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Risk analysis of pedestrian and vehicle safety in windy environments

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ABSTRACT

Recent events in the UK, in which fatalities have occurred due to the existence of high wind speeds around new developments, have highlighted the need for a consistent set of criteria that can be used to assess the effect of new buildings on the safety of vehicles and pedestrians. This paper presents a risk analysis for assessing the risk of such incidents that unifies current rather disparate methodologies, and presents a novel and consistent risk based framework for the assessment of future building developments. The paper first discusses the nature of current methodologies, and argues that methods that are based on the probability distribution of wind velocities alone are not wholly adequate. The new methodology takes the wind velocity probability distribution functions that can be obtained from wind tunnel measurements and convolutes these with the cumulative distribution functions for human and vehicle instability in high winds to give a risk of an accident occurring and the consequences of the calculated risk. It is argued that such a risk based methodology allows for greater consistency in the application of any pedestrian/vehicle movement restrictions or alleviation methods. Finally other potential applications and extensions of the method are discussed – specifically the application of the proposed methodology to wind comfort studies and also to the problem of passenger instability caused by the slipstreams of trains.

1. Introduction

In the design of tall buildings it is normal practice to carry out a wind comfort study to assess the pedestrian wind environment around the base of the building, usually through a wind tunnel test or through CFD calculations (see the excellent "virtual" review by Blocken and Stathopoulos (2013) for further details). The data obtained from such a study is used in conjunction with local wind data to find the probability that, at different points around the building, specific wind speeds will be exceeded. These wind speed probabilities are then compared with a range of different criteria that indicate whether that particular point around the building will be suitable for different activities – e.g. sitting, walking etc. In some situations where high winds are expected, the possibility of "distress" is also considered – i.e. the probability of wind speeds exceeding levels that are regarded as dangerous for pedestrians. The wind speed criteria themselves can take on a variety of different forms and can be based on mean wind speeds, gust wind speeds, or some combination of mean and gust – see Table 1 for a collation of criteria from a wide variety of sources. In 2011 in Leeds in Northern England, a large lorry blew over close to the base of a recently erected tall building during windy conditions, killing one pedestrian and injuring another (Daily Telegraph, 2011, BBC, 2013). Since this building was completed in 2007, there have been numerous reports of pedestrians finding the wind conditions in the vicinity of the building uncomfortable at best and dangerous at worst, with a number of incidents of pedestrians being blown off their feet. This has led to a renewed interest in the distress criteria that are currently being used in the UK, and in the development of criteria for the stability of vehicles around new developments. When a building is being designed, the information that is required is an indication of the risk that pedestrians or vehicles will be blown over, that can be compared with a range of other risks and assessed for their acceptability. If these risks are not acceptable, then either building modifications will be required to bring the risk values to acceptable levels, or some operational criteria will need to be developed to exclude pedestrians or vehicles from specific areas, again such that the risk of an incident falls to acceptable levels. Such a consideration of risk requires both a consideration of the wind conditions around the building and of the behaviour of pedestrians or vehicles in high winds. Now, insofar as there is an agreed current practice, this is not the procedure that is generally carried out, with pedestrian distress and vehicle restriction criteria being based on wind speed magnitudes and probabilities of exceedance only – i.e. the effect of the wind on pedestrians and vehicles themselves is not usually considered except in an implicit way through the accepted criteria. The author

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Table 1
Wind speeds for pedestrian distress.

Author	Mean wind speed (m/s)	Gust wind speed (m/s)	Notes
Melbourne (1978)		23	Mean plus 3.5sd's
Penwarden (1973)	15–20		
Hunt et al. (1976)		15 (control of walking) 20 (danger)	Mean plus 3sd's
Lawson (2001)	14.1–17.3		
Soligo et al. (1998)	11.9–15	22.2–27.8	Mean plus 3.5sd's Compilation
Bottema et al. (1992)	10	15 (elderly people) 20 (young people)	Mean plus 2sd's
White (1992)		20	Compilation
LDCC (in Lawson (2001))		15	
Peters (1999)		12.5–20	Train gust
BRB (1971)		11 (passengers) 17 (trackside workers)	Train gust
CEN (2009)		15.5 (passengers) 22.0 (trackside workers)	Train gust

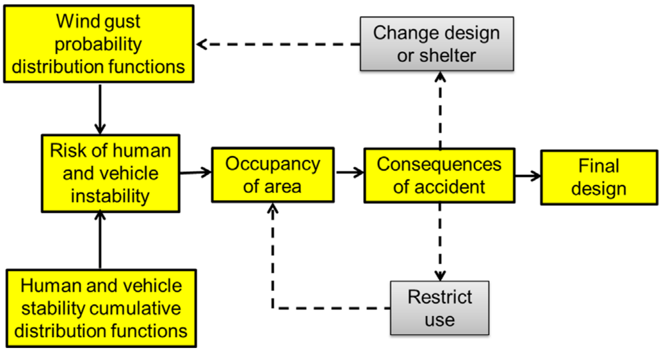

Fig. 1. Outline of the methodology.

would contend that, although such methodologies might be simple and pragmatic, they do not address the fundamental issue of the risk of an incident occurring. This paper will thus seek to address this point in what follows. The method that will be described is reasonably straightforward and is illustrated in Fig. 1. Firstly the cumulative wind speed distributions for instability for pedestrians and road vehicles are specified in a consistent way (Sections 2 and 3). These cumulative distributions are then convoluted with a wind gust speed probability distribution (which can be obtained from wind tunnel tests or unsteady CFD calculations) to give a risk of a pedestrian or road vehicle becoming unstable at a particular site (Section 4). Through a consideration of the occupancy of the area being considered, and the consequences of an accident, suitable alleviation methods can be developed, either through building modifications, or through restrictions on occupancy. An example of the use of this analysis framework is presented in Section 5. In Section 6 we consider how this framework might be extended and applied to other related problems (wind comfort assessment and passenger stability in train slipstreams). Brief conclusions and suggestions for further work are drawn in Section 7. An appendix derives the form of the Weibull probability distribution as it applies to gust speeds.

2. Pedestrian stability in high winds

In terms of response to wind gusts, there is a very great deal of person to person variation, as might be expected. This variation was assessed in Jordan et al. (2008), through the use of wind tunnel experiments where groups of students of both sexes were subjected to sudden gusts and their displacement measured. Note that these gusts are not necessarily representative of wind conditions around the base of buildings. Typical results are shown in Fig. 2 for pedestrians facing the oncoming wind (although very similar forms were found for other stances – with side or back to the oncoming wind for example). From a range of data such as this, for different pedestrian stances relative to the wind, we can express the c.d.f. of a particular group of individuals becoming unstable in a particular gust velocity u_i in a simple linear form

$$\mu = 0 \quad \text{for} \quad u_i < a$$

$$\mu = \frac{u-a}{b} \quad \text{for} \quad a < u_i < a+b$$

$$\mu = 1 \quad \text{for} \quad a+b < u_i \tag{1}$$

where a and b take on values that one would expect to be a function of size/weight/gender proportion etc. i.e. the form of Fig. 2 is approximated by straight line distributions. Now it is reasonable to assume that the form of the cumulative distribution will remain the same for any particular gender/age mix in the population being considered, but the values of the parameters a and b can be expected to vary from population to population.

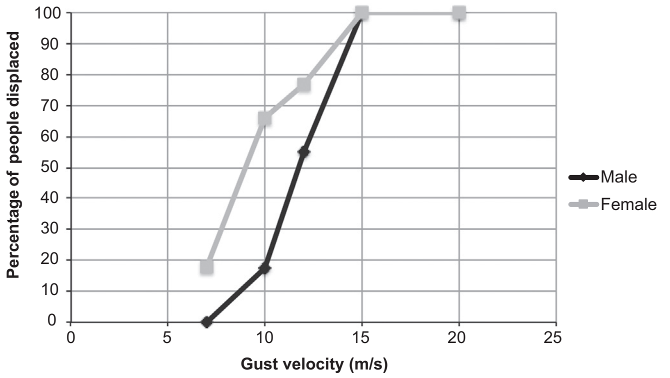

Fig. 2. CDF of displaced sample in sudden wind gust (facing oncoming wind) (Jordan et al., 2008).

3. Road vehicle stability in high winds

The road vehicles that are of particular concern in this paper are large vans and lorries, of the type studied in Sterling et al. (2010). Before considering how vehicle instability in high winds should be calculated, two observations need to be made. Firstly, whilst a number of investigations have carried out studies of vehicles in high winds, using models of the vehicle dynamic system of varying levels of complexity, all of these are too complex for routine use in the situation studied here, where the level of uncertainty concerning the nature of the wind field, acceptable risk etc., implies a simple, easily applied method is required. Secondly observations suggest that the type of accident of overwhelming concern is when such vehicles overturn about their leeward wheels. This in fact offers a possible way forward for a simplification. If we assume that this is the only instability mechanism of importance, a simple calculation can be carried out that only requires information on the rolling moment coefficient about the leeward wheel track – in a very similar way to that reported for trains in Baker (2013). That paper shows that, in the low yaw angle (ψ) range, these coefficients collapse onto a simple