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TURBOMACHINERY LABORATORY
TEXAS A&M ENGINEERING EXPERIMENT STATION

TEXAS A&M UNIVERSITY

Frequency dependence of piles‘ dynamic stiffness

Marco Giancotti	GE Oil & Gas
Alessio Margiotta	GE Oil & Gas
Maurizio Orlando	University of Florence
Paolo Spinelli	University of Florence

Presenters/Authors bios

Marco Giancotti
TMS Industrial Plants
Infrastructures Eng. Manager
GE Oil & Gas
Florence, Italy

Marco holds a master degree in Mechanical Engineering and has 25 years of experience in the industry.
He joined GE Oil & Gas in the 1997, immediately starting his journey on modularization projects.
He's author of 1 patent.

Alessio Margiotta
TMS Industrial Plants
Civil & Structural Eng. Manager
GE Oil & Gas
Florence, Italy

Alessio holds a master degree cum laude in Civil Engineering and has 12 years of experience in the industry.
He joined GE Oil & Gas in the 2011, adding strong competences on modularization to his diversified background.

Maurizio Orlando
Associate Professor of Design of Structures
School of Engineering
University of Florence

Maurizio holds a master degree in Civil Engineering and a Ph.D. in Structural Engineering. He has 20+ years of experience in cooperating, as a member of the Florentine civil engineering firm GPA & Partners, with the industry including GE Oil & Gas.
He's author of several papers relevant but not limited to Industrial steel & R.C. structures and rehabilitation of existing buildings.

Paolo Spinelli
Full Professor of Design of Structures
School of Engineering
University of Florence

Paolo holds a master degree in Civil Engineering and has 35+ years of experience in cooperating with engineering firms & companies including GE Oil & Gas. He is one of the founder of the Civil Engineering Firm GPA & Partners, based in Florence and London.
He's author of several papers relevant but not limited to Industrial steel & R.C. Structure and rehabilitation of existing buildings.

Abstract

The evaluation of the dynamic behavior of deep foundations for Turbomachinery Modules is not a simple task due to uncertainties in the evaluation of the soil shear modulus and the approximations introduced with published literature formulas for complex stiffness (impedance) functions of piles.

The direct measurement of the dynamic response of full scale piles can be an efficient method to reduce considerably these uncertainties and to get a reliable evaluation of the dynamic response of deep foundations.

The above should also positively impact both the risks and the engineering schedule in the execution phase of the projects, reducing the dynamic analysis cases.

The authors present herein the results of full-scale dynamic tests on piles, which have been performed by applying sinusoidal forces to their top.

Problem Statement

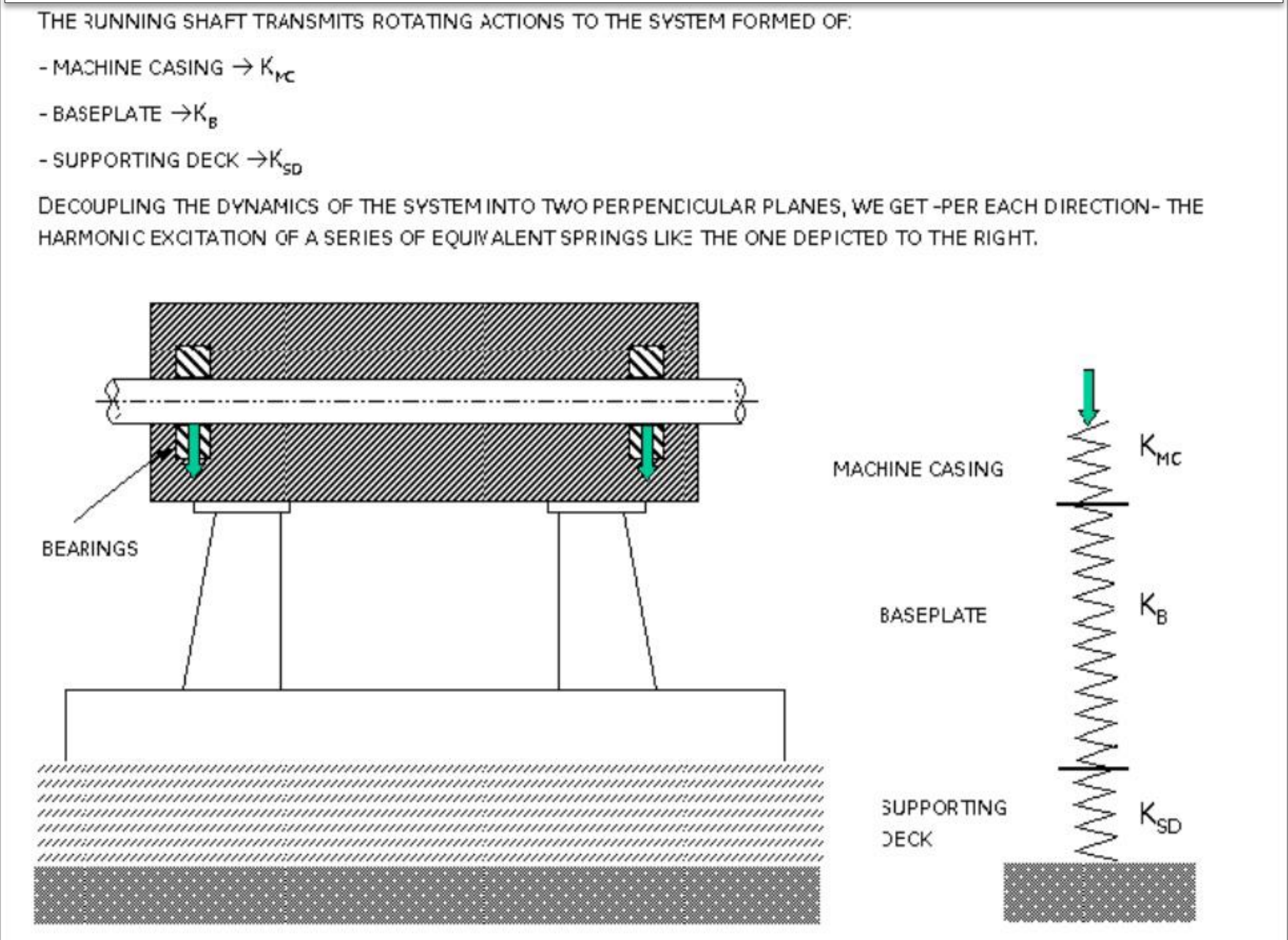
The dynamic stiffness requirements for TM foundations bearing points are usually set from TM manufacturers with the purpose of validating the hypothesis under with the rotordynamic lateral analysis has been performed and the dynamic loads on foundation have been generated.

API RP 684 states:

when bearing support stiffness, including effects of frequency dependent variation, are less than 3.5 times the bearing (oil film) stiffness values, the support stiffness values derived from modal testing or calculated frequency dependent support stiffness (and damping) values shall be used for the lateral rotordynamic analysis.

The bearing support stiffness includes everything past the bearing's oil film all the way to ground.
The term (module) "supporting deck" , see picture on the right, includes the entire foundation system, which is made by sub-foundation (i.e. piles), foundation and supporting structure.

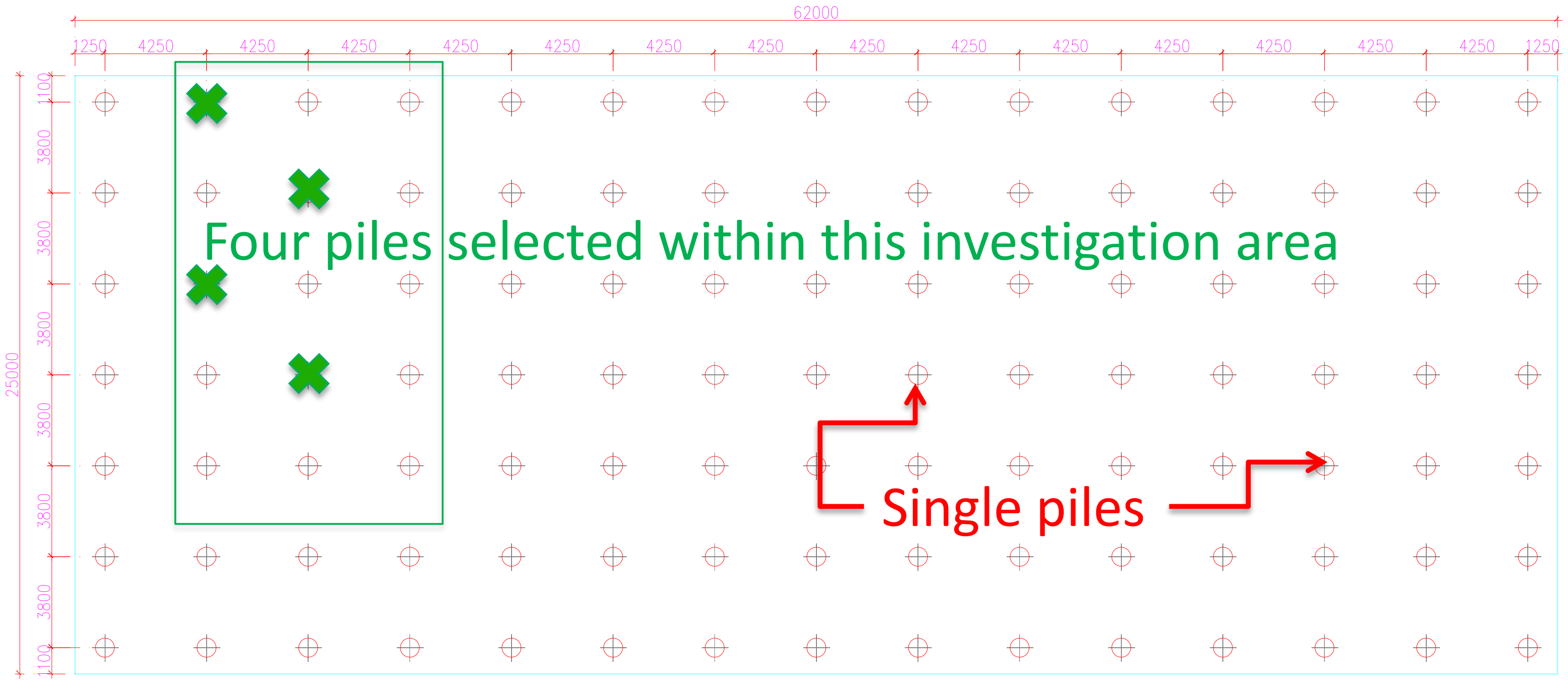
GENERIC REPRESENTATION OF A ROTATING MACHINE INSTALLED ON A STEEL DECK



Case study location: Avenza yard (Italy)

<u>Turbomachinery Module’s erection & testing bay foundation</u>

R.C. slab (62m x 25m) sitting on 7x15 (=105) piles (ϕ 800mm, L 20m) arranged at a distance of 4.25 x 3.80 m (average spacing five diameters).

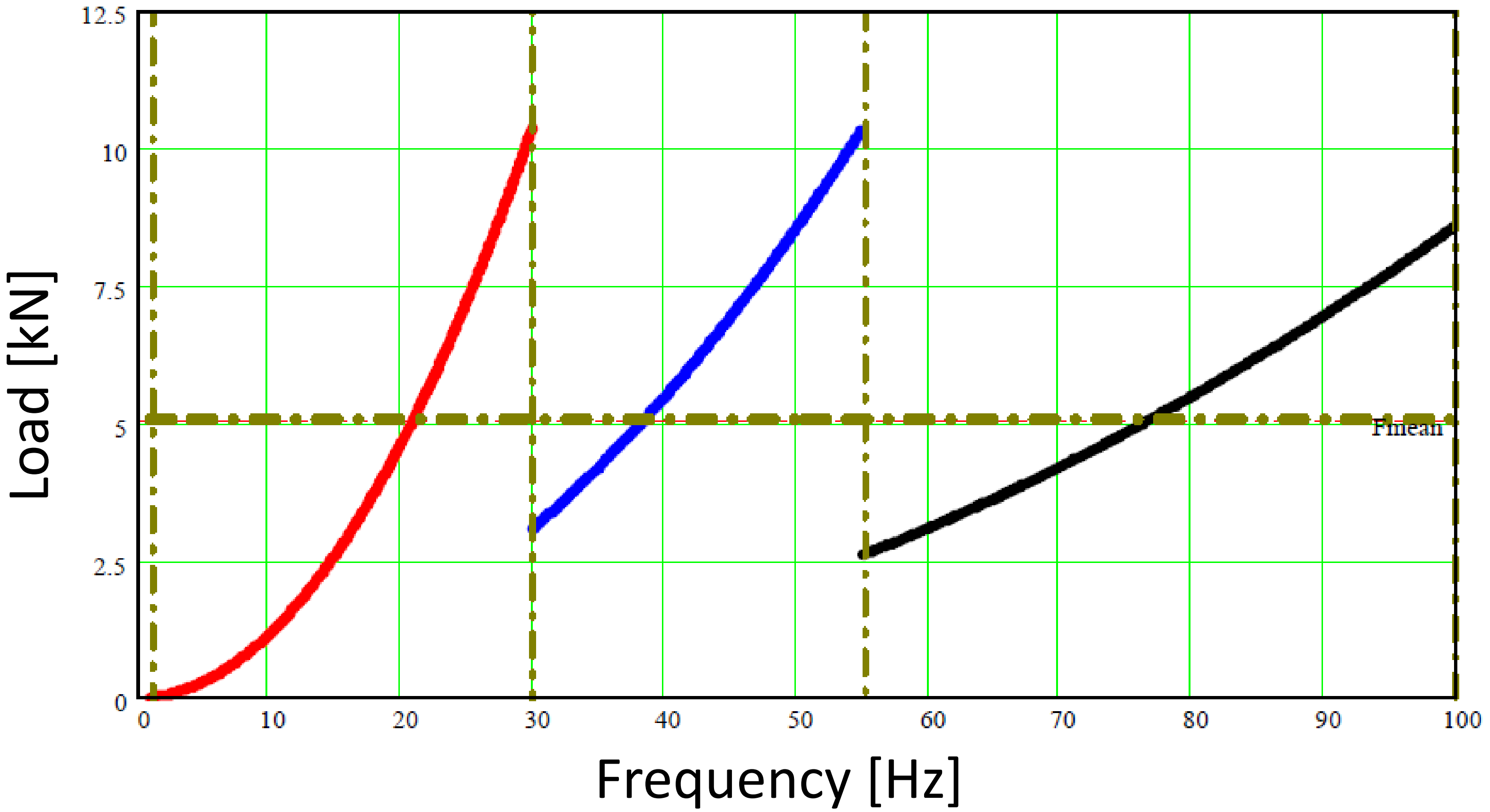


Piles Layout (left) and piled slab under construction (above)

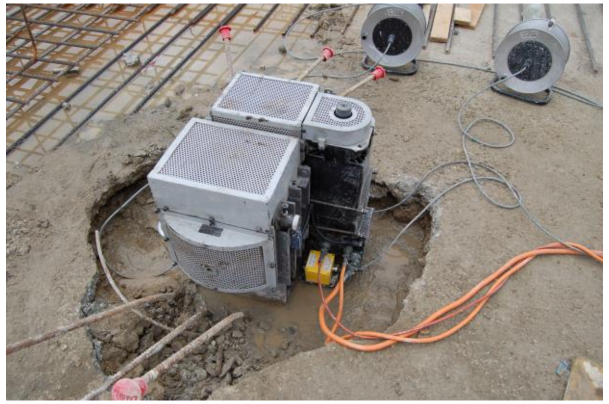
The on-site investigation’s purpose was to detect the dynamic response of the foundation piles, both in the vertical and in the transverse directions.

Experimental campaign

The investigation consisted in applying to the head of four, relatively close, foundation piles a sinusoidal dynamic force, by means of a mechanical exciter (Vibrodine), over a wide frequency range (1 to 100 Hz).

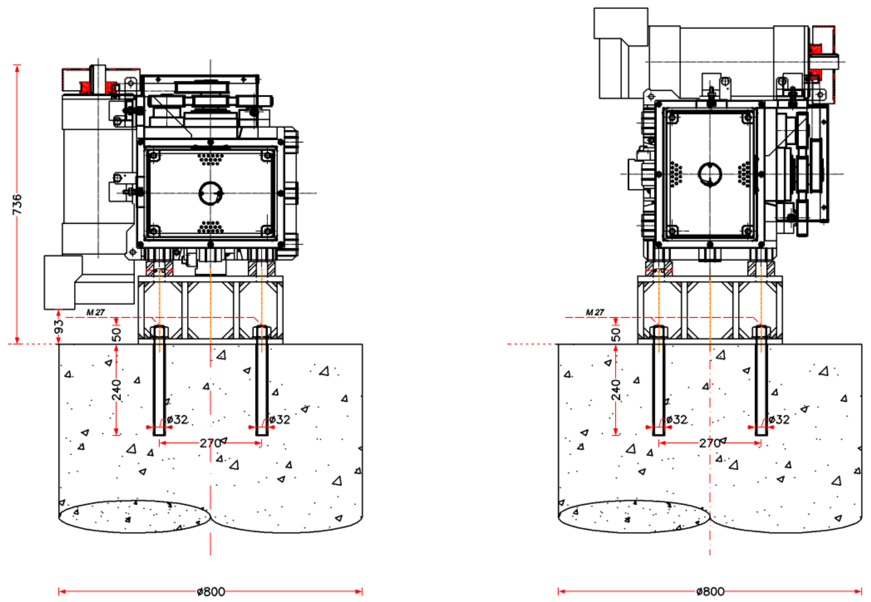


Load-frequency curves for different layouts of the Vibrodine



Horizontal excitation

Vertical excitation



Vibrodine 20 kN ÷ 100 Hz

Experimental campaign

Sensors on excited pile and on surrounding piles

Thanks to a seismometric triaxial sensors' (velocimeters) network, both the dynamic response of the directly excited pile and those of the other piles has been measured.

Results Summary

QUANTITY / PARAMETERS	Symbol	Unit measure	VERTICAL EXCITATION OF			
			Pile A	Pile B	Pile C	Pile D
Dynamic stiffness (*)	K	kN/mm	923	835	897	919
Dynamic Damping (*)	B	kN/(mm/s)	3.320	3.324	1.890	3.571
Propagation speed............. (Pos. A-V)	V_R	m/s		133	127	104
Propagation speed............. (Pos. B-V)	V_R	m/s	138	133	134	142
Propagation speed............. (Pos. C-V)	V_R	m/s	152	135		131
Propagation speed............. (Pos. D-V)	V_R	m/s	124	144	129	

(*) Average values measured in the field 10 ÷ 100 Hz.

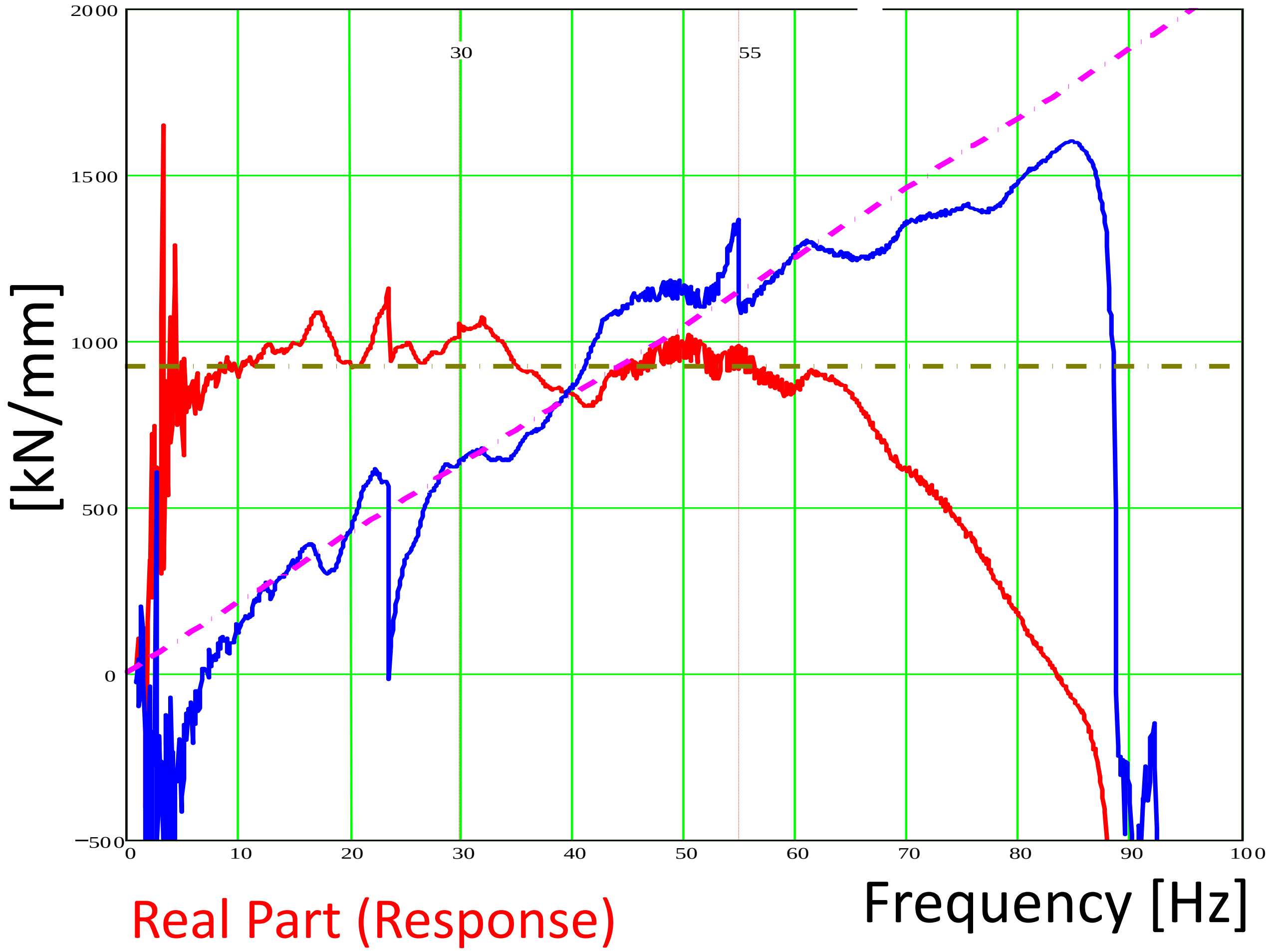
Relatively stable results under vertical excitation

QUANTITY / PARAMETERS	Symbol	Unit measure	HORIZONTAL EXCITATION OF			
			Pile A	Pile B	Pile C	Pile D
Dynamic stiffness	K	kN/mm	151	97	48	180
Dynamic mass	M	kg	5300	3389	1248	10722
Equivalent length	L_{eq}	m	4.2	2.7	0.993	8.5
Resonant frequency	f_o	Hz	26.8	26.9	31.2	20.6
Propagation speed............. (Pos. A-O)	V_R	m/s		122	122	103
Propagation speed............. (Pos. B-O)	V_R	m/s	50		80	65
Propagation speed............. (Pos. C-O)	V_R	m/s	71	52		50
Propagation speed............. (Pos. D-O)	V_R	m/s	123	159	105	

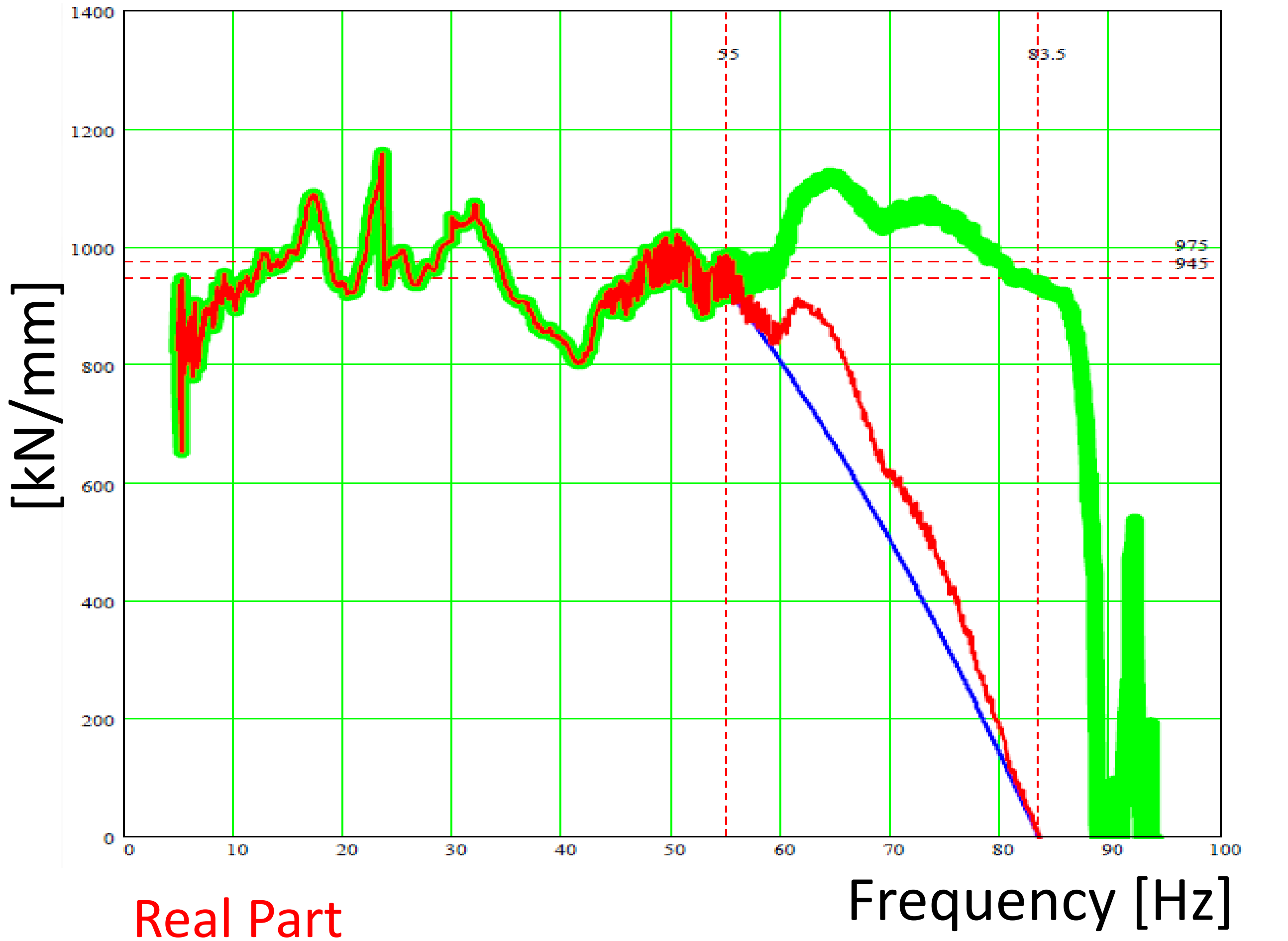
Big variance under horizontal excitation

Results under vertical excitation

- Registered Impedance function for one single pile



Real Part (Response)
Imaginary Part (Damping)



Real Part
Inertial contribution
Stiffness (Real-Inertial)

It is noted that the real part of the vertical impedance function remains almost constant in the range of frequencies up to 60Hz, decreasing at higher frequencies.

Results under vertical excitation

To understand the decreasing trend of the real part of the vertical impedance function for high frequencies, one has to take in mind that the real part of the mechanical impedance does not represent only the dynamic stiffness, but it represents the term $(K - M\,\omega^2)$, which contains the dynamic stiffness minus an inertial term:

$$R \,/\, \delta = [K - M \times (2 \times \pi \times f)^2] + i \times [B \times (2 \times \pi \times f)]$$

At high frequencies inertial forces become predominant with respect to elastic forces, so that a decreasing trend is found in the graph of the real part above 60÷70 Hz.

At low frequencies the inertial term $(M\,\omega^2)$ is low so the dynamic stiffness is the dominating addend of the real part of the mechanical impedance, but the same doesn't happen at high frequencies. In other words the approximation that the real dynamic response of a pile is given by the dynamic load divided by a (constant) dynamic stiffness is not correct for high frequencies, when the inertial term become predominant.

Results under vertical excitation

The dynamic stiffness for high frequencies may be evaluated searching for the "best-fitting" analytical function F(f) of real part of the vertical impedance:

$$F(f) = [K - M \times (2\times\pi\times f)^2]$$

that is, searching for K and M values which minimize the error:

$$\varepsilon(K, M) = [\Sigma_i \, [F(f_i) - F_{exp,i}]^2 \,]^{½}$$

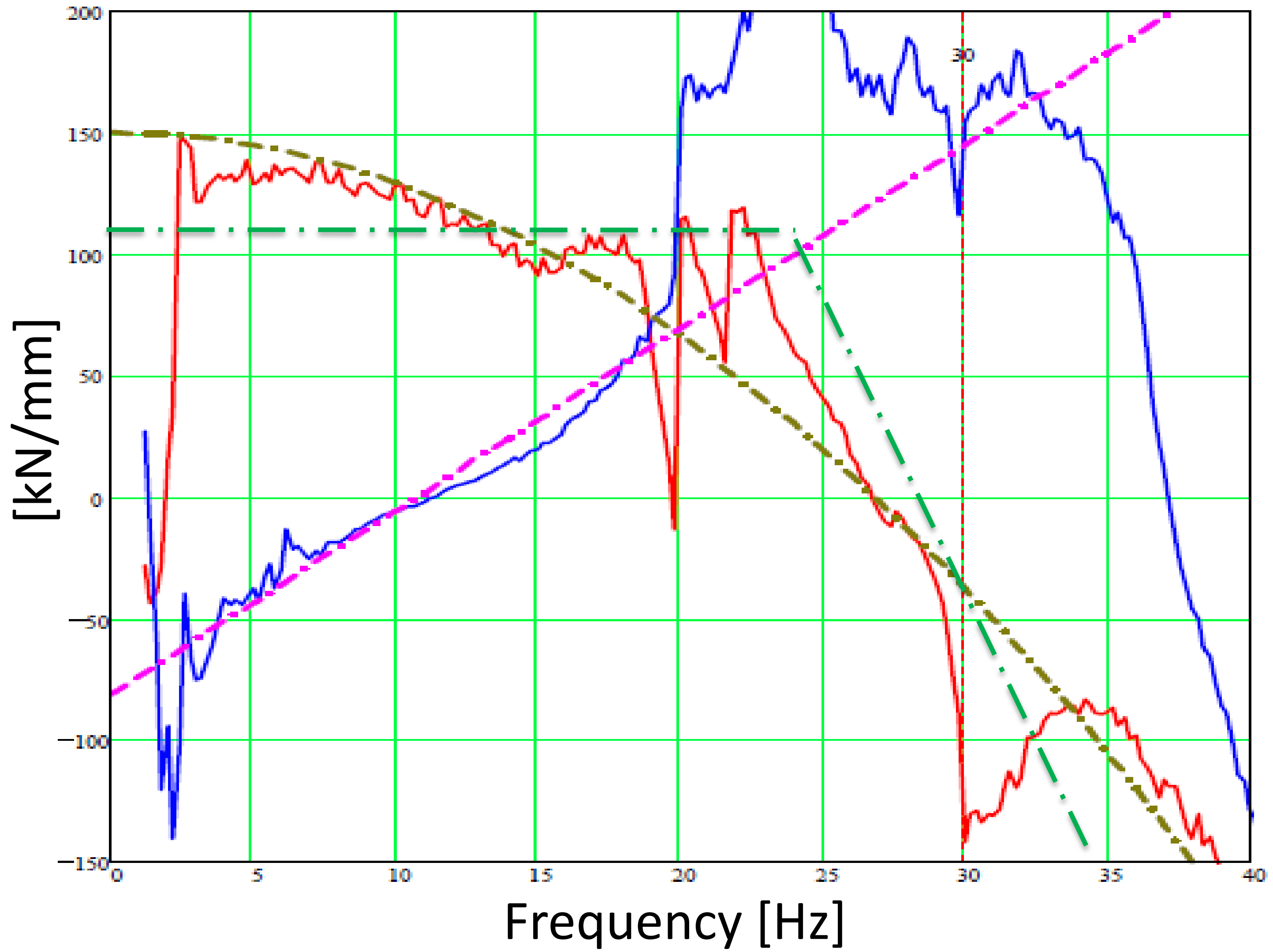
where f_i are *n* frequency values chosen in the high frequency interval and $F_{exp,i}$ is the experimental value of the real part of the vertical impedance for $f=f_i$.

One calculates derivatives of $\varepsilon(K, M)$ with respect to both K and M and put these derivatives equal to zero; the resulting system of two linear equations in two variables allows for calculating K and M values which minimize the error.

Successive numerical refinements may be performed to improve fitting of experimental data.

Results under horizontal excitation

- Registered Impedance function for <u>horizontal excitation</u> on a single pile



Real Part (response)

Imaginary Part (Damping)

Real Part simplified trend

It is noted that the real part of the horizontal impedance function remains almost constant for frequencies up to 25Hz, decreasing at higher frequencies. The experimental values have to be corrected in order to take into account the actual restraint given by the slab foundation; the stiffness of the pile with the fixed cap is twice the stiffness of the same pile with free cap.

Predictive formulas (*) for dynamic stiffness of piles

<u>Single Pile Vertical Dynamic Stiffness</u>

$K'_v = (k_v \cdot A_p \cdot E_p)^{0.5}$

$k_v = [1,48 + 17/(L/D)]\ G_s$

<u>Single Pile Horizontal Dynamic Stiffness</u>

$K'_h = 4\ \beta^3\ E_p\ J_p$

$\beta\ = (k_h\ /\ 4\ E_p\ J_p)^{0,25}$

$k_h = 2\ G_s \div 4\ G_s$

L pile lenght
D pile diameter
G_s soil dynamic shear modulus
A_p pile section area
E_p Young modulus of pile
J_p Moment of inertia of pile

Condition for these formulas: end bearing piles

(*) Spring and Dashpot Coefficients for Machine Foundations on Piles - O'Rourke & Dobry

Results comparison with predicted dynamic stiffness of piles

- Single Pile Vertical Dynamic Stiffness (Calculated, O'Rourke & Dobry)
  K'_{vc} = 1700 kN/mm
- Single Pile Horizontal Dynamic Stiffness (Calculated, O'Rourke & Dobry)
  K'_{hc} = 460 kN/mm

- Single Pile Vertical Dynamic Stiffness (Experimental range, 4 piles)
  K'_{ve} = 860 ÷ 1140 kN/mm ➔ avg 1000 kN/mm
- Single Pile Horizontal Dynamic Stiffness (Experimental range, 4 piles, corrected)
  K'_{he} = 100 ÷ 360 kN/mm ➔ avg 230 kN/mm

- $K'_{vc} / K'_{ve} = 1.7$ $K'_{hc} / K'_{he} = 2.0$ Calculated/experimental ratio ≈ 2
- $K'_{vc} / K'_{hc} = 3.7$ $K'_{ve} / K'_{he} = 4.3$ Vertical/horizontal ratio ≈ 4

Lessons Learnt

- There's a great variance of results under horizontal excitation. Dynamic excitation magnitude used was probably too high with respect to Turbo Machinery normal operations unbalancing loads. Gaps between soil and piles' top are more easily created, impacting horizontal tests results.
- Representative sample (four piles) to be increased (to minimum five piles on each lot/area), neglecting extremes of experimental results.
- Tests on single pile have to be interpreted to get the behavior of a piled slab. Consider to test also group of piles connected by a slab portion in order to directly capture the horizontal behavior of fixed cap piles and realistic inertial contribution to the real part of the impedance.

Conclusions

- Tests on single piles confirm substantial unvariance of the real part of the vertical impedance with frequency at least up to 50÷60 Hz, up to when the intertial contribution becomes dominant; the same happens in horizontal direction but at lower frequencies
- There's a gap between experimental and theoretical results. Only the Kv/Kh ratio remains similar.
- Despite better correlation with literature formulas can be found, test campaign on piles are always advisable in order to reduce the analysis cases during project execution phase.