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HUMAN COMFORT ANALYSIS OF REINFORCED CONCRETE BUILDINGS WHEN SUBJECTED TO WIND LOADINGS

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Nowadays, modern tall buildings present greater slenderness and have been constructed with more challenging structures that encompass the experience and knowledge of structural designers. As a result, these buildings have become more sensitive to dynamic excitations, related to wind loads, more vulnerable to problems related to excessive vibrations and human discomfort. In this context, structural systems with few beams have being widely used in the buildings design practice. However, this design strategy may cause two kinds of problems: reduction of the bracing system of the building and excessive vibrations. Therefore, it is vital in such cases, the verification of the global stability, using sensitivity indexes and design parameters, as well as the development of a dynamic structural analysis, based on a human comfort evaluation. Thus, this research work aims to investigate the dynamic structural behaviour of a 30 stories reinforced concrete residential building, with 90m height, when subjected to the non-deterministic wind dynamic actions, based on a proper consideration of the soil-structure interaction effect. The present study considered the results of a dynamic structural analysis for serviceability limit states, when the human comfort was investigated. The structural model nondeterministic dynamic response, in terms of displacements and peak accelerations was obtained and compared to the limiting values proposed by several authors and design standards. The investigated building presented very low natural frequencies, with the fundamental frequency value around 0.25 Hz. This fact becomes very relevant due to the slenderness of the structure and the utilised structural system, which may be subjected to excessive vibrations. Thus, based on the nondeterministic structural dynamic analysis and having in mind the evaluation of the peak acceleration values, it can be concluded that the building presents a perception level classified as “perceptible”, when the human comfort of the investigated building was analysed.

1 INTRODUCTION

Currently, a constructive technique widely used in the design of buildings at Rio de Janeiro/RJ, Brazil, is based on structural systems composed of slabs with large spans, without the use beams, and supported directly on the columns. This technique, applied in tall buildings projects, may cause some problems, such as the reduction of the building global structural stiffness and also the possibility of excessive vibrations [1].

The modern tall buildings present greater slenderness and their structural systems present natural frequencies with very low values, and in these situations it is important that the designer to perform more sophisticated and accurate analysis related to the investigation of the building structural behaviour [1-2].

Structural systems designed for tall buildings move due to wind actions, considering that these structures have become more slender and also more sensitive to dynamic excitations like wind loadings and thus more vulnerable to problems related to excessive vibrations. The excessive vibrations not only interfere in human comfort, but it also may cause fatigue of the structural elements or even a general collapse of the building in a worst case scenario [1-2].

On the other hand, significant research efforts in the past five decades have provided a better understanding related to the static and dynamic structural behaviour of tall buildings, when the occupant response (human comfort), associated to wind-induced building vibrations is evaluated. Despite these efforts, the human comfort remains a major challenge in the design of new tall and super-tall buildings subjected to wind dynamic loadings [1-2].

Another relevant design situation is associated to the soil-structure interaction; having in mind that nowadays, in current practice, this effect is usually disregarded and the buildings structural models are investigated based on the rigid support hypothesis. However, it is very important to study the results considering the soil-structure interaction effect properly. Such consideration may influence the global stiffness and also change the natural frequencies of the buildings, leading to different structural responses results, both in static analysis and also in the human comfort assessments, when the excessive vibrations are investigated.

This way, this research work aims to investigate the dynamic structural behaviour of a 30 story reinforced concrete building, when subjected to the non-deterministic wind dynamic actions. The effect of the soil-structure interaction is considered in the analysis, based on the complete numerical modelling of the piles and foundation system.

Thus, the developed three-dimensional numerical model adopted the usual mesh refinement techniques present in finite element method simulations implemented in the ANSYS computational program [3]. The numerical model was developed using three-dimensional beam finite elements to simulate the beams and columns and the reinforced concrete slabs were rep-resented by shell finite elements.

Finally, the present study has considered the results of a structural dynamic analysis for serviceability limit states, when the human comfort was investigated [1]. The investigated building nondeterministic dynamic response (displacements and peak accelerations), was calculated, analysed and compared to the limiting values proposed by design standards [4].

2 INVESTIGATED STRUCTURAL MODEL

The investigated reinforced concrete building presents 30 stories, total height of 90m, storey height equal to 3.0 m and rectangular dimensions of 21.50m by 17.30m, as presented in Figs. 1 and 2. The structural system is formed by massive slabs with a thickness equal to 18cm, beams with sections of 30cm x 60cm and columns with sections of 30cm x 80cm. In addition, it is fair to mention that the building doesn't have beams splitting the internal spans of the slabs, but only peripheral beams connect the columns forming the global frame that composes the structural bracing of the building [1], see Figs. 1 and 2.

The concrete presents a compressive strength (f_{ck}) equal to 45MPa, modulus of elasticity (E_{cs}) of 34GPa, Poisson's ratio (ν) equal to 0.2 and density (γ_c) of 25kN/m³. In relation to the loads, permanent (1.0 kN/m^2) and accidental (1.5 kN/m^2) loadings were added to the concrete slabs of all 30 stories and the total weight of the masonry was distributed over the concrete slabs (2.8kN/m^2).

It must be emphasized that along this investigation, three different situations were studied. The first one, considering the building modelled based on the rigid supports hypothesis; the second and third cases, considered the numerical modelling of the piles and foundation system, based on two different soils, with geotechnical profiles previously known (see Fig. 3), aiming to examining the soil-structure interaction effects on the building structural behaviour.

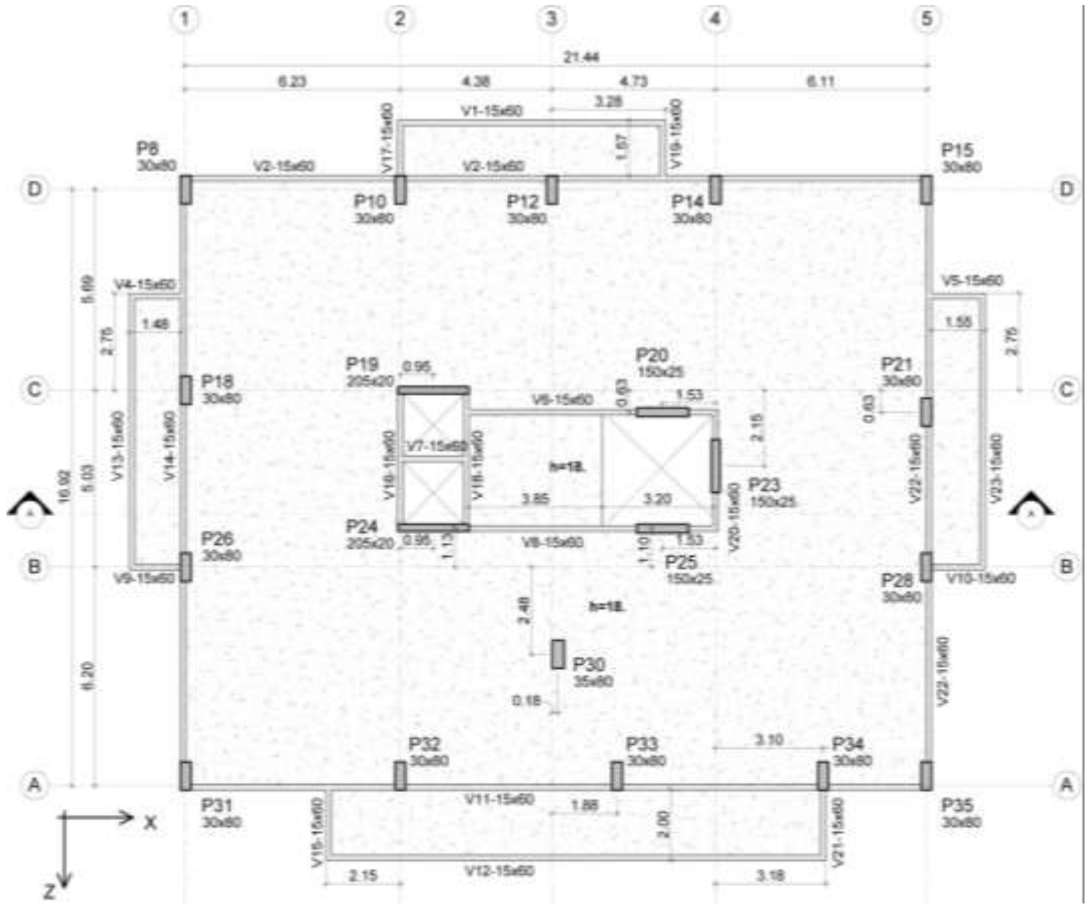
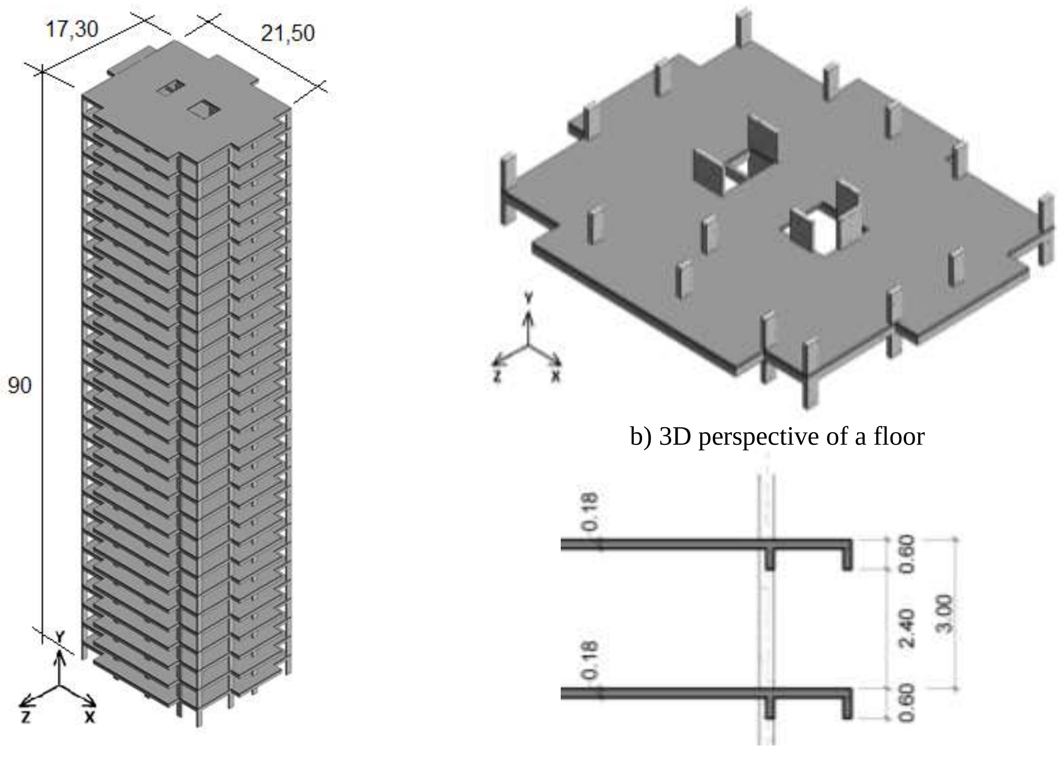


Figure 1: Investigated building: floor structural plan (units in meters)

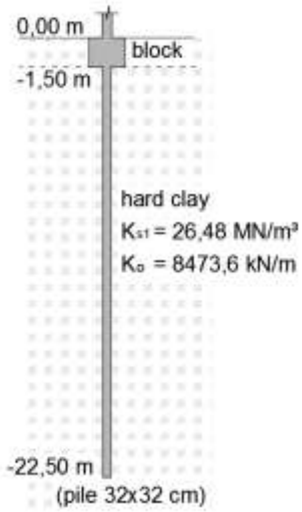


b) 3D perspective of a floor

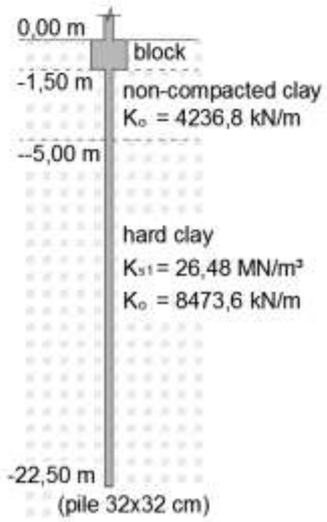
a) 3D model perspective

c) Structural section of the beams

Figure 2: Building structural model



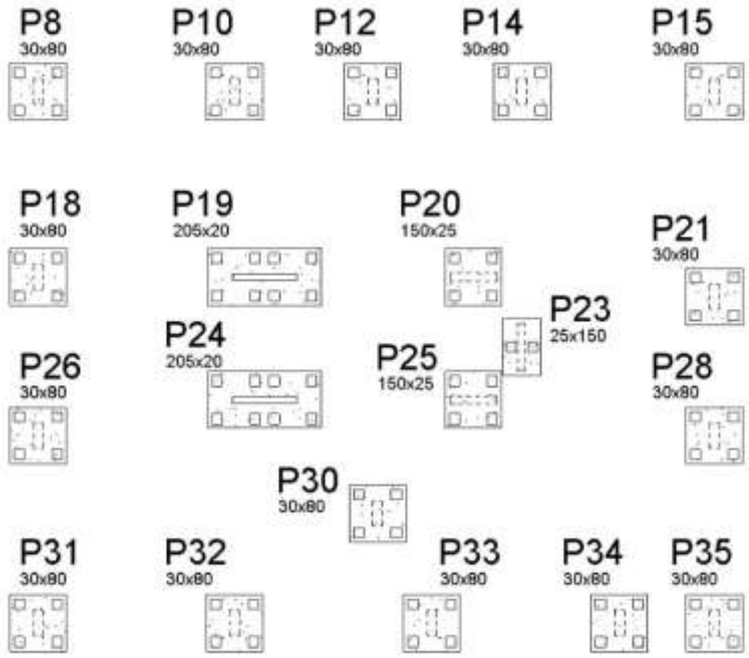
a: Soil 1 (hard clay)



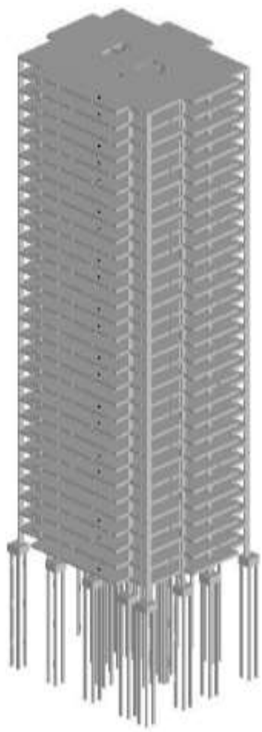
b: Soil 2 (non-compacted clay + hard clay)

Figure 3: Geotechnical profile of the investigated soils

In reference to the study of the piles, the usual analysis methodology for the formulation of the soil-structure interaction problem uses the theoretical concept of the reaction coefficient, originally proposed by Winkler [2]. According to Terzaghi [5] the horizontal reaction coefficient (k_h) for piles in cohesive soils (clays), does not depend of the pile depth. This way, aiming to determine the dimensions of the piles and foundations a static analysis was performed, where the support reactions of the concrete columns on the foundation were calculates. Based on these values, it was possible to determine the geometry of the foundation system and piles, as shown in Fig. 4.



a: Foundation structural system



b: 3D perspective

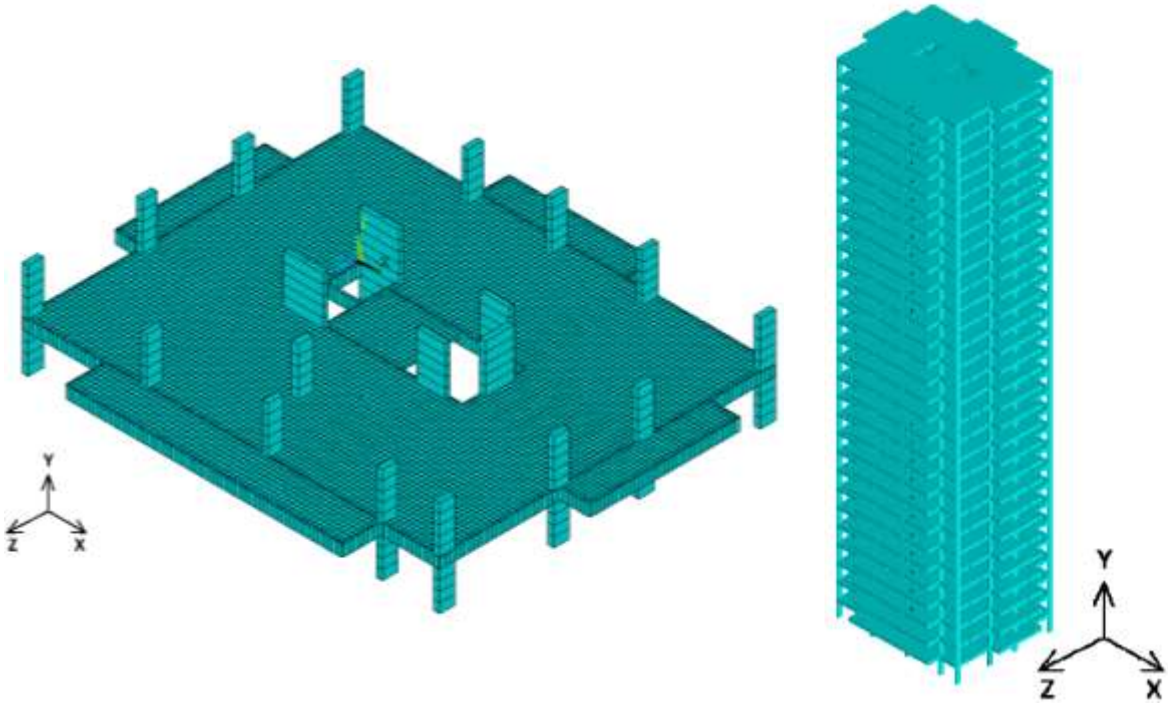
Figure 4: Structural model of the investigated foundation system

3 FINITE ELEMNT MODELLING OF THE BUILDING

The proposed computational model, developed for the reinforced concrete building dynamic structural analysis, adopted the usual mesh refinement techniques present in finite element method simulations implemented in the ANSYS computational program [3]. In this numerical model, the concrete floor girders were represented by three-dimensional beam elements (BEAM44 [3]), where flexural and torsion effects are considered. The concrete slab was represented by shell elements (SHELL63 [3]), see Fig. 5.

In this investigation it was considered that the reinforced concrete have presents an elastic behaviour. In addition, the complete interaction between the concrete slab and beams was also considered in the analysis, i.e., the numerical model coupled all the nodes between the concrete beams and slabs, aiming to prevent the occurrence of any slip.

It must be emphasized that the developed numerical model presents an appropriate degree of refinement, allowing a good representation of the dynamic behaviour of the investigated building. The support conditions considered in the rigid support hypothesis (without the modelling of the soil-structure interaction), restrict the columns at the bottom (sections of the base of the FEM model), so that the displacements (horizontal and vertical) are constrained.

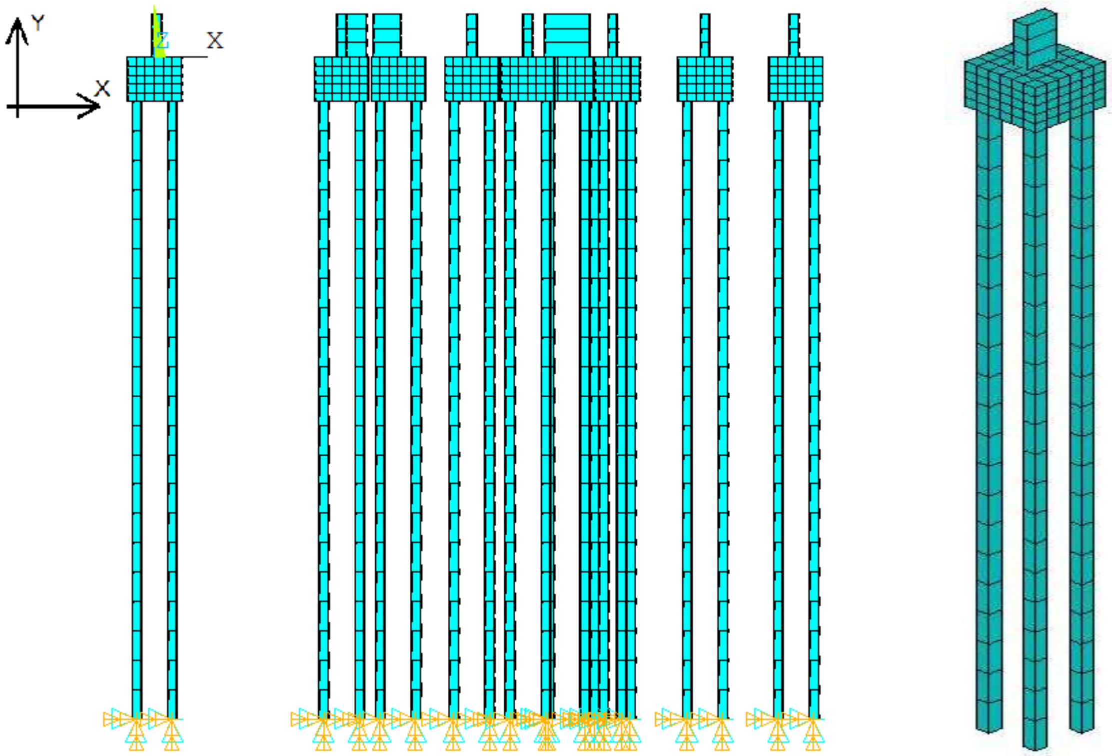


a: FEM: 3D floor perspective b: FEM: 3D global perspective

Figure 5: Finite element model of the investigated 30 story building [1]

In relation to the modelling of the foundation structural system, solid finite elements (SOLID45 [3]) were used to represent the concrete blocks, as shown Fig. 6. The foundation piles, in its turn, were modelled based on the use of three-dimensional beam elements (BEAM44 [3]), where flexural and torsion effects are considered.

On the other hand, in order to simulate the horizontal resistance of the investigated soil imposed on the piles, the BEAM44 finite element [3], also included in its formulation the effect related to the foundation stiffness (spring effect: horizontal stiffness k_o), calculated for the pile and soil used in the structural analysis, when the soil interaction effect is considered in the investigation.



a: FEM: 3D foundation structural system perspective b: FEM: 3D global perspective

Figure 6: Views of the foundation's numerical model

In sequence, Table 1 presents the number of nodes, elements and degrees of freedom for the building FEM, when it is represented based on the rigid supports hypothesis, and when it was modelled considering the soil-structure interaction effect (modelling of the foundation structural system). As expected, it can be seen an increase in the degree of refinement of the building finite element model when the soil-structure interaction effect is considered along the investigation, as presented in Table 1.

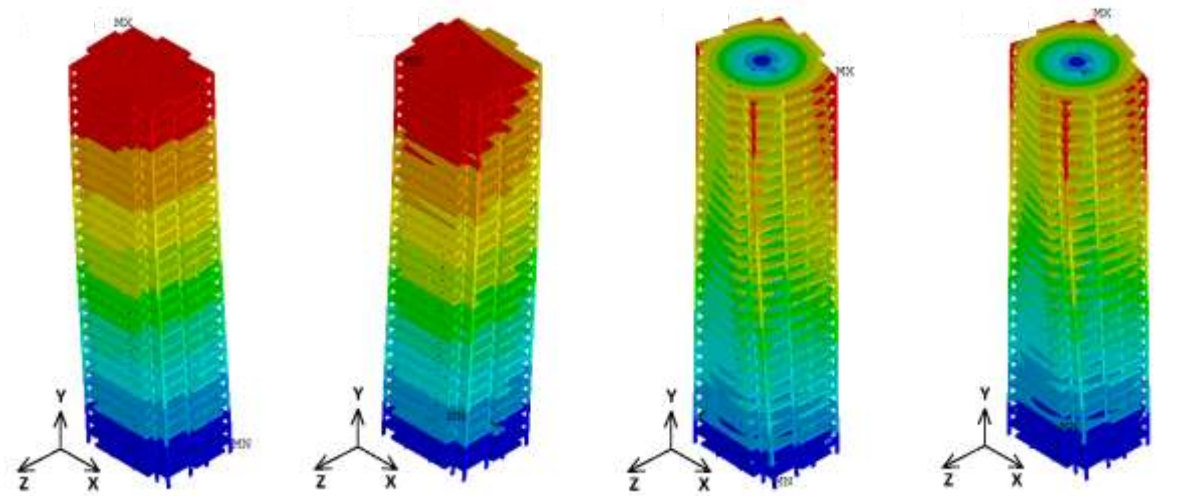
Table 1: FEM: nodes, elements and degrees of freedom

FEM (Characteristics)	Rigid supports	Foundation system	FEM (Modifications)	
Nodes	232552	240812	8260	+ 3,55 %
Elements	245880	251588	5708	+ 2,32 %
Degrees of freedom (DOF)	1395246	1425042	29796	+ 2,13 %

4 NATURAL FREQUENCIES AND VIBRATION MODES OF THE BUILDING

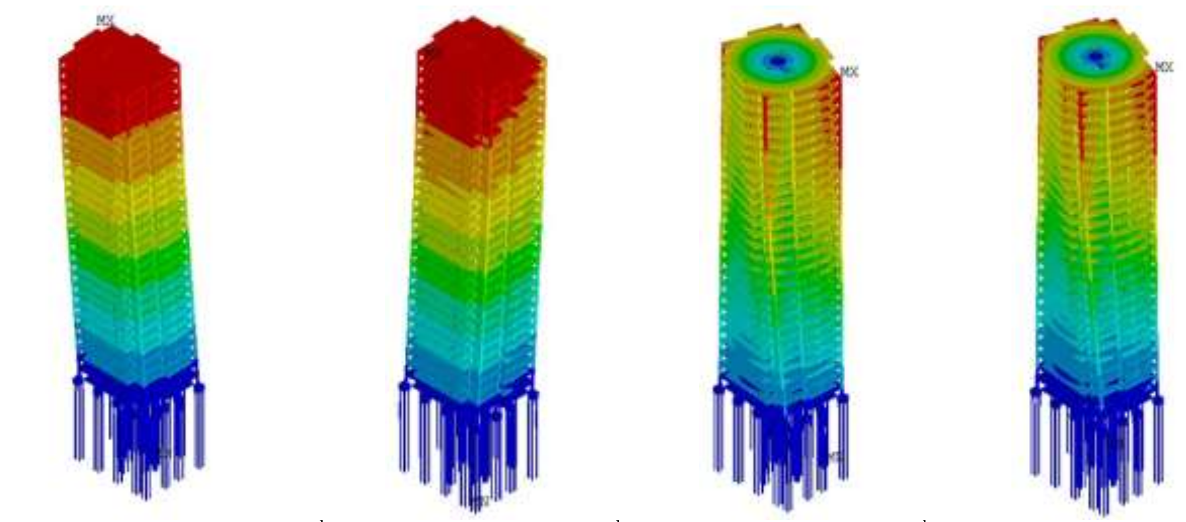
First of all, the reinforced concrete building natural frequencies were determined with the aid of the numerical simulations, see Table 2, while the corresponding vibration modes are illustrated in Figs. 7 and 8. It must be emphasized that the investigated structural model can vibrate in many different ways and these different mode shapes of vibrating present their own natural frequency, so that each natural frequency can be determined based on the solution of the classical eigenvalue and eigenvector mathematical problem.

It is important to emphasize that the fundamental frequency of the building, considering the rigid supports, is equal to 0.25 Hz (f_{01} = 0.25Hz). This fact is relevant, because according to NBR 6123 [5], buildings with natural frequencies less than 1Hz, in particular those with low structural damping, may present important fluctuation responses along the wind direction.



1st Mode (f_{01}= 0.25Hz) Bending around X-axis
2nd Mode (f_{02}= 0.26Hz) Bending around Z-axis
3rd Mode (f_{03}= 0.34Hz) Torsion around Y-axis
4th Mode (f_{04}= 0.49Hz) Torsion around Y-axis

Figure 7: Building vibration modes with rigid supports



1st Mode (f01= 0.23Hz) Bending around X-axis
2nd Mode (f_{02}= 0.24Hz) Bending around Z-axis
3rd Mode (f_{03}= 0.32Hz) Torsion around Y-axis
4th Mode (f_{04}= 0.49Hz) Torsion around Y-axis

Figure 8: Building vibration modes with soil-interaction (Soil 1: hard clay**)**

Table 2: Natural frequencies of the investigated building

Rigid supports (Hz)		Soil 1: hard clay		Soil 2: non-compacted clay + hard clay	
		Hz	Variance	Hz	Variance
f_{01}	0.25	0.23	-8%	0.21	-16 %
f_{02}	0.26	0.24	-8 %	0.22	-15 %
f_{03}	0.34	0.32	-6 %	0.28	-18 %
f_{04}	0.49	0.49	0%	0.49	0%
f_{05}	0.76	0.73	-4 %	0.65	-4 %
f_{06}	0.81	0.75	-7 %	0.67	-17 %
f_{07}	1.01	0.98	-3 %	0.87	-14 %
f_{08}	1.42	1.38	-3 %	1.26	-11 %
f_{09}	1.44	1.39	-3 %	1.27	-12 %
f_{10}	1.74	1.69	- 3 %	1.54	-11 %

It is fair to mention that in this investigation, the soil-structure interaction effect did not induced significant modifications on the vibration modes of the investigated building, see Figs. 7 and 8. However, this effect has produced modifications on the values of the natural frequencies, see Table 2 and Fig. 9.

It is possible to observe that the modelling of the soil-interaction effect provokes a decrease in the natural frequencies values, see Table 2 and Fig. 9. It must be emphasized that only for the fourth vibration mode there was no change in the frequency value, because this vibration mode is related to the torsion of the building, and is not being affected by the consideration of the effect of the soil-structure interaction.

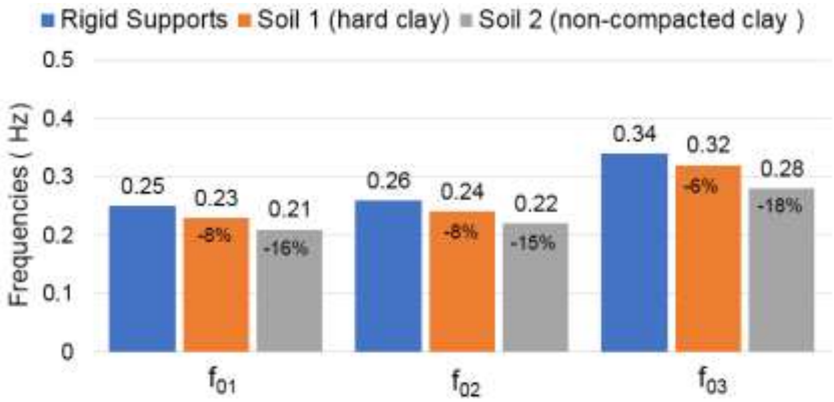


Figure 9: Comparison between frequencies - (1st to 3rd modes)

Observing the numerical results obtained in this investigation, it is possible to establish that the soil type influences the global structural stiffness of the building, see Table 2 and Fig. 9, and consequently, changes the values of the natural frequencies of the system. This conclusion is important, because when the resonance effects related to the wind actions on buildings are considered, these differences are significant and deserve the designer's attention.

5 NONDETERMINISTIC DYNAMIC ANALYSIS

Based on the analysis methodology previously developed by Barboza [2], considering the wind PSD functions related to the Kaimal spectrum, which considers the influence of the height of the building, and also using the computational program ANSYS [3], forced vibration analyses were made on the investigated building, in which the wind was simulated considering nondeterministic loadings, acting at the negative direction of the global axis Z.

In this work, the numerical results were obtained considering the wind acting on the building during a total interval of 10 minutes (600 seconds [4]). Figure 10 presents a generic horizontal dynamic force, in the time domain, applied to the column 32 (P32, see Fig. 1), at height Z = 90m, obtained according the analysis methodology previously developed by Barboza [2]. It is possible to evidence the random character of the wind actions.

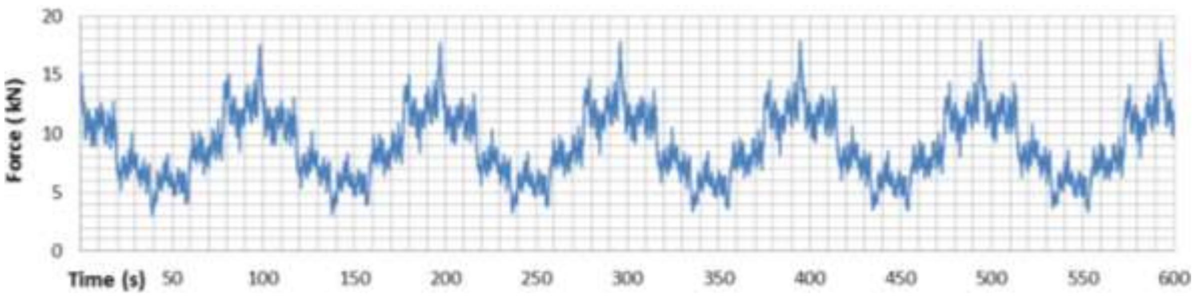


Figure 10: Nondeterministic wind action in time domain [1].

In sequence, Fig. 11 presents the nondeterministic wind action, in frequency domain, for the same dynamic loading applied to the column 32 (P32, see Fig. 1), at height Z = 90m. The main energy transfer peak observed in the dynamic structural response of the building is associated with the natural frequency value of 0.25 Hz (see Table 2), related to the resonance existing between the resonant harmonic of the dynamic excitation (5th harmonic) corresponding to the wind action, acting at the negative direction of the global axis Z, and the 1st vibration mode of the structure (bending with respect to the X-axis, see Figs. 7 and 8).

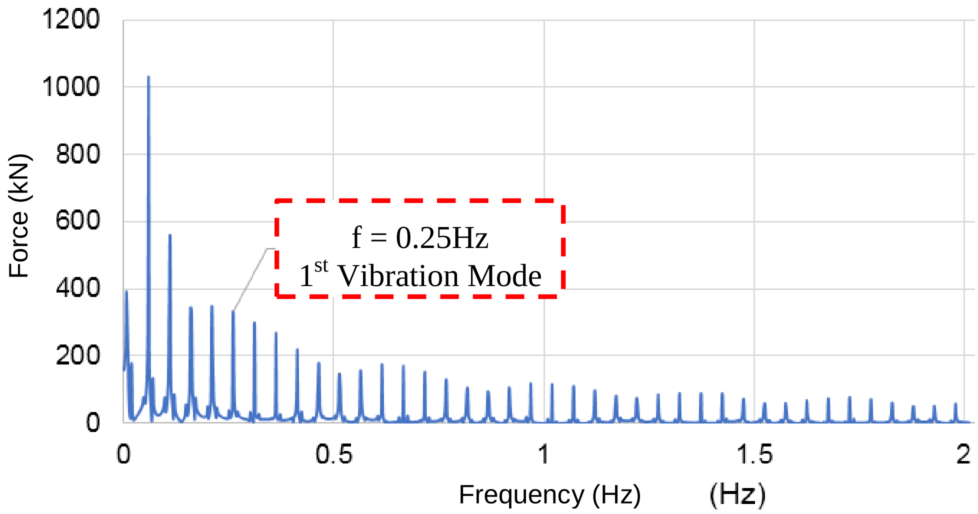


Figure 11: Nondeterministic wind action in frequency domain

The nondeterministic wind action leads the analysis for an adequate statistical treatment of the calculated results. Therefore, considering a normal distribution, it is possible to obtain the mean value (*m*), standard deviation (σ) and characteristic values of the responses with a degree of reliability of 95%, through Equation (1). The results related to the use of ten temporal series are presented in Tables 3 and 4.

$$U_{z_{95\%}} = 1{,}65\ \sigma + m \tag{1}$$

Table 3: Investigated building: displacements and accelerations (rigid supports hypothesis)

Loading Series	Displacements (m)		Accelerations (m/s²)	
	Transient phase	Permanent Phase	Transient phase	Permanent Phase
1	0.1619	0.1046	0.2939	0.0860
2	0.1660	0.1115	0.3076	0.0849
3	0.1648	0.1081	0.2932	0.0855
4	0.1595	0.1059	0.2825	0.0661
5	0.1622	0.1177	0.2864	0.1044
6	0.1640	0.1057	0.2751	0.0727
7	0.1647	0.1097	0.2595	0.0921
8	0.1734	0.1257	0.2948	0.1113
9	0.1711	0.1076	0.3019	0.0930
10	0.1632	0.1146	0.3055	0.1004
Mean	0.1651	0.1111	0.2900	0.0896
Standard Deviation	0.0042	0.0066	0.0148	0.0138
$U_{z95\%}$	0.1721	0.1220	0.3144	0.1124

Table 4: Investigated building: displacements and accelerations (Soil 1: hard clay)

Loading Series	Displacements (m)		Accelerations (m/s²)	
	Transient phase	Permanent Phase	Transient phase	Permanent Phase
1	0.1867	0.1162	0.2933	0.0731
2	0.1925	0.1260	0.3061	0.0897
3	0.1909	0.1219	0.3145	0.0763
4	0.1864	0.1183	0.3414	0.0736
5	0.1889	0.1322	0.3031	0.1010
6	0.1929	0.1193	0.3313	0.0830
7	0.1927	0.1213	0.3022	0.0936
8	0.2027	0.1394	0.3477	0.1184
9	0.1993	0.1216	0.3081	0.0908
10	0.1899	0.1265	0.3118	0.0995
Mean	0.1923	0.1243	0.3160	0.0899
standard deviation	0.0052	0.0070	0.0181	0.0142
$U_{z95\%}$	0.2009	0.1359	0.3458	0.1134

The maximum horizontal translational displacements calculated at the top of the structural model, after the statistical treatment of the results, based on the use of ten series of nondeterministic wind loadings, can be seen in Fig. 12. It must be emphasized that the values of displacements calculated with the consideration of the soil-structure interaction effect were higher than those obtained when the rigid supports hypothesis is considered in the dynamic analysis, as illustrated in Fig. 12.

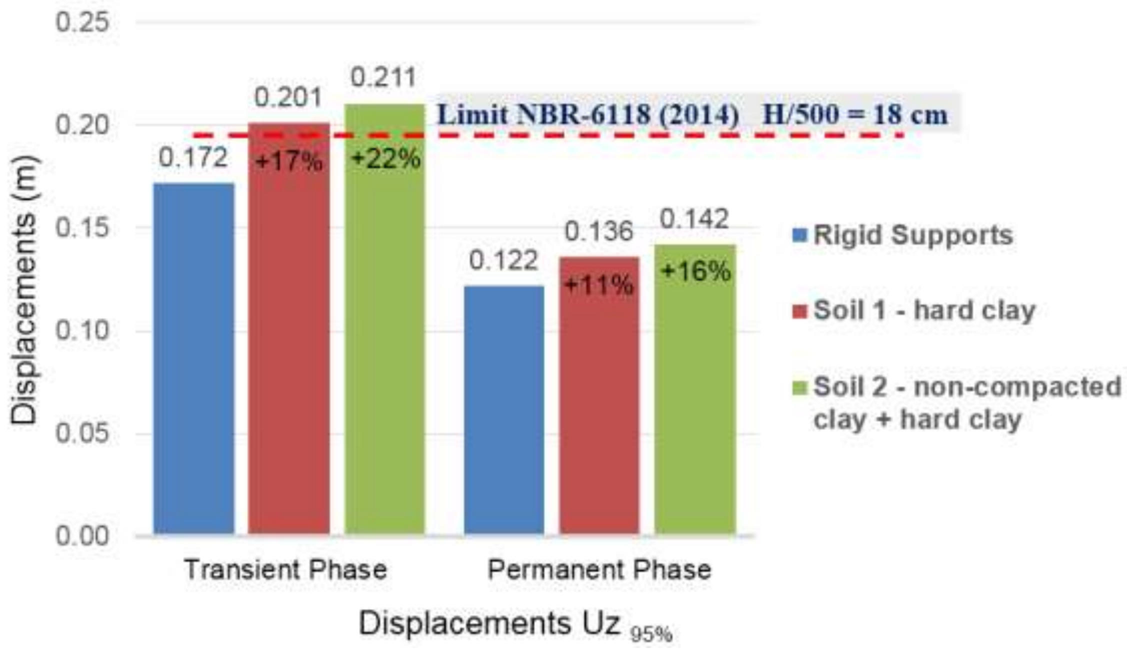


Figure 12: Investigated building nondeterministic structural response: maximum displacements

In sequence, Fig. 13 presents the horizontal translational displacements, obtained in the time domain (Series 1 of 10), considering the two studied hypothesis: rigid supports and soil-structure interaction effect (Soil 1, see Fig. 3). It is possible to verify that the modelling of the soil-structure interaction effect produced values of horizontal translational displacements higher than those related to the rigid supports model.

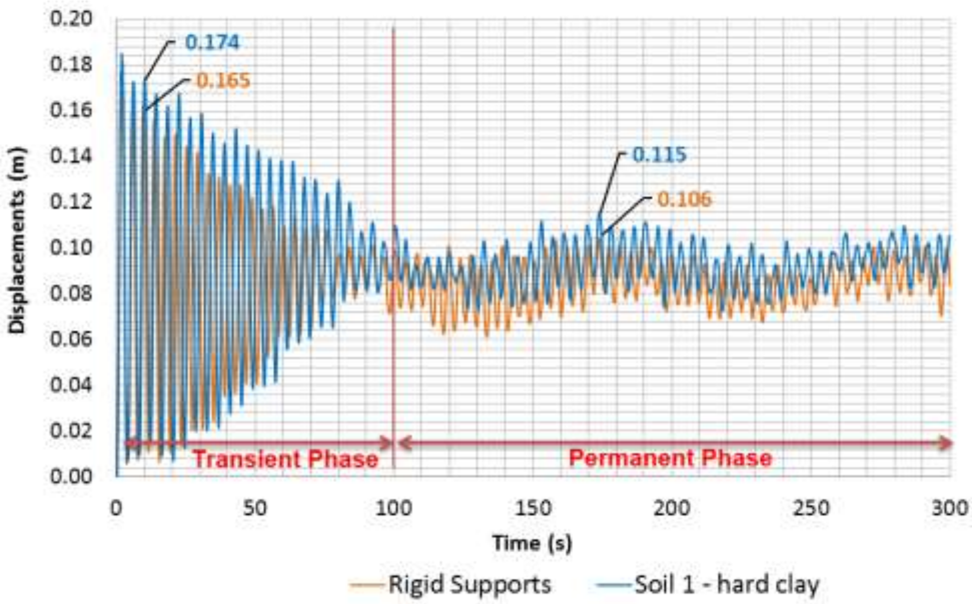


Figure 13: Horizontal translational displacement at the top of the building in the time domain

After that, the maximum accelerations calculated at the top of the structural model, considering the statistical treatment of the results, based on the use of ten series of nondeterministic wind loadings, can be observed in Fig. 14. Again, it can be seen that the values of accelerations calculated with the consideration of the soil-structure interaction effect were higher than those obtained when the rigid supports hypothesis is considered in the dynamic analysis, see Fig. 14. It is important to note that the structural model meets the normative criterion referring to the horizontal translational displacements, but does not meet the criterion related to human comfort established by NBR 6123 [4].

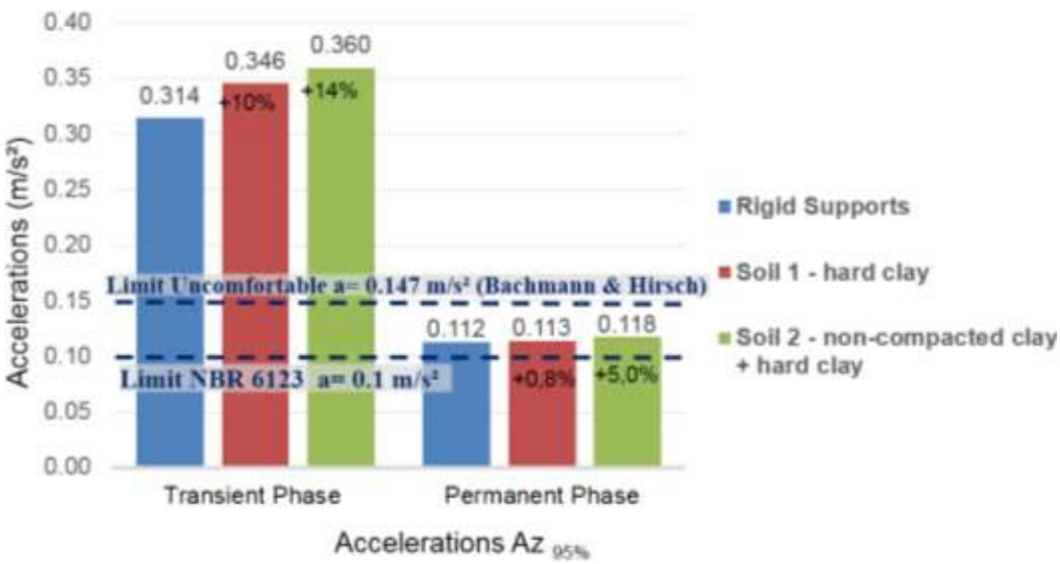


Figure 14: Investigated building nondeterministic structural response: maximum accelerations

In sequence of the study, Fig. 15 presents the accelerations at the top of the building in the frequency domain. It is possible to observe that the participation of the 5th harmonic of the nondeterministic loading series coinciding with the 1st natural frequency of the analysed structural model (characterizing the resonance), is responsible for the highest acceleration energy peak transfer.

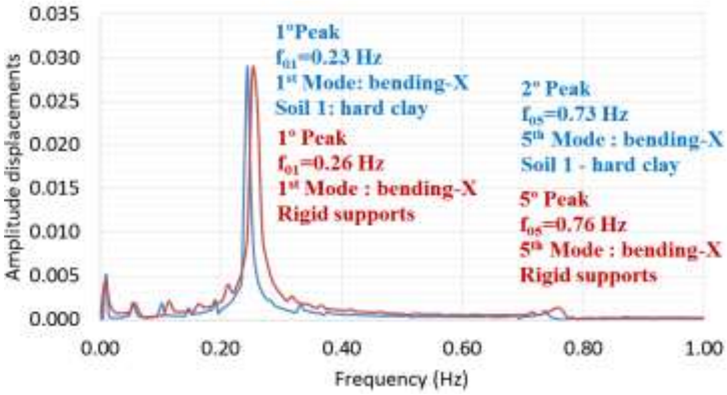


Figure 15: Accelerations at the top of the building in the frequency domain

6 CONCLUSIONS

This research work analysed the dynamic structural response of a 30 story reinforced concrete building, when subjected to the nondeterministic wind dynamic actions. The effect of the soil-structure interaction was considered in the analysis, based on the complete numerical modelling of the piles and foundation system. The three-dimensional finite element model of the investigated building was developed, based on the use of the ANSYS [3] computational program.

The results found along this study become evident the relevance of the consideration of the soil-structure interaction effect properly. It was possible to verify that consideration soil-structure interaction caused modifications on the global structural stiffness of the building and, consequently, the natural frequencies values were modified and there was an increase in the horizontal translational displacements and accelerations, due to the nondeterministic wind actions. This way, it is possible to conclude that the soil type also influences the global dynamic structural behaviour of the investigated building. This conclusion is important, because when the resonance effects related to the wind actions on buildings are considered, these differences can be significant and deserve the designer's attention.

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