Journal of Wind Engineering & Industrial Aerodynamics 166 (2017) 37–47

Contents lists available at ScienceDirect

Journal of Wind Engineering and Industrial Aerodynamics

journal homepage: www.elsevier.com/locate/jweia

Incoming windblown sand drift to civil infrastructures: A probabilistic evaluation

Lorenzo Raffaele[a,d,*], Luca Bruno[a,d], Davide Fransos[b,d], Franco Pellerey[c]

[a] *Politecnico di Torino, Department of Architecture and Design, Viale Mattioli 39, I-10125 Torino, Italy*
[b] *Optiflow Company, Chemin de la Madrague-Ville 160, F-13015 Marseille, France*
[c] *Politecnico di Torino, Department of Mathematical Sciences, Corso Duca degli Abruzzi 24, I-10129 Torino, Italy*
[d] *Windblown Sand Modeling and Mitigation Joint Research Group, Italy-France*

ARTICLE INFO

Keywords:
Windblown sand
Drift potential
Uncertainty quantification
Probabilistic approach
Monte Carlo

ABSTRACT

The accurate prediction of windblown sand drift events approaching human infrastructures and activities is fundamental in arid lands. In both scientific literature and technical practice sand drift estimation is carried out in mean terms. Typically, sand drift net direction and intensity are assessed by means of the resultant drift potential. However, windblown sand suffers a number of epistemic and aleatory uncertainties, related to both the wind and the sand fields. The windblown sand drift estimation in probabilistic terms is useful in the infrastructure design perspective and allows to obtain characteristic values of windblown sand transport. In this study windblown sand is considered as an environmental action in analogy to wind action. Several uncertainties involved in the phenomenon are considered: threshold shear velocity and 10-min average wind velocity are assumed as random variables. Monte Carlo approach is adopted within a bootstrapping technique in order to assess sand drift in probabilistic terms. The proposed approach is applied to five sites in the Arabian Peninsula. Directional statistics of the sand drift are given for each site.

1. Introduction

Windblown sand is of interest for several engineering fields in arid environments (e.g. Middleton and Sternberg, 2013; Stipho, 1992), from environmental to civil engineering. In particular, windblown sand interacts with a number of civil structures and infrastructures, such as roads (e.g. Redding and Lord, 2004; Dong et al., 2004), railways (e.g. Zhang et al., 2007, 2010; Cheng and Xue, 2014), industrial facilities and pipelines (e.g. Alghamdi and Al-Kahtani, 2005), farms (e.g. Wang et al., 2010), town an buildings (e.g. Rizvi, 1989; Bofah and Al-Hinai, 1986). Windblown sand transport results from soil erosion and involves sedimentation around built obstacles. In particular, windblown sand effects on civil structures comprehend, but are not limited to: wind erosion and foundation scouring, moving sand dunes encroaching infrastructures, sand accumulation around structures and infrastructures. Due to the nature of these effects, they can lead to several incremental costs in infrastructure management, e.g. loss of capacity and increased maintenance costs (Zakeri, 2012), but also to disastrous events, such as train derailment (Cheng et al., 2015). The design of such infrastructures requires the accurate estimation of the amount of incoming windblown sand that attacks the structure. It significantly vary in space and time. Indeed, on the one hand, line-like infrastructures cross different regions with a wide variety of geomorphological characteristics. On the other hand, infrastructure design must ensure the service life prescribed by standards. Hence, a probabilistic approach to design is necessary to take into account the inborn variability of the phenomenon.

The amount of incoming windblown sand is defined as the mass per unit time and per unit length, and usually called *incoming sand drift*. Phenomenologically, windblown sand is a multi-physics phenomenon which includes wind and sand subfields. Hence, sand drift depends on both the wind velocity and the sand characteristics. The modelling framework to sand drift evaluation has been first introduced by Fryberger and Dean, 1979. Their seminal work still grounds the current scientific and technical literature in several application fields, such as fundamental research (e.g. Al-Awadhi and Al-Awadhi, 2009; Barchyn and Hugenholtz, 2011), geomorphology (e.g. del Valle et al., 2008; Bogle et al., 2015; Kilibarda and Kilibarda, 2016; Yang et al., 2016), paleo sedimentology (e.g. Yang et al., 2014), climatology (e.g. Bogle et al., 2015), coastal management (e.g. Riksen et al., 2016), civil engineering (e.g. Dong et al., 2004; Zhang et al., 2010; Cheng et al., 2015). In the Fryberger and Dean, 1979 framework, the so-called Drift Potential (DP) is defined for each wind direction, while the Resultant Drift Potential (RDP) and the Resultant Drift Direction (RDD) stand

---

[*] Corresponding author at: Politecnico di Torino, Department of Architecture and Design, Viale Mattioli 39, I-10125 Torino, Italy.
E-mail addresses: lorenzo.raffaele@polito.it (L. Raffaele).

http://dx.doi.org/10.1016/j.jweia.2017.04.004
Received 6 February 2017; Received in revised form 15 March 2017; Accepted 7 April 2017

Nomenclature

DP	Drift Potential
HW	Hybrid Weibull
MC	Monte Carlo
RDD	Resultant Drift Direction
RDP	Resultant Drift Potential
SD-WA	Sand Deterministic - Wind Averaged
SWP	Sand Wind Probabilistic
D	drift potential
F	probability distribution function
F_0	wind calm rate
N	number of occurrences
Q	sand transport rate
R	resultant drift potential
T	reference time
T_r	recording time
U	wind velocity
U_{10}	10-min averaged wind speed
$c.o.v.$	coefficient of variation
d	sand grain diameter
d_r	sand grain reference diameter
f	probability density function
g	gravitational acceleration
k	Weibull shape parameter
p	percentile
sk	skewness
u_*	shear velocity
u_{*t}	threshold shear velocity
z_0	roughness length
Δt	sampling interval
$\Delta\theta$	sector width
θ	wind direction
λ	Weibull scale parameter
μ	mean value
ρ_a	air density
ρ_b	packed bulk sand density
σ	standard deviation
#	cardinality
0	calm wind

for the magnitude and direction of the vector sum of DP over the directions, respectively. These quantities are called ”potential” because they provide a measure of sand-moving capacity of the wind blowing over an ideal sand bed, neglecting the local covering of the ground surface (Pye and Tsoar, 2009). Fryberger and Dean, 1979 obtain DP per reference time (usually 1 year) by cumulating the sand transport rate Q over the wind speed recording time, and rescaling it on the reference time. In turn, Q results from the vertical integration of the horizontal windblown sand flux. Several semi-empirical models to predict Q have been proposed so far, reviewed e.g. in Dong et al. (2003); Kok et al. (2012); Sherman and Li (2012). Among them, modified Bagnold type models are the most widely adopted in literature (see for instance the field studies by Fryberger and Dean, 1979; Al-Awadhi and Al-Awadhi, 2009; Barchyn and Hugenholtz, 2011; Sherman and Li, 2012; Sherman et al., 2013; Yang et al., 2014; Liu et al., 2015). In particular, the model proposed by Lettau and Lettau (1978) is the most adopted one. They all relate Q to the wind shear velocity u_* and the threshold shear velocity u_{*t}, that is the shear velocity above which sand transport occurs. Usually, such a threshold is assessed as a function of the sand grain diameter d by means of semi-empirical expressions (e.g. Bagnold, 1941; Iversen and White, 1982; Shao and Lu, 2000; McKenna, 2003). According to the Authors, it is worth pointing out that the current approach within the Fryberger and Dean, 1979 framework is:

- deterministic with respect to the sand subfield. Indeed, the expressions of the threshold shear velocity u_{*t} used so far are purely deterministic;
- time-averaged with respect to the wind subfield. The wind speed inborn variability is accounted for, but only the mean value of DP is retained because the rescaling on the reference time is tantamount to averaging.

Let us call such approach as Sand Deterministic - Wind Averaged (SD-WA).

Despite SD-WA approach is generalized in practice, windblown sand phenomenon is affected by several sources of uncertainty. They can be generally classified in *aleatory* and *epistemic* uncertainties (Zio and Pedroni, 2013). Let us introduce a complementary categorization referring to the wind and sand subfields introduced above. *Epistemic* uncertainties are associated with the lack of knowledge about the properties and conditions of the phenomena to be modeled. They can be further ascribed to model, parameter and measurement uncertainties. Wind-field epistemic uncertainties are generally well quantified, because of its long-standing modelling, while sand-field ones have been only recently highlighted with respect to threshold shear velocity (e.g. Barchyn and Hugenholtz, 2011; Raffaele et al., 2016) and sand transport rate (e.g. Barchyn et al., 2014). *Aleatory* uncertainties refer to inherent randomness of natural phenomena. Let us introduce a further categorization referring to the wind and sand subfields introduced above. Wind-related aleatory uncertainties affect the velocity and other environment variables. Sand-related aleatory uncertainties take place at both the microscopic scale, i.e. grain irregular shape, grain size distribution, grain relative position on the sand bed (e.g. Nickling, 1988; Duan et al., 2013; Edwards and Namikas, 2015), and the macroscopic scale, i.e. soil vegetation covering, soil sediment availability, soil moisture and soil crusting (see e.g. McKenna Neuman and Nickling, 1989; Lancaster and Baas, 1998; Shao, 2008; Hoonhout and de Vries, 2016). The statistical description of wind speed is long-standing and well established, as reviewed e.g. by Carta et al. (2009). Conversely only recently the Authors proposed the statistical description of threshold shear velocity (e.g. Raffaele et al., 2016). The cited paper substantially contributes to the background of the present study. It includes a comprehensive review on the uncertainties that affects both experimental measurements and modelling of u_{*t}. In the light of this, a statistical modelling is developed, based on advanced copula-based quantile regression. Joint probability density functions of the sand grain diameter and u_{*t} are derived, as well as the conditional probability density functions of the threshold shear velocity for given values of the diameter.

Both the engineering design needs and the shortcomings of the SD-WA approach pave the way for the probabilistic description of the incoming sand drift. According to the Authors, it can be regarded as equivalent to other environmental actions, in analogy to wind action. Hence, let us briefly outline in the following to which extent the incoming wind speed U is analogous to the sand transport rate Q and to the drift potential DP. First, in wind engineering the wind speed is defined in probabilistic terms due to the uncertainty related to inborn wind variability only. The probabilistic representation of sand transport rate is recommended a fortiori and it is more difficult at the same time, since it is affected by more uncertainties. The variability of both wind and sand features should be taken into account. Second, most of the wind effects on structures, e.g. equivalent static loads or flutter, are related to extreme values of the incoming wind speed. Conversely, windblown sand effects on civil structures are mainly induced by the cumulated values of current values of Q over time, that is DP. In this