03	2012-12-11	*Inclined pile group with tall building (real earthquake)
04	2012-12-13	* Vertical pile group with tall building (real earthquake)

Note: \* means the test has been repeated.

Table 4: List of dynamic centrifuge tests

### 3 PERFORMANCE OF INCLINED PILES WITH SEISMIC SOIL-PILE-SUPERSTRUCTURE INTERACTION (SSPSI) UNDER EARTHQUAKE EXCITATIONS

#### 3.1 Frequency response of the superstructure

For each soil-pile-superstructure configuration the first six small base shaking tests (Table 3) are used to evaluate the frequency response of the superstructures. In this framework, transfer functions are calculated between the accelerations measured on the top of the buildings and those measured near the soil surface. The estimated frequency responses are listed

in Table 5. As mentioned before, the frequencies of the buildings (short and tall) under fixed-base conditions are tuned at 2.0 Hz. When the buildings are supported by pile groups embedded in dense sand, the SSPSI induces a decrease of the response frequency of the superstructure.

Configurations	Frequency of top mass (Hz)
IS	1.94
VS	1.80
IT	1.70
VT	1.62

Table 5: Frequency response of the superstructure (short and tall buildings) on inclined and vertical pile groups

The presence of inclined pile reduces the effect of the SSPSI on the frequency response of the superstructure. For the case of the short and slender superstructures installed on the inclined pile groups, the frequencies are 0.14 Hz and 0.08 Hz higher than when they are supported by the vertical pile groups. In addition, an increase of the height of the gravity center of the superstructure enhances the SSPSI on the frequency response of the superstructure for both pile group configurations (-0.24 Hz and -0.18 Hz for the inclined and the vertical pile groups respectively).

#### 3.2 Stresses in piles

##### 3.2.1 Residual bending moments

Due to the permanent deformation of the soil and the influence of the superstructure, embedded deep pile foundations deviate from their initial position during an earthquake event. As a result, residual bending moments appear along the pile. Figure 6 shows the accumulated residual bending moment profiles for the successive earthquake events. The peak values, such as the peak values normalized by the peak values obtained for the short building supported by the vertical pile group, are given in Figure 7.

The presence of inclined piles changes the shape of the residual bending profiles. Inclined piles induce a “C” shape curve while an “S” shape curve appears for vertical piles. For both configurations, the type of superstructure has an effect on the depth of the maximum residual bending moment. In the case of the inclined pile group, when a short building is supported the depth of the maximum residual bending moment increases from 4 to 6 pile diameter and almost constant for the strong earthquakes. The increase of the height of the gravity center increase the depth of the maximum residual bending moment: it appears at a depth of around 6D for the first two small earthquakes and during and after the strong earthquakes, the depth increases up to 10D. Concerning the vertical pile group, when a slender building is supported it is difficult to identify the depth of the maximum residual bending moment due to the shape of the profile). However, it can be located at about 5 pile diameters when a short building is supported.

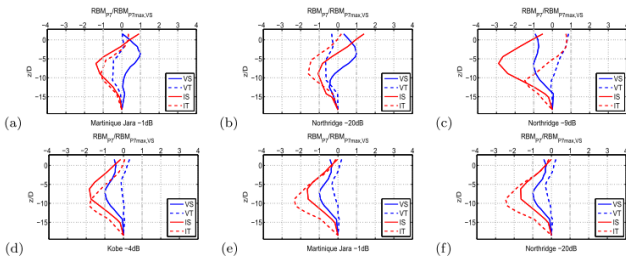


Figure 6: Normalized residual bending moment profiles

Concerning the performance of inclined piles, for all configurations (type of superstructure and input), their presence increase the maximum residual bending moment in the piles. However the impact level depends on the type of superstructure, the base shaking and the loading history. It is shown in Figure 7 that for the first two small earthquakes the influence of inclined piles is similar for the two types of superstructures. When strong earthquakes are applied however, the effect of inclined piles is more pronounced when a short super-structure is supported. For the last two small earthquakes, the effect of inclined piles is more pronounced for the slender superstructure. This is certainly due to the accumulation of residual bending moments from the previous earthquake events.

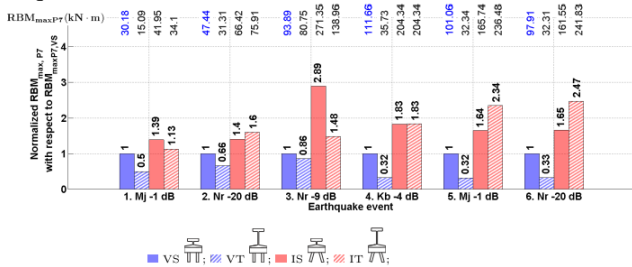


Figure 7: Normalized residual bending moments

### 3.2.2 Total bending moments

Figure 8 shows the envelop curve of the maximum total (residual + dynamic) bending moments normalized by the maximum total bending moment obtained in the case of the short building supported by the vertical pile group. Due to the presence of the residual bending moments the curves are no symmetric and it is difficult to define a general shape. Qualitatively speaking, the response of the vertical pile group is more significant.

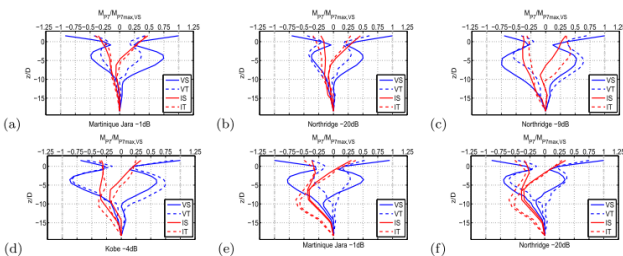


Figure 8: Normalized envelope curves of the maximum total resultant bending moments

Figure 9 shows the ratios between the peak values of the total bending moment. The presence of inclined piles reduces the maximum total bending moment for both short and slender

superstructures. However, the good performance of the inclined piles is influenced by the type of superstructure and the base shaking frequency content. A better performance is found for the short superstructure. Contrary to the slender superstructure, this performance is not influenced by the frequency of the base shaking.

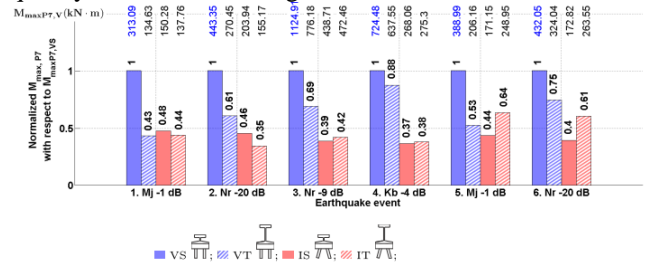


Figure 9: Normalized total bending moments at pile head

### 3.2.3 Axial forces

Figure 10 shows the normalized total axial force profiles for the different configurations. For the friction piles, a reduction of the axial force with increasing pile embedded depth is observed, although in some cases the axial force profiles are distorted. Due to small number of instrumented compression strain gauges it is difficult to precisely determine the shape of the axial force profiles.

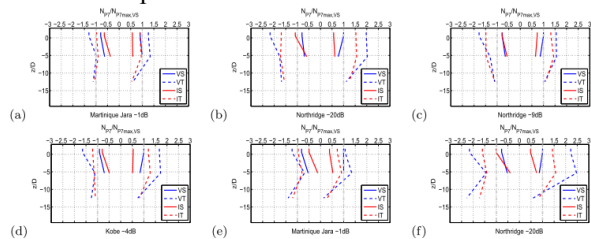


Figure 10: Normalized axial forces

According to the results shown in Figure 11, for both, short and slender superstructures, inclined piles introduce a smaller or equal axial force to the vertical ones. For both configurations, the increase of the gravity center results in more significant axial forces.

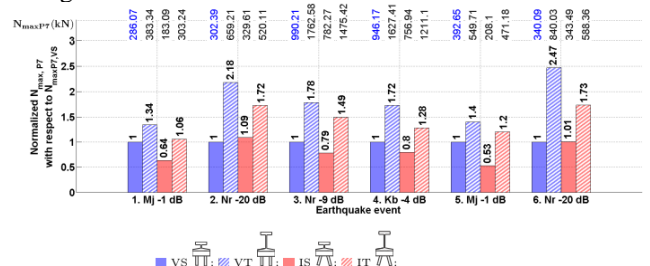


Figure 11: Normalized maximum axial forces

## 4 CONCLUSIONS

In this study, the performance of inclined piles and the soil-pile-superstructure interactions (SSPSI) are analyzed and discussed. Cross comparisons are carried out considering the presence of inclined piles and the position of the gravity center of the superstructure. The main conclusions are the following:

1. Superstructures supported by inclined piles group have higher resonant frequencies. This is probably due to the

higher horizontal stiffness provided by the inclined piles. In addition, regardless the pile group configuration, an increase of the gravity center of the superstructure results in a decrease of the resonant frequency.

2. For all the configurations tested, in terms of residual bending moments, inclined piles have a poor performance compared with the vertical piles. Furthermore the performances are influenced by the superstructure, the input and the loading history.
3. For the same type of superstructure (short or slender), less total bending moment and axial force appear in the piles for the inclined pile configuration.
4. For both inclined and vertical pile configurations, an increase of the gravity center induces higher axial forces in the piles.
5. In terms of total bending moments, the presence of inclined pile reduces the maximum total bending moment below and above the soil surface. In addition a higher gravity center of the superstructure may have a beneficial effect on the performance of both inclined and vertical configurations. However this effect is more pronounced for vertical pile group.

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