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# Effects of non-erodible particles on aeolian erosion: Wind-tunnel simulations of a sand oblong storage pile

B. Furieri [a,b,*], S. Russeil [a,b], J.M. Santos [c], J.L. Harion [a,b]

[a] Univ Lille Nord de France, F-59500 Lille, France
[b] Mines Douai, EI, F-59500 Douai, France
[c] Universidade Federal do Espírito Santo, DEA, 29060-970 Vitória, ES, Brazil

## HIGHLIGHTS

- Oblong stockpile models made of bimodal sand exposed to erosion in wind tunnel.
- Emitted mass flux of particles continuously measured during experimental tests.
- Decrease of particle emission over time is found for all tests.
- Strong influence of non-erodible particles percentage on mass emitted.
- Erosion zones identified by photographs of pile surface.

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## ABSTRACT

Non-erodible particles have strong influence on the aeolian erosion phenomena. An oblong stockpile model of sand (bimodal granulometry) was implemented to perform wind-tunnel experiments as similar literature works have only carried out experimental investigations on a flat bed of particles. Thus, the influence of the fluid flow structures around the complex obstacle will be analysed. The tested configurations consisted of two different values of non-erodible particles cover rate (10% and 20%), and three free stream velocities (6, 7 and 8 m $s^{-1}$). Good repeatability was found. The results showed that the largest amount of particles emitted was for the highest wind velocity and the smallest cover rate. The temporal decreasing of emitted mass flux was found steeper for larger amount of non-erodible particles and higher velocity. The mass flux of particles decreases very strongly in the first four minutes of measurements and the cover rate influences this downward sloping. The same analysis applies for the effects of the free stream velocity. The qualitative analysis (high quality photographic system) of the stockpile surface gradual change has shown that non-erodible particles aggregation induces a pavement effect on some areas of the pile. This analysis indicated typical wind erosion zones: high wall friction on the crest line and lateral sides; low wall friction on the windward wall near the ground and on the recirculation downstream the leeward wall. The results and discussions presented here allows for the understanding of the impact of non-erodible particle on dust emissions.



## 1. Introduction

The phenomenon of dust emission from piles of granular material exposed to wind erosion has been studied by many researchers using different tools such as computational fluid dynamics, field and wind-tunnel experimental analysis. The studies of Cong et al. (2011), McKenna-Neuman et al. (2009) and Roney and White (2006) are examples of aeolian erosion investigation of diffuse sources found in literature. Cong et al. (2011) carried out a CFD study (validated by precedent field and experimental measurements) to verify the role of porous fences in reducing dust emissions which was confirmed. McKenna-Neuman et al. (2009) have evaluated some environmental control techniques of diffuse dust emissions from mine tailings by wind-tunnel simulations. Roney and White (2006) estimated dust emission by means of wind-tunnel experiments in which near surface steady-state concentration profiles and velocity profiles are obtained in order to use a control volume approach to estimate emission rates. The estimated emission rates are comparable to those obtained from field

* Corresponding author. Mines Douai, EI, F-59500 Douai, France.
*E-mail address:* furieribruno@gmail.com (B. Furieri).

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studies and lend to the validity of the wind-tunnel method for determining fugitive dust emission rates.

The granular material subjected to wind erosion is constituted by particles that are classified based on their inertia, as erodible or non-erodible. Discussions concerning non-erodible particles and the erodibility of surfaces were carried out in various studies (Gillette and Stockton, 1989; Roney and White, 2006, 2010; Benkhaldoun et al., 2012; Webb and Strong, 2011). In general, the authors have concluded that the amount of particles emitted due to wind erosion is strongly attenuated by the presence of non-erodible particles.

The studies of McKenna-Neuman and Nickling (1995), Li and Martz (1995) and Descamps et al. (2005) performed, over flat beds of particles, numerical simulations and experimental wind-tunnel tests. The emitted mass flux was found to decrease with time due to the presence of non-erodible particles causing a phenomena called "pavement effect" which represents the influence of non-erodible particles on the taking-off of erodible particles. The "pavement effect" is the erodible surface covering by the non-erodible particles, i.e., erodible particles are impeded to take-off.

Other studies have carried out numerical and theoretical investigations about the local impact of non-erodible particles, i.e., at the scale of one particle (Raupach et al., 1993; Gillies et al., 2007; Turpin et al., 2010). These studies analysed the micro-scale features of the fluid flow, using numerical simulations around a given number of non-erodible particles. Raupach et al. (1993) have developed a theory to describe the dependence upon roughness density of a ratio of threshold friction velocities (between a surface without and a surface with roughness elements). Gillies et al. (2007) have evaluated the shear stress behaviour on complex rough surfaces. A drag plate was constructed to measure the surface shearing stress on representative surface samples in a wind-tunnel boundary layer. In Turpin et al. (2010), the numerical domain is a narrow area surrounding one particle or an array of well defined particles. The numerical simulations results indicated that the mean friction velocity decreases as the number of non-erodible particles increases and the amount of dust emitted depends on the friction velocity. Thus, the emitted mass flux tends to decay as non-erodible particles cover the stockpile surface.

Summing up the literature, numerous works have already performed wind-tunnel simulations of flat beds, sinusoidal or conic piles to investigate the influence of non-erodible particles on dust emission. However, none of them examined oblong piles. Thus, experimental wind tunnel tests on oblong piles (for instance, those found in industrial sites of steel production) are firstly carried out in the present study. The shape and dimensions of the pile were similar to those tested in the studies of Turpin and Harion (2009) and Furieri et al. (2012) in which the air flow pattern on and around the oblong shaped stockpile is discussed. In the present work, the wind-tunnel tests are carried out for two proportions of non-erodible particles (mass of non-erodible particles divided by the total mass of particles in the stockpile) and three free stream velocity values using a bimodal distribution of sand (two main mean particles diameters, 125 μm and 850 μm). The expected results aims to give a better comprehension of the local fluid flow mechanisms surrounding the non-erodible particles as well as the global quantification of the influence of velocity and cover rate on the emissions.

## 2. Experimental set-up

### *2.1. Wind-tunnel and measurements procedures*

The experimental investigation was conducted in a wind-tunnel. During the experimental measurements weighing of the stockpile model was performed and high quality photographs were taken using a system installed perpendicularly above the wind-tunnel test section.

The wind-tunnel presented in Fig. 1 has the same fundamental characteristics of that described by Furieri et al. (2012) in which a surface flow visualization technique was performed. At the inlet of the test section, a turbulent boundary layer was created by means of several obstacles placed upstream the zone of measurements. The test section was modified in order to allow continuous weighing of the sand stockpile mass. Fig. 1 presents the weighing system placed inside an airtight box underneath the circular plate (test section). The airtightness is necessary to avoid flow disturbances. The weighing device is the electronic balance BEL Engineering Mark K30.1 which has a resolution of 0.1 g. Records measurements at a frequency of 5 Hz are controlled by a program developed within Labview software. Typical records present high signal-to-noise ratio caused by:

- turbulence inherent to the fluid flow,
- vibrations of the circular plate ((iii) in Fig. 1) and
- instabilities of the balance support system ((i) in Fig. 1).

The plot (A) in Fig. 2 shows the time series of raw data and its post-treatment. The procedure to obtain the final curve that represents the temporal variation of emitted mass flux (emitted mass per units of time and surface of the eroded pile) is presented in the plots (B)–(E) in Fig. 2. In order to process the raw data, five steps were followed:

- (1) Calculation of the moving average (period of 60 s) to reduce the data fluctuations seen in (A) in Fig. 2. The graphic (B) in Fig. 2 represents the result of this averaging procedure;
- (2) Discretization of the mass evaluated each minute (plot (C)). For instance, the mass of time instant equal to 1 min is the average of the data measured between 0′30″ and 1′30″;
- (3) Calculation of the discretized emitted mass as shown in Equation (1):

$$m_{\text{emitted}}(t_i) = m_{\text{initial}} - m(t_i) \quad (1)$$

where, $m_{\text{emitted}}(t_i)$ is the calculated emitted mass, $m_{\text{initial}}$ is mass at the beginning of the experiment and $m(t_i)$ is the mass at the time instant $i$. $i$ varies from 0 (beginning of experiment) to $N$ (end of experiment);

- (4) Calculation of the emitted mass flux (Equation (2)). The emitted mass flux is the amount of emitted mass to the free stream flow per unit of area and time. (E) in Fig. 2 shows the time series of emitted mass flux;

$$Q_{t_i} = \frac{m_{\text{emitted}}(t_i) - m_{\text{emitted}}(t_{i-1})}{(t_i - t_{i-1}) \cdot S} \quad (2)$$

where, $Q$ is the emitted mass flux in g min$^{-1}$ m$^2$, $t$ is the time in minutes, $m$ is the mass in g and $S$ is the area of the stockpile model surface in $m^2$.

- (5) Fitting with an exponential curve (Equation (3)) as seen in (E). Values of the coefficients $A$ and $b$ are determined by means of the least square method.

$$Q_{(i)} = A \cdot e^{-bt_i} \quad (3)$$