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Numerical simulation of fluid-structure-soil interaction on the CAARC standard tall building

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Abstract. In the present work, the effects of the wind action over a tall building are evaluated considering the influence of soil-foundation interaction. The numerical model is developed in this work from a partitional coupling scheme, in which the physical media involved are solved sequentially, and may present independent discretization and solution methods. The Finite Element Method (FEM) is adopted for the spatial discretization of all physical media, where linear hexahedral elements with underintegration techniques are used. Load transfer between soil and structure is performed by a three-dimensional contact algorithm based on the penalty method and infinite elements are employed at the boundaries of the soil computational domain to avoid the reflection of waves to the region of interest. Due to the high computational demand, a hybrid parallelization model based on CUDA-OpenMP techniques is employed to accelerate the processing time associated with the present simulations. Numerical results obtained from aerodynamic and aeroelastic analyses are compared with numerical and wind tunnel measurements reported by other authors. It was observed that the building response to the wind action was influenced by the soil-foundation interaction, where a good agreement was obtained with respect to the reference results.

Keywords: Computational Wind Engineering, Fluid-Structure-Soil Interaction, Finite Element Method.

1 Introduction

The advances observed in the last decades in material technology and construction techniques have led to increasingly lighter and slender structures. As a result, these structures have shown greater susceptibility to the wind action, where aeroelastic instability phenomena may arise. In this sense, experimental analysis in wind tunnels has been the most used alternative to evaluate the wind action on buildings and structures. However, numerical simulations have become a very attractive tool for Wind Engineering studies in recent decades due to the increasing advance in computer technology, which can provide data that is often difficult to obtain in wind tunnel tests (see Blocken [1]). In the wind tunnel practice on building aerodynamics, the CAARC (Commonwealth Advisory Aeronautical Council) tall building model is a traditional application adopted to calibrate experimental techniques (Fig. 1a) and can also be used to validate numerical models (Fig. 1b).

It is observed that, in general, the tests in wind tunnels are carried out considering ideal support conditions, in other words, ignoring the effects of soil-foundation-structure when considering the foundation resting on a rigid base or simulating only the physical properties of the structure in the case of aeroelastic analysis (see Melbourne [2]; Thepmongkorn et al. [3]). On the other hand, fluid-structure numerical models developed for Computational Wind Engineering (CWE) applications also usually neglect the interaction effects of superstructure with foundation and soil (see Braun and Awruch [4]; Huang et al. [5]).

Nevertheless, it is known that the soil behavior can contribute to dissipate dynamic energy and, usually, the soil presence in the numerical model leads to damping increase and higher structural stiffness (Jia [6]), modifying the dynamic structural response (Menglin et al. [7]). It is also verified that the soil consideration in small-scale models employed in wind tunnel tests would present an additional challenge, mainly due to the similarity conditions to be respected. In this case, a numerical model may be the best alternative to resolve this problem.

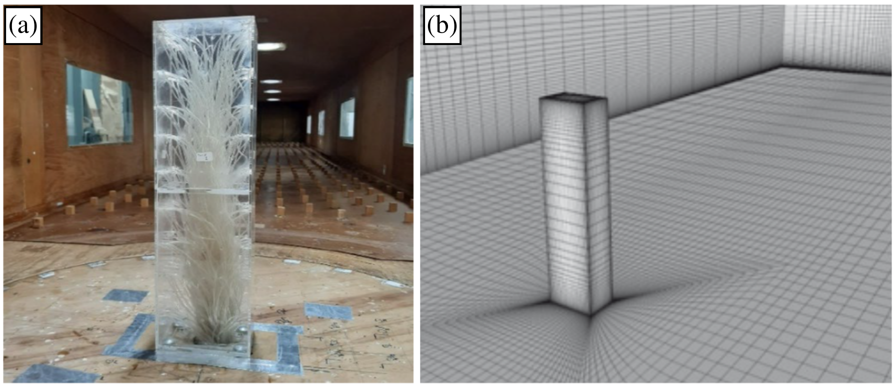

Figure 1. Aerodynamic analysis of the CAARC building: (a) experimental model by Fontes-Silva et al. [8] and (b) numerical model by Braun and Awruch [4]

Thus, the present work seeks to numerically evaluate the effects of the wind action over the CAARC standard tall building model, considering the influence of soil-foundation interaction. Results obtained from aerodynamic and aeroelastic analyses are compared with numerical and wind tunnel measurements reported by other authors.

2 Numerical model description

According to many engineering problem, differential equations are usually adopted in order to describe a physical problem analytically. In the case of problems involving viscous fluids, the differential equations that describe the wind flow are given by the well-known Navier-Stokes equations and the mass conservation equation. The air is modeled as a three-dimensional incompressible turbulent flow and remains in constant temperature. In this sense, time discretization of the flow fundamental equations may be carried out using second-order Taylor series expansions, followed by spatial discretization performed using the Bubnov-Galerkin's weighted residual scheme in the FEM context. The present numerical scheme is known as the explicit two-step Taylor-Galerkin, where eight-node hexahedral elements with one-point quadrature are used for spatial discretization.

Turbulent flows are very common in problems of fluid dynamics, although they are very difficult to simulate numerically due to the smaller scales observed in the turbulence flow, which are associated with the smaller eddies of the flow field. Turbulence simulation is usually performed considering a turbulence model that statistically reproduces turbulence effects over the main flow. In the present work, Large Scale Simulation (LES) with the dynamic sub-grid scale model is employed for turbulent analysis.

In the same manner, the fundamental equations for structural dynamics under isothermal condition are defined by momentum and mass conservation equations, in addition to a material constitutive law. The numerical model for elastic body (structure and soil subsystems) analysis is obtained applying the Bubnov-Galerkin's weighted residual scheme on the fundamental equation, considering a FEM framework, which leads to the well-known dynamic equilibrium equation. Two underintegration techniques (one-point quadrature and $\bar{\mathrm{B}}$ method) are employed in order to evaluate the element matrices and variables using the eight-node hexahedral finite element.

In the present work, structure and soil are considered taking into account an elastoplastic material model, where a corotational approach is adopted to deal with physical and geometric nonlinearities. Note that the contact formulation is also inherently nonlinear, since the contact surface is not known previously. Geometrically nonlinear effects are considered when displacements and rotations are relatively large, while physical nonlinearity occurs when the stress-strain relationship is no longer linear, or when material properties change with the applied loads.

It is possible to observe that spatial discretization of semi-infinite medium problems is difficult for FEM models, since the finite element mesh must extend to a distance where boundary effects can be neglected. The problem becomes even greater in the case of dynamic problems, because the dynamic energy can be trapped inside the mesh due to reflection of waves when a fixed boundary condition is utilized. Therefore, it is necessary to employ special boundary conditions when soil-structure interaction problems are analyzed using the FEM. Due to its simplicity, infinite elements are used in this work, which are responsible for providing a quiet boundary, where no wave reflections are expected.

In order to take into account the nonlinear behavior, the system of nonlinear equations obtained in the structural analysis is solved using the Newton-Raphson method, considering an incremental-iterative approach. In addition, the equation of motion is discretized in the time domain employing the Generalized-α method. Load transfer between soil and structure is performed using a three-dimensional contact model based on the penalty method with a node-to-surface formulation. In this way, small interpenetrations are allowed between bodies in contact and the non-penetrability condition is loosened. A partitional coupling scheme is employed for fluid-structure interaction analysis, in which the physical media involved are solved sequentially, and may present independent discretization and solution methods. Subcycling and synchronizing algorithms for non-matching meshes between the fluid and structure fields are also included in the present model.

Finally, due to the high computational demand, a hybrid CUDA-OpenMP approach is employed in this work to improve processing efficiency for large scale simulations, where the structural analysis is performed by the CPU (Central Process Units) and wind flow analysis is performed by the GPU (Graphics Processing Units). A detailed description about the present numerical model may be found in Visintainer [9].

3 Numerical application

3.1 Aerodynamic analysis

The CAARC standard tall building model is characterized as a rectangular prism with flat walls and with no architectural element. The building full-scale dimensions are defined as follows: height (H) = 180 m, length (L) = 30 m and width (W) = 45 m. The CAARC building was extensively analyzed in different wind tunnels as a standard model to investigate the wind effects on tall buildings. Geometrical characteristics of the computational domain and boundary conditions adopted in the present simulations are shown in Fig. 2, where the mesh configuration employed for the fluid domain is also presented. A geometric scale of 1:250 is considered in computational modeling and the geometrical limits are based on the work by Huang et al. [5]. A mesh convergence study was performed and the chosen mesh is composed of 532,715 hexahedral elements and 515,424 nodes, where the minimum element height is about 2x10^{-3} m.

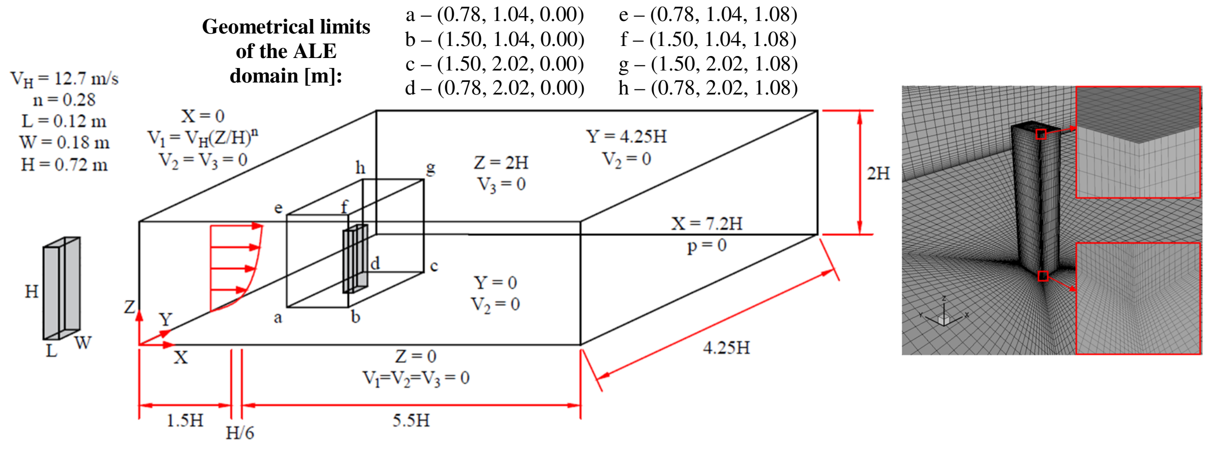

Figure 2. Geometrical characteristics and boundary conditions defined for the CAARC building analysis

The aerodynamic analysis is carried out considering a smooth wind flow (with no inflow turbulence) aligned with the X-axis of the computational domain, which is modeled using a boundary layer profile defined by a power law equation (see Fig. 2). Physical and geometrical properties utilized in fluid characterization are specified as follows (in a reduced scale): specific mass ρ = 1.25 kg/m³, dynamic viscosity μ = 1.825 x 10^{-5} Ns/m², volumetric viscosity λ = 0 Ns/m², artificial compressibility parameter c_f = 42.33 m/s, reference velocity V_H = 12.7 m/s and characteristic dimension W = 0.18 m. Notice that the previous parameters leads to a Reynolds number Re = 156,575. It is important to mention that a LES approach with dynamic sub-grid scale modeling is employed for turbulence analysis. The aerodynamic analysis is performed considering a time interval of 9 s, with a time step Δt

= 6.75 x 10^{-6} s.

The aerodynamic coefficients computed here are shown in Tab. 1, where the time-mean (C_{Fx} and C_{Fy}) and root mean square ($C_{\sigma Fx}$ and $C_{\sigma Fy}$) values for drag and lift forces are compared with the results reported by other authors. One can observe that results obtained here are very similar to experimental predictions presented by Obasaju [10] for smooth flow, where drag coefficient obtained in the present simulation is 20% and 10% lower than that predicted numerically by Huang et al. [5] and Braun and Awruch [4], respectively.

Table 1. Aerodynamic coefficients obtained for the CAARC building model

References	Aerodynamic coefficients			
	C_{Fx}	$C_{\sigma Fx}$	C_{Fy}	$C_{\sigma Fy}$
Present work	1.463	0.039	0.010	0.066
Braun and Awruch [4]	1.660	0.076	0.008	0.106
Obasaju [10] – smooth flow	1.490	0.060	-0.039	0.092
Huang et al. [5] – low turbulence	1.830	0.060	0.006	0.134

Measurements of mean pressure coefficients over the building perimeter at Z/H = 2/3 are presented in Fig. 3, where results obtained in this work are compared with other experimental and numerical predictions. Five experimental tests and three numerical simulations reported by other authors are used for comparison. Four out of these experimental investigations were conducted in different institutions and reported by Melbourne [2], while one of these is presented by Goliger and Mildford [11]. In addition, numerical simulations performed by Braun and Awruch [4], Huang et al. [5] and Shirkhanghah and Kalehsar [12] are also considered. A good agreement can be verified between the predictions obtained in this work for mean pressure coefficient and the respective measurements performed experimentally and numerically by other authors. Observe that results obtained on the front wall of the building ($0 \leq X'/L \leq 1.5$) showed a smaller discrepancy with the reference results than that observed when the remaining building walls are considered. Huang et al. [5] noticed that these differences may be attributed to experimental tests that were performed with years of difference, different blockage ratios and different characteristics of flow velocity profiles and turbulence intensity.

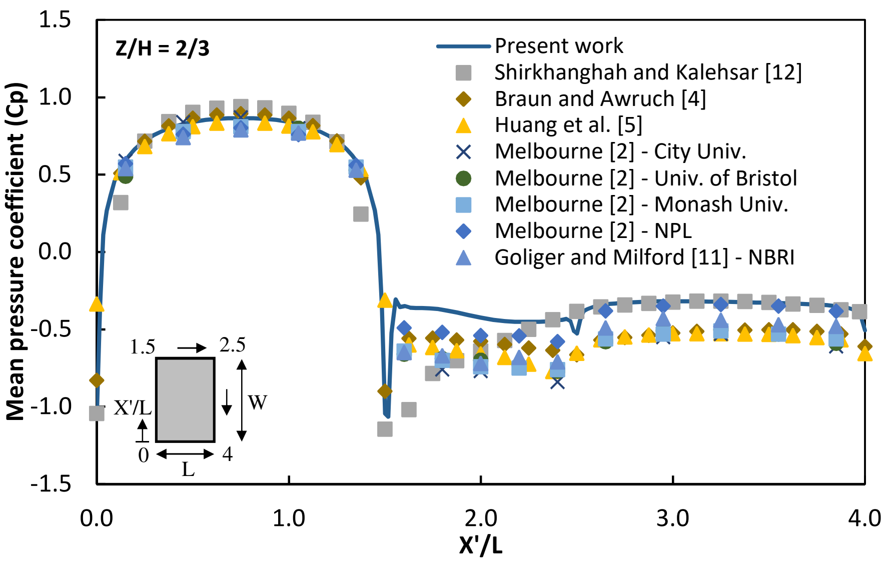

Figure 3. Mean pressure coefficients at Z/H = 2/3 for the CAARC building model

A three-dimensional view of the flow pattern around the CAARC building model may be obtained from the streamlines shown in Fig. 4. One can see that flow separation is observed at edges of the lateral and top walls, where air masses are directed upwards and later return to lower altitudes in the far wake region. A recirculating region is observed in front of the building near the floor of the computational domain, where a portion of the air masses, up to 0.75H, is directed downwards after colliding with the building.

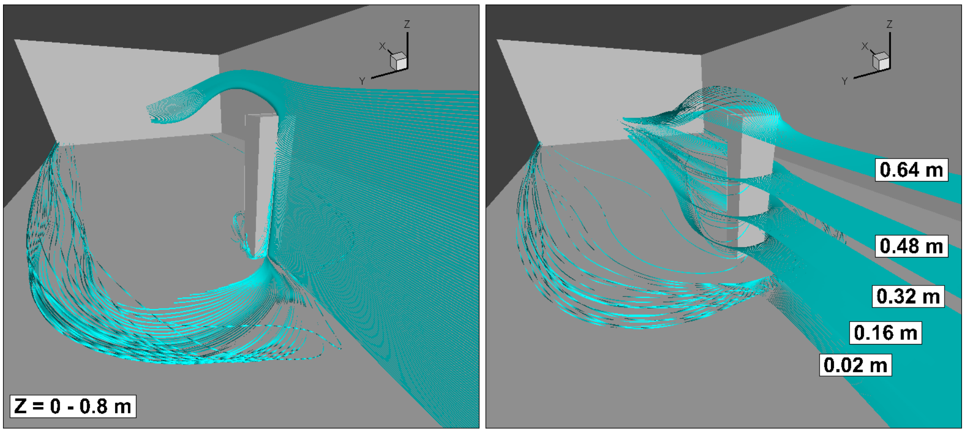

Figure 4. Three-dimensional streamlines obtained from the mean flow field for the CAARC building model

3.2 Aeroelastic analysis

The aeroelastic behavior of the CAARC building model is studied here considering different support conditions and five different reduced velocities ($V_{red} = V_H/f_n W$, where $f_n = 3.161$ is the structural natural frequency in a reduced scale): 2, 4, 6, 8 and 10. Initially, the building is numerically modeled considering a rigid base (RO models) in order to validate the present algorithm. After that, soil and foundation are added to the numerical models (LEO and NLO models) to evaluate their influence on the aeroelastic response of the structure, whose predictions are compared with the numerical results reported by Shirkhanghah and Kalehsar [12].

Geometrical characteristics and mesh configurations defined for building structure, foundation and soil modeling are shown in Fig. 5. Observe that non-matching meshes between the fluid and deformable solids are utilized. The CAARC building is spatially discretized using 2,220 hexahedral finite elements, considering an arrangement 6x10x37 according to the global axes. A raft footing is considered in this problem and modeled using 240 hexahedral finite elements with a spatial distribution of 10x12x2. Building structure and foundation are resting on a soil modeled with 8,760 hexahedral finite elements and 1,200 hexahedral infinite elements, located next to the side walls of the soil computational domain. Initially, the one-point quadrature technique is employed for all elements of the computational mesh. Nodes located on the base of the computational domain are totally fixed.

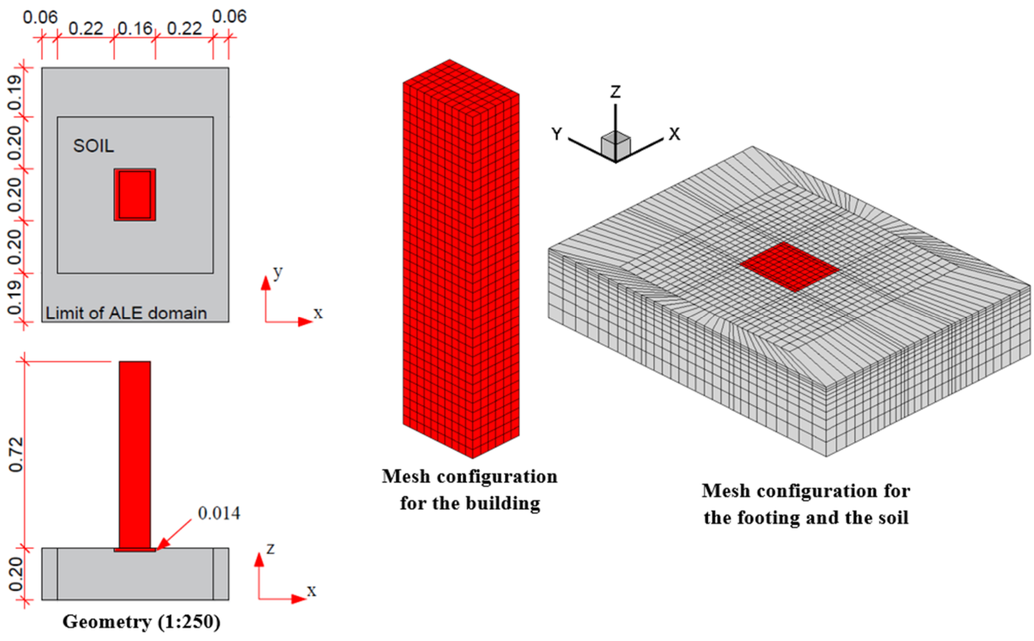

Figure 5. Geometrical characteristics and mesh configuration used for the aeroelastic analysis of the CAARC building model

Considering the geometric scale of 1:250, the footing dimensions are 0.16x0.20x0.014 m, while the soil domain is modeled with the following dimensions: 0.60x0.60x0.20 m. Observe that the geometry of the infinite elements is defined by the geometrical limits of the ALE domain, where mesh motion is permitted. Gravity loads are considered is this problem during the structural analysis, where structural and geostatic initial stress field are defined before wind load application.

The flow Reynolds number *Re* = 156,575 is maintained constant throughout the range of wind velocities analyzed by modifying the dynamic viscosity value, where different time steps are adopted according to the wind reduced velocity, from $\Delta t = 1.50\text{x}10^{-5}$ s to $7.50\text{x}10^{-5}$ s. The artificial parameter *c* is obtained here by setting the Mach number equal to 0.3. The aeroelastic analysis is performed over 2 s after the flow field is fully developed, considering 20 subcyles and spectral radius $r_\alpha = 0.8$. It is assumed that building and foundation structures have elastic behavior with properties specified as follows, respectively: Young's modulus $E = 1.25\text{x}10^6$ N/m² and $1.12\text{x}10^8$ N/m²; Poisson's ratio $\nu = 0.25$ and 0.20; and specific mass $\rho = 160$ kg/m³ and 2,400 kg/m³. On the other hand, two models are considered for the soil material: one considering an elastic behavior (LEO models) and the other assuming the Drucker-Prager yield criterion (NLO models), assuming coincidence along the outer edges with the Mohr-Coulomb surface. The soil properties are defined as follows: Young's modulus $E = 1.082\text{x}10^6$ N/m²; Poisson's ratio $\nu = 0.30$; specific mass $\rho = 2{,}160$ kg/m³; angle of friction $\phi = 46.22°$; and cohesion $c = 7.2$ N/m². Observe that the previous parameters are already scaled and no structural damping is considered in the models.

The contact interface between soil and foundation is considered with a friction coefficient $\mu_c = 0.84$ and different penalty parameters are used here according to the wind reduced velocity, ranging from $8\text{x}10^3$ N/m to $1.2\text{x}10^4$ N/m for the normal penalty parameter (k_N) and $2\text{x}10^3$ to $4\text{x}10^3$ for the tangential penalty parameter (k_T).

Mean and rms structural responses obtained from the time histories are normalized by the length (*L*) of the CAARC building and presented in Fig. 6 for the different models simulated as functions of the wind reduced velocity. The results obtained here are compared with the suggested curve presented by Melbourne [2], which represents a best fit to the experimental data, experimental predictions reported by Thepmongkorn et al. [3] and numerical results presented by Braun and Awruch [4] and Shirkhanghah and Kalehsar [12]. Notice that the curve obtained here for normalized mean displacements ($\bar{x}$/L) along the wind direction, considering the RO models, showed a good agreement with the reference results, particularly with the function proposed by Melbourne [2]. In contrast, the curve referring to the normalized rms displacements (σ_x/L) along the wind direction obtained with the present model, using the RO models, showed a similar result to those presented by Melbourne [2] and Thepmongkorn et al. [3].

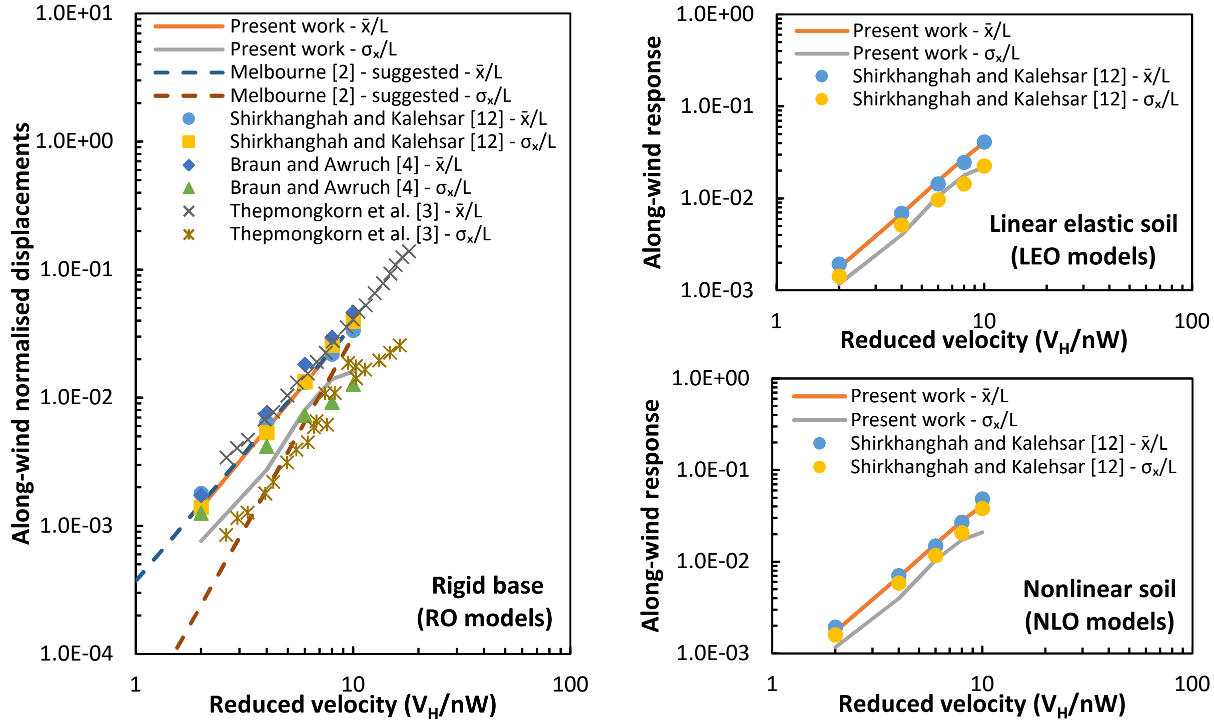

Figure 6. Along-wind normalized displacements as functions of the wind reduced velocity

Figure 6 shows that the soil presence in the numerical models (LEO and NLO models) led to higher values of $\bar{x}/L$, on average 20% higher, when compared to the models with rigid base (RO models) for all velocities evaluated in the present work. The same effect was observed with the σ_x/L values. In addition, results obtained in this work for LEO and NLO models are very similar and the curves of $\bar{x}/L$ obtained in this work for LEO and NLO models showed a good correlation with the results reported by Shirkhanghah and Kalehsar [12], although some differences can be noted when the curves of σ_x/L are compared. It is important to mention that numerical instabilities were observed during the analysis corresponding to the NLO models, which required the element technology of soil elements to be changed from one-point quadrature to the $\overline{B}$ method in order to ensure numerical stabilization.

4 Conclusions

Numerical simulations were performed in the present work in order to evaluate the effects of the wind action over the CAARC standard tall building model considering the influence of soil-foundation interaction. Regarding the aerodynamic analysis, measurements of mean pressure coefficients over the building perimeter and aerodynamic coefficients obtained in this work showed a satisfactory agreement with numerical and experimental results presented by other authors, reproducing the circulation patterns observed experimentally. Results obtained from the aeroelastic analysis showed a good agreement with the reference results and that the structural response was affected by the soil presence in the numerical models, leading to higher values of the mean along-wind displacements. Although results concerning numerical efficiency were not presented in this work, the hybrid CUDA-OpenMP approach showed a significant reduction in the processing time when compared with the processing time obtained with the corresponding serial algorithm.

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