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Dynamic lateral response of under-reamed vertical and batter piles

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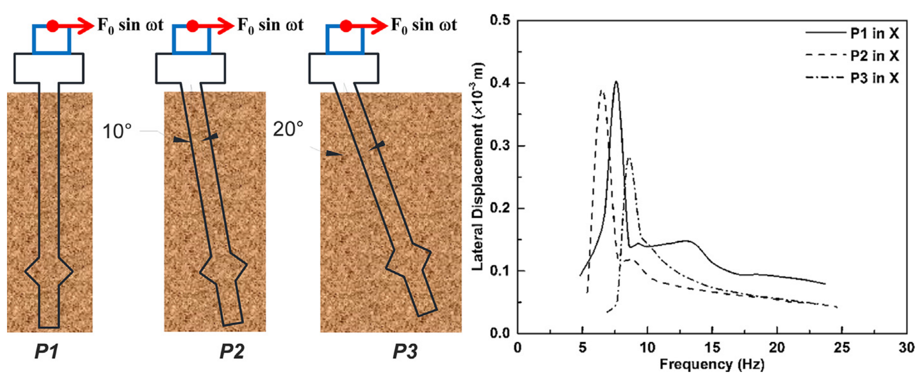
HIGHLIGHTS

- Dynamic lateral tests on cast in situ bored RCC model single piles with pile cap.
- Dynamic lateral response of combined batter and under-reamed piles.
- Dynamic response of the piles were studied in both the lateral directions.

GRAPHICAL ABSTRACT



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ABSTRACT

Dynamic lateral response of three under-ream reinforced concrete piles constructed in silty sand {vertical, *P1* ($\beta = 0°$); and batter piles *P2* ($\beta = 10°$) and *P3* ($\beta = 20°$)} having equal length of 2.5 m, shaft diameter 0.2 m and under-ream bulb of diameter 0.5 m were considered for this experimental study. Dynamic loads were generated using an oscillator motor assembly mounted on top of pile cap and the response of these piles were recorded in real time using three accelerometers placed along the depth of the pile cap. These piles were subjected to varying dynamic load by changing the eccentricity setting of the oscillator in the frequency range of 0–40 Hz. The test results show that the resonant frequency of the soil-pile system decreases; and peak lateral displacement increases with increase in the force level. The variation of rotational stiffness and the damping ratio of the soil-pile system with force level did not follow a clear trend. Thus the presence of an under-ream bulb in a batter pile does not have a significant influence on the lateral behaviour of batter piles.

1. Introduction

Pile foundation is generally preferred over shallow foundation constructed in the relatively less stiff soil, to carry large superstructural vertical load and bending moment. In addition, during application of lateral dynamic loads, pile foundation is subjected to reversal low/high strain in subsequent cycle and experiences more bending moment, resulting in the mobilization of the passive pressure of the surrounding soil-mass leading to failure of the soil-pile system or structural failure of the pile itself. To carry large bending moment and reversal axial compression and tension, generally, batter piles are preferred in spite of construction difficulties.

During the 1991 Costa Rica earthquake, [M_w 7.6] batter pile groups supporting the Rio Vizcaya Bridge and Rio Banano Bridge, failed due to insufficient design of pile to cap connection as reported by Priestley, Singh, Youd and Rollins [1], and during the 1989 Loma Prieta earthquake, [M_w 6.9] due to inadequate reinforcements at the top of the piles, unsatisfactory performance of

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batter piles has been reported by Mitchell, Tinawi and Sexsmith [2].

Some international standards have recommended not to prefer batter piles in seismic prone areas, like the French seismic code AFPS [3] states that, "*Inclined piles should not be used to resist seismic loads*" whereas, the Euro code EC8 [4] is less restrictive stating that, "*It is recommended that no inclined piles be used for transmitting lateral loads to the soil. If in any case, such piles are used, they must be designed to carry safely axial as well as bending loading*". Use of batter piles at ports was not recommended by Werner [5]. During last many seismic events, batter piles delivered poor performance and were not recommended to use in seismic conditions.

During the 1987 Edgecumbe earthquake [M 6.3], Berrill, Christensen, Keenan, Okada and Pettinga [6] has performed a study on batter piles supporting the bridge at the pier of Landing Road Bridge and found that the batter piles provided additional necessary lateral stiffness to the pile groups. Additionally, Kastranta, Gazetas and Tazoh [7] have observed, during the 1995 Kobe earthquake [M 6.9], batter piles supporting the quay walls of Maya Wharf survived severe seismic shaking indicating the better seismic performance of inclined piles. Thus, case studies conducted by various researchers and engineers, extended their confidence on seismic performance of batter piles using them smartly to withstand large lateral dynamic loads. In the last decades, several researchers have investigated the nonlinear response of piles (Manna and Baidya [8] Biswas, Manna and Choudhary [9] Wu, Yamamoto and Yao [10] Qin and Guo [11] Fatahi, Basack, Ryan, Zhou and Khabbaz [12] Boominathan, Krishna Kumar and Subramanian [13] Chatterjee, Choudhury, Rao and Mukherjee [14] Hu, Fu, Xia and Xie [15] Subramanian and Boominathan [16] Zheng, Liu and Ding [17]) and conducted centrifuge tests on model piles to understand the performance of batter piles under seismic loading (Escoffier, Chazelas and Garnier [18] Tazoh, Sato, Jang, Taji, Gazetas and Anastaspoulos [19] Tamura, Adachi, Sakamoto, Hida and Hayashi [20] Gerolymos, Giannakou, Anastasopoulos and Gazetas [21] and Giannakou, Gerolymos, Gazetas, Tazoh and Anastasopoulos [22]). Hokmabadi, Fakher and Fatahi [23], studied the lateral behaviour of steel monopiles in marine sand through full scale field tests. Recently, soil pile interaction in pile groups (*i.e.* considering vertical and batter piles) has also been studied. The influence of soil pile interaction on the behaviour of multi storey buildings were examined in detail by Hokmabadi and Fatahi [24] and Hokmabadi, Fatahi and Samali [25]. The batter angle plays a very effective role in determining the interaction factor of pile groups as reported by Ghasemzadeh and Alibeikloo [26]. Ghazavi, Ravanshenas and El Naggar [27], reported that the use of batter and vertical piles in a group, increase overall efficiency of the soil-pile system. The batter piles were even more advantageous in supporting lateral loading according to Gazetas and Mylonakis [28].

In the last decade, significant studies on under-reamed piles have been carried out by researchers. The uplift capacity of under-reamed piles were thoroughly examined by Peter, Lakshmanan and Manoharan [29] Niroumand, Kassim, Ghafooripour and Nazir [30] Harris and Madabhushi [31] Nazir, Moayedi, Pratikso and Mosallanezhad [32]. The influence of the position of under-reamed piles in a pile group was elaborated by Alielahi, Mardani and Daneshvar [33]. The effects of half and full under-reamed bulbs in single piles were studied by Farokhi, Alielahi and Mardani [34]. The bearing capacity and the failure mechanisms of under-reamed piles were reported by Qian, Ren and Yin [35] Qian, Zhao and Xie [36]. These ample literatures are mostly focused on either analytical or experimental investigation of lateral and uplift behaviour of under-reamed piles.

A few studies on the lateral behaviour of batter piles under dynamic load have been conducted either by experimental investigation on scaled models or by numerical investigation using finite element method. In authors' capacity, none of the studies have been reported on the dynamic lateral response of combined batter and under-reamed pile. In this study, various experiments have been conducted on reinforced concrete model pile to explore the

Fig. 1. Location of the considered site [37].

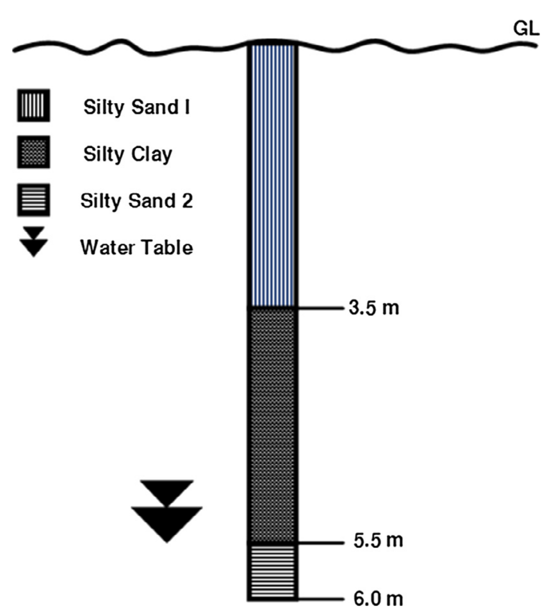

Fig. 2. Soil profile at the considered site.

Table 1
Soil properties at the considered site.

Property of soil	Silty sand 1	Silty clay	Silty sand 2
Density (kN/m^3)	16.20	13.40	15.90
Moisture content (%)	12.00	30.00	50.00
Specific gravity	2.68	2.72	2.66
Liquid limit (%)	–	40.00	–
Plastic limit (%)	–	25.56	–