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An experimental and numerical study of the aeolian erosion of isolated and successive piles

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1 **An experimental and numerical study of the aeolian**
2 **erosion of isolated and successive piles**

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7
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9 **Abstract** Open storage yards at industrial sites usually comprise several piles of
10 granular materials, representing a particulate matter source that may significantly
11 deteriorate air quality. The aeolian erosion of stockpiles is affected by changes in
12 airflow patterns due to the pile shape and the presence of nearby piles or build-
13 ings. The aim of this study was to analyse the impact of wind erosion of successive
14 parallel stockpiles on flow behaviour and particle emissions. A wind tunnel exper-
15 iment was conducted in six configurations: one isolated pile and two successive
16 piles separated by gaps of $0.9h$ and $1.8h$ (h is the pile height) oriented to 60° and
17 90° with respect to the main wind flow direction. The particles in the piles had a
18 bimodal particle size distribution consisting of sand that was erodible (white) and
19 non-erodible (black) in the investigated velocity range. The contrasting colours
20 enabled the visualisation of the non-erodible sand accumulation. The mean field
21 of the wall shear stress distribution and flow pathlines predicted by numerical
22 simulation were associated with the experimental erosion patterns. The emitted
23 mass was experimentally quantified as the difference between the initial and final

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24 stockpile weights. Downstream pile had a large impact on the aeolian erosion as
25 it was highly eroded as a result of the impact of the particles emitted from the
26 upstream pile. The emissions of the two consecutive stockpiles were greater than
27 twice the emissions from an isolated stockpile for both orientations. Additionally,
28 emissions were lower for configurations in which the piles were perpendicular.

29 **Keywords** Wind Erosion · Pavement · Fugitive Emissions · Turbulent flow ·
30 Wind Tunnel · Emission Measurements

31 1 Introduction

32 Diffuse emission from the aeolian erosion of granular materials from stockpiles or
33 exposed granular beds may be difficult to quantify due to the large extension and
34 shapes of the sources and the factors that affect the process such as atmospheric
35 conditions (e.g., wind velocity and direction, precipitation, humidity and temper-
36 ature), particle size distribution, modification of the wind flow due to the presence
37 of obstacles and topography (e.g., flat or inclined surfaces). Granular materials
38 typically have a wide particle size distribution, including larger grains that may
39 not be lifted by wind. As erosion occurs, the concentration of the coarser particles
40 on the pile surface increases. It has been verified that the accumulation of these
41 grains plays a protective role in particle emissions, whether on a flat or an inclined
42 surface [13, 21, 28, 29, 38]. Non-erodible particles create wake zones, reducing the
43 drag on pile zones that would otherwise be erodible. A temporal decrease thereby
44 occurs for the emitted mass flux, and the total amount of particles emitted due to
45 wind erosion is strongly reduced, which is known as the pavement phenomenon.

46 The most widely used methodology to estimate fugitive dust emissions has
47 been developed by the USEPA (United States Environmental Protection Agency)
48 [35], based on data from wind tunnel experiments for two geometries of isolated
49 stockpiles and three wind flow directions, and does not consider the pavement
50 phenomenon. The rapid decrease in aeolian emissions linked to a wide size dis-
51 tribution is mentioned in USEPA [35], but it is not explicitly incorporated in the
52 proposed method. The particle size distribution is also not explicitly incorporated
53 into the method. So, if the model was applied to two granular materials with very
54 different particle size distributions but the same maximum particle diameter, it
55 would result in similar emission values. Experimental results show that wind ero-
56 sion emissions can be widely different with the same maximum particle diameter
57 but a greater proportion of larger particles which are non-erodible. Furthermore,
58 the various configurations of different piles shapes that can be found at industrial
59 sites are not covered by the elements provided by USEPA [35]. Industrial facilities
60 usually contain more than one storage pile, which greatly affects erosion patterns
61 since piles act as obstacles to the free path of atmospheric flow, modifying the
62 flow field dynamics. Therefore, it is important to broaden the models application
63 to more realistic situations. Several researchers have already performed this using
64 both numerical (Computation Fluid Dynamics - CFD) and experimental (wind
65 tunnel) approaches to investigate the physical phenomenon of wind erosion of
66 granular materials beds and storage piles [8, 16, 17, 22, 24, 25, 32, 37, 39].

67 Badr and Harion [3] and Torano et al. [30] numerically predicted the wind
68 flow over isolated piles in different scenarios with various geometries and wind

orientations and used the USEPA formulation for the emission factor to quantify particle emissions using the friction velocity previously calculated by CFD. Turpin and Harion [33] investigated the flow structures over coal stockpiles in an actual power plant configuration. The authors performed numerical simulations in a configuration that included three coal stockpiles and different buildings in the surrounding area, and found that upstream buildings significantly increased emissions from the piles. Nevertheless, if the stockpile was located upstream of the buildings in the configurations tested by Turpin and Harion [33], then the erosion processes was slightly attenuated by a flow stagnation zone upstream of the buildings. The authors concluded that all wind perturbations including surrounding buildings and stockpiles have an impact, and must be accounted for in dust emissions estimation. Diego et al. [6] and Cong et al. [5] employed similar techniques to estimate dust emissions by integrating CFD data into the USEPA methodology. The former work studied the wind flow around an arrangement of two parallel flat-crested stockpiles separated by a gap of $0.44h$ (where h is the height of the piles) and highlighted the different contribution from each pile to the total eroded dust. The latter work evaluated dust emissions in an open yard with a complex geometry (16 stockpiles arranged in 4 columns) varying the pile shape (flat-topped oval and conical), the gap between the piles ($0.6h$ and $1.2h$) and the orientation of the wind direction (from 0 to 90°). In both studies, a sheltering effect created by the neighbouring piles was noticed, which resulted in lower dust emissions. It is found that the front pile created a downstream shelter, then the wind velocity over the back pile was reduced. However, Cong et al. [5] verified that the total dust emissions are greater when the gaps between piles are larger. The authors implied that a gap larger than the shelter area completely exposes the downstream piles to wind erosion, similar to an isolated pile. In addition, it has been suggested that more studies with arbitrary space variation between the piles are necessary to better understand the role of the stockpile layout in limiting wind erosion in an actual yard. Furieri et al. [11] compared emissions (using CFD and emission factors) from an isolated and two successive oblong stockpiles separated by $0.9h$ and $1.8h$ gaps oriented by 60° to the main wind flow direction. Numerical results showed that an isolated stockpile emitted less dust than each pile in the successive pile configuration. Therefore, a protective role of the upstream pile was not observed. Ferreira and Fino [7] performed wind tunnel experiments to study the erosion of an isolated sinusoidal pile and the interference effect resulting from two closely spaced piles (gaps of 0 and h). The authors found that the aeolian erosion of the downstream pile was considerably larger due to flow disturbances induced by the first pile. Therefore, the literature is contradictory, and the wind erosion of two parallel piles still requires additional investigation.

This study aimed to investigate, through numerical and experimental approaches, the impact of several configurations of parallel piles on wind erosion and the effect on emissions of the proportion of non-erodible particles. The parameters analysed were (i) wind velocity, (ii) the orientation of the piles to the main flow direction and (iii) the gap distance between the piles. A wind tunnel experiment was performed to estimate and compare emissions from an isolated sand pile and from two successive piles. The particles that constituted the piles had a bimodal particle size distribution encompassing erodible and non-erodible particles in two different proportions. The accumulation of non-erodible particles enabled an analysis of the erosion patterns of the piles. Numerical simulations with

118 identical configurations were carried out to obtain the wall shear stress distribu-
 119 tion on the pile surface and the flow pathlines, which support our understanding
 120 of the physical phenomena.

121 2 Experimental study

122 The experiment was conducted in the wind tunnel facilities at the Industrial En-
 123 ergy Department (IMT Lille Douai, France). Figure 1 shows the experimental
 124 set-up and the principal dimensions of the wind tunnel. Multiple roughness obsta-
 125 cles were placed in rows close to the tunnel entrance to enable the formation of
 126 a turbulent boundary layer. The validation of the experimental profiles upstream
 127 the test section is based on the comparison between measured profiles of velocity
 128 and turbulent kinetic energy (carried out in the same wind tunnel by Turpin [31]
 129 and Furieri et al. [12]) and the profiles of fully developed turbulent boundary layer
 130 from the literature [26]. In the vicinity of the wall, the velocity profile follows the
 131 linear law and then, moving away from the wall, follows the logarithmic law. The
 132 wind-tunnel generates a fully developed turbulent boundary layer at the level of
 133 the measurement zone with a thickness greater than the stockpile height ($\delta = 16$
 134 $cm > h = 7.7 cm$). More details of the wind-tunnel characteristics are given by
 135 Furieri et al. [12] and Turpin [31]. The Reynolds number of the fluid flow inside the
 136 wind-tunnel is approximately between 36000 and 48000 based on the free stream
 137 velocity (from 6 to 8 m/s) and stockpile height.

138 A bimodal granulometry of sand with density equal to $2650 kg/m^3$ was used
 139 to represent erodible and non-erodible particles: fine white sand and coarse black
 140 sand with ranges of diameters from 56.0 to 194.2 μm and from 700.0 to 1300.0
 141 μm , respectively. The sand colours allowed the visualisation of high shear stress
 142 zones, which were marked by the accumulation of non-erodible particles.

143 The threshold friction velocities $u_{t_{min}}^*$ and $u_{t_{max}}^*$ at which the largest erodible
 144 particles (194.2 μm) and the smallest non-erodible particles (700.0 μm), re-
 145 spectively, are lifted from a horizontal surface were calculated using the take-off
 146 criterion obtained by Shao and Lu [27]:

$$u_{t_s}^* = 0.11 \sqrt{\frac{\rho_P - \rho}{\rho} gD + \frac{\gamma}{\rho D}}, \quad (1)$$

147 where $u_{t_s}^*$ is the threshold friction velocity, ρ is the fluid density, ρ_P is the particle
 148 density, g is the gravity, D is the particle diameter and γ is a surface energy that
 149 characterises the cohesion. Shao and Lu [27] recommended values of γ ranging
 150 between 1.65×10^{-4} and $5.00 \times 10^{-4} kg/s^2$. In the present work, $\gamma = 2.86 \times$
 151 $10^{-4} kg/s^2$ was adopted. This value was calculated by fitting Equation 1 to the
 152 experimental threshold required to lift loose particles as proposed by Kok and
 153 Renno [19].

154 Figure 2 shows the take off-criterion, the fine and coarse sand size ranges used
 155 for the experiments and the friction velocities $u_{t_{min}}^* = 0.23 m/s$ and $u_{t_{max}}^* = 0.42$
 156 m/s . The corresponding freestream flow velocities U_{min} and U_{max} , determined
 157 based on $u_{t_{min}}^*$ and $u_{t_{max}}^*$, were calculated using the expression proposed by Kurose
 158 and Komori [20]:

$$u^* = u_{smooth}^* (1 + 0.00431h^+), \quad (2)$$

160

161 where h^+ is the dimensionless mean diameter of the non-erodible particles ($h^+ =$
 162 $h_{NEP} u_s^* / \nu$, where h_{NEP} is the mean diameter of the non-erodible particles, and
 163 ν is the kinematic viscosity), and u_{smooth}^* is the friction velocity in a smooth wall.
 164 It is calculated by the relation proposed by Mollinger and Nieuwstadt [23]:

$$u_{smooth}^* = 0.036U_\infty + 0.033. \quad (3)$$

165

166 Equation 2 represents the effects of roughness elements on the vertical velocity
 167 profiles. Specifically, in the present experiments the roughness length is assumed
 168 to be the diameter of the coarse (non-erodible) particles. Therefore, Equations 2
 169 and 3 yielded $U_{min} = 5.5 \text{ m/s}$ and $U_{max} = 9.5 \text{ m/s}$. Three different velocities
 170 were experimentally tested: 6, 7 and 8 m/s . These velocities were between U_{min}
 171 and U_{max} , the minimum and maximum velocities at which the finer and the coarse
 172 particles remained erodible and non-erodible, respectively, for a horizontal surface.
 173 However, the threshold friction velocity $u_{t_s}^*(\theta)$ on a surface with a slope $\tan \theta$ is
 174 different from that found in a flat bed due to the distinct relative contributions of
 175 the forces acting on the particle. If the slope is positive (flow upwards), gravity is
 176 a resistive force, and thus, the friction velocity must be stronger to lift the grains.
 177 In contrast, if the slope is negative (flow downwards), the friction velocity required
 178 to lift the particles is lower than the threshold friction velocity for the beds.

179 The sand stockpile models were formed inside the wind-tunnel using a device
 180 similar to an industrial hopper, shown in Figure 3(a). Furieri et al. [13] have
 181 performed several tests to ensure that the pile shape and dimensions given by this
 182 device were reproducible. The dimensions of the sand stockpile had a scale ratio
 183 of approximately 1:200 to an actual stockpile, and they are shown in Figures 3(b)
 184 and 3(c): 7.7 cm (height), 23.6 cm (length), 57.9 cm (width), and 34.5° of angle
 185 of repose. It must be mentioned that the experiments did not accurately simulate
 186 full-scale conditions because the pile dimensions were smaller than the saturation
 187 length, the length that transport requires for saturation (i.e., to reach the saturated
 188 flux), which is approximately 1 to 2 m [1]. Therefore, the experimental sand piles
 189 did not behave in a similar way to piles of scale several metres from the erosion
 190 point of view: the first would be primarily eroded by aerodynamic entrainment,
 191 while the second would be subject to impact entrainment.

192 Configurations of one isolated stockpile and two successive stockpiles were used
 193 in the wind tunnel experiments. For the two pile configuration, the edge-to-edge
 194 separations tested were $0.9h$ and $1.8h$, where h is the height of the pile. The effect
 195 of the stockpile orientation to the main wind flow direction was analysed for 60°
 196 and 90° . The piles were built with a mixture of the erodible and non-erodible sand
 197 with two different mass fractions of non-erodible particles (α_{NE}): 10 and 20%.
 198 The six pile configurations used in the 36 tests are shown in Table 1.

199 After determining the initial stockpile mass and setting it on the wind tunnel
 200 floor, the free stream velocity was set by a frequency controller, and the fan was
 201 turned on. The duration of the flow was 15 minutes in all cases. No additional
 202 emissions occurred after this period, and a progressive pavement process that

203 finally suppressed erosion at the eroded areas was observed. A camera installed over
 204 the wind-tunnel ceiling (transparent glass wall) registered the erosion evolution by
 205 analysing the contrasting colours (black and white sand). The photographs were
 206 taken at the beginning of the experiment and every 30 seconds for 5 minutes. The
 207 last picture was taken after 15 minutes. These pictures allowed for a qualitative
 208 assessment of the temporal evolution of different wind erosion exposure zones on
 209 the pile.

210 For the two parallel pile configuration, each pile was weighed separately after
 211 the experiment. The mass of particles emitted was calculated as the difference
 212 between the initial and final stockpile weights.

213 The repeatability of the experimental measurements was tested using the con-
 214 figuration with $\alpha_{NE} = 20\%$, orientation 90° , $1.8h$ gap and $U_\infty = 7 \text{ m/s}$. The
 215 emitted mass for the three different tests of repetitions had a reasonable coeffi-
 216 cient of variation equal to 4.5% (the coefficient of variation is defined as the ratio
 217 of the standard deviation to the mean and is given by 23.3 and 524.3 grams,
 218 respectively).

219 3 Numerical simulations set up

220 Numerical simulations were performed to solve the flow structure over several pile
 221 configurations representing the wind tunnel experiment (see Table 1). The three-
 222 dimensional Reynolds Averaged Navier-Stokes equations of mass and momentum
 223 were solved using the commercial software Fluent 15.0 [10], providing the mean
 224 fields of the flow properties. The $k - \omega$ Shear Stress Transport (SST) model was
 225 used to incorporate turbulence effects. The governing equations of transport are
 226 described below.

227 - Continuity equation:

$$\frac{\partial(\rho u_i)}{\partial x_i} = 0 \quad (4)$$

228 Where, t represents the time [s]; ρ is the specific mass of the fluid [kg/m^3]; u_i
 229 is the instant component of the velocity in the i direction [m/s]; x_i identifies the
 230 coordinate in the direction i [m].

231 - Momentum conservation:

$$\frac{\partial(\rho u_i u_j)}{\partial x_j} = \frac{\partial \tau_{ij}}{\partial x_j} - \rho \delta_{3i} g \quad (5)$$

$$\tau_{ij} = 2\mu S_{ij} - \left(p + \frac{2}{3}\mu \frac{\partial u_k}{\partial x_k} \delta_{ij} \right) \quad (6)$$

$$S_{ij} = \frac{1}{2} \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) \quad (7)$$

232 Where, δ_{ij} represents the Kronecker Delta, g is the acceleration of gravity
 233 [m/s^2], p is the mechanical pressure [N/m^2], τ_{ij} is the stress tensor [N/m^2], μ is
 234 the molecular viscosity [$kg/m.s$] and S_{ij} is strain rate tensor [$1/s$].

235 A variant of the $k-\omega$ model is the $k-\omega$ SST (Shear Stress Transport) model.
 236 Boussinesq hypothesis is used in the turbulence closure model. The $k-\omega$ SST is

237 indicated for flow with adverse pressure gradients. This model includes two mod-
 238 ifications: (i) The turbulent kinematic viscosity is modified according to equation
 239 10 which best represents the shear stress transport effects for this type of flow
 240 and (ii) the addition of a term in the equation 9 of the diffusion of ω is a specific
 241 function that allows the validity of the equations in the zones near the wall or
 242 distant.

243 The model uses the following two transport equations for k and ω :

$$\frac{\partial k}{\partial t} + \frac{\partial k}{\partial x_j}(\bar{u}_j) = P_k - \beta^* k \omega Y_k + \frac{\partial}{\partial x_j} \left[(\nu + \sigma_k \nu_t) \frac{\partial k}{\partial x_j} \right] \quad (8)$$

$$\frac{\partial \omega}{\partial t} + \frac{\partial \omega}{\partial x_j}(\bar{u}_j) = \alpha S^2 - \beta \omega^2 + \left[(\nu + \sigma_\omega \nu_t) \frac{\partial \omega}{\partial x_j} \right] + 2(1 - F_1) \sigma_\omega \frac{1}{\omega} \frac{\partial k}{\partial x_i} \frac{\partial \omega}{\partial x_i} \quad (9)$$

244 Where the coefficients and auxiliary relations are given by:

$$\nu_t = \frac{a_1 k}{\max(a_1 \omega, SF_2)} \quad (10)$$

$$F_1 = \tanh \left[\left[\min \left[\max \left(\frac{2\sqrt{k}}{\beta^* \omega y}, \frac{500\nu}{y^2 \omega} \right), \frac{4\sigma_\omega 2k}{CD_{k\omega} y^2} \right]^4 \right] \right] \quad (11)$$

$$CD_{k\omega} = \max \left(2\rho \sigma_\omega \frac{\partial k}{\partial x_i} \frac{\partial \omega}{\partial x_i}, 10^{-10} \right) \quad (12)$$

$$F_2 = \tanh \left[\left[\max \left(\frac{2\sqrt{k}}{\beta^* \omega y}, \frac{500\nu}{y^2 \omega} \right) \right]^2 \right] \quad (13)$$

$$P_k = \min \left[\min \left(\tau_{ij} \frac{\partial u_i}{\partial x_j}, 10\beta^* k y \right), C_{lim} \rho \epsilon \right] \quad (14)$$

245 The tensor of the turbulent stresses is treated as:

$$\tau_{i,j} = \mu_t \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} - \frac{2}{3} \frac{\partial u_k}{\partial x_k} \delta_{i,j} \right) - \frac{2}{3} \rho k \delta_{i,j} \quad (15)$$

246 The constants of k - ω *SST* model are summarized as follows: $\sigma_k = 0.85$; $\sigma_{k,1} =$
 247 1.0 ; $\sigma_{\omega,1} = 0.5$; $\sigma_{\omega,2} = 0.856$; $\beta_1 = 0.075$; $\beta_2 = 0.0828$; $\beta^* = 0.09$; $\alpha_{\infty,1} = \frac{5}{9}$; $\alpha_{\infty,2} =$
 248 0.44 ; $a_1 = 0.31$; $C_{lim} = 10$.

249 This turbulence model was chosen based on a study performed by Badr and
 250 Harion [2], who simulated analogous configurations under similar flow conditions
 251 and compared the results using different closure models. Figure 4 presents the com-
 252 putational domain dimensions and boundary conditions. The numerical model of
 253 the stockpile presents a not evolving surface during erosion. The pile retained its
 254 shape during erosion in the proposed model. A no-slip condition was set at this
 255 boundary. The inlet boundary conditions for the velocity, the turbulent kinetic
 256 energy and the specific dissipation rate were retrieved from a converged field ob-
 257 tained by previous numerical simulations of a flat plane surface with the same
 258 dimensions, for which a periodic streamwise flow was set. In these precursors nu-
 259 merical simulations, we imposed a mass flow rate correspondent to the desired
 260 free stream velocity. The converged vertical velocity profile is logarithmic. The

inlet profiles of wind velocity and turbulence of the numerical simulations were validated using the experimental data carried out by Turpin [31] in the same wind tunnel described in Section 2. A fully developed flow was assumed for the outflow conditions, that is, all flow variables except pressure were assumed to have a zero normal gradient. The SIMPLEC algorithm was used for pressure-velocity coupling [36]. Symmetry conditions were applied to the upper domain boundary (normal gradients of all variables were set to zero). Finally, no-slip conditions were imposed for the lateral boundaries, the ground and the pile surface.

The geometries and meshing were generated with Gambit software (Geometry and Mesh Building Intelligent Toolkit) [9]. The mesh was built by an extrusion of triangular face cells from the pile and ground walls towards the upper wall of the computational domain creating triangular-based prism cells (see Figure 5). The grid is irregular following the shape and orientation of the geometries. A mesh refinement near the walls ($y^+ < 5$) was required due to the expected intense gradients close to these areas and due to turbulence modelling requirements. Mesh sensitivity tests were previously carried out for similar configurations [2]. Turbulence model choice was based on previously validated numerical calculations performed by Badr and Harion [2] and Turpin et al. [34]. For the different configurations, the computational grids ranged from 3800000 to 5300000 cells. The simulations with two successive piles arrangement required the larger number of cells in order to allow sufficient refinement between the piles.

4 Results

The results are presented in three sections. In the first section, the erosion patterns are interpreted in the light of the numerical data of the basal shear stress map. Then, a general overview of the pavement process for a tested case is presented. Finally, the mass loss measurements for the different configurations are discussed in the third section.

4.1 Comparison between basal shear stress maps and erosion patterns

As previously mentioned, the erosion patterns were identified by the agglomeration of non-erodible (black) particles in the final experimental images, after the pavement phenomenon. The surface distribution of the black particles enabled the identification of pile zones in which the shear stress was great enough to erode fine particles (i.e., white particles) and offers support to the investigation of the effect of a second stockpile on the erosion pattern. This section mainly focuses on the experiment in which the wind erosion was more evident ($U_\infty = 8 \text{ m/s}$ and $\alpha_{NE} = 20\%$) to highlight the erosion patterns in different areas of the piles surface.

The numerical results are presented in dimensionless form as local shear stress values were divided by a reference shear stress value (τ_{ref}) obtained for an undisturbed zone where the flow was not affected by the stockpile. Although the shear stress increased with an increase of the wind flow velocity, the flow pattern characteristics given by τ/τ_{ref} remained quite similar for each velocity tested. Similarly,

303 the mean fluid flow pathlines around the piles were coloured based on the ratio of
 304 the velocity to a reference free stream velocity (U_∞).

305 The isolated stockpile will subsequently be referred to as pile p_1 , and the
 306 upstream and downstream piles in the successive arrangements will be referred to
 307 as piles p_2 and p'_2 , respectively. Distinctive wind erosion regions are highlighted
 308 according to the degree of wind exposure. To facilitate the analysis, 4 zones were
 309 highlighted on the isolated stockpile and are designated as A_1 , B_1 , C_1 and D_1 ,
 310 and 4 zones were highlighted on each pile for the successive configurations and are
 311 designated as A_2 , B_2 , C_2 and D_2 in pile p_2 and A'_2 , B'_2 , C'_2 and D'_2 in pile p'_2 .

312 4.1.1 Stockpiles oriented perpendicularly to the main wind flow direction

313 Figures 6 and 7 show the photographs taken after the pavement phenomenon,
 314 the mean wall shear stress distribution and pathlines, respectively, for an isolated
 315 stockpile and two stockpiles oriented 90° to the main flow direction (separated by
 316 gaps of $0.9h$ and $1.8h$).

317 Figure 6(a) shows that no erosion occurred in the stagnation zone A_1 . Indeed,
 318 this zone was characterised by intense deceleration and wall shear stress levels near
 319 zero (see Figures 6(b) and 6(c)). The incident flow was progressively accelerated
 320 towards the crest and the lateral sides of the pile forming region B_1 , where the
 321 highest levels of shear occurred due to a strong velocity gradient (Figures 6(b)
 322 and 6(c)). Therefore, these areas were the most vulnerable to wind erosion, which
 323 explains the accumulation of non-erodible black particles seen in Figure 6(a).

324 Figure 6(c) shows the flow separation from the pile surface on the crest and the
 325 lateral sides, as a result of a strong adverse pressure gradient. The separation led to
 326 a wake region downstream of the pile (zone C_1), with low wall shear stress levels
 327 and weak erosion (see Figures 6(a) and 6(b)). Figure 6(c) reveals two counter-
 328 rotating vortices on the lateral sides that interact with the separation from the
 329 crest. The complex three-dimensional structures formed in this recirculating region
 330 created a small zone with higher shear (zone D_1), in which a slight accumulation
 331 of black sand was noticeable (see Figures 6(a) and 6(b)). Between the two main
 332 counter-rotating vortices there is a flow acceleration region that slightly affects the
 333 bottom of the leeward wall.

334 Similarly, Figures 7(b) and 7(c) show a deceleration upstream pile p_2 (region
 335 A_2 , with low levels of shear) and a flow acceleration towards the slope and sides
 336 (region B_2 , with high levels of shear). Nevertheless, especially for the gap of $0.9h$,
 337 the dimensionless values of shear stress for the piles oriented 90° (region B_2) were
 338 higher than for the pile with no interference (region B_1), with maximum values of
 339 8.6 and 6.9, respectively. These findings are consistent with the erosion patterns
 340 observed in Figure 7(a).

341 An asymmetrical pattern was detected in the experimental and numerical re-
 342 sults, despite the symmetrical geometry. The literature reported similar behaviour
 343 of the flow around geometrical symmetric obstacles [14, 15, 18, 40] as a conse-
 344 quence of the bi-stable intermittent nature of the flow in which the wake switches
 345 randomly at irregular intervals from the sides of the pile between the two stable
 346 states. The numerical simulation of bi-stability is a difficult task, due to its very
 347 long timescale. The average timescale of the RANS numerical simulations may not
 348 be sufficiently large to comprise the switch of the wake timescale.

Figure 7(a) revealed an accumulation of sand on the ground between the piles for the closely spaced configuration ($0.9h$ gap). In addition, the interference of pile p'_2 in the leeward wall of pile p_2 was more important in this case. When comparing the $0.9h$ gap to the $1.8h$ gap, the zone of ineffective erosion C_2 was smaller, and the black zone of high erosion D_2 was larger. For the $1.8h$ gap, the wake region of pile p_2 resembled the wake region of pile p_1 and the extent of areas C_2 were comparable, except for the narrow region of high friction that was impacted by the vortex (zone D_2) that was transposed to the lateral side due to the bi-stability.

A more severe erosive impact was observed for the second stockpile on the windward wall of pile p'_2 . Figure 7(a) shows that a very high concentration of black particles in this area, which indicates a zone vulnerable to erosion, particularly with the $0.9h$ gap. In pile p'_2 , zone B'_2 is the region with the highest shear stress values because of the impact of the vortex structure shown in Figure 7(c). On the other hand, zone A'_2 has low shear level and the pathlines velocities were lower (see Figures 7(b) and 7(c)). Unexpectedly, the erosion patterns demonstrated that this zone was characterised by high erosion (see Figure 7(a)). Two possible mechanisms could explain this unexpected observation: the intermittent behaviour of the vortices due to bi-stability and the impact of the emitted particles from pile p_2 .

In the wake zone behind pile p'_2 , the regions C'_2 and D'_2 were also highlighted. The similarity between these zones can be noticed for the $0.9h$ and $1.8h$ gaps; however, in both cases, D'_2 is larger than the corresponding zone in pile p_1 (zone D_1), which emphasises the impact on the downstream pile.

4.1.2 Stockpiles oriented 60° to the main wind flow direction

Figures 8 and 9 show the photographs after the pavement phenomenon, the mean fields of the wall shear stress distribution and the flow pathlines, respectively, an isolated stockpile and two stockpiles oriented 60° to the main flow and separated by $0.9h$ and $1.8h$ gaps.

The wind exposure patterns were similar on piles p_1 and p_2 for the configurations oriented 60° to the main flow direction. Progressive flow acceleration up the slope and towards the lateral sides was observed on the windward wall of these piles (see Figures 8(c) and 9(c)). Zones A_1 and A_2 had low levels of shear and ineffective erosion whereas the opposite occurred in zones B_1 and B_2 (see Figures 8(a), 8(b), 9(a) and 9(b)). The highest friction levels in zones B_1 and B_2 were found on the lateral sides of the pile facing the wind. In addition, the shear peak values were higher for the 60° orientation than for the 90° orientation.

Figures 8(c) and 9(c) show that a single main helical vortex was formed downstream of the stockpiles p_1 and p_2 . The flow separation near the crest of these piles led to a wake regions on the leeward wall (zone C_1 and C_2 , respectively), with low wall shear stress levels and weak erosion (see Figures 8(a), 8(b), 9(a) and 9(b)). The impact of this vortex can be clearly observed in zones D_1 and D_2 , a region with higher friction and significant agglomeration of black particles, although it had a weaker effect on pile p_1 . Moreover, the vortex had a greater effect on the closely spaced piles. Indeed, it impinged on the windward p'_2 pile wall increasing the friction on the upper part of region B'_2 .

The unexpected situation in zone A'_2 with a low shear stress level and a high erosion rate was also seen for the 60° orientation. This situation can be again

396 attributed to the impact of the emitted particles from pile p_2 . Further evidence
 397 supporting the effect of particles in saltation from pile p_2 on the erosion of pile p'_2
 398 can be seen in Figure 10, which shows the final photographs and the dimensional
 399 contours of the shear stress for the velocities 6 and 8 m/s with the $1.8h$ gap and
 400 $\alpha_{NE} = 20\%$. In this figure the results are presented in the dimensional form in
 401 order to compare the absolute values of the shear stress for both velocities. The
 402 highlighted area in zone B_2 (red line) was highly eroded for $U_\infty = 8 m/s$ due to
 403 the high levels of shear and the windward wall of pile p'_2 was also highly eroded,
 404 as shown in Figure 10(a). Accordingly, as erosion is weaker for $U_\infty = 6 m/s$,
 405 the red region in zone B_2 and its corresponding directly frontal region in pile
 406 p'_2 remained uneroded (see Figure 10(b)). Similarly, the upper part of region A'_2
 407 (highlighted with blue line) was highly eroded, suggesting emissions due to the
 408 impact of saltating particles from region D_2 of pile p_2 .

409 A significant concentration of coarse black particles in the windward wall of
 410 pile p'_2 , as shown in Figure 9(a), reinforces the strong impact of a second parallel
 411 stockpile on erosion, especially for the smaller gap ($0.9h$).

412 The patterns on the leeward walls of pile p'_2 behaved in a similar manner as
 413 the leeward walls of piles p_2 although with much less erosion intensity. In Figure
 414 9(a), zone D_2 is larger than zone D'_2 , especially for the $1.8h$ gap.

415 4.2 Visual analysis of the erosion patterns

416 Figure 11 illustrates the experimental temporal evolution of wind erosion for both
 417 granulometries (with $\alpha_{NE} = 10$ and 20%) and for the lowest and highest wind
 418 velocities ($U_\infty = 6$ and $8 m/s$). Considering that similar pavement phenomenon
 419 behaviour was observed for all arrangements, a configuration with an orientation
 420 60° and a $0.9h$ gap was chosen to represent a typical case.

421 As mentioned in Section 2, the pavement phenomenon was observed after 15
 422 minutes of wind exposure for all configurations, which means that the final erosion
 423 patterns are well represented in the fifth column of photographs shown in Figure
 424 11. The extent of the final eroded areas varied little with the increase of α_{NE} ,
 425 although the final concentration of non-erodible particles in these areas was higher
 426 for $\alpha_{NE} = 20\%$ than for $\alpha_{NE} = 10\%$, especially for $U_\infty = 8 m/s$. On the other
 427 hand, a significant increase of the eroded areas occurred as flow velocity increased.
 428 For instance, modifications of the windward surface of the upstream pile are almost
 429 imperceptible for $U_\infty = 6 m/s$ whilst the same region was highly eroded for
 430 $U_\infty = 8 m/s$.

431 The temporal evolution of the pavement shown in the Figure 11 indicates that
 432 the phenomenon occurred faster in tests with a larger amount of non-erodible
 433 particles and higher velocities. Indeed, for $\alpha_{NE} = 20\%$ and $U_\infty = 8 m/s$, after 30
 434 seconds a larger quantity of black particles accumulated than with $\alpha_{NE} = 10\%$ and
 435 $U_\infty = 6 m/s$, and after 1 minute and 30 seconds, the observed pattern was found
 436 to be very close to the final pattern. This behaviour was related to a temporal
 437 decrease in the emitted mass flux. The highest pavement rate for $\alpha_{NE} = 20\%$
 438 supports previous findings in the literature [13].

439 4.3 Emission estimates

440 Table 2 shows the emitted mass measurements from an isolated stockpile (p_1) and
 441 from each stockpile in the successive arrangement (p_2 and p'_2). The first result
 442 worth noting is the remarkable amount of sand emitted from the downstream pile
 443 p'_2 . In all test cases, the emissions were higher for the pile p'_2 , compared to either
 444 pile p_2 or p_1 , which is consistent with the experimental erosion patterns discussed
 445 in Section 4.1. The reason for this result is the emissions from the upward wall of
 446 pile p'_2 due to the impact of saltating particles from pile p_2 (see Figure 10).

447 Pile p'_2 had higher emissions in the 60° arrangement if the stockpiles were
 448 separated by a $0.9h$ gap because of higher shear stress values, a greater effect
 449 of the main vortex shed from pile p_2 and interactions between the piles (more
 450 energetic saltation particles). These facts do not apply to pile p_2 (wall shear stress
 451 distribution on pile p_2 is quite similar for both gaps for the orientation of 60°),
 452 and the critical importance of the gap on the emitted mass for this pile was not
 453 observed. Nevertheless, the shear levels of pile p_2 were higher than those of pile
 454 p_1 , and the amount of emitted mass was also higher.

455 On the other hand, with the piles oriented 90° to the main flow, pile p'_2 and pile
 456 p_2 had higher emissions for stockpiles separated by a gap distance of $1.8h$. However,
 457 this result is ambiguous because, as mentioned in Section 4.1.1, an accumulation of
 458 sand in the floor between the piles was noticed for the $0.9h$ gap. This mass was not
 459 counted in the balance as emitted because it was hard to distinguish from which
 460 pile it arose (it was even hard to separate the sand from the piles). For the same
 461 reason, a rigorous comparison of the emitted mass from piles p_2 (with $0.9h$ gap)
 462 and p_1 is difficult; however, we noticed that the values were close. Nevertheless,
 463 emissions from pile p_2 were slightly lower for stockpiles separated by a gap distance
 464 of $1.8h$ than from an isolated stockpile. Therefore, the emissions of each pile in
 465 the configuration with two piles depend on the orientation of the flow. It was only
 466 the upstream pile of a pair in the 90° orientation that experienced less erosion than
 467 an isolated pile.

468 Figure 12 shows the total emitted mass amount from successive stockpiles
 469 compared to twice the amount from an isolated stockpile (which could mimic a
 470 situation in an open industrial yard in which the piles are far enough away from
 471 each other to not interfere) for all tested configurations. The total amount from
 472 the two successive stockpiles was greater for both orientations, and in some cases,
 473 the emitted mass could be more than three times higher, compared to two times
 474 the value from an isolated pile.

475 Furthermore, Figure 12 highlights that erosion was greater in configurations
 476 with a main wind flow direction oriented 60° than in those oriented 90° to the
 477 piles, especially if the piles are separated by a gap distance of $0.9h$. In addition,
 478 for the same value of the free stream velocity, emissions with $\alpha_{NE} = 20\%$ were
 479 approximately half that of emissions with $\alpha_{NE} = 10\%$. Therefore, the proportion
 480 of non-erodible particles has a considerable effect on particle emissions.

481 5 Conclusion

482 The purpose of this study was to investigate the aeolian erosion of stockpiles with a
 483 bimodal granulometry formed by erodible and non-erodible sand using wind tunnel

484 experiments. Numerical simulations were performed to supply wind flow data (i.e.,
485 shear stress distribution and pathlines) in order to support an understanding of
486 the phenomenon.

487 Temporal evolution of the pavement phenomenon was analysed using top view
488 photographs of the piles, studying the progress of wind erosion exposure zones.
489 It has been verified that the phenomenon occurred faster for larger amounts of
490 non-erodible particles and higher velocities.

491 Wind flow modifications and their effects on wind erosion were numerically
492 and experimentally assessed for two pile orientations to the main wind flow di-
493 rection (60° and 90°) and three different arrangements: an isolated stockpile and
494 two successive stockpiles separated by $0.9h$ and $1.8h$ gaps. For the perpendicular
495 arrangement it was observed highly eroded zones in which the incident flow ac-
496 celerated on the crest and lateral sides and zones of weaker erosion downstream
497 of the piles, after the flow separation. For the orientation of 60° , the erosion was
498 stronger due to higher shear stress values and the effects of the main vortex on the
499 leeward wall of the piles. A strong impact on the downstream pile was observed for
500 both orientations. The downward wall of these piles had a highly eroded region,
501 even though the shear stress values were low (zone A'_2) due to the impact of the
502 eroded particles from the upstream pile. Therefore, it is important to consider this
503 behaviour in future numerical modelling studies. With the exception of zone A'_2 ,
504 good agreement was found between the numerical distribution of the wall shear
505 stress and the agglomeration of non-erodible particles on the stockpile surface.
506 The results indicate that, in addition to the wind velocity, the orientation of the
507 pile to the prevailing wind direction also plays an important role to limit aeolian
508 erosion in actual storage yards. Industries yards may redesign their piles arrange-
509 ments according to the most frequent wind direction based on local meteorological
510 data. Oblique piles shown to be more eroded when located near to each other. On
511 the other hand, perpendicular piles presented a protective effect. It is a general
512 recommendation that the stockpiles should be oriented perpendicular to the wind
513 direction.

514 The experimental quantification of the mass emitted revealed that the emis-
515 sions from two consecutive stockpiles are greater than twice the emissions from
516 an isolated stockpile for both orientations. The presence of a successive pile had a
517 strong effect and increased erosion. In other words, the total emitted mass would
518 be underestimated if it was taken as twice the emissions calculated for an isolated
519 stockpile. In addition, the piles oriented 60° emitted larger amounts of mass than
520 piles oriented 90° in all configurations, especially for the $0.9h$ gap. Therefore, the
521 results may suggest that a larger single pile has less impact than two parallel piles.
522 However, experiments with gaps larger than $1.8h$ should be conducted.

523 The emission models of wind erosion are based on the local wall friction velocity
524 which are well transposable at the real scales. Based on the work of Chew et al. [4]
525 the Reynolds number of our experiments and numerical simulations (about 25000)
526 satisfies the independence criterion. However, it is important to note that for stud-
527 ies involving atmospheric particle transport to describe the physics of particulate
528 matter or sediment transport, scaling parameters considering particles character-
529 istics should be considered. We propose for future works, studying the dispersion
530 of emitted particles (multiphase flow), that the drag force and gravitational force
531 on particles should satisfy similarity conditions. These days, few works are devoted
532 to these investigations.

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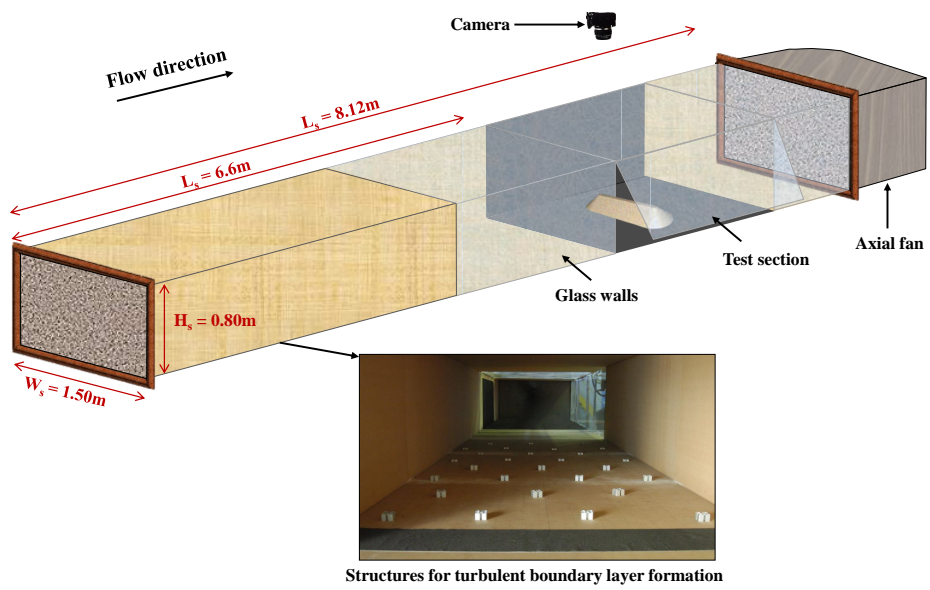


Fig. 1: Wind tunnel scheme

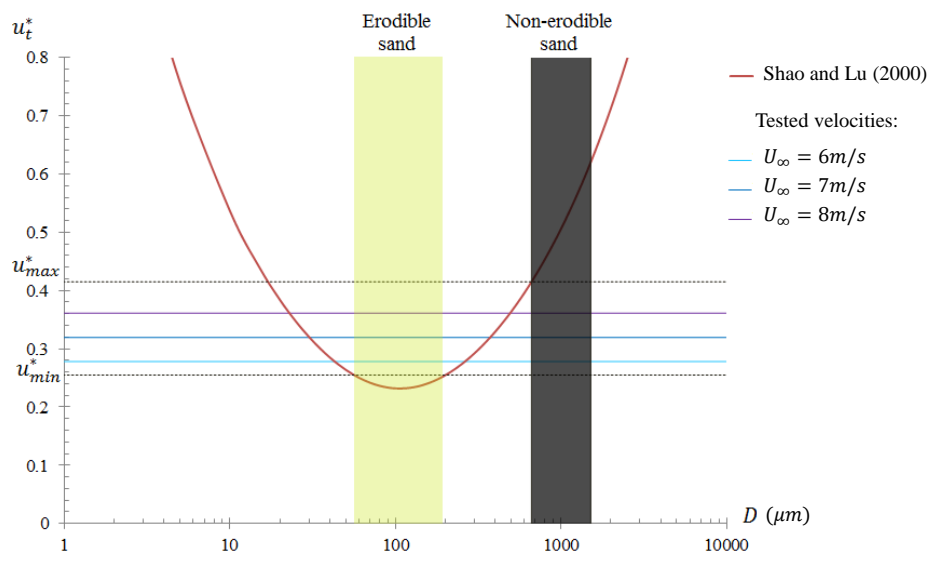
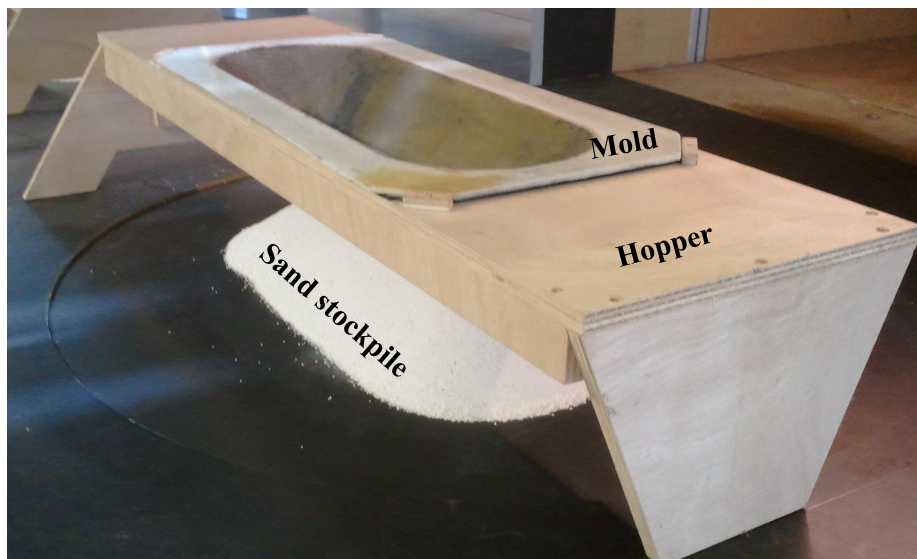
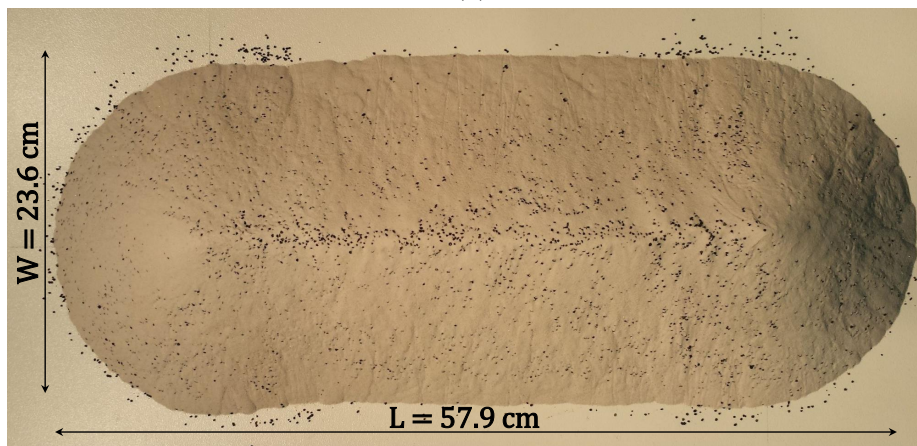


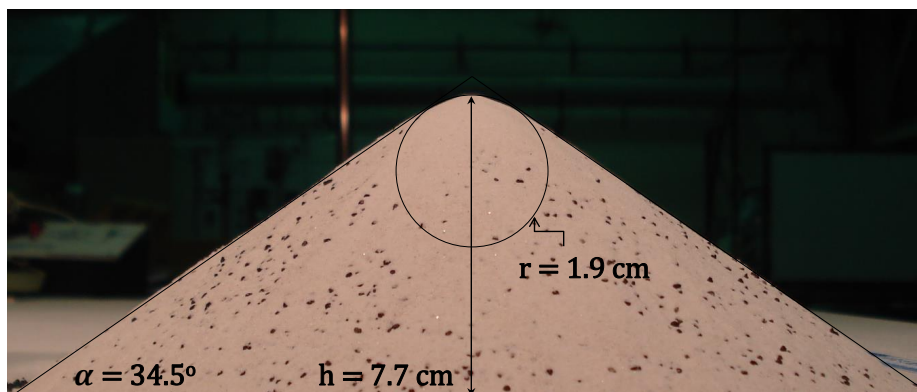
Fig. 2: Take-off criterion for a horizontal surface



(a)



(b)



(c)

Fig. 3: (a) Device used for the construction of the sand stockpile model and the mean dimensions of the sand stockpile in (b) Top and (c) Side views

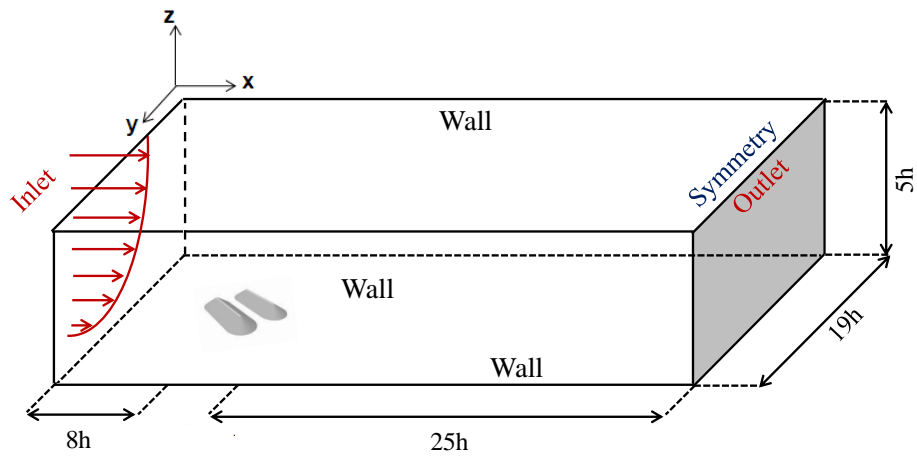


Fig. 4: Computational domain

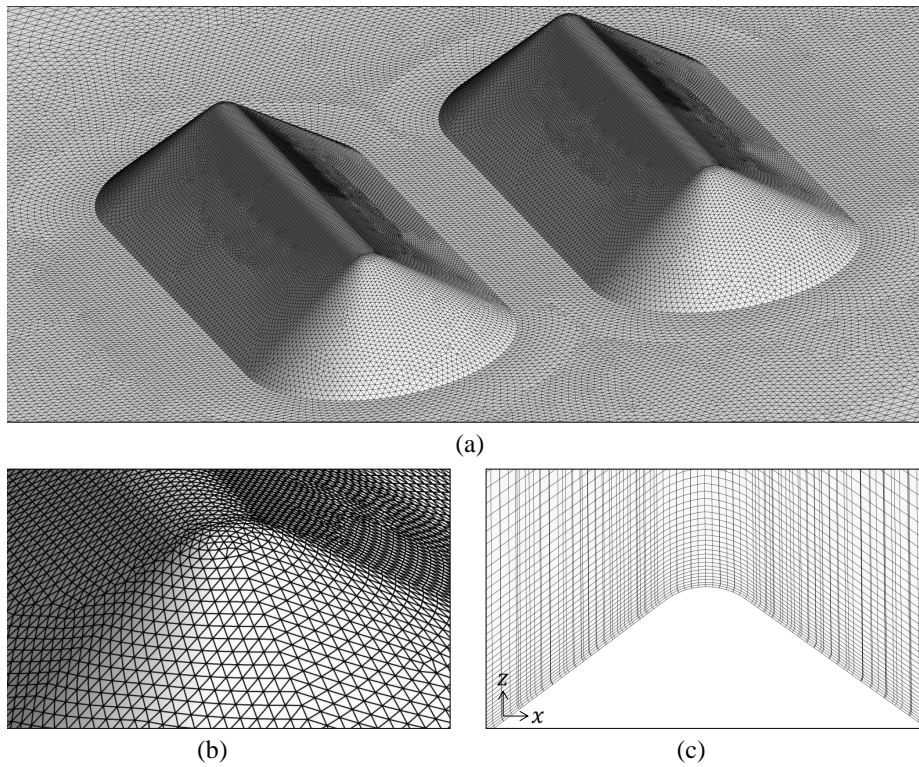


Fig. 5: (a) Perspective view of the mesh over the two piles, (b) Zoom of the mesh near the crest, and (c) Transversal cut of the domain over the pile

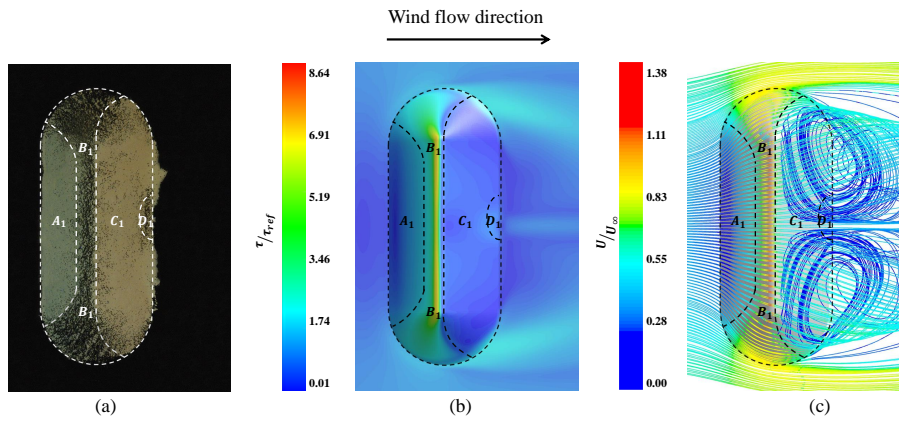


Fig. 6: Experimental and numerical results for an isolated stockpile (pile p_1) exposed to a perpendicular wind flow: (a) Top view of the eroded sand stockpile after the pavement phenomenon, (b) Mean wall shear stress on the pile surface and on the ground and (c) Mean flow pathlines over the pile. Four wind erosion regions are highlighted according to the degree of wind exposure: zones A_1 , B_1 , C_1 and D_1 .

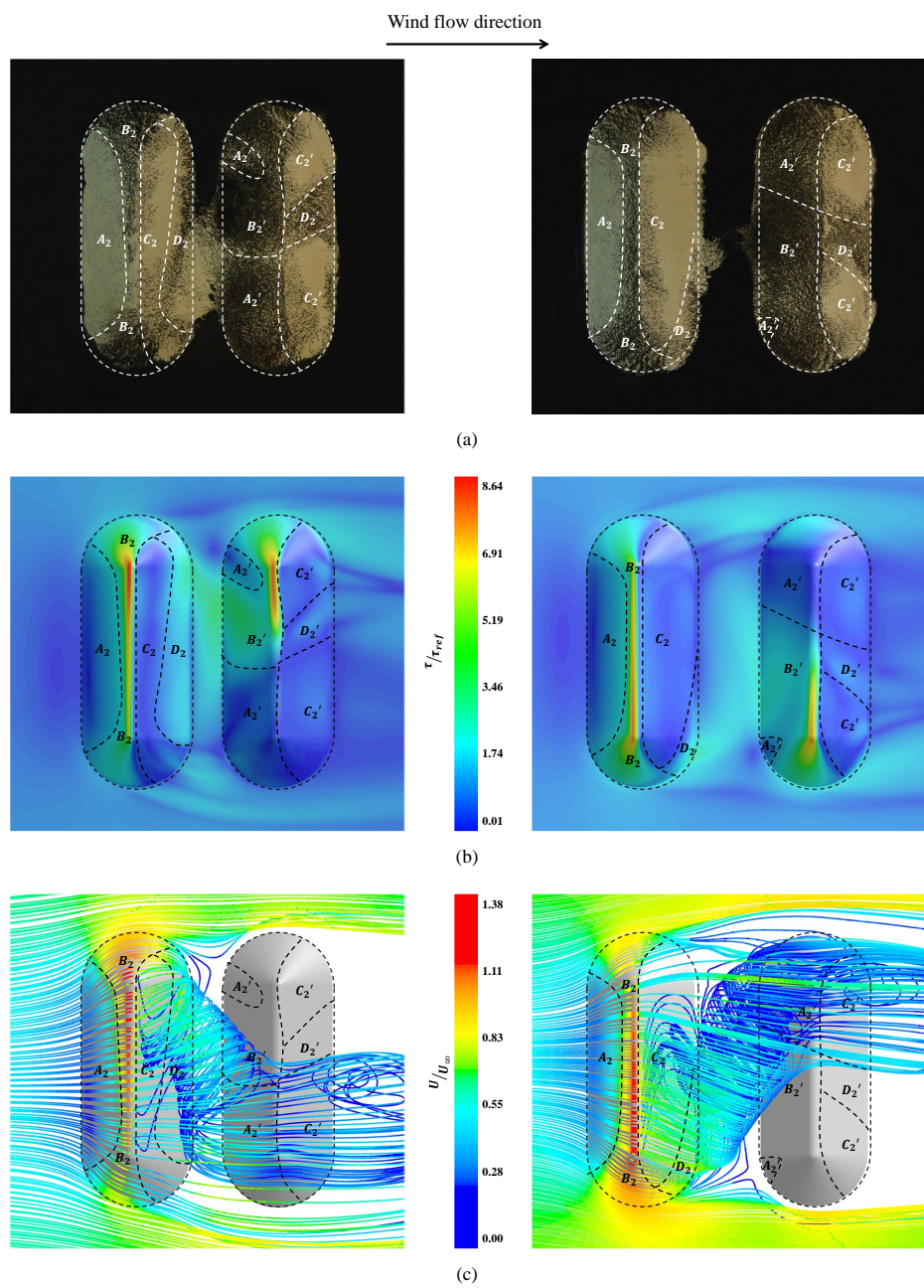


Fig. 7: Experimental and numerical results for two parallel stockpiles oriented 90° separated by $0.9h$ and $1.8h$ gaps: (a) Top view of the eroded sand stockpiles after the pavement phenomenon, (b) Mean wall shear stress on the pile surfaces and on the ground and (c) Mean flow pathlines over the piles. Four wind erosion regions are highlighted on each pile, according to the degree of wind exposure: zones A_2 , B_2 , C_2 and D_2 in the upstream pile (pile p_2) and zones A'_2 , B'_2 , C'_2 and D'_2 in the downstream pile (pile p'_2).

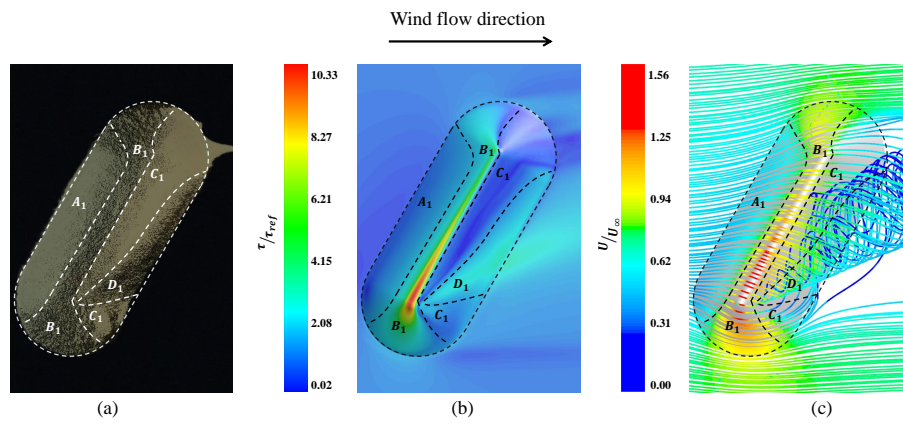


Fig. 8: Experimental and numerical results for an isolated stockpile (pile p_1) oriented 60° to the main flow: (a) Top view of the eroded sand stockpile after the pavement phenomenon, (b) Mean wall shear stress on the pile surface and on the ground and (c) Mean flow pathlines over the pile. Four wind erosion regions are highlighted according to the degree of wind exposure: zones A_1 , B_1 , C_1 and D_1 .

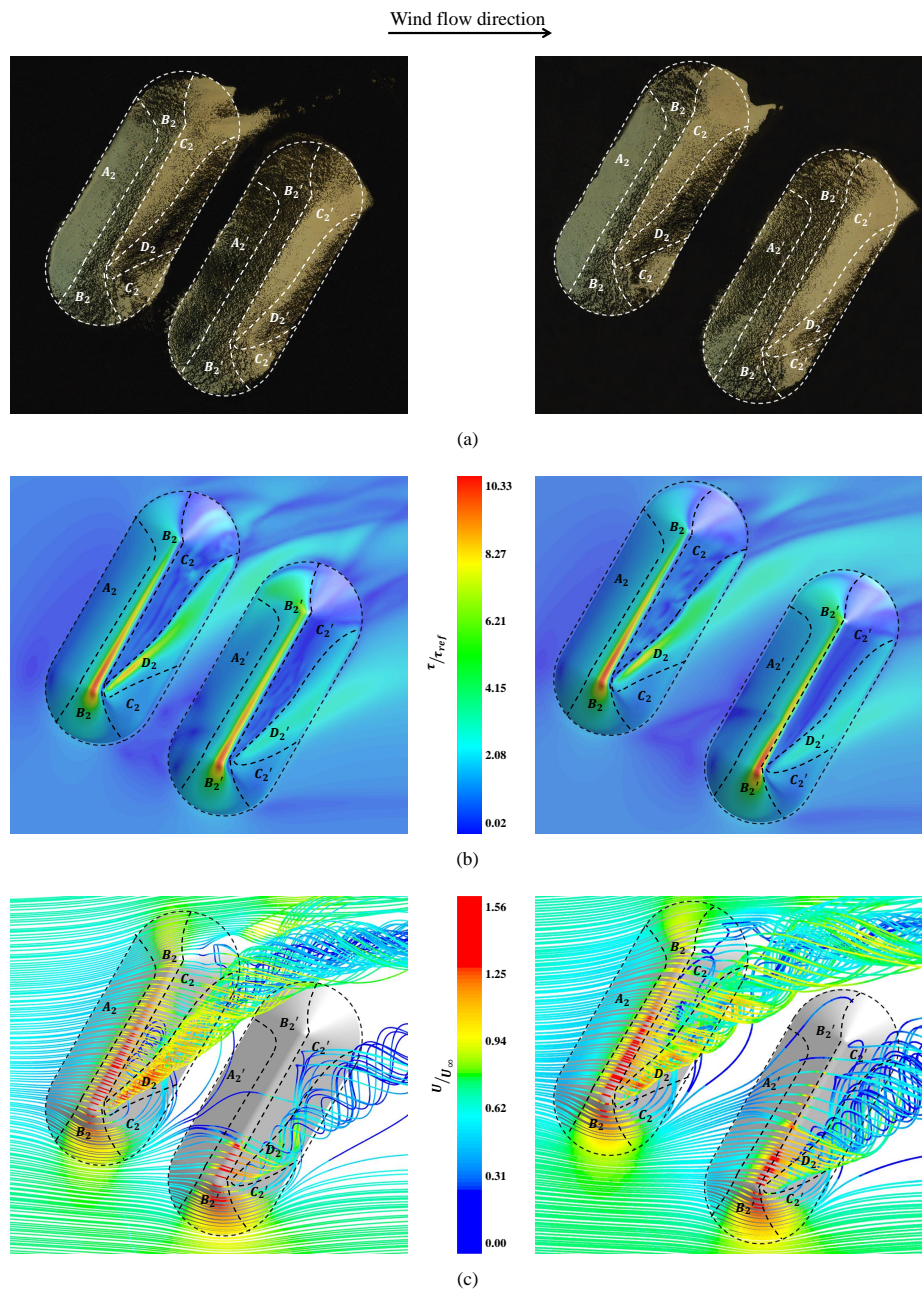


Fig. 9: Experimental and numerical results for two stockpiles oriented 60° and separated by gaps $0.9h$ and $1.8h$: (a) Top view of the eroded sand stockpiles after the pavement phenomenon, (b) Mean wall shear stress on the pile surface and on the ground and (c) Mean flow pathlines over the piles. Four wind erosion regions are highlighted on each pile, according to the degree of wind exposure: zones A_2, B_2, C_2 and D_2 in the upstream pile (pile p_2) and zones A'_2, B'_2, C'_2 and D'_2 in the downstream pile (pile p'_2).

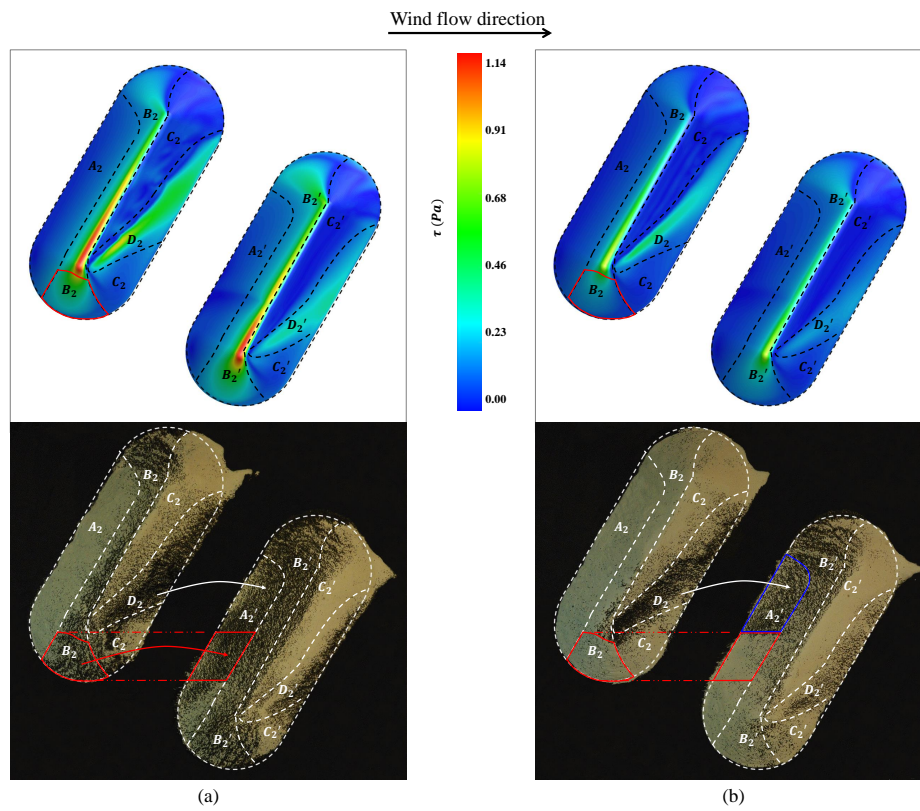


Fig. 10: Impact of the emitted particles from the upstream pile p_2 in two stockpiles oriented 60° with $\alpha_{NE} = 20\%$ and separated by the $1.8h$ gap for (a) $U_\infty = 8 \text{ m/s}$ and (b) $U_\infty = 6 \text{ m/s}$

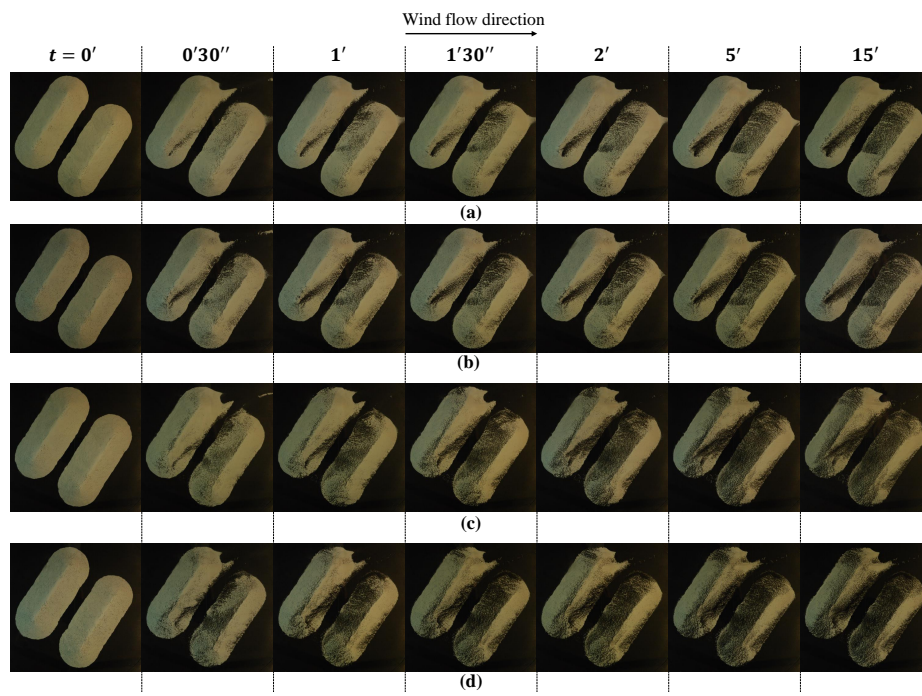


Fig. 11: Temporal evolution of the pavement phenomenon for two stockpiles oriented 60° to the main flow separated by a $0.9h$ gap: $U_\infty = 6 \text{ m/s}$ with (a) $\alpha_{NE} = 10\%$ and (b) $\alpha_{NE} = 20\%$, $U_\infty = 8 \text{ m/s}$ with (c) $\alpha_{NE} = 10\%$ and (d) $\alpha_{NE} = 20\%$

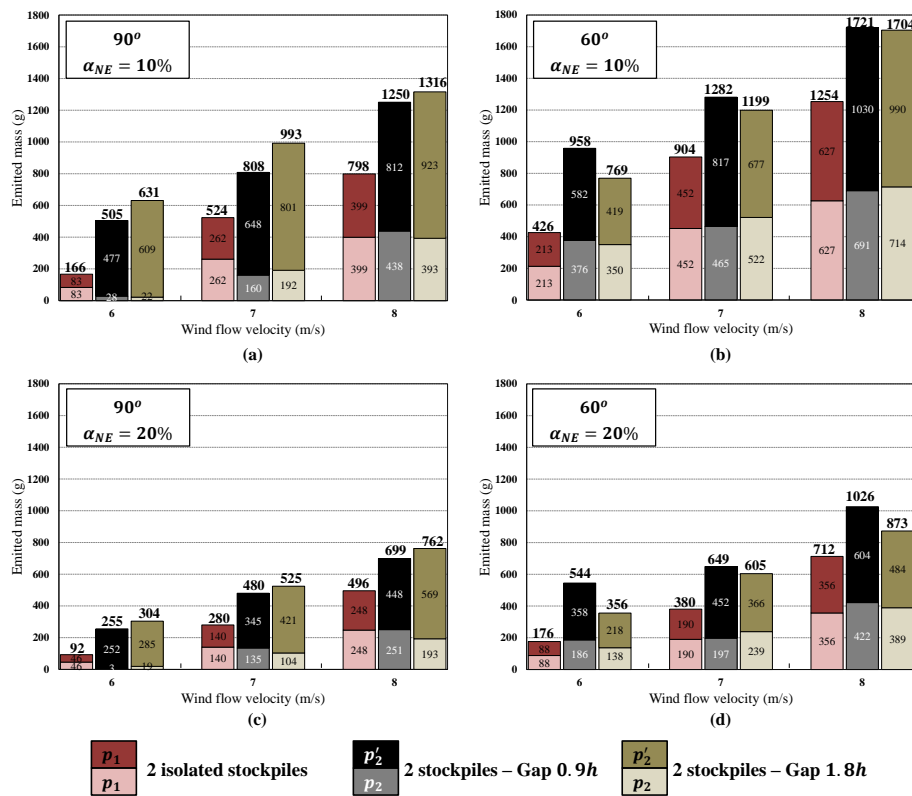


Fig. 12: Experimental quantification of the total amount of emitted mass from the successive stockpiles separated by the gaps of 0.9h and 1.8h compared to twice the amount from an isolated stockpile, for the configurations: $\alpha_{NE} = 10\%$ oriented (a) 90° and (b) 60° , and $\alpha_{NE} = 20\%$ oriented (c) 90° and (d) 60°

Table 1: Tested configurations. The pile dimensions are: 7.7 cm of height, 23.6 cm of length and 57.9 cm of width

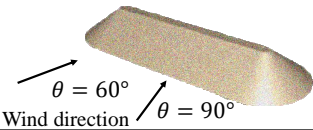
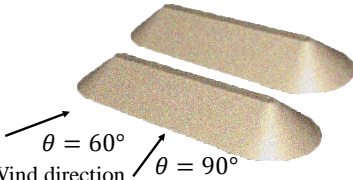
Configuration	Velocity (m/s)	Gap	α_{NE}
	6, 7, 8	-	10%, 20%
	6, 7, 8	0.9h, 1.8h	10%, 20%

Table 2: Emitted mass measurements for an isolated stockpile and for two successive piles with gaps of $0.9h$ and $1.8h$ (h is the stockpile height)

Configuration		Emitted mass pile p_1 (g)		Emitted mass successive piles (g)				
α_{NE} (%)	U_∞ (m/s)	90°	60°	Gap	90°		60°	
					pile p_2	pile p'_2	pile p_2	pile p'_2
10	6	83.2	212.9	0.9h	27.8	477.1	376.3	581.6
				1.8h	22.2	609.0	350.3	418.7
	7	261.6	451.8	0.9h	160.4	647.9	464.6	816.7
				1.8h	191.5	801.0	521.7	677.1
	8	399.2	626.6	0.9h	438.4	811.8	690.5	1029.8
				1.8h	393.1	922.9	714.3	989.9
20	6	46.3	88.2	0.9h	3.2	252.0	186.4	358.2
				1.8h	18.7	285.4	137.5	218.1
	7	140.3	190.1	0.9h	135.4	345.2	197.1	451.7
				1.8h	103.6	420.7	238.7	365.7
	8	247.8	356.4	0.9h	250.7	448.3	421.9	604.1
				1.8h	192.9	569.1	389.0	483.7