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Centrifuge modeling of batter pile foundations under earthquake excitation

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ABSTRACT

Although batter pile foundations are widely used in civil engineering structures, their behavior under seismic loadings is not yet thoroughly understood. This paper provides insights about the differences in the behavior of batter and vertical piles under seismic soil-pile-superstructure interaction. An experimental dynamic centrifuge program is presented, where the influences of the base shaking signal and the height of the gravity center of the superstructure are investigated. Various seismic responses are analyzed (displacement and rotation of the pile cap, total shear force at the pile cap level, overturning moment, residual bending moment, total bending moment and axial forces in piles). It is found that in certain cases batter piles play a beneficial role on the seismic behavior of the pile foundation system. The performance of batter piles depends not only on the characteristics of the earthquakes (frequency content and amplitude) but also on the type of superstructures they support. This novel experimental work provides a new experimental database to better understand the behavior of batter pile foundations in seismic regions.

1. Introduction

Batter piles, also called inclined or raked piles, are widely used in civil engineering constructions where substantial lateral resistance is required. However, many building codes or standards like AFPS 1990 [1] and Eurocode-8 [2] do not recommend the use of batter piles in seismic regions. Although less conservative, codes like ACI318-05 and ACI318-11 recommend to pay attention to the potential damages at the junction of the batter piles and the superstructure. The main drawbacks of the batter piles often mentioned by engineers are the following: large forces induced onto the pile cap, reduction in bending capacity due to the axial forces, unfavorable rotation on the cap and residual bending moment due to the soil settlement before the earthquake [3]. Several case histories, for example, the wharf failure in the port of Oakland in 1989 during the Loma Prieta earthquake and the port of Los Angeles in 1994 during the Northridge earthquake reveal the unsatisfactory performance of batter piles.

However, recent studies show that batter piles can have a positive performance. As reported by Gazetas and Mylonakis [4], batter piles, if properly designed, can play a beneficial role both for the structure they support and the piles themselves (reduction of the bending moments in the piles). Research studies from Pender [5] and Berrill et al. [6] also suggest important beneficial effects from batter piles. The argument about whether the use of batter piles in seismic regions is detrimental or beneficial is therefore still unsettled. In 2004, Harn [7] pointed out that the poor performance of batter piles in past earthquakes may due to the lack of knowledge and analytical tools. Using displacement based design, advanced numerical tools and appropriately detailed batter piles can result in significant project savings.

Several experimental studies on the performance of batter piles in the static domain have already been performed. From 1972 to 1995 Meyerhof and his colleagues conducted experimental campaigns (reduced model scale at 1 g) to investigate the bearing capacity of batter piles in soils [8–14]. They proposed an empirical equation to predict the ultimate strength of batter piles under arbitrary load combinations (horizontal and vertical forces). With the development of the centrifuge modeling technique, static tests on batter piles have also been performed on reduced scale models [15–19]. It was observed that batter piles in general increase the horizontal resistance of the foundations.

Centrifuge dynamic tests on batter piles are relatively rare. Escoffier et al. [19] performed centrifuge tests on pile foundations in dry sand by applying a horizontal impact loading on the pile cap with a magnetic hammer. Two pile groups were studied: a 1×2 (two piles in one row) vertical pile group and a 1×2 pile group

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Nomenclature

Roman symbol

SSPSI	Seismic Soil-Pile-Superstructure Interaction
Mj	Martinique Jara earthquake (Jara station EW)
Nr	Northridge earthquake (Tarzana station 090)
Kb	Kobe earthquake (DAI8-G, N43W)
C.G.	center of gravity of superstructure
IS	inclined (batter) pile group with short superstructure 
VS	vertical pile group with short superstructure 
IT	inclined (batter) pile group with tall superstructure 
VT	vertical pile group with tall superstructure 
P7	one pile in the 1 × 2 pile group, on the 'Porte' side
P8	one pile in the 1 × 2 pile group, on the 'Pivot' side
BS	base shear force acted on the foundation
OM	overturning moment acted on the foundation
RBM	residual bending moment
RBM_{max}	maximum residual bending moment
RBM_{P7}	residual bending moment on pile P7
$RBM_{P7\ max,VS}$	maximum residual bending moment on pile P7 in vertical pile group with short superstructure
M	total bending moment
M_{P7}	total bending moment on pile P7
$M_{P7\ max,VS}$	maximum total bending moment on pile P7 in vertical pile group with short superstructure
N	axial force in the pile
N_{P7}	axial force in pile P7
$N_{P7\ max,VS}$	maximum Axial force in pile P7 in vertical pile group with short superstructure
z	depth below ground surface
D	external diameter of pile
D_{pile}	center-to-center distance between piles

with one batter pile. Two pile bearing conditions (floating and end bearing) were considered. The tests indicated a more complicated translation-rocking mode for the inclined pile group. Its stiffness was found higher and the resulting movement smaller than that of the vertical pile group. In both groups, the center of rotation of the cap was near the vertical face of the pile cap towards the front pile side. In terms of bending moment profiles, the presence of the batter pile resulted in a decrease of the maximum bending moment below the soil surface in both piles. In addition, the influence of the batter pile on the maximum bending moment at the pile cap interface seemed to be negligible in the front pile, whereas it resulted in an increase of the maximum bending moment in the rear pile. For the batter pile group, the compression load in the front pile and the tension load in the rear pile were increased by a factor of 1.7 and 2.0, respectively.

In 2012, Escoffier [20] performed dynamic centrifuge tests on batter piles. The dynamic loads were applied using an earthquake simulator [21] at the bottom of the model. As in the previous study, two configurations (a 1 × 2 vertical pile group and a 1 × 2 pile group with one batter pile and end-bearing pile configuration) were studied using earthquake time histories. The results of the seismic tests showed that the batter pile resulted in an increase of the response frequencies corresponding the translation-rotation mode at the pile cap and reduced by two times the maximum horizontal acceleration of the cap. The analysis of the bending moments and axial loads in the piles indicated that with the batter pile, larger residual bending moments were developed and the direction of the axial loads in the piles did not change. Escoffier reported that for batter pile foundations the residual bending moments cannot be ignored in the evaluation of the performance of batter piles.

Okawa et al. [22] performed centrifuge tests on pile groups embedded in loose sand. The first was a 2 × 4 pile group composed of 8 vertical piles and the second a 2 × 4 pile group with 4 batter piles with an inclination of 10° and 4 vertical piles. A short superstructure was placed on the footing to study both kinematic interaction and inertial effects. The presence of batter piles decreased the horizontal acceleration amplitude at the footing and the superstructure. Larger axial forces were observed in the batter piles.

Boland et al. [23,24] performed dynamic centrifuge tests with two models (named SMS02 and JCB01) constructed as a generalization of the pile supported wharf structures common at the Port of Oakland (POOAK), the Port of Los Angeles (POLA) and the Port of Long Beach (POLB) in California. In terms of maximum moments, results clearly showed an increase (from 1.4 to 3.9 times) in recorded pile moments when all vertical piles were used for nearly identical input base accelerations. The shear forces within the batter pile heads were greater (9–20 times) than those recorded in the vertical piles for the same dynamic event. Without batter piles, the shear forces in the vertical piles and the wharf displacements increased significantly [25].

Juran et al. [26] conducted a series of centrifuge tests on vertical and batter micropile groups. The tests showed that with increasing inclination angle the natural frequency of the network system increased. Compared with vertical piles, a reduction of 40% of the response in terms of acceleration of the superstructure (pile cap) was observed when batter piles were used. In general, increasing the pile inclination resulted in smaller pile cap displacements, and larger axial forces and bending moments in the piles at the pile cap connections.

Giannakou et al. [27,28] studied numerically, in the time domain, the performance of batter piles. Both soil and batter pile groups were modeled using linear elastic constitutive models. Five inclinations were considered. The authors found that for seismic loadings and purely kinematic conditions, the negative reputation (larger bending moments and axial forces) of batter piles was more-or-less confirmed. However, when the total response was considered (kinematic and inertial response of the structural system), their influence can be beneficial. Among the different parameters studied, the performances of batter piles in terms of displacements, bending moments and axial forces depend on the ratio of the overturning moment versus the shear force transmitted to the piles from the superstructure.

Shahrour and Juran [29] performed numerical analysis of the seismic behavior of a micropile system containing batter micropiles. It was found that the inclination of the micropiles allowed an effective mobilisation of their axial resistance, leading to an increase in the stiffness and a reduction in both shear forces and bending moments.

This paper presents a comprehensive experimental seismic centrifuge program on the performance of batter piles in order to better understand their behavior. Several important factors are studied such as Seismic Soil-Pile-Superstructure Interaction