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Lateral impact loading and snap-back testing to estimate linear and nonlinear dynamic response of near-shore piles

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Abstract – This paper presents some results of dynamic lateral loading tests on a near-shore steel pipe pile vibrodriven into soft marine clay. Two typologies of tests are carried out on a free head pile: impact load tests and free vibration tests at different load levels. The aim of this experimentation is to investigate the dynamic soil-water-pile interaction and determine the dynamic characteristics of the whole system by means of the two different typologies of test and for different levels of the dynamic input. The obtained results show the complex dynamic behaviour of the vibrating soil-water-pile system in terms of natural frequencies and damping ratios. The values obtained from the two test typologies are compared and the variations with the level of the input force, due to the nonlinear behaviour of the system, are discussed.

Keywords: Pile foundation, dynamic testing, soil-water-pile interaction, impact load test, free vibration test.

I. INTRODUCTION

The dynamic behaviour of a soil-water-pile system under lateral loading is of great interest for a large class of near-shore structures which are usually founded on single pile or pile group. The estimation of the stiffness and damping of the soil-water-pile system at different level of strain is a key step in the structural modelling and in the verification procedures when considering these structures subjected to dynamic load (earthquake motion or any dynamic action). Although a fairly large number of theoretical studies on the dynamic soil–pile interaction have been published, there is much to do in the experimental field. Very few dynamic tests with lateral excitation on full-scale piles in field conditions, and even less on near-shore piles, are available in the literature. A comprehensive list of references describing experimental campaign on piles may be found in [1].

The lack of experimental evidences on the dynamic interaction of soil-pile system, especially in near-shore conditions, was the main motivation of the experimental programme carried out at the "Mirabello" harbour in La Spezia (Italy) on a near-shore steel pipe pile vibro-driven for a depth of 9.5 m into soft marine clay. The pile was instrumented and subjected to dynamic lateral excitation, i.e. impact tests and free vibration tests, with the aim to study the dynamic behaviour at small and large strain. The results of impact load tests relevant to the single pile and to the pile system have been already discussed in two previous papers [2, 3].

II. SOIL CHARACTERIZATION AND TEST DESCRIPTION

The test field, located in the tourist port "Mirabello" in La Spezia (North-West Italy), consists of a steel pipe piles vibro-driven into soft marine clay (Fig. 1). Several site explorations (1973, 1981, 1991, 1992 and 2008) were carried out before the construction of this new section of the harbour. A large volume of soil was investigated by means of laboratory tests, e.g., Oedometer test, and in-situ tests conducted up to a maximum depth of about 50 m, e.g., Dilatometer Marchetti Test (DMT), Cone Penetration Test (CPT), Standard Penetration Test (SPT), Piezocone Test (CPTU), Field Vane Tests (FVT), and Multichannel Analysis of Surface Waves (MASW). The soil stratigraphy and a CPT profile representative of soil conditions in the proximity of the test site is reported in Fig. 1 whereas the main soil properties of each soil layer, derived by the geotechnical investigations, are summarized in Table 1. In particular layer A is composed by mud and loose clayey silt, layer B by normal consolidated slightly silty clay, layer C by slightly sandy and silty clay, layer D by sand and dense silty sand with heterogeneous coarse lenses and finally layer E by

overconsolidated silty clay and clayey silt. The pile, 15.5 m long, is embedded for a depth of 9.5 m into soft marine clay. While the pile head elevation is 1.0 m above mean sea level (m.s.l.). The pile diameter and thickness are of 711 mm and 11 mm, respectively; the head of the pile is kept free and is stiffened with two steel profiles, welded in a crux shape.

As regards the instrumentation, a total of 19 strain gauges (SG) are used to measure the longitudinal strains along the pile P1. Strain gauges are placed at selected levels along three generatrices of the pile, spaced 120 degrees apart, to capture the cross section average strains (elongation and curvature of the pipe), i.e. 11 strain gauges are located along the main generatrix and 4 along each of the two secondary generatrices l and r (Fig. 2).
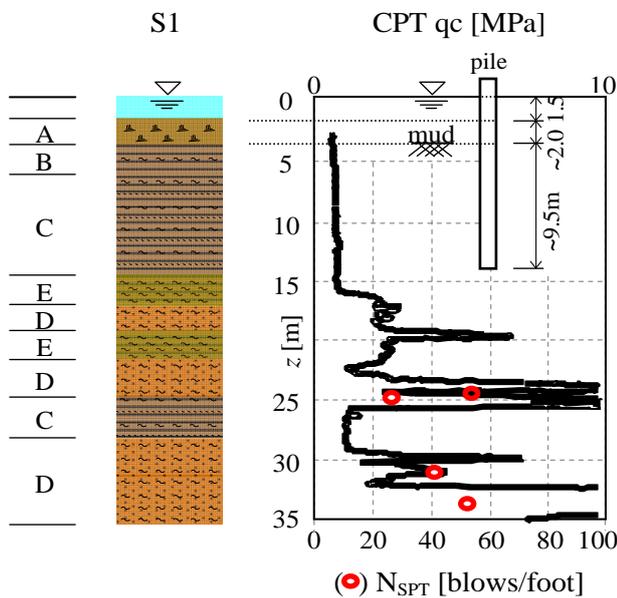

Fig. 1. Subsoil profile.

Table 1. Geotechnical parameters.

Soil type	Borehole		CPT		DMT		FVT	
	P.P. [kPa]	V.T. [kPa]	qc [MPa]	fs [kPa]	Cu [kPa]	OCR	Cu [kPa]	Cur [kPa]
A			0.37	13	14		20	5
B		22	0.45	14	19		25	8
C	68	44	0.82	18	40	3.00	47	12
D			7.90	100				
E	120	50	2.25	120	82	5.00	108	22

P.P. = resistance to penetration measured by pocket penetrometer, V.T. = shear strength measured by pocket scissometer, qc = cone resistance, fs = sleeve friction, Cu = undrained shear strength, OCR = over consolidation ratio, Cur = undrained residual shear strength.

Narrower measure points are considered for the pile portion where maximum curvatures are expected. During installation, the measuring instruments were carefully protected both chemically and mechanically, from the marine environment and pile vibro driving (Fig. 3a, Fig. 3b, Fig 4a). The measurement chain also includes signal conditioners, one spectrum analyzer, one data acquisition systems, and a computer with dedicated software (Fig. 3c).

Two different typologies of test were performed: impact load and free vibration tests. Impact load test makes it possible to investigate a wide range of frequencies with few hammer blows and short acquisition times (few seconds). Since a low amount of input energy is supplied to the system at each frequency, this test allows analysing the system behaviour only at small strains at which a linear behaviour is expected, whereas it is not suited to investigate the non-linear behaviour of the system which can occur at higher strain levels.

For tests described in this paper, an instrumented hammer equipped with a load cell was adopted having a mass of 5.5 kg (Fig. 4b). With this hammer a maximum impact force of about 50 kN was reached, with a frequency spectrum characterized by a constant force level up to about 100 Hz. Therefore, this hammer permitted to investigate the soil–water–pile behaviour, at small strain, in a wide range of frequencies, ranging between approximately 0.5 Hz to 100 Hz. A sets of 10 horizontal hammer impacts were given in y-direction and the time histories of the impact load and strains where recorded.
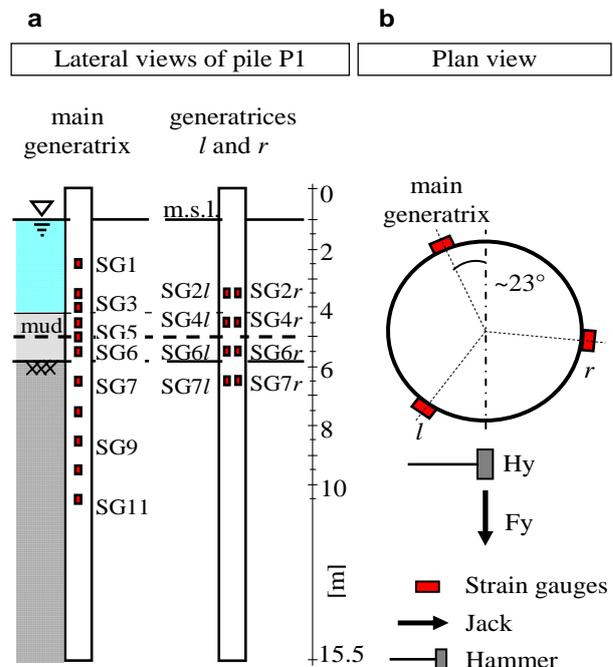

Fig. 2. (a) Pile P1 instrumentation; (b) plan view.

Before the tests, the sea water and soil levels inside and outside the pipe were measured, the ambient noise mainly due to marine waves was registered, and preliminary tests were conducted to setup the data acquisition system, type and entity of the impact, and proper gains for the accelerometer signals. A sampling rate of 10 kHz was chosen to achieve high resolution in time domain, and an acquisition time duration of 2 s, including a pretrigger of 0.1 s, was considered to catch the entire duration of the pile oscillation.

The free vibration tests allow investigating the dynamic behaviour of the system at different strain levels, by varying the level of force which is usually imposed with a standard hydraulic actuator. For tests described in this paper the load is applied using a double acting jack with a capacity of about 400 kN, placed on the wharf and connected to the pile P1 by means of steel cables. The quick release of the load was achieved thanks to the failure for traction of a "calibrated pin" that consists of a steel element placed along the steel cable between jack and pile (Fig. 4c).
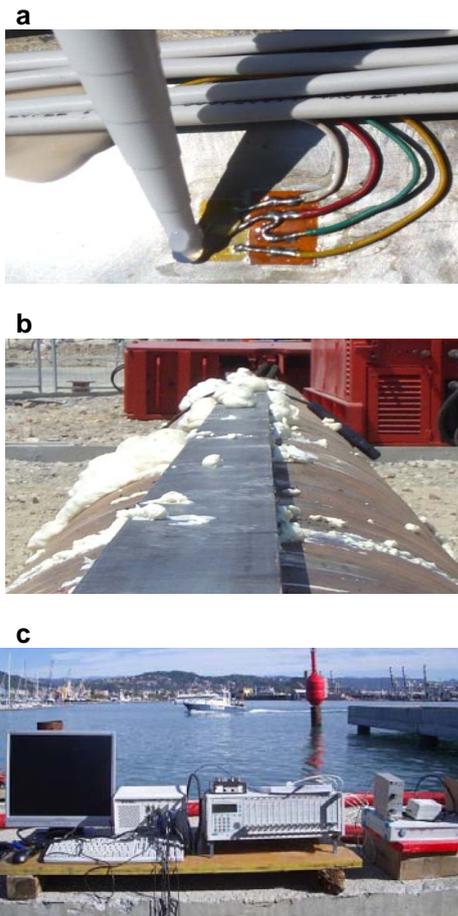
The load level was measured by an analogical pressure transducer applied on the hydraulic pump actuating the jack. 5 tests in y-direction were performed at increasing load amplitudes (2.8 kN, 6.9 kN, 18 kN, 24 kN and 58.1 kN). The lowest level was designed so as to obtain a strain level greater but comparable to that obtained with the impact load test. Carrying out free vibration tests at greater force levels allows the investigation of the effects of nonlinear behaviour of the soil on the dynamic behaviour of the system. A time acquisition of 4 s, including a pretrigger of 2 s and a sampling rate of 5 kHz were used.

Fig. 3. Instrumentation: (a) a strain gauge; (b) protection of cables and strain gauges along a generatrix; (c) measurement chain.
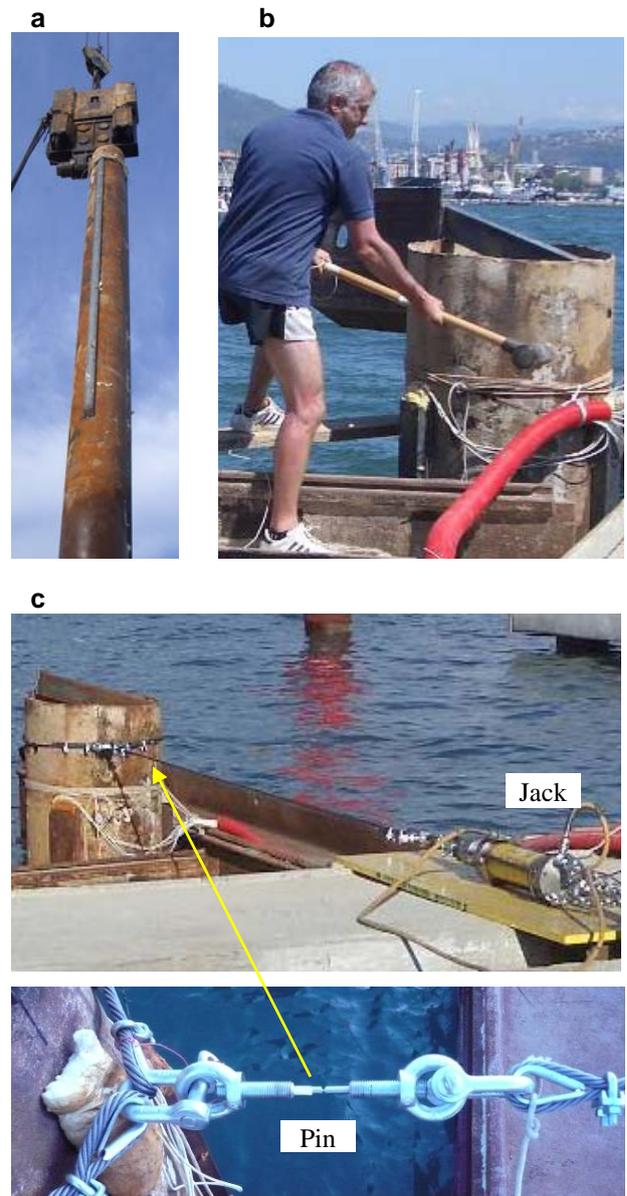

Fig. 4. (a) Vibro-driving of the instrumented pile; (b) impact load test; (c) free vibration test: traction system for pulling-back and pin for quick release.

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III. EXPERIMENTAL RESULTS AND DISCUSSION

A. Results at low level of force

In this section results of impact load tests and free vibration tests at low force level are presented in order to discuss the dynamic behaviour of the soil-water-pile system at small strain.

In Fig. 5 the time histories of the longitudinal strains recorded along the pile P1 by SG1, SG5, and SG9 during the two test typologies are reported. Those relevant to free vibration tests are raw signals while those relevant to impact load tests are 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.

Time histories relevant to the impact load test reveal a first peak with high amplitude due to the impact. The peak is characterized by a time delay due to the travelling time of the impulse, which depends on the distance between the sensor and the hammer impact point. After the peak, the measurements show a damped harmonic oscillation at the frequency of the first bending mode of the system. Oscillations are practically undetectable at SG1 and SG11, where strains are too small to be captured by sensors, considering their sensitivity and noise. Time histories relevant to free vibration test show nearly constant values before the release, due to the quasi-static manner of the loading. After the quick release, free damped oscillations of the pile are manifest at nearly the first natural frequency of the soil-water-pile. From a qualitative point of view, a part from the amplitude, the graphs are very similar and the damped harmonic oscillations are almost proportional. The maximum values of strain amplitude, proportional to pile bending moment, are attained in the pile section located just below the soil surface.

The modal properties of the soil–water–pile system, such as natural frequencies, damping and mode shapes are obtained by means of an experimental modal analysis that utilizes the measured excitation applied to the pile head and the system response measured at discrete locations by strain gauges. Both the excitation and response time histories are transformed into the frequency domain to define Frequency Response Functions (FRFs), which are the Fourier transform of response measurement normalized by the Fourier transform of the input. Natural frequencies are obtained by means of the peak picking method, selecting the frequencies corresponding to the peak values of the FRF amplitude. As regards damping ratios of the soil-water-pile system at small strain, they are estimated from the strain gauge signals by means of the logarithmic decrement, working in time domain. The procedure is applied fitting the first eight peaks to obtain a mean value representing the damping of the system during almost the entire oscillation of the pile.
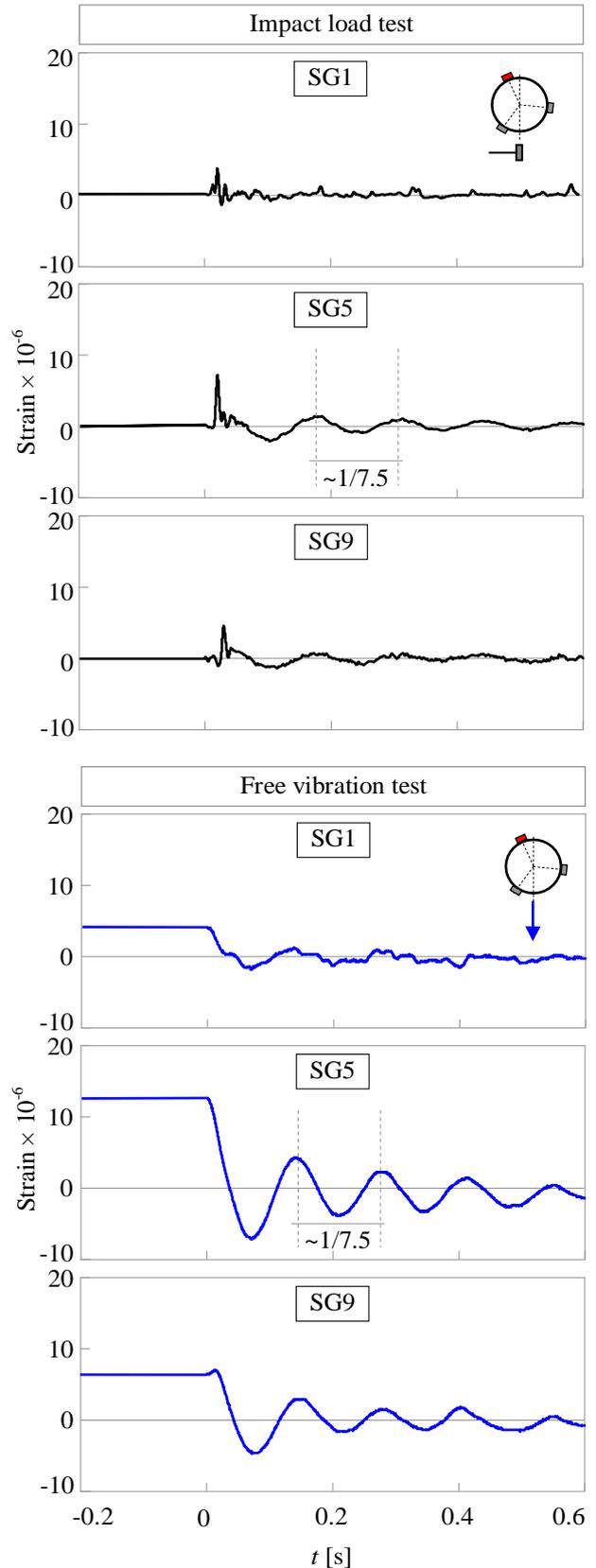

Fig. 5. Time histories of SGs signals.

Fig. 6 shows the first natural frequencies and damping ratios evaluated from SGs along the pile for impact load and free vibration tests, while, in Table 2 the mean value and the standard deviation of the first natural frequency and damping ratio of the whole soil-water-pile system, obtained as average among the values relevant to all the SGs, are reported. These values obtained for the two test typologies are very close, revealing, in both cases, an elastic response of the system even if the strain level induced by the free vibration test is about half a order of magnitude greater than the one caused by the impact load test.

B. Results at high level of force

To study the dynamic behaviour of the soil-water-pile system at higher strain and to investigate the effects of soil nonlinearities, free vibration tests at four higher load levels were performed; the maximum force (58.1 kN) is about 20 times the minimum one (2.8 kN).

Table 2. Natural frequencies and damping ratios obtained from impact load and free vibration tests.

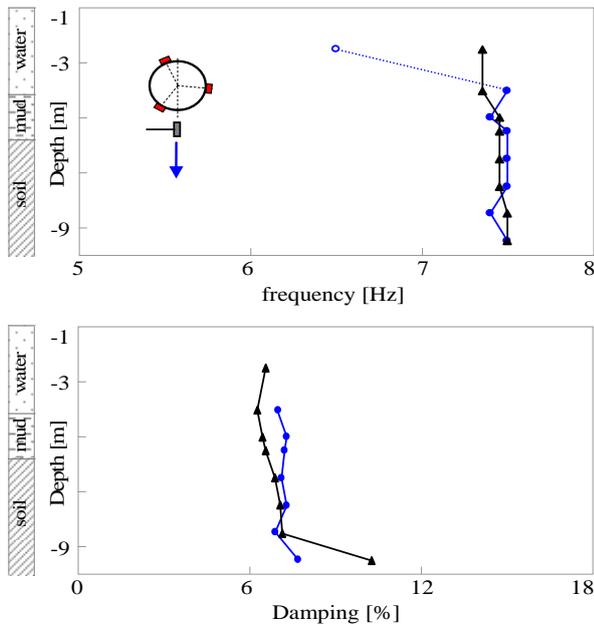|	Impact load		Free vibration	
	Mean value	Standard deviation	Mean value	Standard deviation
f [Hz]	7.44	0.06	7.47	0.05
damping [%]	7.2	1.4	7.2	0.3

Fig. 6. First natural frequencies and damping ratios evaluated from SGs along the pile for free vibration and impact load tests

In Table 3 the value of the force producing the traction failure of the pin (maximum quasi-static force) and the quick release of the pile, obtained for each test, is reported. The actual loading exerted by the jack is derived from the values recorded by two strain gauges (SG3 and SG5) located in the portion of the pile above the ground (where the longitudinal strain vary linearly with depth) by considering the elastic properties of the pile.

Fig. 7 shows the FRFs obtained from the ratio between the complex spectrum of pile response in terms of strains along the pile and the complex spectrum of the load applied at the pile head. Three observations can be done. (*i*) The resonance frequency gradually decreases as the load level increases due to a reduction of the stiffness of the soil-pile system which can be attributed to a nonlinear behaviour of the soil surrounding the pile; the resultant of soil reactions is thus located at deeper position and, consequently, the free-standing length of the pile increases while the embedded length decreases, making the system more flexible.

Table 3. Maximum quasi-static force achieved during free-vibration tests.

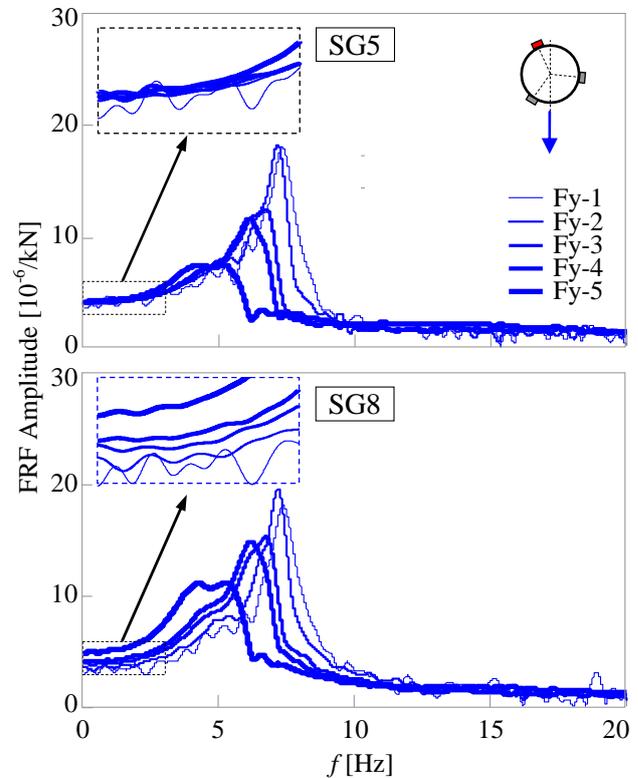| Test		Fy-1	Fy-2	Fy-3	Fy-4	Fy-5
Force		2.8	6.9	18.0	24.0	58.1

Fig. 7. FRFs of SG5 and SG8 obtained from free vibration tests at different load levels.

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(*ii*) The width of the resonant peak increases and the amplitude reduces with the load level as a consequence of the nonlinearity in soil behaviour that generally increases the hysteretic damping. (*iii*) The static value of FRF (amplitude at 0 Hz) related to SGs located along the pile section above the ground level (e.g. SG5) remains constant as the load level increases whereas that related to SGs located in the embedded portion of the pile (e.g. SG8) increases with loading as a results of the non linear soil behaviour.

Fig. 8 shows the mean values and standard deviations of the first natural frequencies and damping ratios obtained from free vibration tests at different load levels and those obtained from impact load test.
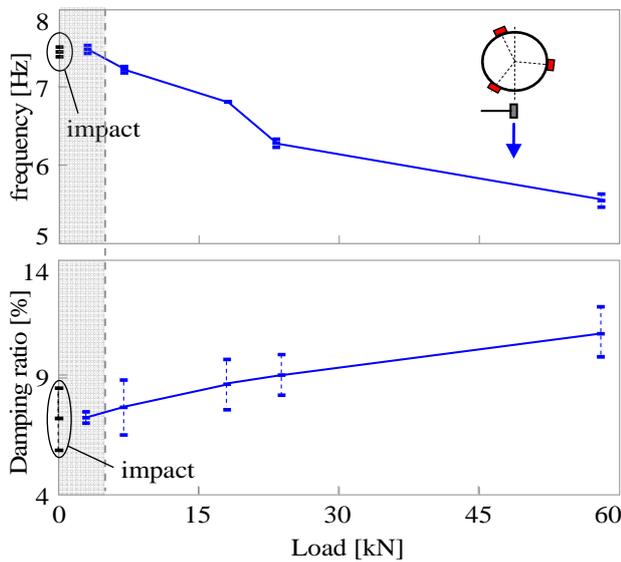

Fig. 8. Mean value and standard deviation of natural frequencies and damping ratios vs load.

The natural frequencies are evaluated by means of the peak picking method while the damping ratios are estimated by means of the logarithmic decrement method fitting the first eight peaks in the time domain. Comparing results obtained from free vibration tests at the lowest load level (Fy-1) with those obtained from impact load tests very similar values of the natural frequencies and damping ratios are observed. Increasing the load level of the free vibration test a decrease of the natural frequency and an increase of the damping ratio, due to soil nonlinearities, are clearly evident.

It is also worth noting that standard deviation of damping ratios is higher than the one of the corresponding natural frequencies. This denotes that the identification of natural frequencies is more accurate compared with the identification of damping ratios.

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