PROVE IN VERA GRANDEZZA E ANALISI NUMERICHE DI PALI CON FORZANTE ORIZZONTALE IMPULSIVA

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Sommario

This paper presents the results of lateral impact load field tests carried out on three steel pipe piles at the tourist port of La Spezia, Italy. The piles are vibro-driven into marine soft clay, with a L-shaped plan layout, kept free at the head. Two test campaigns are carried out, the first 1 week and the second 10 weeks after vibro–driving of the piles. The dynamic behaviour of the complex soil–water–pile system at very small strain is discussed. In particular, the response of the single pile and the mutual interaction between loaded and receiver piles are presented. The variation in dynamic behaviour of the whole system in time (for the two campaigns), due to re–consolidation of the soil close to the pile subsequent to the vibro–driving, is observed. The experimental data are compared with the results obtained from a 3-D finite element models of the whole soil–water–pile system considering both a solid and a shell model for the piles and linear behaviour for the soil.

Introduction

In recent years, the question of soil–pile dynamic interaction has received a great deal of attention; modern codes suggest that it should be accounted for in the seismic design of pile foundations and superstructures. The stiffness and damping characteristics of the soil–pile system during earthquake motion depends on the mechanical properties and geometrical characteristics of soil and piles as well as their mutual interaction. In both research and advanced practice, this problem may be approached with numerical (finite element models) or analytical methods (Dobry R. e O'Rourke M.J. 1983, Nikolau A.S. et al. 2001, Dezi F. et. al. 2009) with different degrees of refinement. The results of these approaches are very sensitive to many parameters that define the dynamic characteristics of the soil-pile system. Experimental results of small– or full–scale laboratory and in–situ tests (Mizuno and Iiba 1992, Imamura et al. 1996, Shimomura et al. 2004) are an essential instrument to calibrate both analytical methods and finite element models. In particular, full–scale in–situ dynamic tests may be used to experimentally evaluate the dynamic characteristics of the soil–pile system and the pile–soil–pile interaction.

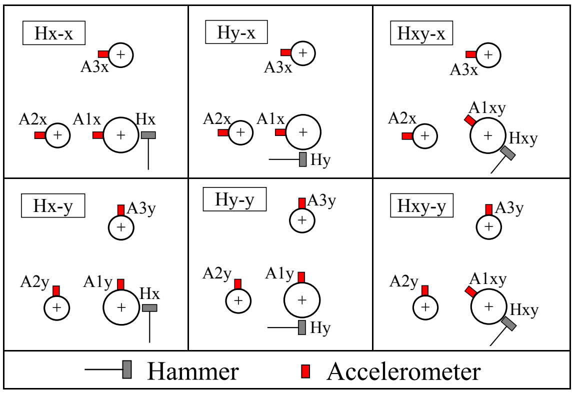
This paper presents horizontal impact load tests carried out on a group of three steel pipe piles, vibro–driven into marine soft clay at the tourist port "Mirabello" in La Spezia, Italy (Dezi et al. 2011). These are part of an extensive experimental program of full–scale field tests on dynamic laterally loaded piles, including lateral harmonic and frequency sweep tests, and snap-back tests. This campaign has the aim of investigating the complex dynamic soil–pile behaviour and the pile-soil-pile interaction. The horizontal impact load tests carried out in two different campaigns (one performed 1 week after pile vibro-driving and the other after 10 weeks) are illustrated and the effects of the soil re–consolidation subsequent to the pile vibro–driving are observed. The experimental results show the dynamic behaviour of the complex soil–water–pile system at very small strain. A 3–D finite element model of the system, with added mass to account for the hydrodynamic effects of the seawater and absorbing boundaries conditions to avoid wave reflections, is developed. Comparisons between numerical and experimental results are discussed, considering both a solid and a shell model for the piles and linear behaviour for the soil.

Horizontal Impact Load

Horizontal impact load tests were carried out by means of an instrumented hammer (equipped with load cell) having mass of 5.5 kg and 4 tips of different hardness. Finite element simulations and, more importantly, several preliminary in situ tests demonstrated that the impact of the hammer with medium–low hard tip induces values of accelerations at the pile heads and longitudinal strains along the pile, measured by the transducers, and greater than the ambient–noise. A maximum impact force of about 50 kN was reached with the hammer used. The impact load test permitted investigating a wide range of frequencies with just a few hammer hits and acquisition time of two seconds at a sampling rate of 10 kHz. Fig. 1a shows a typical time history of a medium intensity impact measured by the load cell of the hammer; the relevant frequency spectrum reported by Fig. 1b may be assumed as flat in the range of interest, up to about 200 Hz. Two campaigns of tests were conducted in two different instants in time: the first, 1 week after installation of the piles (August 2009), the second, after ten 10 weeks (October 2009). The tests were repeated both to assess the functioning of the measuring instruments immediately after vibro–driving and after two months in marine environment, and to evaluate differences with time in the dynamic behaviour of the pile–soil–pile system. Six different test configurations were considered varying the direction of the impact at the head of pile P1 and the measuring direction of the accelerometers at each pile head (Fig. 2a). These configurations permitted studying the propagation of the dynamic input from one pile to the other through the soil–water–piles system for different directions and pile spacing. For each configuration a set of 10 horizontal hammer impacts were given and the time histories of the impact load, acceleration at each pile head, strains and pore fluid pressure along the pile P1 were recorded. 60 tests were carried out in each campaign.

Numerical Modelling

A finite element modelling of the soil-water-piles system is initially used to perform preliminary analyses to calibrate the test setup. Successively, a more accurate 3–D finite element model is developed in ABAQUS (2009) and opportunely calibrated adjusting material parameters on the basis of field test results.

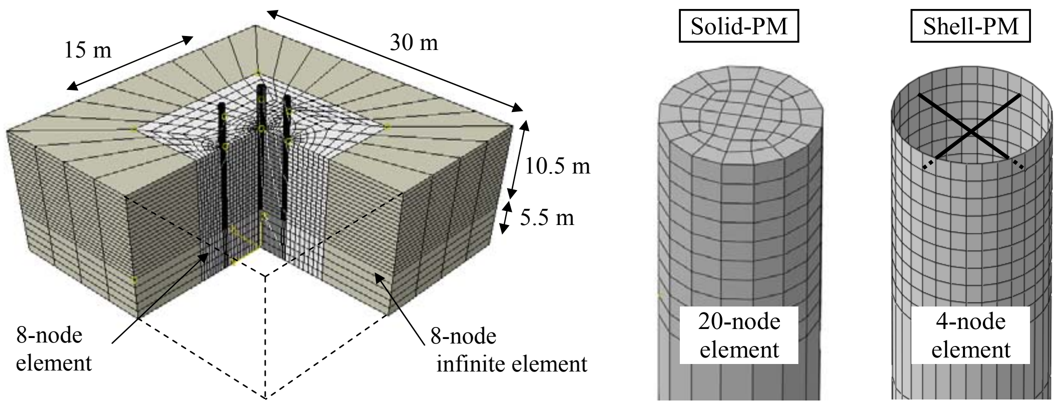


a)

b)

Figure 2. a) Impact Load Test Configurations and b) Test Hxy-y

The numerical model is used to better understand the mechanisms involved in the dynamic behaviour of the complex soil-water-piles system and is developed to enable further advanced investigation. Fig. 3a shows the 3-D finite element model of the soil-water-piles system. The soil surface is considered at the mean level of the first layer consisting of mud. A 30×30×16 m parallelepiped section of soil is considered. The upper part of the parallelepiped is divided into 21 0.5 m thick horizontal layers while the remaining section is divided into 5 1.1 m thick layers. The soil is modelled with 8-node brick elements, more refined near the piles. At the lateral boundaries the radiation condition is assured by using absorbing boundaries constituted by 8-node infinite elements (Fig. 3a). The model is fully restrained at the base. Since the energy of the impact is very low, the following assumptions are considered: i) the gap at the soil-pile interface is neglected and the contact between piles and soil is modelled with a tie constraint; ii) the system is considered to behave in a linear elastic fashion. A homogeneous soil profile is considered since a uniform shear wave velocity value of 60 m/s has been estimated from the geotechnical investigations in the upper 20 meters. For the steel pipe piles a solid model (Solid-PM) is firstly considered (Fig. 3b) with the aim of minimizing the local effects in the hammer impact zone due to radial and circumferential modes and emphasizing the mean behaviour of the pile which is mainly characterized by the bending modes. 20-node brick elements are adopted and the piles are divided into three regions: emerged, submerged and embedded sections, having a length of 1.0, 4.0 and 10.5 m, respectively. For each region a vertical 0.5 m thick mesh is adopted and the pile solid cross section is divided into 32 elements. A mesh refinement is realized around the area of hammer impact on pile P1 in order to create an impact area equal to that of the hammer tip. In order to catch the contribution of the pile radial-circumferential modes and reproduce the experimental response of the loaded pile, i.e. the punctual acceleration measured by the accelerometer, a second model (Fig. 3b) is also developed, in which the piles are modelled with 4-node shell elements (Shell-PM). The circumference is divided into 16 elements and the two stiffeners at the pile head are modelled by two beam elements.



a) b)

Figure 3. a) 3-D Finite Element Model; b) Soil Model; c) Solid and Shell Pile Models

Table 1. Pile and Soil Properties

	Solid-PM			Shell-PM		
Parts	ρ [t/m^3]	*E* [kN/m^2]	ν	ρ [t/m^3]	*E* [kN/m^2]	ν
P1 emerged	0.48	$2.50 \cdot 10^7$	0.3	7.8	$2.00 \cdot 10^8$	0.3
P1 submerged	2.35	$2.50 \cdot 10^7$	0.3	38.6	$2.00 \cdot 10^8$	0.3
P1 embedded	2.16	$2.50 \cdot 10^7$	0.3	35.5	$2.00 \cdot 10^8$	0.3
P2,P3 emerged	0.50	$2.36 \cdot 10^7$	0.3	7.8	2.00·108	0.3
P2,P3 submerged	2.37	$2.36 \cdot 10^7$	0.3	36.8	2.00·108	0.3
P2,P3 embedded	2.18	$2.36 \cdot 10^7$	0.3	33.9	2.00·108	0.3
Soil	1.68	$1.57 \cdot 10^4$	~0.5	1.68	1.57·104	~0.5

The mechanical characteristics of the steel piles modelled with solid or shell elements are reported by Table 1. With reference to the Solid-PM, the Young's modulus and density of the steel piles are opportunely modified to account for the difference between the real cross section of the piles (hollow section) and that of the model (solid section). Furthermore, in both models, the density of the different pile regions are adjusted to account for the masses of soil and water inside the pile. Finally, even the water outside the submerged section of the piles is taken into account by means of an added mass which determines a further modification of the pile density in that section. For both models, the hammer impact is simulated by a uniform pressure applied on an area equal to that of the hammer tip, characterized by the time history of the impact recorded during the test. Furthermore, a proportional damping of 2% is assumed.

Single Pile Response

The response of the single pile subjected to impact load tests is mainly evaluated from the strain gauge signals. Fig. 4 shows, with black line, the time histories of the longitudinal strains recorded by four strain gauges of the main generatrix of pile P1 during the test Hxy-x of the second campaign, and with light blue line, those obtained with the Solid-PM. The experimental signals were filtered by a Butterworth low-pass filter with a cut-off frequency of 100 Hz to nearly eliminate the effects due to cross sectional deformation and noise which are mainly characterized by high frequency content. A first peak due to the impact load is observed: this is characterized by a time delay which increases with the distance of the strain gauge from the hammer impact point. After peak, the signals show a damped harmonic oscillation at the frequency of the first bending mode of the system. With reference to the harmonic oscillation, the strains reach the maximum values for strain gauges located just below the soil surface (SG5), where the maximum bending moments occur, and decrease with depth (SG8, SG10) and near the pile head (SG1) where bending moment values are smaller. Furthermore, strain records at the pile head are less smooth than the others, due to residual ambient noise and radial-circumferential modes. The time histories of the strains obtained with the Solid-PM fit the experimental results very accurately; the model catches the first peak and the final part of the signals, in terms of amplitude, frequency content and damping while minor discrepancies between the experimental and numerical signals are observed after the first peak. Fig. 5a shows the first two mode shapes and relevant profiles of bending moments obtained from the Frequency Response Functions (FRFs) relative to strain gauges of the main generatrix. Fig. 5b shows the mean FRF of strains measured by SG5 and SG8 during test Hxy-x of the first campaign (black line) and the second campaign (light-blue line).

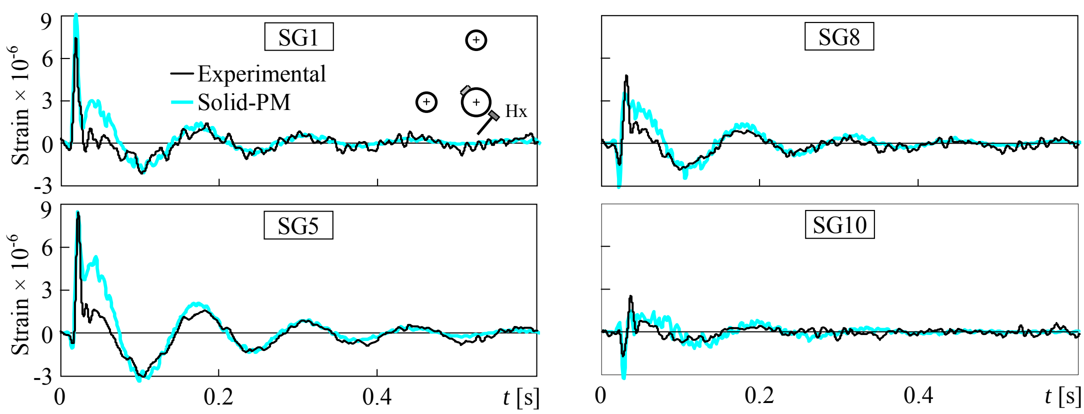
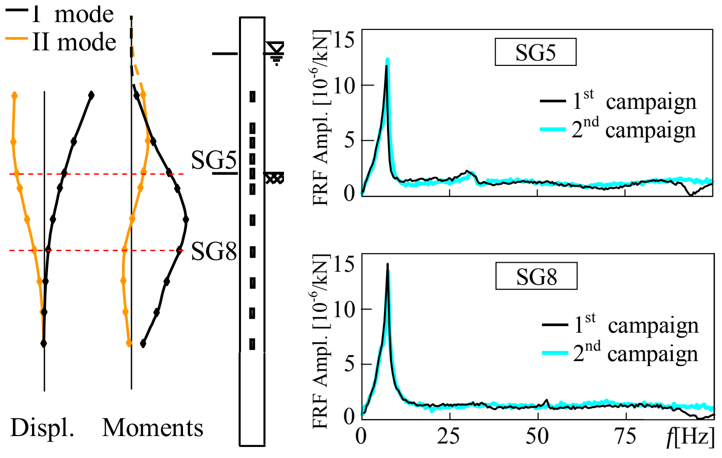


Figure 4. Time Histories of Strains

For SG5 two peaks are evident which identify the natural frequencies of the first and second bending modes; for SG8 the first peak is evident while the second cannot be caught since the instrument is placed near an anti-node for the second bending mode shape. By applying the half power bandwidth method to the FRF peaks the modal damping ratios of the soil-water-pile system is obtained (Ewins, 2000). In the table of Fig. 5c the natural frequencies and modal damping resulting from Hxy–x tests of each campaign are listed. For the second campaign greater values of natural frequencies and smaller values of modal damping are obtained: this may be attributed to the soil re-consolidation subsequent to the pile vibro-driving installation. The table reports also the natural frequencies obtained from tests Hx-x and Hy-y: the discrepancy between the frequency values, along the different directions are mainly due to the UPN profiles that determine a dissymmetry of the pile cross section.

Pile Group Response

The response of the pile group to the impact load is evaluated from the accelerometer signals. Fig. 6 shows the acceleration time histories measured at the pile heads during the Hx-x test of the second campaign and those obtained with numerical models. In Fig. 6a the accelerometer signal (A1x) recorded at the head of the loaded pile is reported with grey line and compared with that obtained with Shell-PM, orange line.



1st campaign		I mode	II mode
Frequency (Hz)	f_x	6.2	29.9
	f_y	6.9	31.2
	f_{xy}	7.0	31.4
Damping(%)	ξ_{xy}	8.4	/

2nd campaign		I mode	II mode
Frequency (Hz)	f_x	6.4	32.3
	f_y	7.4	32.1
	f_{xy}	7.4	31.8
Damping(%)	ξ_{xy}	6.9	/

c)

Figure 5. a) Mode Shapes and Relevant Profiles of Bending Moments; b) Average FRFs of Strain Gauge Signals; c) Natural Frequencies and Modal Damping of Soil-Water-Pile System

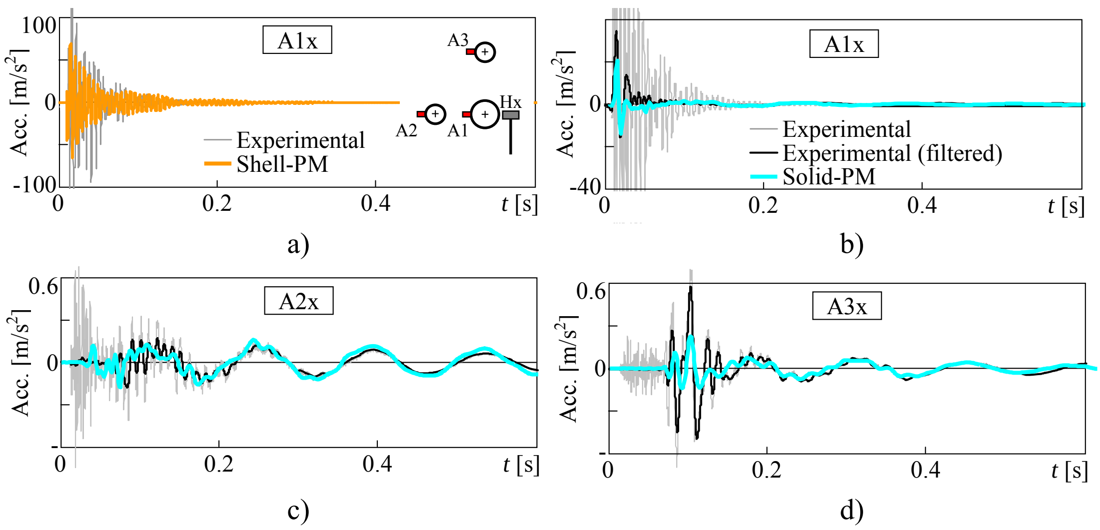


Figure 6. Time Histories of Accelerations at the Pile Heads

A1x is characterized by very high values, high frequency and damping due to the effects of the radial-circumferential modes which are predominant near the hammer impact point. Shell-PM catches with acceptable precision this behaviour and a better approximation may be reached by refining the mesh. In Fig 6b A1x is filtered by a Butterworth low-pass filter with a cut-off frequency of 100 Hz (black line) and compared with the acceleration obtained with the Solid-PM (light-blue line). After the high filtering process, to reduce the effects of radial and circumferential modes and noise, the signal is characterized by lower peaks, caused by the impact load, in the first part and a damped harmonic oscillation at the frequency of the first bending mode of the system. The Solid-PM is in relatively good agreement with the filtered signal being capable to describe the pile flexural behaviour.
The acceleration time histories of the receiver piles P2 (A2x) and P3 (A3x) are reported in the two graphs at the bottom of Fig. 6. The signals are two orders of magnitude smaller than the signal of the loaded pile P1. They are characterized by an initial time delay, due to the propagation time of the input, followed by: a first part with high frequency content is evident in the raw signal while is highly attenuated by the low-pass filter; a second transitory part, in which the maximum value is attained in pile P3; and a final part with a damped harmonic oscillation at the frequency of the first bending mode of the soil-water-pile system. This behaviour is due to different types of waves propagating from the source pile to the receiver piles. The first part of the signals may be primarily attributed to propagation of compression waves whose effects are more significant in pile P2, closer to the loaded pile and positioned in the direction of the impact. The second part of the signals is quite different for the two piles: A3x shows higher peak values mainly due to shear waves that, propagating orthogonally to the impact direction, have a primary effect on pile P3; A2x is, instead, characterized by lower peaks probably due mainly to surface (Scholte) waves.

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