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Micropile foundation subjected to dynamic lateral loading

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Abstract

Thanks to their ease of installation, even in access-restricted spaces, micropiles are increasingly adopted for the seismic rehabilitation of existing structures. Moreover, both vertical and inclined micropiles are often used as foundation system for new constructions, ground improvements and many other applications. In order to deepen the knowledge of the dynamic behavior of those systems under horizontal loading, an extensive experimental study was carried out in an alluvial silty soil deposit on two single vertical micropiles and on a group of four inclined micropiles connected at the head by a concrete cap. Several testing procedures are exploited, in order to investigate the dynamic behavior of micropiles under different loading conditions and increasing force level, with special attention on the role of execution techniques and foundation configuration.

Keywords: Micropiles; Battered Piles; Dynamic Soil-Pile Interaction; Dynamic Identification Techniques.

1. Introduction

Micropiles are small-diameter cast-in-situ bored pile formed by cement grout injection and equipped with lost, steel reinforcement element. They are increasingly used as foundations of new constructions and to strengthen foundations of existing structures in seismic zones, thanks to their simplicity of execution. Despite their growing use, results from static and cyclic lateral load tests on micropiles are limited [1], as well as dynamic test on small-scale prototypes [2]. Concerning in-situ dynamic tests, most works focus on piles [3, 4, 5], while field test on real

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scale micropiles are almost absent. Moreover, various phenomena need further investigations, such as the role of execution stages and construction techniques, that can be particularly significant in the case of micropiles. To investigate these aspects, an experimental campaign was carried out, that includes both two single vertical micropiles and a group of inclined micropiles. In the present paper, results obtained from ambient vibration, lateral impact loading tests and free vibration tests are discussed.

2. General description of the experimental field study

The field campaign started in 2015 (currently, the instrumented micropiles are still periodically monitored), and has multiple research objectives. Among them, the study aims at improving the knowledge of the dynamic and cyclic behavior of micropiles, paying attention to the role of execution techniques and inclination angle of the foundation elements; verifying the applicability of existing numerical and theoretical approaches for the investigation of real soil-micropile system; develop new in situ test procedure to get information on the dynamic response of the soil-foundation system that can be directly used in the seismic design of foundations; investigating phenomena related to the development of non-linearity in the soil-micropile system.

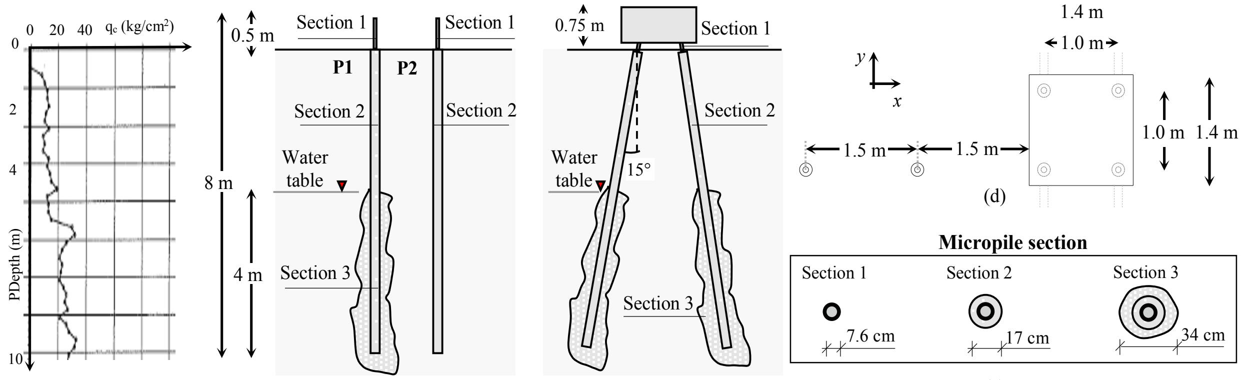
The experimental field campaign is performed in an alluvial silty deposit on IRS (Injection Répétitive et Sélective) micropiles. They are small diameter cast-in-situ bored piles formed by cement grout injection, equipped with a hollow-core steel bar and finally completed by multi-step high pressure grouting at predetermined depths via valves a manchèttes placed along the bar. In this study, the traditional execution stages were suitably modified to allow the preliminary instrumentation of the hollow-core steel bar of the micropiles, and to limit damages of the sensors induced by mechanical stresses during the in-situ installation and the high-pressure injection stages.

2.1. Geotechnical description of the site

Micropiles are installed in an industrial zone nearby Ancona (central Italy). The geology of the area, which has a flat topography, is characterized by alluvial deposits consisting predominantly of clayey and silty materials. A specific geotechnical investigation campaign was carried out including vertical boreholes to a depth of 15 m, 2 CPTs (Fig. 1*a*), and several laboratory tests. Furthermore, the profile of the shear wave velocity, V_s, with depth and the fundamental period of the deposit were evaluated from passive and active geophysical survey techniques (MASW, ESAC, HVSR). The micropiles shafts are embedded in a homogeneous alluvial silty-clayey layer with poor mechanical properties (Tab. I), characterized by average V_s = 180 m/s. The water table is located 3.5 m deep in the upper stratigraphic unit. The seismic bedrock is recognized at a depth of 75 m from the ground level.

2.2. Micropiles and instrumentation

Micropiles reinforcement is constituted by 8 m long steel pipe bars, assembled trough the junction of 4 elements (each element is 2 m in length). The outer diameter of the circular cross section of each pipe is 76.1 mm, and 6 mm thick. From the head of the micropiles, the 3rd and 4th elements are equipped with four 50 cm spaced valves a manchèttes for high pressure injections. The 4th element is also provided with a bottom plug for the grout injection at the micropile tip. In this experimental study, elements were assembled in lab to allow the proper installation of measuring devices along the pipe. Once the sensors were mounted and zealously protected, the pipes were transported in situ for the installation. Firstly, soil borings were made with a diameter of 170 cm and a length of 7.5 m. Then, after the first grouting of each borehole, the instrumented pipes were carefully inserted. The upper 50 cm of the pipes were left above the ground level to allow the execution of the lateral dynamic tests. After 48 hours from the first grouting, additional grout was injected via valves a manchèttes in one of the two vertical micropiles using a packer with double effect piston: when the packer was at the required depth, the grout was injected at a pressure of 6÷8 MPa. The cement slurry used for both the first and the secondary (selective) grouting has a water cement ratio of 0.5. In the sequel, the IRS vertical micropile is referred to as P1, while the non-injected one as P2 (Fig. 1*b)*. The other four micropiles are positioned with an angle of in inclination of 15° with respect to the vertical direction, along the *y* axis (Fig. 1*c)*. The inclined micropiles are completed with a concrete cap on the top. In Fig. 1*d* a plan view of the test site is shown. Finally, the different micropiles sections are reported in Fig. 1*e*.



(a) (b) (c) (d) (e)

Fig. 1. (a) q_c profile in the first soil layer; lateral view of (b) single micropiles and (c) group; (d) plan view of the field; (e) piles section.

Table I. Geotechnical properties of superficial alluvial layer

Unit weight (saturated)	γ	17-19	kN/m³	Undrained cohesion	c_u	20-40	kPa
Friction angle	φ'	24-26	°	Oedometric modulus	E_{oed}	2000-3000	kPa

The instrumentation included permanently installed Strain Gages (SGs), to measure the longitudinal strains along the shafts during the dynamic loading. The choice of the position of the sensors was suggested by the results of a preliminary soil-pile interaction analysis performed with the 3D model for the inertial and kinematic interaction model presented in [6, 7]. Moreover, depending on the typology of test performed, micropiles and the cap were instrumented with suitable accelerometers and displacement transducers.

3. Experimental tests

Several testing procedures were adopted for the study, to investigate the single micropiles and the group under different loading conditions. This work focuses on the results obtained from ambient vibration, impact, and snap back tests on the single vertical micropiles, and impact load tests on the group.

3.1. Ambient vibration tests

Ambient vibration tests allow investigating the dynamic response of full scale structures (bridges, buildings, dams, chimneys and silos, etc..) in the elastic range, by acquiring the response of the system to natural vibrations (e.g. anthropic activities noise, micro tremors, wind...). To the authors knowledge, this procedure was not adopted before to investigate the dynamic lateral behavior of a soil-micropile system. Concerning the vertical micropiles, two accelerometers per micropile were positioned on the pile head (i.e. measuring along two orthogonal axes called x and y), as shown in Fig. 2*a*. A time length of about 1500 seconds and a sample frequency of 200 Hz are adopted for the acquisitions.

3.2. Impact load tests

For impact load tests on the single vertical micropiles, a pipe extension was rigidly connected at each micropile head to facilitate the execution of the impacts and the identification of the dynamic parameters. Two set of tests (Fig 2*b*) were performed: the first set (SET A) was characterized by a maximum force level of about 400 N to avoid the saturation of the accelerometer (at 10 g), while the other (SET B) was characterized by a higher force level in order to acquire the signal of strain gauges embedded in the soil. The present paper focuses on the results of SET A, for which impulses were imparted along x and y orthogonal directions and the accelerometers were applied to the micropile so that the signal was acquired along the same direction of the impact. 10 impacts for each direction were imposed, to get a reliable averaged response. A sampling frequency of 2048 Hz was chosen to get high resolution in time domain, and an acquisition duration of 2 s was considered, to investigate the entire duration of the oscillation.

Concerning impact load tests on the group, seven uniaxial accelerometers (measuring along *x*, *y* or *z* axis) were used to allow for a proper recognition of the rocking motion coupled with the translational modes of vibration, and for any eventual roto-traslational mode in the horizontal plane (Fig. 2*c*). For single micropiles and the group, a sampling frequency of 2048 Hz was chosen to get high resolution, and an acquisition duration of 2 s was considered.

3.3. Free vibration tests

Free vibration test allows identifying natural frequencies and damping of the soil-micropile system, alongside with its flexural deformed shapes, by studying the decrement of the vibrations. The horizontal load was applied on the vertical micropiles using a double acting hydraulic jack, which has a capacity in tension of 20 t. Releases were carried out on both P1 (along *x* direction) and P2 (along *y* direction), as shown in (Fig 2*d*). The quick release of the load was achieved thanks to “calibrated steel pins” (Fig 2*e*), consisting of a steel element, the cross section of which was opportunely determined so that it failed once a predetermined load was reached. After the pin failure, the micropile underwent a number of steadily decreasing horizontal oscillation around its equilibrium position. The instrumentation comprises SGs, displacement transducers on the pile head, and two accelerometers (placed at the same height of the displacement transducers, but diametrically opposed in cross section). Releases induced by four force levels were investigated: 12–18–24–30 kN; for each force level, 2 tests were carried out, for a total amount of 8 shear pins per pile. In Fig 2*f* a view of the mechanical scheme adopted for the realization of the test is provided.

4. Results

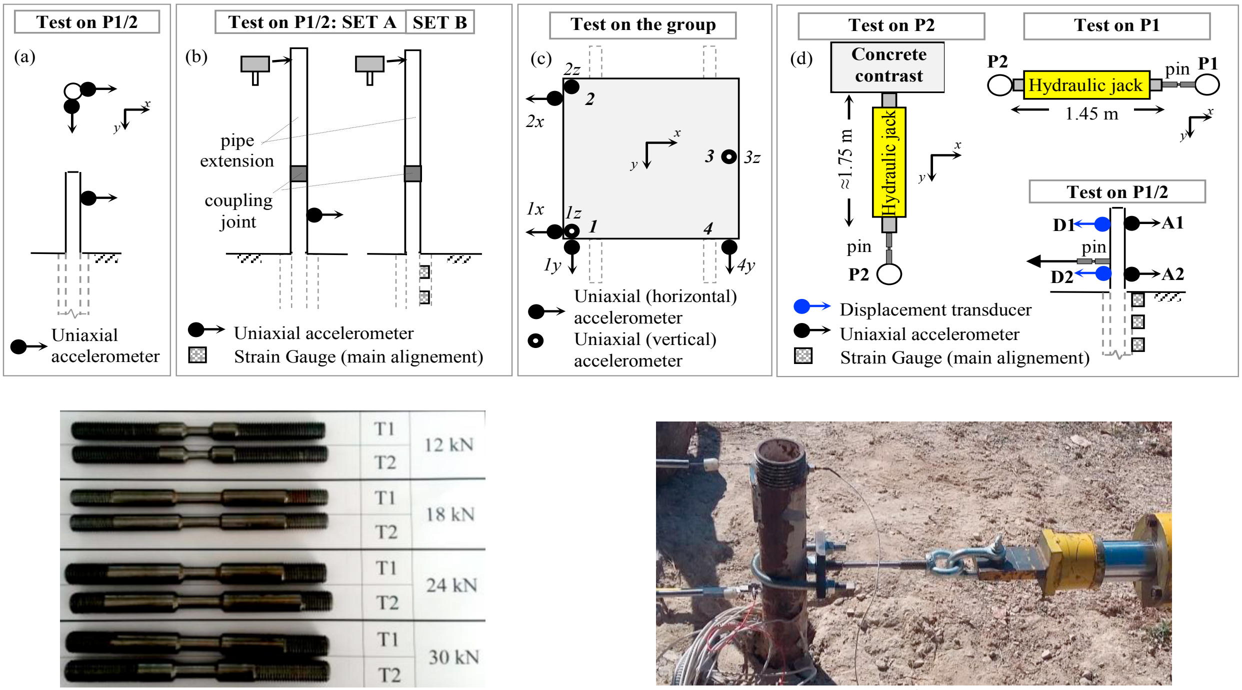
Some of the results obtained from tests performed on single vertical micropiles and micropiles group are presented in the following. In particular, results relevant for single vertical micropiles are presented in terms of ambient vibration, impact load and snap back tests, while those relevant for the inclined micropiles group are presented in terms of impact load tests.

4.1. Single Micropiles

Results of ambient vibration tests are here presented in terms of Power Spectral Density (PSD) function for P1 and P2 along *x* and *y* axis. From the superposition of *x* and *y* PSD functions for P1 (Fig. 3*a*) it appears clearly the dynamic behavior along the two orthogonal directions is substantially different, especially in terms of fundamental frequencies. On the other hand, results for P2 are very similar in the two directions (Fig. 3*b*). This fact can be attributed, at least partially, to the directionality of the high-pressure injections executed on P1.

Results of impact load tests for SET 1 are here presented in terms of modulus of Frequency Response Function (FRF) of the registered acceleration at P1 and P2. Results refer to the averaged values obtained from 10 impacts. Coherently with results of the previous tests, the comparison of averaged FRFs obtained considering impacts along both directions (Fig. 3*c, d*) shows that for the injected micropile a marked difference exists between the behavior along the two direction (the pile seems stiffer along the *y* direction), especially for the second mode, while the non-injected micropile doesn’t show significant differences between the behavior along *x* and that along *y* axis.

In order to investigate the dynamic properties of the single vertical micropiles in the non-linear field, free vibration tests were performed on both P1 and P2. Given the high level of the forces, the traditional frequency-domain representations based on Fourier Transform, such as PSD of FRF, are not suitable. In fact, as shown in Fig. 3*e* for a specific input, time histories of acceleration change its features throughout time, and therefore, their characteristics in the frequency domain should be investigated point by point. This can be done via Stockwell Transform [8], shown in Fig. 3*f*, thanks to which it is possible to see that the first resonance frequency decreases as the time passes; this can be attributed to the widening and deepening of a gap at the interface between the micropile and the soil, as a result of the oscillation of the pile, as well as to the degradation of properties of grout and surrounding soil in the shallower portion of the soil pile system.



(e) (f)

Fig. 2. Test setup for (a) ambient vibration tests, (b) impact load tests on single micropiles, in SET A and B, (c) snap back tests (d) impact load tests on group; (e) calibrated steel pins; (f) mechanical scheme for free vibration tests

4.2. Micropiles group

In Fig. 3*g, h* results of impact load tests on the group are shown, in terms of FRF of acceleration recorded along the direction of impact and in the vertical direction. It can be observed that along the direction in which micropiles are inclined the fundamental frequency of the group is higher. Moreover, a greater damping is observed: with the half power bandwidth method, a damping of 13% can be estimated in y direction, while it is about 10% in x direction. Comparable results can be found in the centrifugal experiments described in [9]. Of particular interest is the different behaviour in terms of roto-translational coupling that can be recognized along the two horizontal directions, in terms of different amplitude of FRF: this may be related to the fact that the rocking motion due to horizontal loading on foundations with inclined piles is in antiphase with the rotation of the structure, while these two contributions are in phase in the direction along which the micropiles behave as vertical.

5. Conclusive remarks

First results of an experimental study carried out on two single vertical micropiles and on a group of four inclined micropiles embedded in alluvial silty soil are presented. Results of ambient vibration tests, horizontal impact load tests and snap back tests one single micropiles and inclined micropiles group are presented pointing out the influence on the micropiles dynamic behaviour of high pressure injections, load level and inclination.

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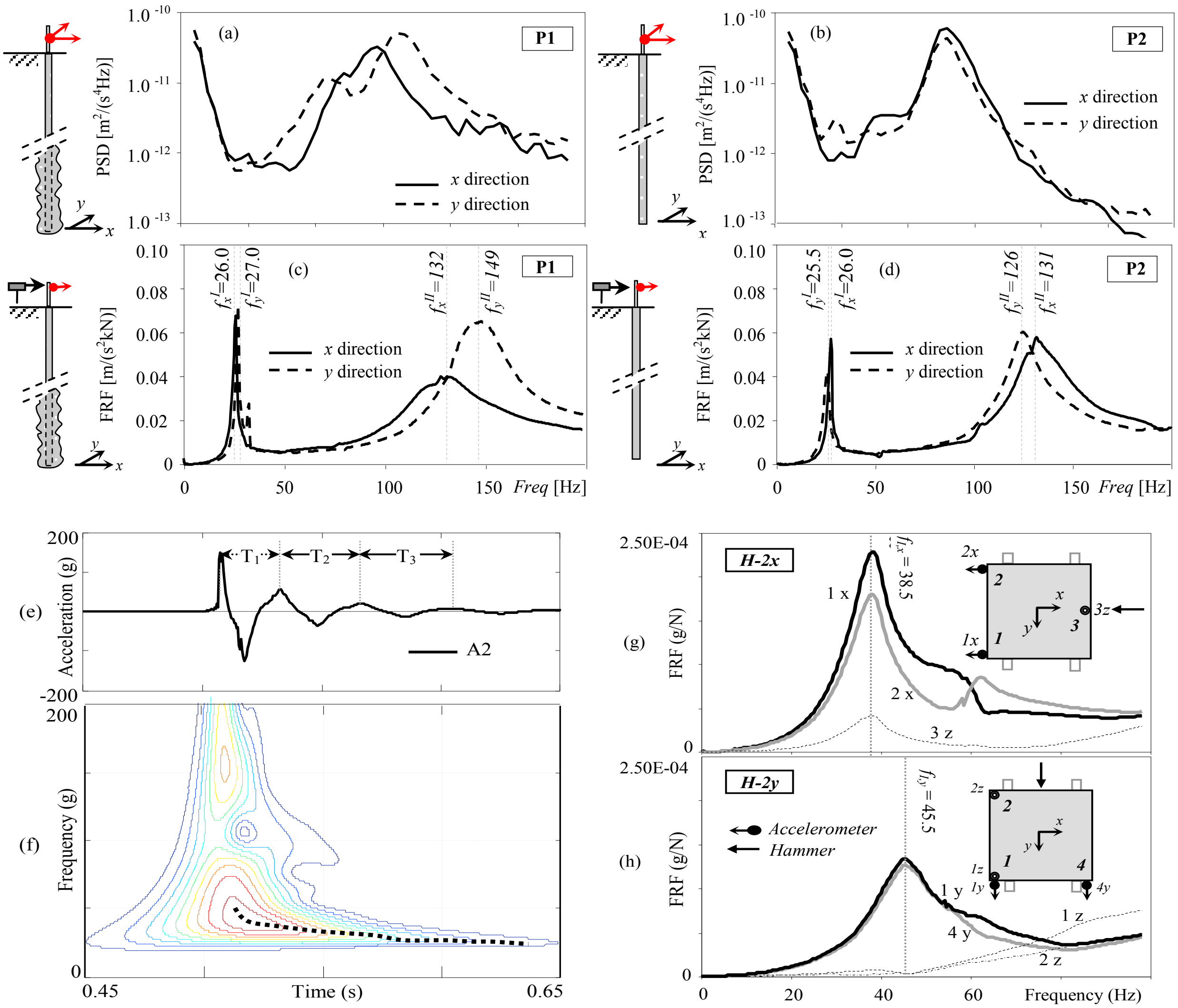

Fig. 3. PSD of acceleration during ambient vibration tests for P1 (a) and P2 (b); FRF of acceleration during impact tests for P1 (c) and P2 (d); (e) Time history and (f) Stockwell Transform of acceleration on the head of pile P2 during one of the Snap Back test (force level: 30 kN); FRF of acceleration on the group, acquired (g) along x and (h) y axes

References

[1] A. Y. Abd Elaziz, M. H. El Naggar, Group Behaviour of Hollow-Bar Micropiles in Cohesive Soils, Can. Geotech. J. 51 (2015) 1139–1150.

[2] I. Shahrour, I. Juran, Seismic behaviour of micropile systems, Ground Improvement 8(2004): 109-120.

[3] F. Dezi, F.Gara, D. Roia, Dynamic response of a near-shore pile to lateral impact load, Soil Dyn Earthq Eng, 40(2012): 34–47.

[4] F. Dezi, F.Gara, D. Roia, Experimental study of near-shore pile-to-pile interaction, Soil Dyn Earthq Eng, 18(2013): 282–293.

[5] F. Dezi, F. Gara, D. Roia, Linear and Nonlinear Dynamic Response of Piles in Soft Marine Clay, J. Geotech. Geoenviron. Eng., 143(2016): 04016085.

[6] F. Dezi, S.Carbonari, G. Leoni, A model for the 3D kinematic interaction analysis of pile groups in layered soils, Earthq. Eng. Struct. Dyn., 38(2009):1281–1305.

[7] F. Dezi, S.Carbonari, M. Morici, A Numerical Model For The Dynamic Analysis Of Inclined Pile Groups, Earthq. Eng. Struct. Dyn., 5(2016): 45–68.

[8] R.G. Stockwell, Localization of the complex spectrum: the S-transform, IEEE Transactions on Signal Processing, 44 (1996):998-1001.

[9] S. Escoffier, J-L Chazelas, J. Garnier, Centrifuge modelling of raked piles, Bull. Earthquake Eng., 6(2008):689-704.