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Sensitivity analysis of wind pressure coefficients on CAARC standard tall buildings in CFD simulations

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ABSTRACT

Constructing tall buildings has been a common trend for many cities due to rapid increase of population, therefore, it is essential to analyze wind pressure around and over these tall buildings. CFD simulation is an effective approach to realize this, in which CAARC (Commonwealth Advisory Aeronautical Research Council) standard tall building has been a well-acknowledged model to validate and calibrate tall building models. Nevertheless, less work has been conducted to study sensitivity of wind pressures over CAARC standard tall building to geometric and computational parameters in CFD simulation. This paper is therefore designed to fill this gap by analysing impacts of various parameters like turbulence model, approaching-flow speed and grid type on wind pressure coefficients over CAARC buildings. In this paper, wind pressure coefficients over CAARC models subjected to four wind directions were numerically analyzed for validating the correctness and effectiveness of numerical model. Sensitivity of wind pressures to geometric and computational parameters was analyzed through comparisons of deviation and absolute deviation. Results indicated that various phenomena such as fluid separation, vortex, wake effect and reattachment were sensitive to wind direction, resulting in great variations in wind pressure. Maximum positive wind pressure coefficients emerged around 0.8–0.85 H of windward surface, while maximum negative one occurred at foreside of top surface. Furthermore, turbulence model had significant influences on the accuracy of numerical results, where Realizable k-ε and SST were the most accurate turbulence models, and standard k-ε and RNG k-ε models were the second accurate ones, but BSL was not recommended for wind resistance design. Approaching-flow speed and grid type exerted insignificant influences on pressure coefficient distribution, while grid resolution had significant effects on negative wind pressure distribution. In general, conclusions obtained in this study can assist structural engineers to select practical geometric and computational parameters in predicting wind pressure distribution against tall buildings.

1. Introduction

In current society, to accommodate rapidly increasing urban population, promoting high-rise and tall buildings should be the only choice for people apart from sacrificing more lands. This has not only altered original wind field, but also exerted significant influences in many aspects, such as urban climate, built environment, human thermal comfort, health conditions, and structural safety [1–5]. Therefore, assessments of wind environment have developed into an indispensable theme to analyze pedestrian wind comfort, urban and building ventilation and wind loads [6–10]. For instance, wind pressure against building façades and rooftops is one of the most critical aspects of structural and architectural designs [5,6,10,11].

On tall buildings, wind pressure over windward sides enlarges along building height because of an exponential increase in wind speed. Wind pressure is a kind of random loads, vulnerable to a range of factors, e.g., building dimension and shapes, surrounding environments and wind characteristics [12–19]. Meanwhile, most tall buildings are characterized by diverse and complex appearances, so phenomena such as separation, vortex, stagnation, reverse flow, reattachment and recirculation around buildings turn out to be complicated [12]. Next is the interference effect of surrounding environments on building wind pressure. In many plots covered by dense tall buildings, wind speed in both horizontal and vertical directions can be strengthened, resulting in

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extremes of local wind pressure and different patterns of wind pressure distribution [14]. Therefore, building envelopes or curtain walls are easily affected. Additionally, patterns of pressure distribution are in relation to wind characteristics like wind direction, wind duration, and turbulent intensity [15–18]. Fluctuating wind, for example, can lead to building vibration, even local or whole damage [20].

Since the 1960s when people started to investigate wind pressure over buildings, four kinds of approaches have been developed and adopted in wind engineering, namely full-scale on-site measurement [21–23], reduced-scale wind tunnel test [24–28], theoretical studies and numerical simulation [29–32] including computational fluid dynamics (CFD). Data and materials obtained from field measurements offer a solid foundation for future advancement of the other three methods. Wind tunnel test and CFD simulation are currently two most used approaches, although their results should be verified firstly by on-site measurements. In accordance with conclusions derived from the above investigations, theoretical method is got involved to summarize some universal rules.

Full-scaled on-site measurements were conducted for a two-storied building in Aylesbury, England [22], a low-rise building at Texas Tech University in Lubbock, USA [23], a 78-storey Central Plaza in Hong Kong [33], China, a 69-storey Diwang Building in Shenzhen, China [34] and an 88-storey Jinmao Tower in Shanghai, China [35]. These measurements have supplied people with real wind loads and building responses which have inherently included full complexity. However, many limitations including changeable wind conditions, limited measuring points, instrument accuracy, safety and investments affect their wide employment in real practice [7]. Reduced-scale wind tunnel test, in accordance with principles of similarity and relativity, allows people to adjust and modify boundary conditions and settings to imitate real models [7,28]. Through this, pressure coefficients on large-size constructions and horizontal wind load can be repeatedly studied. However, there are difficulties in achieving similarity requirements, otherwise the accuracy of results cannot be guaranteed. Likewise, the number of measuring points over building surface is also restricted due to limited space [28].

CFD technology, compared with full-scale on-site measurements and reduced-scale wind tunnel test, is capable of offering data of all points in the whole wind field. Meanwhile, in CFD simulation, full-scale models are readily created, extricating buildings from requirements of similarity and relativity. More importantly, CFD simulations make parametric studies available through altering ground surfaces, approaching-flow conditions, surrounding physical environments, building configurations and arrangements [32]. Therefore, CFD has been adopted to assess wind pressure characteristics over building surfaces. For example, Elshaer et al. investigated the impacts of tall building corners on aerodynamic performances like mean drag coefficient and mean lift coefficient [6]. At the same time, effects of increasing buildings during urban development on tall building pressure coefficients were investigated by them via CFD simulation [36]. In addition, the impacts of dimension on the mean pressure coefficients on rectangular-shaped and oval-shaped tall buildings were numerically investigated [17,18].

To ensure the correctness and accuracy of numerical results, it is essential to validate and verify relevant models. Particularly, standard tall building model proposed by Commonwealth Advisory Aeronautical Research Council (CAARC) is also adopted to calibrate numerical results. Wind pressure coefficients over standard tall building were respectively measured by City University (CU, England), University of Bristol (BU, England), Monash University (MU, Australia), National Physical Laboratory (NPL, England) and National Aeronautical Establishment (NAE, Canada) and published in the 5th International Conference on Wind Effects on Buildings and Structures, London, 1975 [37]. Afterwards, CAARC models were experimentally analyzed through aeroelastic model [38,39]. In recent years, CAARC standard tall building has been numerically investigated in the aspects of mean and root mean square aerodynamic coefficients, wind-induced vibration, peak loading and surface pressure fluctuations, and assessments of interference effects [40–44]. Nevertheless, to the best of our knowledge, little work has been carried out to investigate the sensitivity of wind pressure coefficients on CAARC standard tall buildings in CFD simulations. Parameters including turbulence model, approaching wind speed, grid resolution and type were determined based on Montazeri and Blocken's research on wind pressures on buildings with balconies [7].

This paper therefore is designed to provide a comprehensive evaluation of variations of wind pressure coefficients over CAARC standard tall buildings in CFD simulations. Specifically, this paper will characterize patterns of wind pressure distribution over CAARC models, which are subjected to four types of wind directions. Afterwards, impacts of geometrical and computational parameters like turbulence model, approaching-flow speed and gird type on wind pressure coefficients over CAARC buildings will be identified. To complete the aim of this paper, the remainder of the paper is structured into the following sections. Section 2 presents parametric settings and boundary conditions of computational domain, followed by grid independence verification and results validation in Section 3. Section 4 presents sensitivity analysis from turbulence model, approaching wind speed and grid types, and then Section 5 concludes this study.

2. Parametric setting and boundary conditions

The model of CAARC standard tall building (with the dimension of 30.48 m × 45.72 m × 182.88 m) was put forward by in 1969 [45], aiming at providing scholars with an effective model to examine the reliability of results of reduced-scale wind tunnel tests. It is suggested that standard model should be set on an open space with flat and smooth terrain. Meanwhile, building surface is kept smooth and attached to nothing. The geometric model of CAARC is shown in Fig. 1(a).

Many institutions have measured the wind pressure coefficients of 20 measuring points at the 2/3 H of CAARC standard tall building in a clockwise direction, as shown in Fig. 1(b). Meanwhile, in their reports, wind pressure coefficients in different scenarios of wind directions have been investigated, and θ in Fig. 1(b) represents the angle between approaching wind and the long side of computational domain L in Fig. 1(a). Apart from CU, BU, MU NAE and NPL, Zhejiang University (ZU) examined wind effects on CAARC building, which was set on the land with surface categories of B (terrain conditions: Open lands, villages, jungles, hills, as well as towns and suburbs with sparse population) and C (terrain conditions: Urban complex with dense buildings) in wind tunnel tests, corresponding to surface roughness of 0.15 and 0.22, respectively [46,53]. Tongji University (TJ) experimentally studied wind pressure coefficients of CAARC standard tall building over terrain with surface roughness of 0.30 [48]. Table 1 summarizes information of various wind tunnel tests over CAARC standard tall building all over the world. Furthermore, it is pointed out that wind pressure coefficients at 2H/3 of CAARC model are sufficient for the purpose of model calibration, as shown in Table 2 [37,46,48], so that this study will also select wind pressure coefficients at 2H/3 of CAARC model for further comparison.

To imitate real environment around CAARC building, only CAARC model was built in the computational domain, and surrounding obstacles that can cause interference effects were not included. Nevertheless, for the establishment of an effective numerical model, many factors should be considered, such as dimension of computational domain, model geometry, grid resolution, boundary conditions, residual setting, and solver control. The following section will briefly introduce the parametric settings in CFD simulation.

2.1. Computational domain and model geometry

Although full-scale building model can be realized in numerical