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Atmospheric boundary-layer simulation for the built environment: Past, present and future

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ABSTRACT

This paper summarizes the state-of-the-art techniques used to simulate hurricane winds in atmospheric boundary-layer (ABL) for wind engineering testing. The wind tunnel simulation concept is presented along with its potential applications, advantages and challenges. ABL simulation at open-jet simulators is presented along with an application example followed by a discussion on the advantages and challenges of testing at these facilities. Some of the challenges and advantages of using computational fluid dynamics (CFD) are presented with an application example. The paper show that the way the wind can be simulated is complex and matching one parameter at full-scale may lead to a mismatch of other parameters. For instance, while large-scale testing is expected to improve Reynolds number and hence approach the full-scale scenario, it is challenging to generate large-scale turbulence in an artificially created wind. New testing protocols for low-rise structures and small-size architectural features are presented as an answer to challenging questions associated with both wind tunnel and open-jet testing. Results show that it is the testing protocol that can be adapted to enhance the prediction of full-scale physics in nature. Thinking out of the box and accepting non-traditional ABL is necessary to compensate for Reynolds effects and to allow for convenient experimentation. New research directions with focus on wind, rain and waves as well as other types of non-synoptic winds are needed, in addition to a more focus on the flow physics in the lower part of the ABL, where the major part of the infrastructure exists.

1. Introduction

1.1. Background

Atmospheric boundary-layer (ABL) involves wind which can be moderate, strong and destructive. Wind engineering analyzes effects of wind on the natural and the built environment and studies the possible damage, inconvenience or benefits which may result from wind. Wind engineering as a discipline grew out of the activities of a number of research establishments around the world in the 1950's and 1960's, including the National Physical Laboratory in Teddington and the Building Research Establishment in Watford [15,37]. Wind engineering draws upon meteorology, fluid dynamics, mechanics, geographic information systems and a number of specialist engineering disciplines including aerodynamics, and structural dynamics. ABL simulation at a relatively high resolution (wind structure) is very important for wind/structural engineering disciplines. The tools used include atmospheric models, wind tunnels, open-jet facilities and computational fluid dynamics (CFD) models. Although hurricanes occurs at large scales, the reproduction of the atmospheric wind characteristics within the lower part of the boundary-layer is very important as the interaction between the wind and the structures occurs in this part of the atmosphere. The physics involved in the ABL are essential for the understanding of wind impact on the built environment and the response of the infrastructure to extreme wind events.

1.2. Wind effects on the built environment and humans

It is true that we do not see the wind, but we can see its effects. A part from its benefits in the field of wind energy and air pollution dispersion, in the fields of building environment and structural engineering, strong winds may cause discomfort and extreme winds can cause widespread destruction. Extreme wind events can attack human safety (wind-induced injuries), lead to traffic accidents, and they can cause infrastructure to become severely damaged or even to reach a complete collapse (see Fig. 1). The wind

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Fig. 1. The Tacoma Narrows Bridge collapse on November 7, 1940 (Photo taken by Barney Elliott, presented according to fair-use principles; http://en.wikipedia.org/wiki/Tacoma_Narrows_Bridge_(1940)).

velocity characteristics and the physical properties of a structure are the most influential parameters that can govern the behavior of structures in a respond to wind actions [36]. Flexible structures tend to experience high oscillations that can cause pronounced damage and affect their serviceability, even under moderate wind speeds. For instance, when Tacoma Narrows bridge (see Fig. 1) collapsed it was moderate wind speed (about 40 mph), but negative aerodynamic damping or 'self-excitation' existed [19]. Besides, higher the wind speed, higher the amount of damage brought to the built environment by a wind event. Wind events can be distinguished based on the overall organization and behavior of the system, their geographic location, wind speed, and the dominant physical processes that produce the damaging winds. Hurricanes are the most powerful and wildly destructive storm systems on earth. In 2005, the well documented hurricane Katrina that ravaged Louisiana caused more than $75 billion in property damage with estimated economic impacts of more than $160 billion. Since the 1900, hurricanes related mortalities are more than 15,000 people in the U.S. According to a report published by the NOAA's National Climatic Data Center [89], in the year 2012, weather and climate disaster events caused losses exceeding $110 billion in damages and 377 deaths across the U.S. This makes the year 2012 as the 2nd costliest on record, after the year 2005. The major driver of damage costs in 2012 was hurricane Sandy at approximately $65 billion. During the 1980–2005 period, the U.S. sustained over $500 billion in overall inflation adjusted damages/costs due to weather and climate extreme events [75]. There is a significant increasing trend in annual aggregate losses in the frequency of billion-dollar disasters [83,103]. Although the fact that advanced forecasts and warnings (improved ability to predict landfall locations) and coordinated capability to evacuate populations at risk can help reduce the mortality [59,112,113,115], the economic impact of hurricanes, and other types of wind storms, on the built environment is huge [114]. Extreme winds can dislodge shingles and other roofing materials without impact from outside forces. Also, wind storms often knock down trees and limbs while sending dangerous, flying debris over long distances. Tree branches falling on cars or houses produce a significant amount of damage in high wind events. Debris can cause extensive damage to the roof and other parts of buildings [88]. Rain can cause additional damage during wind storms.

In calm (i.e., windless) weather, raindrops fall vertically. In wind, raindrop paths are oblique; the vertical component is called precipitation and the horizontal component is called wind-driven rain. While precipitation wets horizontal and sloped surfaces, wind-driven rain also humidifies vertical surfaces. The amount of water striking an enclosure in this way makes wind-driven rain a potentially damaging moisture source [54,82]. Wind-driven rain can cause water penetration into residential homes and damage to the walls, ceilings, interiors that leads to major disruption of households.

Besides its economic impact on the structures and the built environment, humans can experience 'mechanical' wind-induced injuries due to collapsed engineering structures, windborne debris and wind-induced traffic accidents [69]. There are various wind-induced problems of ground vehicles in cross-wind which may lead to vehicle overturning and wind-induced course deviations [15]. Large commercial trucks, high-sided and emergency vehicles (e.g. fire trucks) are especially vulnerable to single-vehicle crashes (e.g., rollover and sideslip) under hazardous driving environments on rural highways [29]. Many single-vehicle accidents have been reported around the world, for example, due to strong cross-wind and other factors ([15,30,49]. Each year, adverse weather alone is associated with more than 1.5 million vehicular crashes, which result in 800,000 injuries and 7000 fatalities in the U.S. [86]. In addition to scattered accidents, series concurrent accidents due to strong winds may turn out to be a catastrophe, especially those happening on the highways that may greatly delay or even obstruct the important transportation line before or upon the landfall of hurricanes [30].

Wind impact on humans and the built environment urged the need for wind tunnel and large scale testing, as well as numerical simulations. Therefore, the research on wind effects on the built environment has received considerable attention and up to the present many studies have been published. In any case, research focusing on the complex interaction between windstorms and the built environment needs an accurate simulation of the ABL.

1.3. Paper layout

This paper presents the state-of-the-art methods used to simulate hurricane winds in the ABL for wind engineering testing. Advantages, limitations, and proposed solutions to challenges associated with recent simulation techniques are discussed. The paper is organized as follows. Section 2 summarizes the basic characteristics of the wind in the ABL to help draw an image of a properly simulated wind. In Section 3, the wind tunnel simulation concept is presented along with its potential applications and advantages and challenges associated with this approach. Section 4 illustrates the simulation of the ABL in open-jet facilities, along with an application example followed by a discussion on the advantages and challenges with testing at these facilities. In Section 5, a short presentation about the potential applications of CFD techniques is given along with its challenges and advantages. Section 6 proposes new directions in wind engineering testing of low-rise structures and small-size architectural features as an answer to challenging questions associated with both wind tunnel and open-jet tests. Section 7 presents recommendations for future research in the area of ABL simulation for wind engineering. The conclusions drawn from the current paper are presented in Section 8.

2. Wind characteristics in the ABL

Wind blowing over the earth is classified according to its characteristics, strength and location. The most common types of winds that produces significant damage to the built environment are tornadoes, hurricanes (or tropical cyclones) and downbursts. Each type has its sole characteristics and its effect on the built environment is unique.