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Wind-Borne Compact Debris Trajectory in Two-dimensional Turbulent Wind Fields

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SUMMARY:
This study examines the failure mechanism of compact wind-born debris (a sphere) by studying the trajectory in a two-dimensional flow domain that simulates atmospheric, turbulent wind field. The wind field simulation includes a vertical gust model that accounts for the aerodynamic interference around roofs, superimposed to random turbulence components in the horizontal and vertical directions. Debris trajectories in the turbulent wind field are predicted through a numerical model. A parametric study is conducted in a Monte-Carlo environment to understand the effects of several input variables on the debris trajectories. This study finds that the debris travel distance and velocity are mainly affected by three critical inputs: distance between source and target buildings, initial wind speed at the source building height, and Tachikawa number (a dimensionless parameter that measures the ratio between aerodynamic and gravity forces). The relationships between the main input parameters are further explored to understand if debris trajectories can be suitably approximated from a pre-generated data set. Details will be presented at the conference.

Keywords: wind-borne compact debris, turbulence, vertical gust, terminal velocity.

1. INTRODUCTION

Damage from wind-borne debris has been considered one of the major causes of building component failure during extreme windstorms. Most researchers (Lin et al., 2007; Moghim et al., 2014) have investigated the trajectories of wind-borne compact debris in uniform wind velocity fields, without considering turbulence, or in an open-terrain condition with homogeneous turbulence. However, there are few studies (e.g., Kordi and Kopp, 2011) available on the topic of compact debris trajectory accounting for local wind fields and building roof aerodynamics.

In this study, wind-borne compact debris, such as roof gravel, trajectories in a two-dimensional (2D) flow domain are estimated using computer-generated turbulent wind fields. The turbulent wind fields are implemented in conjunction with existing numerical models from a previous study (Moghim and Caracoglia, 2012) to simulate the liftoff conditions. In addition, parametric studies are conducted numerically to investigate the effects of various systemic variables, such as mean wind velocity, debris release height (initial liftoff position), and Tachikawa number, on the behavior of wind-borne compact debris trajectories, incorporating the random nature of turbulence.

2. METHODS

In this study, a 2D domain is employed. As shown in Figure 1, there are two types of buildings in a typical debris trajectory problem. Source building is where the roof gravel becomes wind-borne debris. “Target building” is where the wind-borne debris can hit and cause damage. The quantity x_{target} is introduced to represent the distance between source and target buildings. The outputs from the numerical simulations are the terminal height (z), relative terminal height ($z_r = z - h_0$), terminal velocity (V), and kinetic energy (KE), as shown in Figure 1.

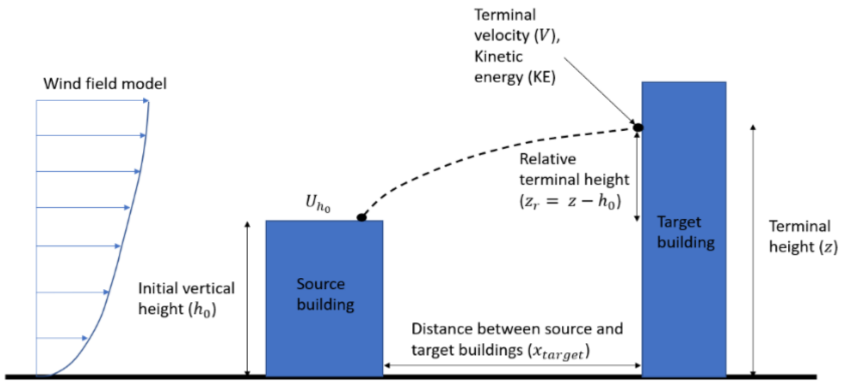

Figure 1. Sketch of the wind-borne debris flight model.

The wind field model implemented in this study includes three components, namely the mean wind profile, the turbulent wind field, and a simulated vertical gust model. The mean wind profile accounts for the variation of mean wind velocity in the vertical direction. The turbulent wind field is simulated using the wave superposition method, developed by Di Paola (1998). A wind field generation approach using propagation of turbulence, derived by the third author in the recent past, is implemented in this work to simulate turbulent wind conditions accurately and efficiently in a 2D domain. The vertical gust model is a simplified step-like upward gust model. The duration and magnitude of the vertical gust are pre-defined with magnitude normalized with respect to the horizontal mean wind speed. The combination of the three models can simulate the complex wind field, associated with turbulence and accounts for interference of nearby building roofs (debris source) and their aerodynamics (Dong et al., 2023).

The nondimensional 2D equations of motion describing the debris trajectories, developed by Tachikawa (1983), are used in this work to simulate the trajectories of spherical compact debris in turbulent wind field by ignoring the rotation of compact debris (i.e., the debris moment coefficients are zero). The equations of motion include two degrees of freedom of a debris element; they are used within a state-space formulation and numerically solved by a 5^{th} order Runge-Kutta method. It was observed that the debris trajectories in turbulent wind are not deterministic even with the same input parameters. Therefore, the numerical solutions must be carried out in a Monte-Carlo (MC) setting, since the computer-generated turbulence, unlike all other inputs, is not deterministic.

3. PRELIMINARY RESULTS

To investigate how the debris trajectories are affected by various conditions, a parametric study is designed and conducted. Inputs that can be changed in this parametric study are divided into three groups, namely the building information, the wind field model, and the debris model. Other associated inputs in the numerical model are the same in any simulation settings.

1. Building information: the height of the source building (h_0) is uniformly selected in a pre-defined range. The distance between source and target buildings is introduced in the post-processing of numerical results.
2. Wind field model: mean wind speed at 10-meter height (U_{10}) is uniformly selected in a pre-defined range.

3. Debris model: Debris drag and lift coefficients (C_D, C_L) can vary randomly for compact debris according to previous studies (Ahsanullah et al., 2021; Chai et al., 2019). The Tachikawa number $(K = 3\rho_a U^2/4\rho_d g d)$ is a function of air density (ρ_a), debris density (ρ_d), debris diameter (d), standard gravity (g), and the wind speed (U) at the height of the source building. The first three parameters follow uniform distributions based on previous study (Doddipatla and Kopp, 2019).

The mean and coefficient of variation (COV) associated with debris travel distance and velocity are investigated with the variables described above. The inputs are independent of each other, resulting in 48 cases accounting for different combinations of input parameters. Example results are presented and discussed below.

Figure 2 shows how K affects the mean and COV of the relative terminal height, z_r at different target distances, x_{target}. The debris have higher values of z_r with larger values of K for any given x_{target} because the larger K represents relatively light debris for the same wind speeds. It can be observed that the relationships between K and mean values and COV may follow second-order polynomials. Figure 3 presents how K affects the mean of $z_r = (z - h_o)$ and the terminal velocity (V) for different combinations of U_{10}, and h_0 (various line styles) for x_{target} = 18 m. It can be found that V increases linearly with respect to K, while z_r reaches certain limits (i.e., second-order polynomials) for larger K values as described before.

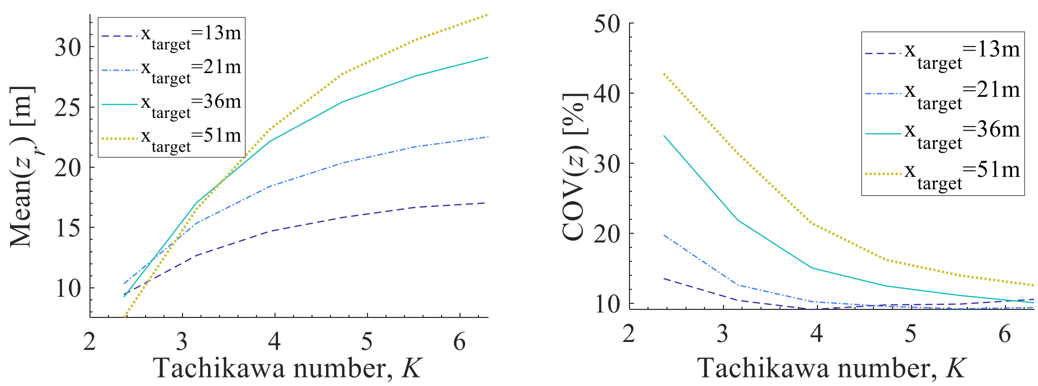

Figure 2. Mean and COV of z_r vs. K when $h_0 = 50\,ft\,[15\,m], U_{10} = 90\,mph\,[40\,m/s]$.

Complete results and discussions about how different inputs (e.g., x_{target}, U_{10}, h_0, etc.) affect the statistical moments of terminal height, relative terminal height and terminal velocity will be presented during the conference. In addition, investigations on the approximate estimation of debris trajectories without solving the physical models are also conducted based on numerical results from the parametric study, which will also be presented at the conference.

4. CONCLUSIONS

This study extends previous research on wind-borne compact debris trajectory and implements a computer-generated turbulent wind field model. The turbulent model includes a vertical gust model that simulates local flow effects and turbulence components in horizontal and vertical directions. Preliminary results show that the numerical debris trajectories must be expressed in statistical moments because of the randomness in turbulent wind fields. The observations of the numerical results also suggest that it is necessary to consider the effects of turbulence and roof aerodynamics; ignoring these effects will significantly under-predict the outputs. More discussions associated with the source building's aerodynamics will be presented at the conference. Various combinations of the inputs were employed in the numerical models to analyze the effects of different inputs on debris trajectory. It was found that the debris trajectories in atmospheric turbulence can be approximated from a pre-generated data set with reasonable accuracy.

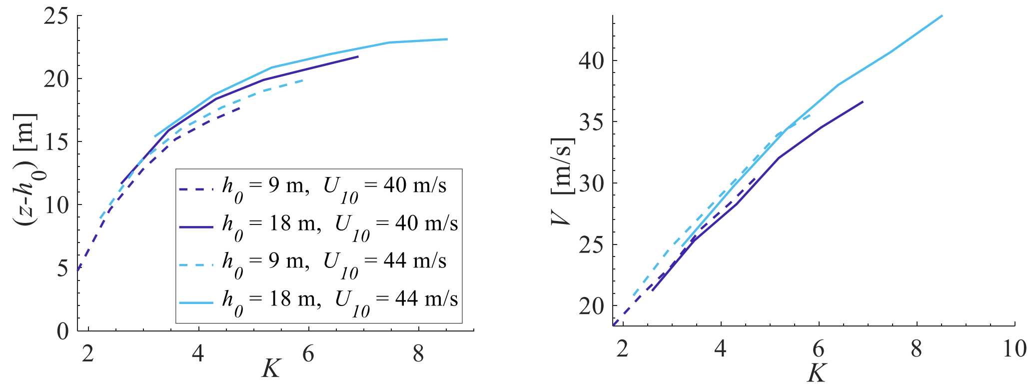

Figure 3. (Left) Mean of $z_r = (z - h_0)$ and (right) mean of V vs. K at $x_{target} = 18\ m$.

The main contribution of this study is the investigation of turbulence and vertical gust effects on compact debris trajectory. In addition, parametric studies that examined the effects of various inputs on debris trajectory in a setting suggest that the complexity of the debris flight problem may be simplified by considering a minimal number of critical inputs. Numerical results, presented in this study, require a more comprehensive investigation that includes experimental validation.

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