IMPLEMENTATION OF A METHOD FOR COMPUTING THE DYNAMIC STIFFNESSES OF FLOATING PILE GROUPS

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ABSTRACT :

A simple method to assess the stiffness of a pile foundation, considering group effects, is presented. The procedure is based on the simple method of Dobry and Gazetas. The procedure is validated with the rigorous solutions of Kaynia and Kausel as well as the Dyna5 software for analysis of foundations. The method is applied to the foundation of four instrumented buildings in Mexico and the results are compared with those obtained using the Mexico City building code provisions and also with experimental data.

KEYWORDS: Floating pile group, soil-structure interaction

1. INTRODUCTION

Analysis of information obtained from seismically-instrumented buildings has shown that in order to estimate adequately the structural response it is necessary to consider the soil-structure interaction (SSI) effects. However, in professional practice SSI effects are not taken into account, except for very few cases. One of the reasons for not including SSI effects is because they require additional, laborious calculations, particularly in the case of buildings supported on foundations with floating piles. In this type of foundations, the piles interact with each other generating a phenomenon known as group effect, which controls the global impedance. This effect is not considered in the Mexico City building code in spite of its great relevance, as is evident from the analysis of responses measured in instrumented buildings.

Because of the need to have a practical method to take into account pile group effects in foundations on floating piles, in this work the simplified method of Dobry and Gazetas (1988), which is based on simple analytical expressions to estimate the impedances in the components of vertical, horizontal and rocking movement, is adopted. Torsional component was not considered by Dobry and Gazetas; therefore, the simplified, approximate solution from Cruz *et al* (2007) is considered.

The above mentioned method was implemented in a computer program which provides similar results to those of Dobry and Gazetas (1988). These authors limited their results to pile-soil stiffness ratio of 1000 and pile groups smaller than 20 piles. To cover the cases of real buildings of Mexico, pile groups up to 350 piles were analyzed, as well as the influence of the ratio Ep/Es (Ep-Young module of pile, Es- Young module of soil) on impedance functions. The results obtained with the computer program were also compared with the rigorous solutions of Kaynia and Kausel (1982). Finally, the application of the method is shown in four instrumented buildings in Mexico.

2. METHODOLOGY OF ANALYSIS

As mentioned, the simplified method used in this work is the one proposed by Dobry and Gazetas (Dobry and Gazetas, 1988; Makris and Gazetas, 1992). The dynamic interaction factors are expressed by simple, analytical formulas that depend on the excitation frequency, the properties of the soil, and the spacing ratio S/d, where *S* and *d* are the separation and diameter of the piles, respectively. For the impedance associated to torsion, Cruz *et al.* (2007) proposed a method based on the analysis of deformations that take place in a group of piles subjected to rotation about the vertical axis. The deformations produced are of both torsional and lateral types. However, it is considered that the deformation due to the torsion mechanism in each pile is small compared with the lateral deformation. Consequently, by means of the same expressions used by Dobry and Gazetas (1988), only the lateral interaction induced by the active pile in the passive pile is considered. Once the factors of lateral interaction are determined, the group impedances are obtained by superposition.

For the application of the simplified method (SM) a computer program was written (Cruz *et al.*, 2007). The program calculates the impedance of a single pile according with the approach of Novak and Aboul-Ella (1978) and Novak and Howell (1978), considering a stratified soil and neglecting shear deformations. To calculate the impedance of the piles with group effects, an equivalent homogeneous halfspace is defined. The interaction factors are calculated taking into account the halfspace properties and the geometric location of the piles. To validate the program, its results were compared with the rigorous solutions provided by Kaynia and Kausel (KK) for groups of 2x2 and 3x3 piles (Kaynia and Kausel, 1982), and with the results obtained using the Dyna5 program (Novak *et al.,* 1995).

In this paper, only the results associated to the stiffness, part of the impedance function, will be presented. The dynamic stiffness was calculated in terms of the dimensionless frequency $a_0 = \omega d/Vs$, where ω is the circular frequency, d is the pile diameter and Vs is the shear-wave velocity. Different pile-soil stiffness ratios were studied, to consider the cases of stiff soil (Ep/Es = 100), soft soil (Ep/Es = 1000) and medium soil (Ep/Es = 550). The calculated curves of stiffness versus a_0 agreed well with the KK rigorous solution for the spacing ratios considered (*S/d* = 2, 5 and 10) and L/d = 15, where L is the pile length. Since the results obtained with Dyna5 present a good agreement with KK solution, in both the lower and upper values of Ep/Es ratios (100 and 1000), then it is assumed that they also will be valid for intermediate values of Ep/Es. The comparison of the vertical stiffness obtained with SM, Dyna5 and KK show that the best agreement is obtained for Ep/Es = 1000, whereas when Ep/Es = 100 the SM method overestimates the stiffness and for Ep/Es = 550 an acceptable agreement is observed. Because the analysis of the rocking component is based on the factors of vertical interaction, the variation of the rocking stiffness with Ep/Es is similar to that of the vertical component. For the lateral component obtained with SM, the results agree with those of Dyna5 and KK, mainly for ratios Ep/Es > 500. The horizontal interaction factors were corrected as indicated in Gazetas (1991) and Makris and Gazetas (1992). Since the analysis of the torsion component is based on the use of factors of lateral interaction, the behavior of the torsion stiffness, regarding the ratios Ep/Es, is similar to that of the lateral stiffness (Cruz *et al*, 2007).

Larger groups of floating piles

In the literature, rigorous solutions are only available for groups of 2 to 16 piles (Kaynia and Kausel, 1982; Roesset, 1984). To solve this obstacle and to have useful results for groups with a variable number of piles, as those related to real cases, larger arrays of piles were analyzed (4x8, 7x7, 10x10, 8x16, 15x15 and 18x18) for different spacing ratio (S/d = 2, 5 and 10). Plots of impedances functions versus dimensionless frequencies presented similar behaviors among them, independently of studied pile arrangements and the number of piles (Cruz, 2007). In general, the best correspondence between SM and Dyna5 was in the frequency interval of $0 < a_0 < 1$ for ratios Ep/Es > 500, whereas for ratios Ep/Es < 500 the good agreement was limited to the interval of low frequencies ($a_0 < 0.1$). Figure 1 shows a comparison for an array of 18x18 piles.

Regarding the vertical component, a satisfactory agreement between SM and Dyna5 was obtained in the analyzed interval of dimensionless frequencies ($0 \leq a_0 . \leq 1$). In the rocking component, SM provides similar results to the program Dyna5 for $a_0 < 0.5$. For the lateral and torsion components, significant differences are observed between SM and Dyna5; an acceptable agreement is observed only for the interval $a_0 < 0.1$. SM shows limitations for groups with larger number of piles and also when the stiffness of the soil is increased in relation to the stiffness of the piles (Ep/Es < 500). This could be explained due to the fact that SM does not consider the interference of the waves taken place by the piles (Dobry and Gazetas, 1988).

The influence of Ep/Es in the performance of SM, compared with the rigorous solutions, can be assessed by analyzing the nature of the interaction factors of the SM. Such factors were obtained from the theoretical solution to the wave propagation caused by a cylindrical, infinitely rigid surface, vibrating in a medium with negligible stiffness (Dobry and Gazetas, 1988; Dwoling and Ffowcks, 1983). Therefore, SM provides better results when a very high contrast of pile-soil stiffness is considered

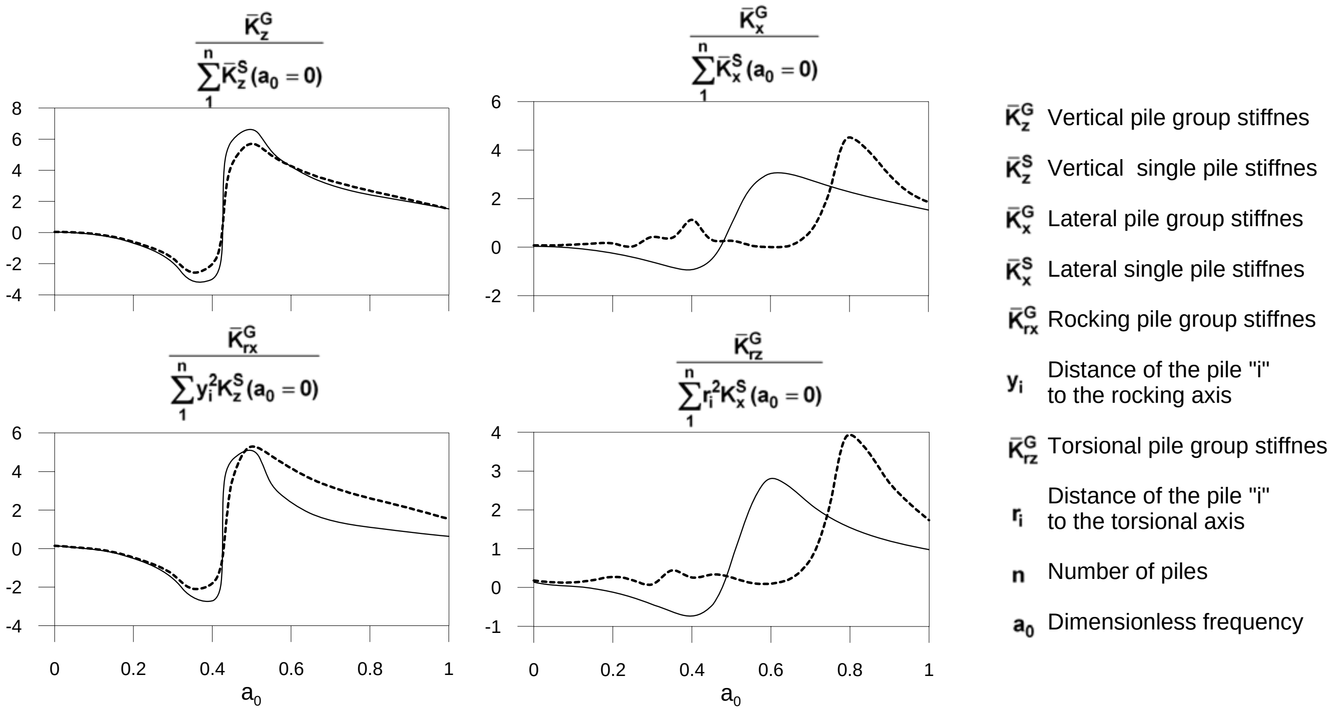

Figure 1 Comparison of MS normalized dynamic stiffness (continuous line) and Dyna5 (interrupted line) for a group of 18x18 piles with Ep/Es > 500, S/d=5 and L/d = 15

3. APPLICATION TO REAL BUILDINGS

The results obtained using the rigorous solution show that the agreement with SM depends mainly on the ratio Ep/Es and dimensionless frequencies a_0. The Ep/Es ratio influence on the value of impedance functions shows that for values of Ep/Es > 500 similar results are obtained between SM and the reference values of solution KK and Dyna5, in the whole range of frequencies studied ($0 \leq a_0 \leq 1$). For Ep/E < 500, the agreement was satisfactory only in the interval of low frequencies ($a_0 < 0.1$).

In the soft soil of Mexico City, the structures for which is feasible to use SM are buildings with 5 to 20 storeys, since such structures possess mixed foundations, like boxes on floating piles. In taller buildings it is common the use of endbearing piles, while for smaller heights it is usually enough with a box, slab-on-grade or spread foundation. Keeping in mind the representative values of fundamental periods of buildings with different structure types with foundation on floating piles in Mexico (Murià Vila and González, 1995) the value a_0 is smaller than 0.1. The piles are composed generally of concrete, and the ratio Ep/Es of these piles varies, from 300 to 1200, in Mexico City, and from 100 at 260, in Acapulco (Cruz, *et at.*, 2007).

With the purpose of evaluating the scope and limitations of the SM, it was applied in four instrumented buildings located in the cities of Mexico and Acapulco (Murià Vila *et al*., 2001, 2004; Correa and Murià Vila, 2005;

Camargo, 2007). Analysis of the SSI effects in the lateral, rocking and torsional components of the buildings were performed by using the provisions included in the Complementary Technical Norms for Earthquake Design of the Mexico City Building code (NTC, 2004), the program Dyna5 and a semi-empirical method (Luco, 1980). The NTC (2004) does not consider the pile group effects. Computer program Dyna5 allows modeling the buildings with and without pile group effects. The method of Luco has been applied before in the four buildings (Murià Vila *et al*., 2001, 2004; Correa and Murià Vila, 2005; Camargo, 2007). The foundations of the buildings are composed of a box supported on floating piles whose characteristics are summarized in figure 2. Values of a_0 and Ep/Es in these buildings are shown in the table 1. SM was applied because the three buildings located in Mexico City satisfy the ratios Ep/Es > 500 and $a_0 < 0.1$ and the SIS building in Acapulco has an Ep/Es < 500 with $a_0 < 0.1$.

Table 1 Parameter of the instrumented building

Building	**City**	**Storeys**	**Fundamental period (s)**			**Pile number**	**d (m)**	**S/d**	**V_s (m/s)**	**a_0**			**E_p/E_s**
			L	**T**	**R**					**L**	**T**	**R**	
TC	México	18	2.56	2.94	1.89	323	0.45	3-4	81	0.01	0.01	0.02	768
PC	México	16	2.78	2.94	2.22	266	0.48	2.5-3	74	0.01	0.01	0.02	1026
JAL	México	14	1.72	2.70	1.75	54	0.46	4-5	68	0.02	0.02	0.02	1051
SIS	Acapulco	16	0.96	1.22	0.73	30	1.20	5-5.5	148	0.05	0.04	0.07	185

L – Longitudinal component T- Transversal component R – Torsional component

To estimate the stiffness associated to SSI effects, the most intense registered earthquake was selected in each one of the buildings. The characteristics of these earthquakes and their maximum horizontal accelerations recorded in the soil and in roof of the buildings are presented in table 2.

Table 2 Principal characteristics of earthquakes considered in the each buildings

Building	**Event**	**Date**	**M_W**	**Ep. Dist. (km)**	**I_{Arias} (cm/s)**	**A_{max} Soil (cm/s^2)**	**A_{max} Base (cm/s^2)**	**A_{max} Roof (cm/s^2)**
JAL	99-3	30/09/1999	7.4	455	19.4	34	33	304
PC	99-3	30/09/1999	7.4	455	20.9	27	28	220
TC	04-2	18/08/2004	5.7	560	0.1	1.8	1.56	3.24
SIS	01-1	10/08/2001	6.1	44	16.4	102	58	166

Static and dynamic stiffness of pile groups and total stiffness (box and piles) obtained with the different methods presented are compared in tables 3 and 4. SM and Dyna5 (D5G) provided similar results and these methods show a better agreement with the semi-empirical stiffness assessed with the method developed by Luco (1980), as opposed to the results obtained with D5 models, which do not consider group effects. Larger group effects were determined for PC building, which has a large number of piles and a smaller ratio S/d, while the smaller group effects were calculated for SIS building, which has the lowest number of piles and the biggest ratio S/d In the four buildings studied, the differences between the horizontal static and dynamic stiffness were less than 7%, and for the rocking and torsional stiffness the differences were between 10 to 60 %. Figure 3 shows the dynamic stiffness obtained with NTC, D5, D5G and SM procedures (contribution of the piles is plotted with bars in dark gray and contribution of the box in bars with light gray) in contrast to the correspondent value obtained with the Luco's method (horizontal line).

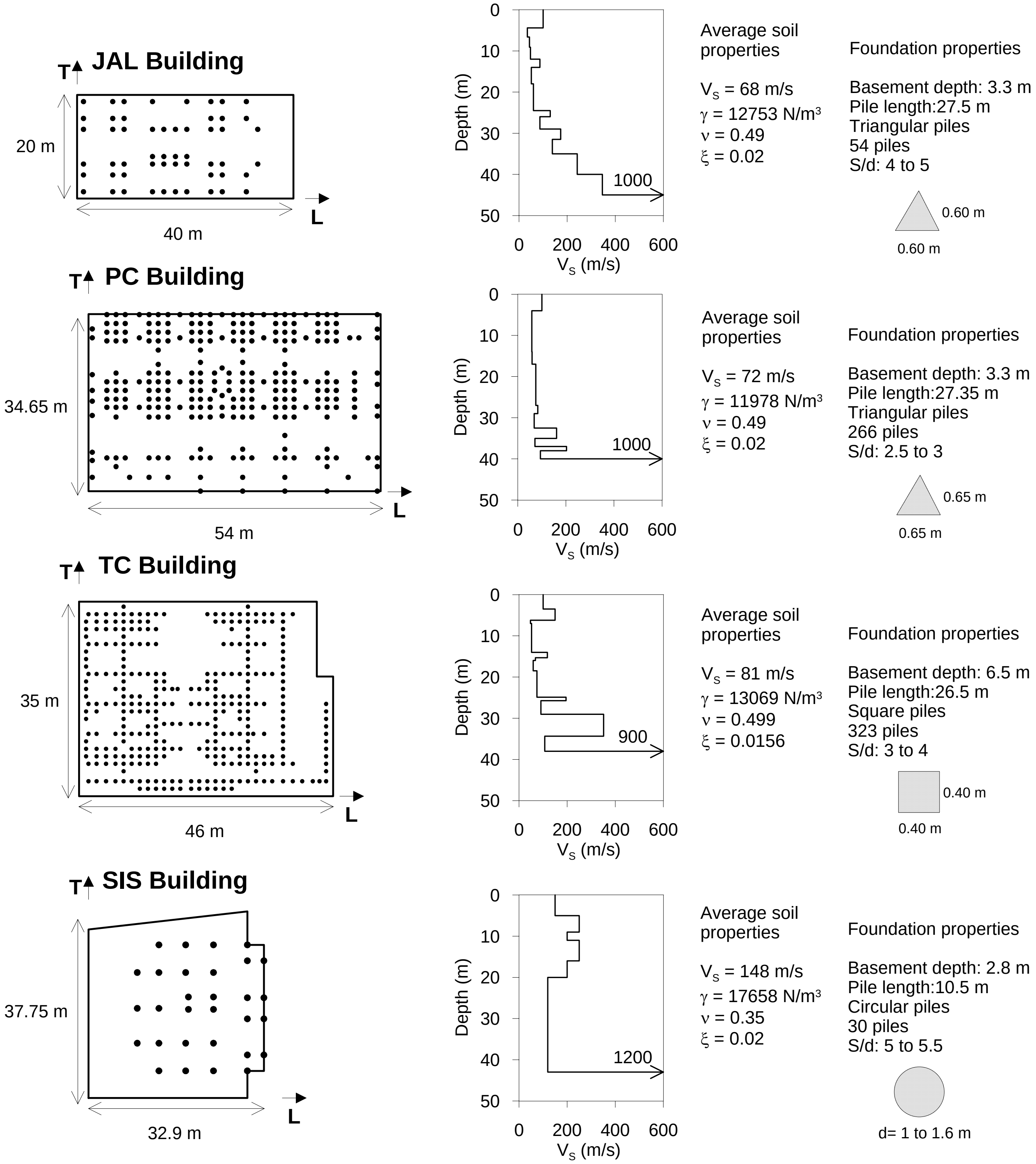

Figure 2. JAL, PC, TC and SIS building foundation plants and relevant soil properties

The above results evidence that including the group effects leads to significant reductions in the total stiffness (SIS of 27 to 46%, JAL of 59 to 72%, TC of 70 to 85% and PC of 85 to 94%), by comparison with the cases where such effects are neglected. These results show a significant dependence on the number of piles and the ratio S/d, and they agree with the results of the experimental tests carried out by Novak (Sheta and Novak, 1982; Novak and El Sharnouby, 1984; El Marsafawi *et al.*, 1990). Also, in the JAL, PC and TC buildings, with more than 10 years of service, the study suggests that the contribution of the box foundation stiffness can be neglected

Table 3. Comparison of lateral, rocking and torsional stiffnesses of piles group

Parameter	**Building**	**Static**				**Dynamic**			
		NTC	**D5**	**D5G**	**SM**	**NTC**	**D5**	**D5G**	**SM**
K_{hL} (N/m x10^9)	**JAL**	1.90	3.50	0.88	0.53	1.90	3.50	0.90	0.53
	PC	11.30	17.99	1.74	0.77	11.30	18.00	1.80	0.73
	TC	11.64	13.77	1.19	0.49	11.64	13.77	1.19	0.46
	SIS	11.70	15.20	5.50	2.47	11.70	15.20	5.70	2.45
K_{hT} (N/m x10^9)	**JAL**	1.90	3.50	0.92	0.53	1.90	3.50	0.90	0.53
	PC	11.30	17.99	1.81	0.77	11.30	18.00	1.80	0.74
	TC	11.64	13.77	1.18	0.49	11.64	13.77	1.23	0.46
	SIS	11.70	15.20	5.48	2.47	11.70	15.20	5.70	2.45
K_{rL} (N/m x10^{12})	**JAL**	0.50	1.14	0.34	0.18	0.60	1.10	0.30	0.16
	PC	8.20	25.86	0.74	0.88	9.20	25.90	1.30	0.69
	TC	9.13	5.36	0.75	0.81	10.24	5.36	0.63	0.54
	SIS	2.07	2.56	1.30	1.49	2.10	3.50	1.30	1.38
K_{rT} (N/m x10^{12})	**JAL**	1.40	3.36	0.83	0.39	1.60	3.40	0.80	0.30
	PC	16.50	38.40	1.25	1.43	18.60	38.40	2.20	1.05
	TC	11.73	6.89	0.97	1.03	13.16	6.89	0.80	0.66
	SIS	2.80	3.45	1.40	1.36	2.80	3.50	1.40	1.27
K_{tor} (N/m x10^{12})	**JAL**	0.27	1.74	0.57	0.19	0.30	1.70	0.60	0.20
	PC	3.70	26.85	1.30	0.86	3.70	26.80	3.20	0.83
	TC	3.22	3.80	0.72	0.50	3.22	3.80	0.64	0.31
	SIS	1.87	2.49	1.25	0.89	1.90	2.50	1.40	1.08

Table 4. Comparison of lateral, rocking and torsional stiffnesses of box and piles group foundations

Parameter	**Building**	**Static**				**Dynamic**				
		NTC	**D5**	**D5G**	**SM**	**NTC**	**D5**	**D5G**	**SM**	**Luco**
K_{hL} (N/m x10^9)	**JAL**	3.70	5.30	1.60	1.25	3.70	4.20	1.60	1.23	1.80
	PC	14.70	19.10	2.82	1.85	14.70	19.00	2.80	1.73	0.87
	TC	13.50	15.85	3.27	2.56	13.50	15.69	3.11	2.38	0.97
	SIS	16.80	20.40	10.73	7.70	16.80	20.40	10.90	7.65	4.60
K_{hT} (N/m x10^9)	**JAL**	3.70	5.30	1.64	1.25	3.70	4.20	1.60	1.23	1.10
	PC	14.70	19.10	2.89	1.85	14.70	19.00	2.80	1.74	0.57
	TC	13.50	15.85	3.25	2.56	13.50	15.69	3.15	2.38	0.72
	SIS	16.80	20.40	10.71	7.70	16.80	20.40	10.90	7.65	4.90
K_{rL} (N/m x10^{12})	**JAL**	0.80	1.45	0.44	0.29	0.90	1.20	0.40	0.26	0.30
	PC	8.80	26.30	1.17	1.31	10.50	26.30	1.70	1.09	0.67
	TC	9.94	6.12	1.52	1.58	10.94	6.05	1.32	1.23	2.77
	SIS	3.72	4.14	2.84	3.03	3.50	4.80	2.60	2.68	2.60
K_{rT} (N/m x10^{12})	**JAL**	2.20	4.16	1.10	0.66	2.30	3.60	1.00	0.50	0.30
	PC	17.70	39.20	2.01	2.19	21.00	39.10	2.90	1.75	5.00
	TC	12.92	8.01	2.08	2.15	14.15	7.88	1.78	1.64	1.52
	SIS	4.28	5.00	2.91	2.87	4.30	4.80	2.70	2.57	2.30
K_{tor} (N/m x10^{12})	**JAL**	0.84	2.03	0.89	0.51	0.80	2.00	0.90	0.50	0.20
	PC	5.70	27.80	2.22	1.78	5.60	27.60	4.00	1.63	0.58
	TC	4.52	5.39	2.31	2.09	4.41	5.26	2.10	1.76	0.72
	SIS	3.91	4.45	3.18	2.81	3.70	4.30	3.20	2.88	2.60

Kh_T- Lateral stiffness in T component, Kh_L- Lateral stiffness in L component,
Kr_L- Rocking stiffness around L component, Kr_T- Rocking stiffness around T component, K_{tor}.- Torsional stiffness

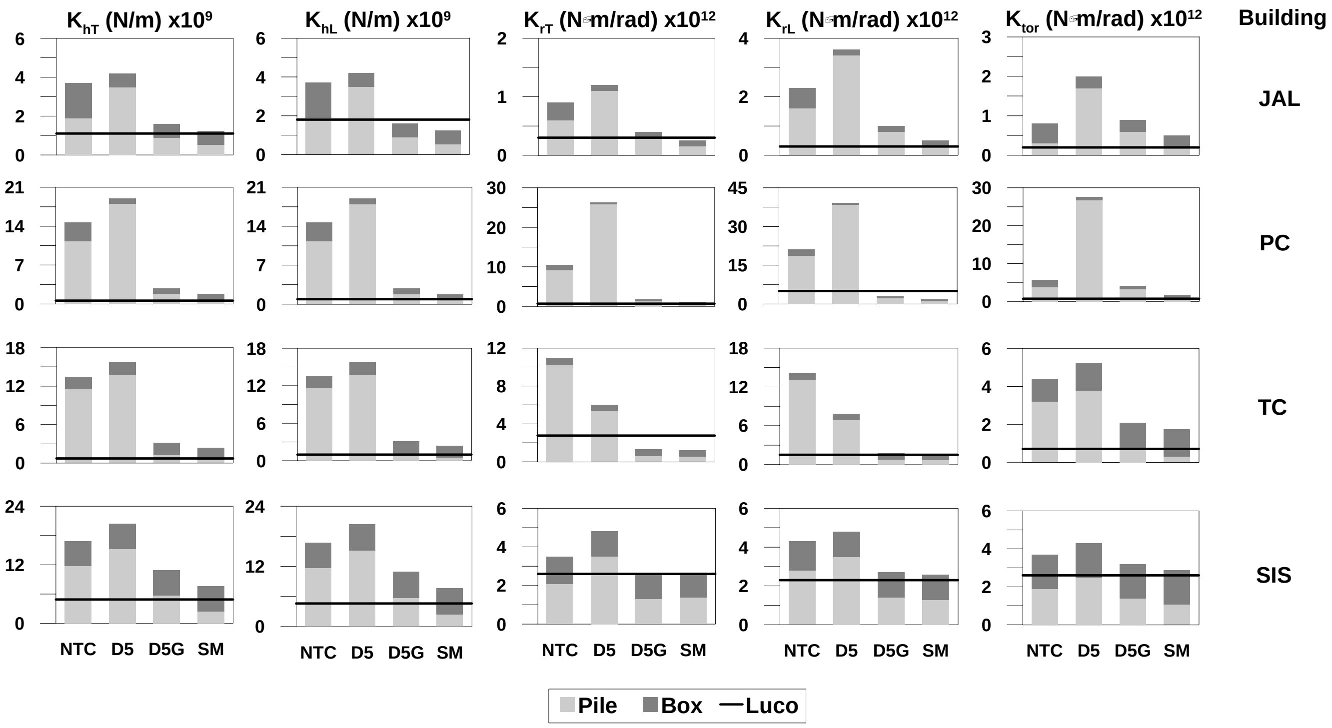

Figure 3 Comparison of dynamic stiffness (Kh_T- Lateral stiffness in T component, Kh_L- Lateral stiffness in L component, Kr_L- Rocking stiffness around L component, Kr_T- Rocking stiffness around T component, K_{tor}.- Torsional stiffness) estimated by NTC, Dyna5 with and without groups effects (D5G and D5), SM and Luco procedures

4. CONCLUSION

The agreement among the results of the simplified method (SM) with the rigorous solutions (KK) and the Dyna5 software was acceptable. The analysis of large group of piles showed that, for the curves of dynamic stiffness, corresponding to the vertical and rocking components, a satisfactory agreement is observed between the SM and Dyna5 for the vertical component in the interval $0 \leq a_0 \leq 0.1$ and for the rocking component the interval is $0 \leq a_0 \leq 0.5$. On the other hand, for the lateral and torsional components an acceptable agreement was only obtained for frequencies $a_0 < 0.1$.

In the analyses carried out to determine the influence of the stiffness ratio pile-soil (Ep/Es), it was found that the correspondence between SM and the rigorous solution KK improves as the value of Ep/Es is increased. From the performed analyses, it was observed that for ratios of Ep/Es > 500, the results of SM and those obtained with the rigorous solution KK or Dyna5 adjust well in the interval of frequencies $0 \leq a_0 \leq 1$. On the other hand, for soft soil conditions, where Ep/Es < 500, acceptable correspondence was observed between SM and KK or Dyna5 in a more reduced interval ($a_0 \leq 0.1$). Since most of the buildings with foundation on floating piles possess frequencies $a_0 < 0.1$, the application of SM is considered feasible.

The application of SM to real buildings led to results that agree satisfactorily with the stiffness obtained with the semi-empirical method of Luco and with the results obtained with Dyna5. Therefore, SM is a simple and efficient alternative for the estimate of stiffness associated of the SSI effects of buildings founded on floating piles.

5. ACKNOWLEDGEMENTS

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