Transactions, SMiRT-25
Charlotte, NC, USA, August 4-9, 2019
Division III

BENCHMARK STUDY ON IMPEDANCE FUNCTIONS OF LARGE PILE FOUNDATIONS

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INTRODUCTION

In the nuclear power industry large pile groups are used world-wide at soil sites with soft and weak near-surface soil layers as foundations for both safety and non-safety related structures. Entire nuclear power plant (NPP) facilities are founded on piles in areas of low to moderate seismicity, as for example in Belgium (Doel 3), Brazil (Angra 2), Canada (Pickering 1, 2, 3 & 4), Germany (e.g. Unterweser, Brunsbüttel, Brokdorf), the Netherlands (Borssele), and United States (Fort Calhoun 1, Point Beach 1 & 2, Robinson 2). Foundations of these NPPs can consist of groups of hundreds of piles. One advantage of NPP structures supported by piles is to indirectly achieve the purpose of a seismic isolation by tuning the natural fundamental frequency of the coupled soil-pile-foundation-structure system in horizontal directions to relatively low frequency values, where spectral accelerations (i.e. seismic demand) of typical ground motion response spectra are usually low. In addition, the response amplification of the NPP structure is further decreased due the inherent radiation damping effects present in pile foundations.

Current nuclear standards and codes (e.g. ASCE 4-16, KTA 2201.3) allow the use of pile-supported foundations for NPP structures, yet do not provide guidance on their seismic analysis. Their regulatory technical review is on a case-by-case basis, as e.g. stated in the US-NRC Seismic Review Plan (SRP). Therefore, the evaluation of pile foundations requires a good understanding of: (a) individual sub-systems: piles, soil, structure, loads; and (b) interaction between sub-systems, under both operational and extreme loading conditions. Because the dynamic behavior of large pile foundations is complex and its mathematical characterization is a challenging task, former as well as current soil-structure interaction (SSI) analyses of pile foundations are most often performed using simplified methods. Rigorous analysis approaches are computationally expensive but allow for a realistic assessment of the complex pile foundation structure interaction, especially under extreme loading.

The main goal of this paper is to present representative results from the extensive verification benchmark performed by Framatome GmbH (former Areva GmbH) with a new pile element implemented in the software package SC-SASSI, cf. SC Solutions (2018). Quality assurance of computational software used as design or evaluation tool as well as its correct application play a crucial role in the safety of NPPs. A companion paper introduces in detail the theoretical background and implementation of the pile element in SC-SASSI, García et al (2019).

DYNAMIC PILE FOUNDATION IMPEDANCE FUNCTIONS AND THEIR IMPORTANCE

Different dynamic loads can act on piles: forces originating from earthquakes, sea/ocean waves, wind, impact (e.g. airplane crash, explosion pressure waves), machine unbalances etc. The emphasis of this paper is the pile dynamic stiffness (complex impedance functions) because it has a strong influence on the response of the building structures supported by the piles under any of the aforementioned loads. The impedance functions are defined as amplitudes of harmonic forces or moments that have to be applied to the pile head in order to generate a harmonic deformation with unit amplitude in the specified direction. Since piles are usually installed in groups, in which they are not widely spaced, they interact with each other. This pile-soil-pile interaction or group effect has a significant impact on the impedance functions.

The matrices [M], [C], and [K] are the mass matrix, the damping matrix, and the static stiffness matrix, respectively. They are constant for a linear system whereby the dynamic stiffness matrix $[\overline{K}]$ is dependent on the excitation frequency *($\omega = 2\pi f$)* and is defined as:

$$[\overline{K}] = [K] - \omega^2[M] + i\omega[C] \tag{1}$$

Thereby, the viscous-damping (frequency dependent) matrix [C] represents the combined effect of radiation and material damping in the piles and the soil medium. The first component (radiation damping) corresponds to energy dissipation due to waves emanating from the soil-pile-foundation interface in perfectly elastic soil. The second part (hysteretic damping) is associated with energy loss due to hysteretic action in the piles and the soil. It is noted that the material (hysteretic) damping is independent of frequency. When working in the frequency domain the material damping (ξ) can be introduced into the above equation by replacing the real stiffness matrix [K] by the corresponding complex one, namely:

$$[K^*] = [K](1 + i2\xi) \tag{2}$$

If viscous damping is not present, equation (2) yields the dynamic stiffness, incl. material damping:

$$[\overline{K}] = [K](1 + i2\xi) - \omega^2[M] \tag{3}$$

Finally considering the frequency dependence, equation (1) can be rewritten as:

$$[\overline{K(f)}] = [K_{Re}(f)] + i\,[K_{Im}(f)] \tag{4}$$

$$\text{with: } [K_{Re}(f)] = [K] - \omega^2[M] \quad \text{and} \quad [K_{Im}(f)] = \omega[C] \tag{5}$$

The real component (K_{Re}) represents the stiffness and inertia of piles and soil, and the imaginary component (K_{Im}) reflects their material damping and most notably the radiation damping of waves propagating away from the foundation. It is obvious from equation (5) that the inertial effect of the mass *($-\omega^2 M$)* leads to a decrease of the K_{Re} term, resulting in negative values at higher frequencies. On the other hand, the term K_{Im} increases mainly linearly with frequency *(ωC)*.

Generally, in calculating the impedance functions of a pile group the pile cap is assumed massless and rigid. The vital role of the pile cap (typically rather thick) is the load distribution among the different piles of the group. The rigidity assumption is usually justified and the kinematics of the rigid pile cap is described by the 6 degrees of freedom of a single point (called foundation reference point), for instance its geometric center. Hence, the size of the frequency-dependent complex valued impedance matrix is 6 by 6 for each discrete frequency.

METHODS TO COMPUTE PILE IMPEDANCE FUNCTIONS

Dynamic pile impedance has been studied for several decades. Most of the methods rely on the availability of Green's functions with which the load transfer from the pile surface to the surrounding soil and corresponding displacements can be calculated. These loading conditions, representing one of the basic differences between the various approaches, ranging from point loads to line loads, ring loads, disk loads, and finally to cylindrical loads. Disk loads are typically used for the pile base. Applying these loadings to individual segments into which the pile is discretized, the soil dynamic displacement field is established, yielding the soil dynamic flexibility matrix; inverting the latter, soil dynamic stiffness matrix is obtained.

Waas and Hartmann (1981, 1984) formulated an efficient semi-analytical method which uses ring loads and is well suited for layered media, properly accounting for the far field (Thin Layer Method, TLM). The semi-analytical methods treat the wave propagation in the horizontal direction analytically and in the vertical direction they employ a finite element discretization. The piles are modeled by beam elements. The inversion of the full flexibility matrix is avoided by using the force method instead of the displacement method. The procedure can therefore be carried out quickly on personal computers.

Kaynia (1982, 1988, 1990) improved the accuracy of the model in a boundary-element type formulation by developing Green's function for cylindrical and disk loads, representing pile-soil interaction forces in layered soil media and by using a consistent stiffness matrix to account for the far field.

Ostadan (1983) developed the Inter-Pile Element Method (IPM) within the framework of the Flexible Volume Method of SASSI (Lysmer et al., 1981). The pile beam elements are connected to inter-pile elements (finite elements) that model the soil between the piles, capable of handling the effects of nonlinearities of the soil between the piles by the equivalent-linear method. The whole pile foundation region is discretized using the aforementioned finite elements. The main advantage of the method is the direct modeling of the soil between the piles. Thus, the effects of pile-soil-pile and soil-cap interaction can be evaluated simultaneously. The main disadvantages of this approach is the considerable modeling effort and significant number of interaction nodes to model large pile groups. The IPM is implemented into the latest SASSI2010 software package (Ostadan, 2012).

Pile Impedance Method (PIM) is also implemented into SASSI2010 (Ostadan, 2012), i.e. the SPILE module. It is based on the rigorous point load solution of a single vertical pile embedded in layered soil profile using an axisymmetric finite element model and non-reflecting lateral boundaries. The PIM is a quick procedure to derive dynamic impedance functions of single piles or pile groups. The small computational effort is achieved through approximate treatment of the pile-soil-pile interaction effects, resulting in much fewer interaction nodes. Verification studies (Ostadan, 2012) indicate that the approximation is good for relatively small foundations (groups of 2×2, 3×3 and 4×4 piles).

García (2002) extended the semi-analytical approach and used Green’s functions formulation for ring and disk loads, to simulate free field displacements in the near field and far field, and implemented it into the framework of the SASSI computer program for simulation of soil-pile-structure systems due to dynamic loads. This evolution has been shown to be technically promising but computationally intensive for many typical project-scale large pile configurations. However, since High Performance Computing (HPC) becomes more and more available at reasonable cost to the analysis engineer, a comprehensive evaluation of pile foundations including pile-to-pile interaction and other effects is now possible. A numerically efficient pile finite-element approach based on the García impedance formulation and extended to support large and varied foundation conditions was developed and implemented in the SC-SASSI software tool (2018), see García et al. (2019).

Johansson and Kaynia (2018) implemented a method to compute the impedance functions of a pile foundation modeled by a full 3D linear elastic FE-model in frequency domain in the software COMSOL Multiphysics (Version 5.4.0.346). Material damping is modeled with frequency independent loss factor. The radiation damping is automatically captured by the model. Perfectly matched layers (PML) are used to prevent reflections from the boundary zone back into the model. The mesh consists of tetrahedral elements.

The SC-SASSI software package (SC Solutions, 2018) – specifically developed to efficiently leverage HPC hardware – is installed on Framatome’s cluster computer. The validation of the new pile element implemented in SC-SASSI is performed through comparative calculations with the aforementioned methods to achieve the high standards and quality requirements in the nuclear industry. A benchmark catalog of problems covering a wide range of pile foundation configurations was prepared in cooperation by Framatome and Hartmann (2017) and includes sample solutions calculated with PILAX (Version 11-2017). The SC-SASSI calculations are accompanied by those of five established methods for pile group impedance analysis implemented in the corresponding software: a) PILES (Version 3.0) based on Kaynia (1982); b) PILAX based on Hartmann (1985); c) SPILE/SASSI2010 based on the Pile Impedance Method (PIM), Ostadan (2012); d) IPM/SASSI2010 based on the Inter-Pile Element Method (IPM), Ostadan (2012); and e) COMSOL based on Johansson and Kaynia (2018). This paper shows characteristic results from the benchmark calculations.

MATERIAL PROPERTIES OF THE SOIL PROFILES

Four basic soil profiles are assumed in this study, namely:

a) Profile A-1: homogeneous half-space with constant shear modulus with depth,
b) Profile A-2: inhomogeneous half-space with parabolically increasing shear modulus with depth,
c) Profile B: a 30 m thick soft soil layer on top of rigid rock, and

d) Profile C: actual soil profile, irregular (multi-layer) soil profile with inversion of the soil stiffness (softer layer trapped between two stiffer layers):
   i. Profile C-1: Profile C with actual Poisson ratio up to 0.498,
   ii. Profile C-2: Profile C with Poisson ratio limited to 0.470, and
   iii. Profile C-3: Profile C with Poisson ratio limited to 0.450.

The four soil properties are summarized in Table 1 and shown in Figures 1 and 2. In case of the inhomogeneous half-space (profile A-2) the function of the shear modulus over the soil depth is defined by the reference modulus at depth $z = d$ (d: diameter of pile) as:

Profile A-1: $$G_s(z) = G^* \quad (6)$$ Profile A-2: $$G_s(t) = G^* \sqrt{\frac{z}{d}} \quad (7)$$

In the frequency domain, shear modulus and material damping are combined to the complex shear modulus:

$$\overline{G_s} = G_s(1 + 2iD_s) \quad (8)$$

Table 1: Material properties of the four basic soil profiles considered in the impedance analysis.

Profile	Density	Reference Shear Modulus	Poisson's Ratio	Shear Wave Velocity	Damping Ratio	Fundamental Horizontal Frequency
	ρ_S	G^*	ν_S	V_S	D_S	f_{S0}
	t/m^3	MN/m^2	-	m/s	%	Hz
A-1	1.75	10.71	0.400	78.23	5	---
A-2	1.75	8.58	0.400	70.02	5	---
B	1.75	10.71	0.400	78.23	5	0.63
C	1.9 … 2.2	13 … 626	0.450 … 0.498	83 … 555	1 … 12	0.43

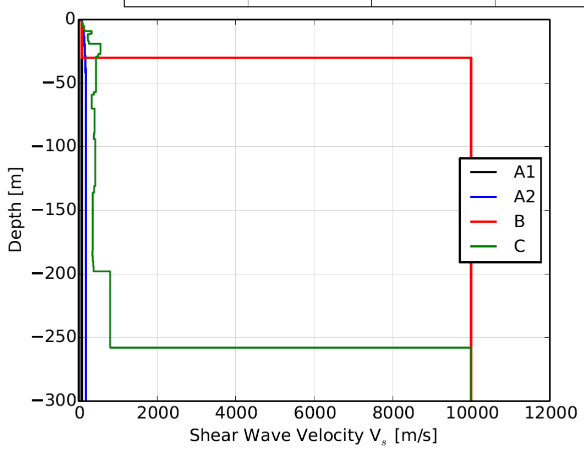

Figure 1. Soil Profiles, Overview

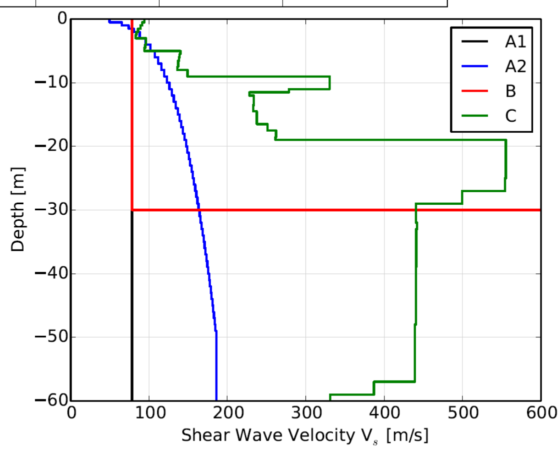

Figure 2. Soil Profiles, Subsurface

PILE FOUNDATION CONFIGURATIONS

The pile foundation configurations of the benchmark cases are symmetrical pile foundations with 1, 16, and 1400 piles and unsymmetrical cases with 76 and 430 piles. The benchmark cases are coupled with a variety of soil profiles. All piles in the configurations associated with the soil profiles A1 and B can be classified as floating piles; those associated with the soil profile C are end-bearing piles. The pile configurations associated with the soil profile A2 are considered to represent a combination of floating and end-bearing piles. Fixed and pinned pile cap conditions are also evaluated. The following material data of the piles is used in the calculations: a) Modulus of Elasticity $E_P = 30000\ MN/m^2$; b) density $\rho_P = 2.5\ t/m^3$, c) Poisson's ratio $\nu_P = 0.25$. Additionally, the following data is provided in Table 2: pile diameter d; pile length L; spacing between piles s; pile damping D_P; average soil elastic modulus for the top 30 m depth E_{s30}. In Figures 3 to 6 the considered pile configurations are shown.

Table 2: Parameters of the considered pile foundation configurations.

Model	Number of Piles	Symmetry	d	L	s	s/d	E_{S30}	E_P/E_{S30}	D_P	Pile Head
			m	m	m	---	MPa	---	%	---
single1	1	---	1.00	25.0	---	---	30 ... 171	200...1000	1.0	pinned/fixed
group16	16	Double	1.00	15 (Profile B) 25 (o/w)	5.0	5.0	31 ... 171	200...1000	1.0	pinned/fixed
group76	76	No	1.00	25.0	3.0	3.0	32 ... 171	200...1000	7.0	pinned/fixed
group430	430	No	0.45 (108 piles) 0.62 (322 piles)	9.0	≈ 2.0	3.2...4.4	171	200	7.0	pinned
group1400	1400	Axial	0.50	15.0	≈ 1.5	3.0	171	200	7.0	pinned

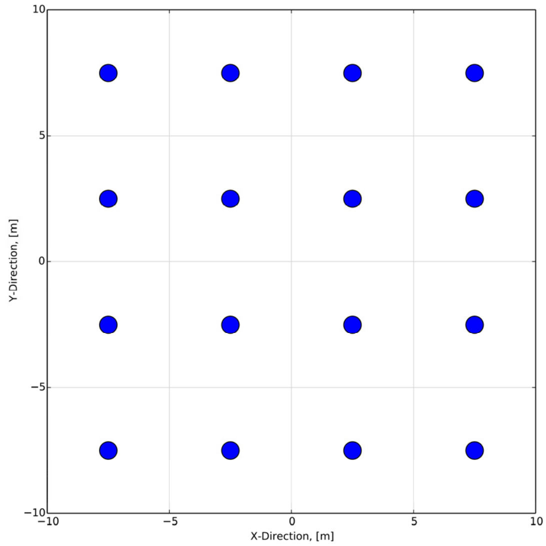

Figure 3. Group of 16 Piles,
d = 1.0 m, L = 15 m or 25 m, s = 5.0 m

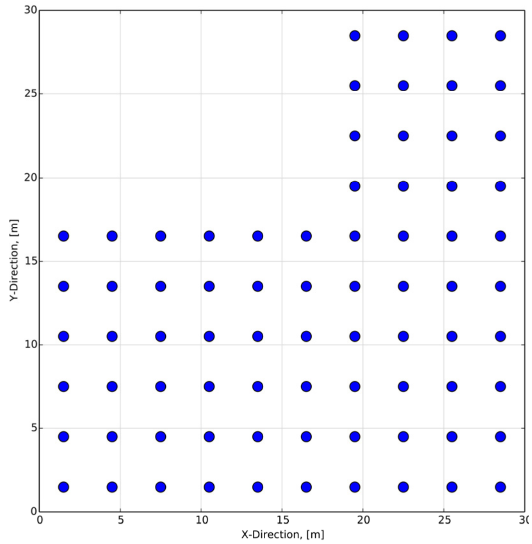

Figure 4. Unsymmetrical Group of 76 Piles,
d = 1.0 m, L = 25 m, s = 3.0 m

BENCHMARK COMPUTATIONAL PROBLEMS AND KEY ANALYSIS ASSUMPTIONS

The benchmark matrix of the 83 performed impedance analyses in the frequency domain for different pile group configurations is shown in Table 3. The impedances are complex 6×6 matrices with the degrees of freedom (DoF): X, Y, Z, XX, YY, and ZZ. The impedances are calculated up to the maximum frequency of $f_{max} = 15\ Hz$ for at least 23 discrete frequency values and then typically interpolated. The following key analysis assumptions are used: a) linear elastic or viscoelastic behavior of pile and soil; b) horizontal layered soil model without reflection at the model edges, lower soil profile edge modeled as rigid or homogeneous elastic half-space; c) full bond between pile and soil; d) rigid and massless pile cap modeled with plate/shell or beam elements; e) no bond between pile cap plate and soil surface (pile cap above soil surface); f) vertical, axially symmetrical piles with full cross section; g) bending or hinged fixation of the pile heads into the pile cap plate; h) analysis results covering the frequency range from 0 to 15 Hz; i) mesh limiting frequency approx. 15 Hz.

KEY SENSITIVITY PARAMETERS OF THE IMPEDANCE BENCHMARK CALCULATIONS

The following key modeling parameters are deliberately varied in order to obtain robust verification results: a) soil profile, b) pile dimension, c) number of piles, d) pile cap, e) Poisson’s ratio (approaching 0.5 may result in numerical instability of the SSI analysis results, see NRC 2011).

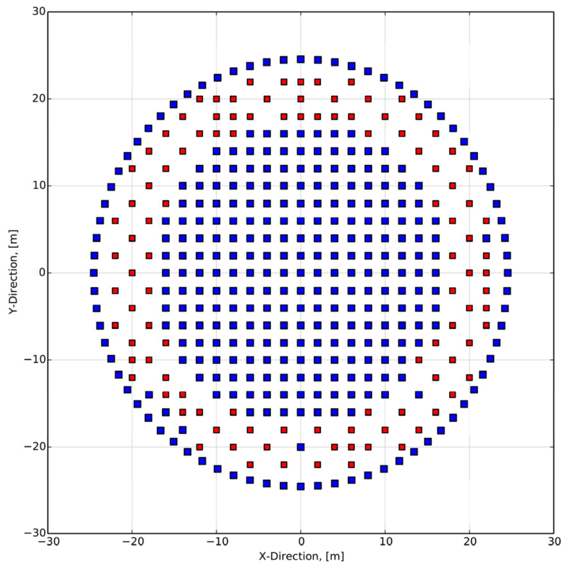

Figure 5. Group of 430 Piles, 108 Piles 0.40×0.40 m (red) and 322 Piles 0.55×0.55 m (blue), L = 9 m

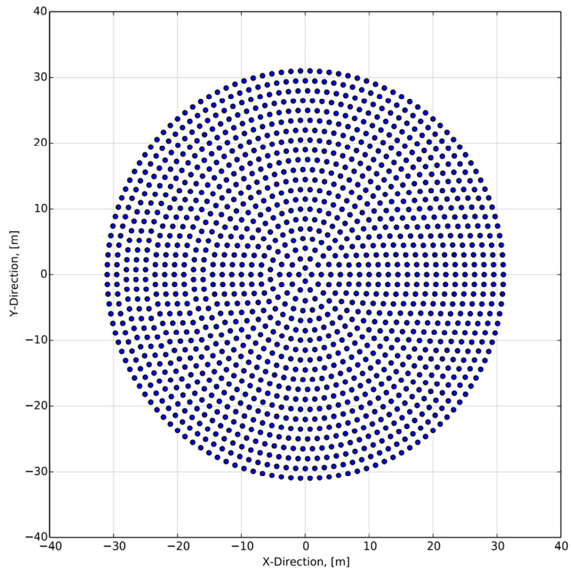

Figure 6. Axially Symmetric Group of 1400 Piles, d = 0.5 m, L = 15 m, s ≈ 1.5 m

Table 3: Benchmark matrix of the performed impedance analyses for different pile group configurations.

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
No.	Piles	Pile Cap	Soil Profile	K_x/C_x	K_y/C_y	K_z/C_z	K_{xx}/C_{xx}	K_{yy}/C_{yy}	K_{zz}/C_{zz}	Hart-mann	Kaynia	SASSI2010		SC SASSI	COM-SOL
												IPM	PIM		
1	1	fixed	A1							X	X	X	X	X	
2		pinned	A1	Fig.7						X	X	X	X	X	X
3		fixed	A2							X	X	X	X	X	
4		pinned	A2							X	X			X	
5		fixed	B							X	X			X	
6		pinned	B							X	X			X	
7		fixed	C1							X	X			X	
8		pinned	C1							X	X			X	
9		fixed	C2											X	
10		fixed	C3											X	
11	16	fixed	A1	Fig.8						X	X	X	X	X	
12		pinned	A1												
13		fixed	A2	Fig.9						X	X	X		X	
14		pinned	A2							X	X			X	
15		fixed	B							X	X			X	
16		pinned	B							X	X			X	
17		fixed	C1							X	X			X	
18		pinned	C1							X	X			X	
19		fixed	C2								X			X	
20		fixed	C3								X			X	
21	76	fixed	C1	Fig.10	Fig.11				Fig.12	X	X	X	X	X	
22		pinned	C1							X	X			X	
23		fixed	C2							X	X			X	
24		pinned	C2												
25		fixed	C3							X	X			X	
26	430	fixed	C1												
27		pinned	C1	Fig.13		Fig.14		Fig.15		X	X	X	X	X	
28	1400	fixed	C1												
29		pinned	C1	Fig.16		Fig.17		Fig.18		X			X	X	

Table 4: Quasi-static stiffness (at 0 Hz) of the impedance functions shown in Figs. 7 to 18

Model	0001-A1-P	0016-A1-F	0016-A2-F	0076-C1-F			0430-C1-P			1400-C1-P		
Figure	Fig. 7	Fig. 8	Fig. 9	Fig. 10	Fig. 11	Fig. 12	Fig. 13	Fig. 14	Fig. 15	Fig. 16	Fig. 17	Fig. 18
Method	K_X	K_X	K_X	K_X	K_Y	K_{ZZ}	K_X	K_Z	K_{YY}	K_X	K_Z	K_{YY}
	MN/m	MN/m	MN/m	MN/m	MN/m	GNm/rad	MN/m	MN/m	GNm/rad	MN/m	MN/m	GNm/rad
Hartmann	76	661	1075	4103	4124	2573	5202	54018	14325	8037	85535	44703
Kaynia	75	641	1080	4090	4110	2560	4660	49900	12500	---	---	---
IPM	86	625	1042	4100	3972	1943	8030	56221	15568	---	---	---
PIM	77	615	1020	3174	3133	1578	---	---	---	---	---	---
SC-SASSI	76	640	1067	4167	4193	2612	5017	51546	13343	7864	85491	44803
COMSOL	76	---	---	---	---	---	---	---	---	---	---	---

DISCUSSION OF THE BENCHMARK RESULTS

Pile foundations show larger interaction effects compared to shallow foundations under dynamic loads. The dynamic pile-soil-pile interaction – also called group effect – occurs between the flexible piles, the enclosed soil and the surrounding soil. The complexity of the dynamic pile-soil-pile interaction is physically established by the strong interference of cylindrical waves originating along the shaft of each pile. As a result, the dynamic stiffness (impedance function) of pile group foundations is strongly frequency-dependent. The impedance functions also depend heavily on the direction of loading. In contrast to a shallow foundation, the horizontal stiffness is considerably lower than the vertical stiffness. The rocking stiffness of a pile group results from the vertical stiffness of the individual piles and the square of their distances to the foundation reference point. Consequently, the rocking stiffness is relatively small for single piles and relatively large for pile groups. Table 4 illustrates these observations for the quasi-static stiffness.

Due to limited space, only selected representative results out of a total of 83 analyses are shown herein, see Figs. 7 to 18. In these figures the solid and dashed lines represent the real (stiffness) and imaginary (damping) parts of the impedance functions, respectively. It is noted that since the fundamental frequencies of the layered profiles are relatively low (see Table 1) the impedance functions are free from significant site resonant effects.

Table 4 presents the quasi-static stiffness (at 0 Hz) of the impedance functions. The table confirms that the static behavior of the pile group is more flexible than the sum of the single piles. Under static loads, pile interaction increases group settlement, redistributes the loads on individual piles, and reduces bearing capacity. However, this reduction is counteracted to some extent by densification of the soil within the group due to pile driving. The static data are useful because at low frequencies, and particularly below the fundamental frequency of a soil profile, the dynamic stiffness is usually quite close to the static stiffness. Fig. 7 shows the horizontal impedance of a single pile installed in a homogeneous half-space.

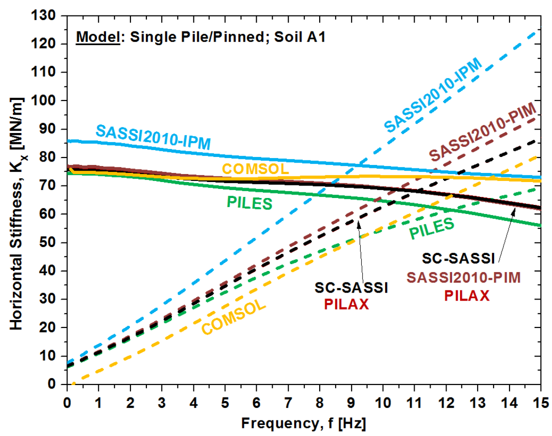

Figure 7 : Single Pile/Pinned, A1, K_X and C_X

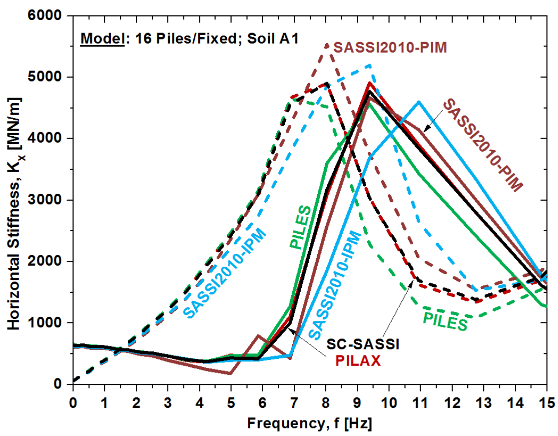

Figure 8 : 16 Piles/Fixed, A1, K_X and C_X

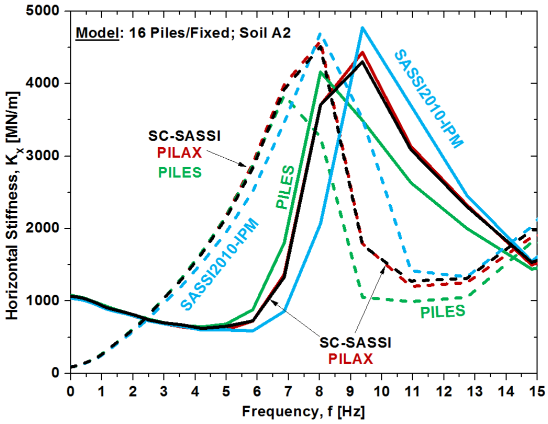

Figure 9 : 16 Piles/Fixed, A2, K_X and C_X

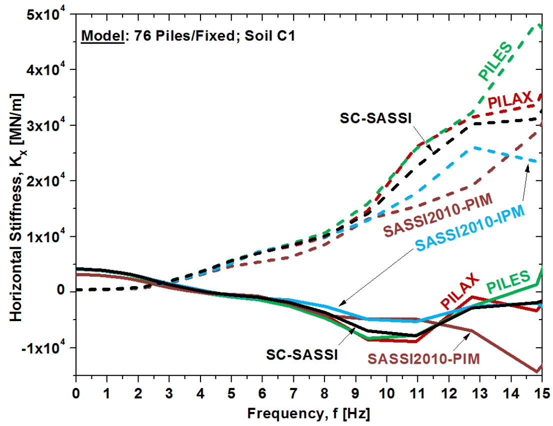

Figure 10 : 76 Piles/Fixed, C1, K_X and C_X

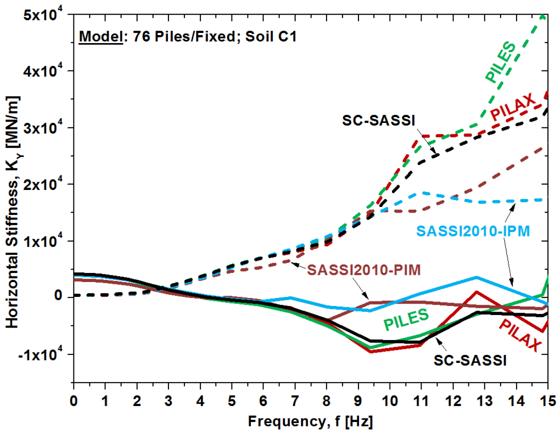

Figure 11 : 76 Piles/Fixed, C1, K_Y and C_Y

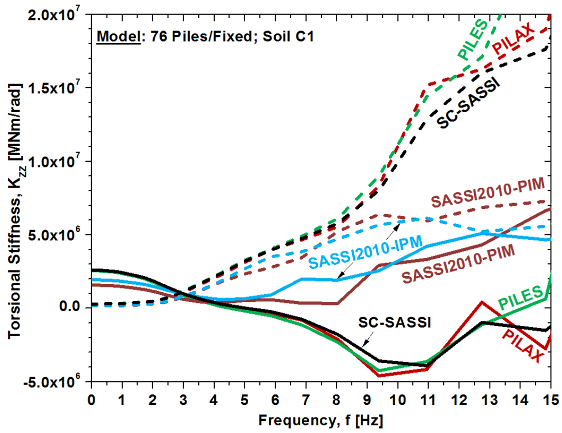

Figure 12 : 76 Piles/Fixed, C1, K_{ZZ} and C_{ZZ}

Figs. 8 and 9 show the horizontal impedances of a symmetric group of 16 piles with $s/d = 5$ and fixed heads, installed in homogeneous *A1* ($E_p/E_{s30} = 1000$) vs. inhomogeneous *A2* ($E_p/E_{s30} = 400$) on top of a half-space. While K_x and C_x for the single pile (Fig.7) changes only slightly with frequency, the curves for the piles in the group of 16 vary considerably, since the dynamic interactions between the piles are significant. For large wave lengths V_s/f of the shear wave in the soil compared to the spacing *s* of the piles (i.e. low frequency range), the soil between the piles moves as a rigid body. The entrapped mass leads to a parabolic downward tendency of the real part up to about 6 Hz (wavelength ≈ 3s). For the frequency range beyond this limit, strong wave-interference occurs. In this case the wavelength of the shear wave is less than the pile spacing *s*. At that point the individual piles move with remarkably different phase angles relative to each other. As opposed to the static case, the piles now stiffen each other. The largest group factor is reached approximately when directly adjacent piles oscillate in opposite phase. This corresponds to a frequency of approx. 8 Hz ($\approx V_s/2s$). Comparing the results in Figs. 8 and 9 from the two somewhat different soil profile properties, as expected slightly higher damping for the homogeneous half-space as well as slightly lower stiffness results. Figs. 10 to 12 show impedances in both horizontal (K_x and K_y) and the torsional K_{zz} DoF of an asymmetric group of 76 piles with $s/d = 3$ and fixed heads, installed in Profile *C1* ($E_p/E_{s30} = 200$ and $\nu = 0.498$). Figs. 13 to 15 and 16 to 18 show impedances for the horizontal (K_x *and* K_y) and the torsional DoF (K_{zz}) of two large pile groups with pinned heads installed in the same profile *C1*, namely: a) 430 piles with $s/d = 3.2\ldots4.4$ *m,* and b) 1400 piles with $s/d = 3.0$ *m,* respectively. The groups of 76, 430, and 1400 piles are more closely spaced. Hence, they are less frequency dependent because the group behavior is not dominated as heavily by the interactions among the piles. It is noted, that radiation damping generally increases with foundation size.

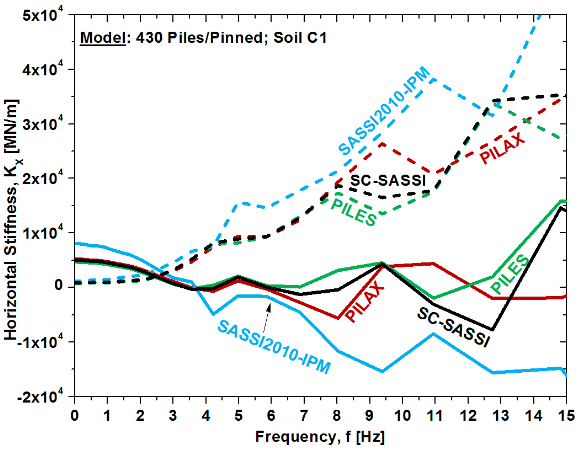

Figure 13 : 430 Piles/Pinned, C1, K_X and C_X

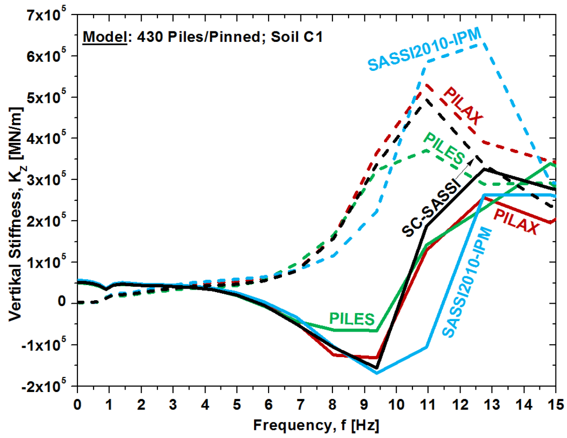

Figure 14 : 430 Piles/Pinned, C1, K_Z and C_Z

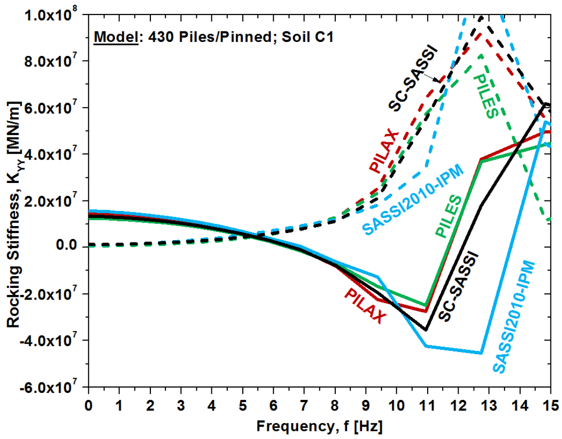

Figure 15 : 430 Piles/Pinned, C1, K_{YY} and C_{YY}

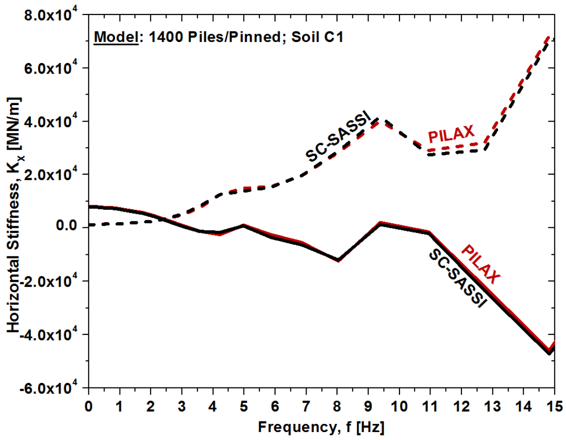

Figure 16 : 1400 Piles, C1, K_X and C_X

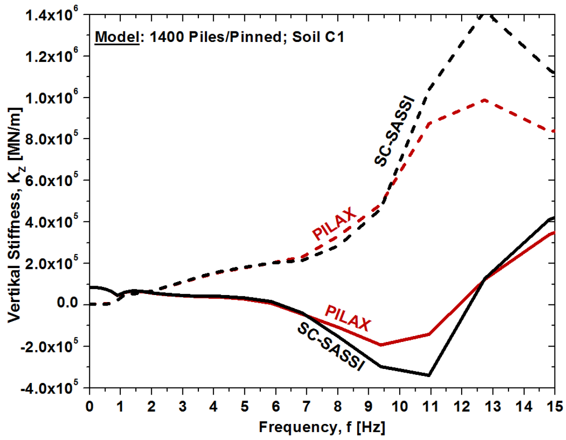

Figure 17 : 1400 Piles, C1, K_Z and C_Z

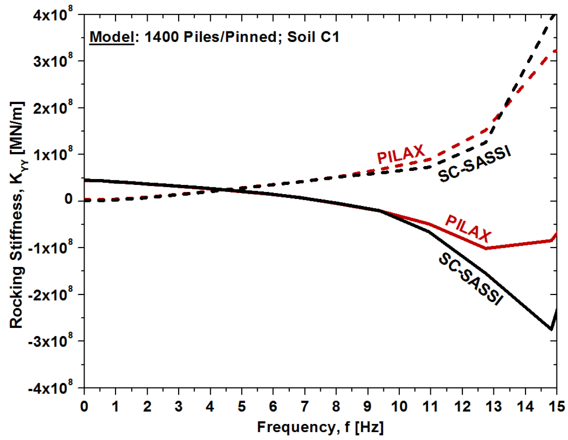

Figure 18 : 1400 Piles, C1, K_{YY} and C_{YY}

The impedances of these large groups indicate a very good agreement between the results from SC-SASSI and the results from PILES based on Kaynia (1982) and PILAX based on Hartmann (1985). Results of the PIM method are not shown in Figs. 13 to 18 because they are currently under careful review for possible numerical instability due to high Poisson ratio ($\nu = 0.498$). IPM results are unavailable for the 1400 group.

All methods for impedance analysis discussed above are essentially linear and thus quite adequate for small displacements. Pile installation method (e.g. driving, boring) can have a significant effect on the soil-pile boundary conditions (soil densification or loosening) and the dynamic behavior at the pile-foundation interface. Generally, for large displacements, piles behave in a nonlinear fashion because of soil nonlinearity at high strain, pile separation (gapping), slippage and friction. In practical applications, these nonlinear effects cannot be directly evaluated with frequency domain analysis, being inherently linear by nature. However, nonlinear effects can be addressed by equivalent linear-elastic modeling in conjunction with sensitivity studies with appropriate variation of the input parameters. To evaluate the aforementioned nonlinear effects, time-domain methods with models made of lumped masses, nonlinear soil resistance-deflection relationships (p-y curves and t-z curves) or finite-elements (e.g. an adapted COMSOL model) should be used. In case of an SSI analysis of a structure where nonlinear behavior is expected whilst the pile foundation is to remain in the linear or within the validity limits of the equivalent linear state – typically required by building regulations – the derived frequency-dependent impedance functions could be transformed for application in nonlinear time domain finite-element analysis.

CONCLUSIONS

The goal of this paper is to present representative results of the extensive verification benchmark performed by Framatome GmbH with a new pile element implemented in the software package SC-SASSI, see companion paper by García et al (2019). A total of 83 impedance analyses performed for different pile group configurations indicate a very good agreement between the results from SC-SASSI and the results from PILES based on Kaynia (1982) and PILAX based on Hartmann (1985). The successful extensive benchmark confirms the state-of-the-art capability of the SC-SASSI pile element to serve as a tested and verified analysis tool that can handle large pile foundations.

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