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A FULLY PREDICTIVE MODEL FOR AEOLIAN SAND TRANSPORT

by L.C. van Rijn¹ and G. Strypsteen²

¹LVRs-consultancy, Domineeswal 6, 8356D Blokzijl, The Netherlands; info@leovanrijn-sediment.com

²Construction TC, Dept. Of Civil Engineering, Bruges Campus, KU Leuven, Spoorwegstraat 12, B-8200, Bruges, Belgium. glenn.strypsteen@kuleuven.be

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Abstract

This paper presents the development, calibration and verification of a fully predictive model for wind-blown dry sand. The model is based on the modification of the well-known Bagnold equation by including the threshold shear velocity, which is also slightly modified to ensure a smoother transition from the non-transport regime to the transport regime. The sand transport rate is related to the static and dynamic grain roughness by using a semi-empirical roughness predictor, which is calibrated based on sand transport data from wind tunnel experiments with a flat mobile sand surface. The model input for dry sand is the wind velocity at one height above the surface and the sand characteristics (d_{50} , d_{90}). The effects of moisture, vegetation and shells on the sand transport process are included by fairly simple expressions which are acting on the shear velocity, the threshold value and the transport rate. In all, 105 high-quality data sets have been used for verification of the proposed predictive model. About 73% of the predicted values are within a factor of 2 of measured values of the transport rate.

1 Introduction

Restoration and maintenance of coastal beach and dune systems require knowledge of aeolian transport processes for the prediction of the system response to wind forces over short to long-term time scales. Accurate aeolian sand transport equations are of utmost importance for modern geomorphology and coastal engineering practices.

Many aeolian equations are available for the prediction of the transport of loose grains along a surface of dry and clean sand without vegetation. Extensive overviews have been given by Nickling and Davidson-Arnott (1990), Kok et al. (2012) and Valance et al. (2015). Most equations are strongly dependent on the bed-shear velocity (u_*) to the power 2 or 3 and to lesser extent on the grain size and composition. One or more empirical coefficients are included based on calibration using data from wind tunnel and field experiments. Although sand transport by wind is easily observable, reliable and accurate data sets of sand transport rates are still scarcely available due to measuring difficulties. Mostly, relatively simple mechanical trapping systems are being used, but reported efficiencies are often below 50%, differing from site to site and sometimes even unknown (Sherman et al., 2014). Hence, corrections are not always possible resulting in biased calibration data. Using such data sets imply that the calibrated models are inadequate yielding poor model performance.

Sherman et al. (1998, 2013) have shown that many models substantially overpredict the measured sand transport rates of high-quality data sets. Similar results were obtained by Horikawa et al. 1986; Dong et al., 2002 and Liu et al., 2006.

Reasons for discrepancies are discussed in detail by Sherman et al. (2013). Important sources of error are the grain size and composition of the bed (uniform versus graded), horizontally non-uniform sand surface conditions related to grain size, relief, crusting and shells, moisture variations and saturation length scales. However, the major source of error most likely is the bed-shear velocity and associated bed roughness height. This latter parameter consists of several contributions, being the static and dynamic grain roughness, form-related roughness if bed forms (ripples) are present and roughness of isolated elements resting on the surface (shells, pebbles, stones, etc). It is common practice to determine the bed shear velocity from the slope of measured velocity profile data using $\kappa=0.4$ (Von Karman coefficient). These shear velocities may be significantly too large

as discussed by Li et al. (2010). High concentrations of saltating particles may lead to the damping of turbulence which can be expressed as a reduction of the κ -coefficient (range of 0.25 to 0.4 based on Li et al., 2010). Similar effects have been extensively observed and described for sediment-laden water flows (Van Rijn 1993). Taking this effect into account, the bed-shear velocities are substantially reduced resulting in smaller predicted sand transport rates (less over-prediction, Sherman et al., 2013). A problem of the methods proposed by Li et al. (2010) and Sherman et al. (2013) is that the modified κ -coefficient is related to the sand transport rate, which is a priori unknown and thus requiring iterative computations. Another problem of the model application proposed by Sherman et al. (2013) is the use of measured bed-shear velocities requiring detailed wind velocity measurements at different levels above the sand surface. Most accurate estimates of the bed-shear velocity even require the use of sophisticated anemometers to measure the instantaneous horizontal and vertical wind velocity components to derive the Reynold stress term. As such, this method is in no way predictive. In principle for engineering practices, it must be possible to get a reasonable estimate of the aeolian sand transport rates at a particular site based on wind velocity data from a nearby meteorological station and available grain size data from local samples.

This paper describes the development of a fully predictive sand transport equation (Section 2) based on the work of Bagnold (1936, 1941) in combination with a roughness predictor (Section 3) to achieve a 'best practice' engineering model for wind-blown sand. High-quality data sets have been used for model calibration and verification of the proposed model (Sections 4). The effects of moisture, shells and vegetation is extensively studied to derive simple coefficients for the predictive transport model (Section 5). Applications of the model for sand transport at the beach parallel to the shoreline and normal to the dune crest are given in Section 6.

2. Sand transport model for saturated conditions

2.1 Modified Bagnold-equation for sand transport

Sand transport commences as soon as the threshold shear velocity is exceeded. Bagnold (1941), Kok et al. (2012) and Valance et al. (2015) and many others have discussed the dominant modes of wind-blown transport. The transport of sand particles in the size range of 100 to 500 μm is dominated by the saltation type of transport (small ballistic type of hops). Very small particles (fine fraction) ranging from 63 to 100 μm are transported in suspension by turbulent eddies. The largest particles (coarse fraction) ranging from 500 to 2000 μm are transported by sliding and rolling as surface creep. The combined transport of particles by rolling, sliding and small hops (saltations) can be defined as bed load transport of particles in more or less continuous contacts with the bed. Bed load transport of particles in a thin transport layer is the dominant mode of wind-blown transport for sand particles (100 to 300 μm). Observations in wind tunnels and in nature show that most of the transport occurs in a thin layer ($< 0.05\text{ m}$) above the sand surface (Ho, 2012). In this thin transport layer, the particle velocity (averaged over the layer thickness) is almost insensitive to the external wind velocity above the transport layer and is approximately equal to 3 to 4 times the critical bed shear velocity ($u_p \cong 3 \text{ to } 4 u_{*,th}$). Particle concentration is so high that the wind velocity is strongly reduced to a value of the order of 0.8 to 1.2 m/s (Kok et al., 2012). An increase of the wind velocity results in an increase of the particle concentration which in turn leads to a decrease of the wind flow speed close to the bed such that the new equilibrium particle velocity remains almost unchanged (Valance et al., 2015).

Above the saltation layer, the suspended particle concentrations are smaller and the air flow is almost unaffected by the presence of the particles. As a result, the particle velocity above the saltation layer increases with increasing wind velocity (Valance et al., 2016).

Many researchers have proposed models for aeolian sand transport under ideal conditions with uniform and steady wind obeying the law of the wall; with almost uniform (size, composition) and dry sand on a horizontal sand surface without vegetation and other obstacles. Uncertainties related to non-ideal conditions as present at field sites are discussed by Sherman et al. (2013). One of the first models for ideal conditions has been formulated by Bagnold (1936) and is most widely used. Sherman et al. (1998, 2013), Strypsteen (2019) and Strypsteen et al. (2019) have shown that the Bagnold-model performs reasonably well in predicting sand transport of high-quality

data sets, but the original equation tends to systematically overpredict (factor 2 to 3). This can be improved by the inclusion of a threshold value. Herein, only the Bagnold-model with minor modifications is proposed to be used as a predictive model.

In most general form, the sand transport in both water and air can be described as: $\phi = \alpha D_*^\beta (\theta - \theta_{th})^\gamma$ with $\phi = q_s / [\rho_s (s-1)^{0.5} g^{0.5} d_{50}^{1.5}]$ = dimensionless sand transport; $D_* = [(s-1)g/\nu^2]^{1/3} d_{50}$ = dimensionless grain size, and $\theta = u_*^2 / [(s-1)gd_{50}]$ = dimensionless shear stress; α , β and γ = coefficients.

Based on this, the modified Bagnold-equation for the transport of dry sand can be derived (see Strypsteen et al., 2019), which reads as:

$$\text{Saturated/equilibrium transport:} \quad q_{s,eq} = \alpha_B \alpha_{ad} \alpha_{shell} (d_{50}/d_{50,ref})^{0.5} (\rho_{air}/g) [(u_*)^3 - (u_{*,th})^3] \quad (2.1)$$

$$\text{Critical shear stress:} \quad u_{*,th} = \alpha_w \alpha_{slope} u_{*,th,B} \quad (2.2a)$$

$$u_{*,th,B} = \alpha_{th} [(\rho_s/\rho_{air}-1) g d_{50}]^{0.5} \quad \text{for } d_{50} > 100 \mu\text{m} \quad (2.2b)$$

$$u_{*,th,B} = \alpha_{th} u_{*,th,100 \mu\text{m}} \quad \text{for } 32 < d_{50} < 100 \mu\text{m} \quad (2.2c)$$

$$\text{Shear stress:} \quad u_* = \kappa \alpha_{veg} u_w / \ln(30z_{wind}/k_s) \quad (2.3)$$

with: $q_{s,eq}$ = mass flux of sediment at equilibrium conditions (saturated transport, kg/m/s); d_{50} = particle size (m); $d_{50,ref}$ = reference particle size = (250 10^{-6} m; 250 μm); ρ_{air} = density of air (≈ 1.2 kg/m³); ρ_s = density of sediment (≈ 2650 kg/m³); $s = \rho_s/\rho_{air}$ = relative density, ν = kinematic viscosity coefficient (m²/s), g = acceleration of gravity (m/s²); u_* = surface shear velocity due to wind forces (m/s); $u_{*,th}$ = surface shear velocity at initiation of motion; threshold shear velocity (m/s); k_s = equivalent roughness length scale of Nikuradse (m); u_w = wind velocity at height z_{wind} above the surface (m/s); κ = constant of Von Karman (≈ 0.4 for conditions without transport); α_B = Bagnold-coefficient for dry sand ≈ 1.5 for uniform sand; ≈ 1.8 for naturally graded sand; ≈ 2.8 for widely graded sand (Bagnold, 1941); herein the value of 2 is used as default value: $\alpha_B = 2$; α_{ad} = adjustment coefficient related to fetch (maximum 1); α_{shell} = reduction coefficient related to the presence of shells; $\alpha_{th} = 0.11$ based on data of Shao-Lu (2000) and Han et al. (2011); ≈ 0.1 based on Bagnold (1941); α_{slope} = coefficient for sand grains at a sloping surface; α_w = moisture coefficient ($=1$ for dry sand); α_{veg} = vegetation coefficient ($=1$ for conditions without vegetation). The effects of moisture (α_w), vegetation (α_{veg}), shells (α_{shell}) are discussed in Section 5. Strypsteen et al. (2019) have shown that the predictive ability of the modified Bagnold-equation (2.1) with $\alpha_B = 2$ is excellent.

2.2 Threshold shear velocity

The value of the wind-induced stress at which saltation is initiated is known as the static fluid threshold shear stress. This threshold value depends not only on the properties of the fluid, but also on the gravitational and interparticle cohesion forces that oppose the fluid lifting. The fluid threshold is different from the dynamic or impact threshold, which is the lowest wind stress at which saltation can be sustained after it has been initiated. The impact threshold is smaller than the fluid threshold because the transfer of momentum to the surface through particle impacts is more efficient than through drag (Kok et al., 2012). Herein, only the dynamic threshold shear velocity based on Equation (2.2) is used with $\alpha_{th} = 0.11$ based on data of Shao-Lu (2000) and Han et al. (2011) whereas $\alpha_{th} \approx 0.1$ based on Bagnold (1941). Experimental data (Kok et al., 2012) show that the measured threshold shear velocities of very fine sediments between 20 and 100 μm are scattered with values between 0.15 and 0.25 m/s. Equation (2.2b) underpredicts the measured threshold values of particles between 20 and 100 μm and therefore the shear velocity of fine sediment is herein assumed to be constant and equal to the threshold shear velocity of 100 μm -sand yielding a constant value of 0.16 m/s (Equation 2.2c).

When a grain is resting on a sloping surface (dune front), the threshold shear velocity is different from that on a horizontal surface. The threshold value increases for upsloping wind flow and decreases for downsloping wind flow. A simple and fairly accurate method is the method of Dey (2003), which has been slightly improved (Van

Rijn 2006): $\alpha_{\text{slope}} = u_{*,\text{th,slope}}/u_{*,\text{th,B}} = [(1+\beta/\varphi)^{0.75}(1+\gamma/\varphi)^{0.37}]^{0.5}$ with β =longitudinal slope angle (positive for upsloping wind flow), γ = lateral slope angle (positive for upsloping flow) and φ = angle of repose (see also Section 6).

2.3 Effect of shear velocity and grain size on sand transport

The results of the modified Bagnold equation based on equations (2.1 and 2.2) are compared to the measured sand transport rates for dry sand (three diameters: 0.44, 0.3 and 0.145 mm, see Section 4.2) of the wind tunnel experiments of Belly (1964), see **Figure 2.1**. Using the default coefficient $\alpha_B=2$ (other coefficients=1) and the measured shear velocities, the measured transport rates are underpredicted by a factor of about 1.5 for 0.44 mm-sand and 0.3 mm-sand and overpredicted by a factor of 1.5 for 0.145 mm-sand (Figure 2.1), which is a fairly good result for a sand transport predictor. It is noted that the original Bagnold model (1941) without the threshold-modification produces equally well results for the data set of Belly (1964). Bagnold(1954) proposed to use $(u_*-u_{*,\text{th}})^3$ as the driving term, but this yields transport values which are much too small (Strypsteen et al, 2019).

Equation (2.1) was also fitted to the three data sets by varying the α_B -coefficient resulting in $\alpha_B = 3.5$ ($R^2=0.82$) for 0.44 mm and 0.3 mm-sand and $\alpha_B = 1.5$ ($R^2=0.9$) for 0.145 mm-sand. This confirms that Equation (2.1) with default settings underpredicts for coarser sand (0.44 mm and 0.3 mm) and overpredicts for finer sand (0.145 mm).

To show that the cubic power relationship between transport and shear velocity is a reasonable approach, the function $q_s = \alpha [(u_*)^3 - (u_{*,\text{th}})^3]^\beta$ was fitted to three datasets resulting in β -values between 0.95 and 1.1 with $R^2 \approx 0.9$. This confirms that the cubic relationship ($\beta=1$) is a good approach.

The measured sand transport rates of the three sands with diameters of 0.44, 0.3 and 0.145 mm show that the transport rate of 0.3 mm is smaller than that of 0.44 mm-sand for $u_* > 0.5$ m/s, but larger for $u_* < 0.5$ m/s. The modified Bagnold equation shows a similar effect for $u_* < 0.45$ m/s, but in a minor way. This effect with smaller and larger transport rates is caused by including the threshold shear velocity in Equation (2.1) and cannot be represented by the original Bagnold model without threshold parameter. The measured sand transport rates of 0.145 mm-sand are much smaller (factor 2 to 3) than those of 0.44 mm and 0.3 mm-sand. The decrease of the transport rate for decreasing grain size is also shown by the Bagnold equation, but the effect is too small for fine sand of 0.145 mm.

Figure 2.1 Wind transport of dry, loose sand particles based on modified Bagnold-equation ($\alpha_B=2$) for sand with $d_{50}=0.44$, 0.3 and 0.145 mm; data of Belly (1964)

2.4 Saturation length scale

Saturated or equilibrium sand transport may differ from the actual transport due to: i) limited fetch length; ii) horizontal variations of roughness, moisture, shells, vegetation and grain size/composition (see overview of Delgado-Fernandez, 2010). Fetch length (F_w) is the distance over which wind blows along the sand surface. Saturation length or adjustment length (L_{ad}) is the distance which is required for approaching saturated or equilibrium transport. This length scale is also known as the critical fetch length ($F_{w,cr}=L_{ad}$). Supply-limited conditions are present if the fetch length is smaller than the adjustment length ($F_w < L_{ad}$). Similarly, when transport

conditions change due to horizontal variation of sand and surface conditions, the transport rate adjusts/adapts to the new conditions within the saturation distance, which depends on the thickness of the sand transport layer, the wind speed and the mixing capacity (turbulence and roughness) and wind speed. Experiments in wind tunnels with dry, loose sand surfaces have shown that the transport layer including the saltation layer and the suspended layer is of the order of 0.1 to 0.5 m for low to high wind velocities and grain diameters between 0.2 and 0.45 mm. Most of the transport takes place in a layer of about 0.05 m (Han et al, 2011; Yang et al. 2019). The adjustment of the boundary layer flow over a rough surface can be described by $\delta \approx 0.2x^{0.6}$ (Granger et al., 2006). Hence, the adjustment length scale for the air flow to adjust over the height of the transport layer of $\delta=0.5$ m is about 5 to 10 m. Given near-surface wind speeds of the order of 5 m/s, the adjustment time scale is about 1 to 2 s. Basically, the adjustment length scale to approach equilibrium conditions in air and in water (Van Rijn 1987) depends on the shear velocity (u_*), the particle diameter (d_{50}) or fall velocity (w_s) expressing the gravity effect and the thickness of the transport layer (δ_s). A classic problem in water is the adjustment of sand transport in a channel with a fine sand bed downstream of a rigid bed channel. The adjustment from zero transport at the entrance of the sand bed to the new equilibrium sand transport value takes about 50 to 100 times the water depth (Van Rijn 1987). Hence, a conservative estimate for sand transport in water and air is: $L_{ad}=100 \delta_s$ (Van Rijn 1987). The thickness of the transport layer (δ_s) in air is assumed to be equal to the saltation height of the sand particles and scales with the particle size (d_{50}), and the excess shear velocity ($u_*-u_{*,th}$). Based on analysis of the data of Yang et al. (2019), a tentative relationship similar to that for the saltation height in water (Van Rijn 1987) is:

$$\delta_{sal} = \alpha_s (d_{ref}/d_{50}^{0.5}) (u_* - u_{*,th})/g^{0.5} \quad (2.1)$$

with $\alpha_s = 150$ and $d_{ref} = 0.00025$ m. Data are given in Table 2.1. Equation (2.1) has the correct dimension of length and shows a decreasing thickness of the transport layer for increasing particle size.

The saturation length is:

$$L_{ad} = 100 \delta_{sal} = 1.5 \cdot 10^4 (d_{ref}/d_{50}^{0.5}) (u_* - u_{*,th})/g^{0.5} \quad (2.2)$$

Very accurate data of the saturation length scale for saltation type of sand transport are not really available, but the wind tunnel data of Han et al. (2012) and Yang et al. (2019) and the field data of Davidson-Arnott et al. (2008) at a Canadian beach with sand of 0.26 mm; Jackson and Cooper (1999) at Benone beach, Northern Ireland; Zhang et al. (2012) and Dong et al. (2012) in China deserts suggest values in the range of 10 to 100 m. Table 2.1 shows computed and measured values of the saltation height and saturation length for a particle of 0.0003 m (0.3 mm) with threshold shear velocity $u_{*,th} = 0.28$ m/s.

Shear velocity u_* (m/s)	Saltation height δ_{sal} (m)		Saturation length L_{ad} (m)	
	Computed	Observed	computed	observed
0.4	0.08	0.1-0.2	8	≈ 10 (wind tunnel)
0.6	0.23	0.2-0.3	23	$\approx 10-50$
0.8	0.36	0.3-0.4	36	$\approx 50-100$ (field)

Table 2.1 Saltation height and saturation length for sand particles of 0.3 mm

Equilibrium sand transport conditions also depend on various limiting effects (small or wide grain size composition; moisture content; armor effects). The adjustment length scale of dry sand is different from that of wet sand. Relatively high transport rates were measured by Davidson-Arnott et al. (2008) in conditions with offshore winds when sand supplied from the dry upper beach was transported over a damp, hard surface on the lower foreshore. Thus, the transport rate may exceed that for dry sand if the sand supply comes from a dry upwind zone and the sand particles are transported over a moist and hardpacked surface. These high transport rates are probably caused by the lower drag losses for sand grains impacting with the hard surface. Where

surface moisture is very high, some saltating grains may adhere to the surface on impact resulting in smaller transport rates. Where bedforms such as ripples or low dunes are present on a wet sand surface, grains resting on the surface in the lee of the bed forms may become wet resulting in higher threshold values leading to smaller transport rates. In these conditions the transport rate will be smaller than for dry sand. A consequence of this is that the spatiotemporal behavior of the limiting factors must be part of the prediction model (process-based approach, see De Vries and Hoonhout (2017) and Hoonhout and De Vries (2019).

A simple approach to deal with adjustment effects due to limited fetch is the use of an adjustment coefficient in Equation (2.1):

$$\alpha_{ad} = (L_{fetch}/L_{ad})^{0.6} \text{ with } \alpha_{ad} = 1 \text{ for } L_{fetch} > L_{ad} \quad (2.3)$$

The power is taken as 0.6 similar to that of air flow layer adjustment (Granger et al., 2006). Using Equation (2.3), the adjustment process proceeds in a progressive way; the sand transport is about 70% of the equilibrium value after 50% of the total adjustment length ($L_{fetch}/L_{ad}=0.5$). If the dry zone of the beach is wider than about 100 m, the adjustment coefficient can be safely neglected. Research is recommended to improve the proposed equations (2.1) and (2.2).

3. Effective bed roughness

3.1 Influencing parameters

The wind velocity in the near-bed region strongly depends on the effective or equivalent bed roughness (k_s) as defined by Nikuradse (Nikuradse 1933, Van Rijn 2011). This roughness length is defined as the equivalent grain roughness replacing any type of roughness yielding the same overall bed roughness (same velocity profile).

It is most logic to assume that the effective roughness (k_s) of the sandy beach surface is related to the:

- grain roughness effects of static and saltating particles (Owen, 1964; Farrell and Sherman, 2016; Field and Pelletier 2018);
- height of the micro bed morphology (ripples), (Pelletier and Field 2016, Field and Pelletier, 2018);
- size of shells or shell fragments/clusters which are sometimes abundantly available, particularly at nourished beaches.

The effective roughness length of an irregular sand surface is strongly related to the presence of flow separation, as controlled by the slopes, curvature and height of the irregularities. Bed irregularities generate additional near-bed turbulent velocity fluctuations (turbulence) enhancing sand transport. In areas with abundant sand supply, the height and wavelength of aeolian ripples may increase with increasing shear velocity and grain size. Little is known about the relative contribution of saltation processes and ripple formation to changes in roughness length (Field and Pelletier, 2018).

Most likely, the static and dynamic grain roughness are the most important components, but the role of form roughness is not yet fully clear. Both effects can be separated by the method of shear partitioning resulting in: $\tau = \tau' + \tau''$ with τ' = grain-related shear stress and τ'' = form drag-related shear stress. Bed-load transport in water flow is mostly related to τ' , whereas suspended load transport is affected by both components ($\tau' + \tau''$).

The field data sets of Sherman et al. (2013), described as a data set closely approaching ideal conditions for dry and unvegetated sand, are herein used to determine the roughness required for perfect agreement of measured and computed sand transport rates using the modified Bagnold-equations (2.1) and (2.2) with $\alpha_B=2$ and $\alpha_{th}=0.11$ (and $\alpha_{ad} = \alpha_{shell} = \alpha_w = \alpha_v = 1$). Thus, it is assumed that the Bagnold equation is perfect and that discrepancies are only related to the uncertainties of the bed-shear velocity. The bed shear velocity is computed by using: $u_* = \kappa u_w / \ln(30z/k_s)$ with: u_w = measured wind velocity at height $z=2$ m above the surface, $\kappa=0.4$ and $k_{s,perfect}$ = roughness height giving perfect agreement of measured and computed sand transport rates. The $k_{s,perfect}$ values were determined by trial and error until perfect agreement of measured and computed transport rates is obtained. This procedure was repeated using a smaller and larger transport coefficients $\alpha_B=1.5$ and $\alpha_B=2.5$ (range given by Bagnold) resulting in larger and smaller $k_{s,perfect}$ values (uncertainty range).

Figure 3.1 shows the ratio of the $k_{s,perfect}$ and $k_{s,measured}$ and the uncertainty range as function of the measured wind velocity at 2 m above the surface. Most values are smaller than 0.3, which suggest that the effective roughness required for sand transport is only a fraction of the overall roughness. When this effect is neglected and the overall roughness (measured shear velocity u_*) is used, the Bagnold-equation systematically overpredicts the measured sand transport rates of Sherman et al. (2013) by a factor of 2 to 5. Thus, most likely, the static and dynamic grain roughness (related to τ') rather than the overall roughness are the dominant components for sand transport, similar to that for sand transport by flowing water (Van Rijn 1993). In **Section 3.4** a roughness predictor will be derived for the static and dynamic grain roughness.

Figure 3.1 Ratio of $k_{s,perfect}$ and $k_{s,measured}$ as function of the wind velocity

3.2 Flat bed

Xian et al. (2002) studied the aerodynamic roughness length (z_o) values of various types of flat surfaces of coarse materials in a wind tunnel and in the Gobi desert in China. The desert surface is mostly flat, unvegetated and covered with gravel. The field results show that the effective bed roughness is of the order of 5 to 10d for the gravel-type surfaces and about 100d for sand-type surfaces with d = average height of roughness elements. The relatively large roughness values of the sand surfaces are most likely caused by the larger roughness elements (cobbles) resting on the bed. Wind tunnel experiments with various types of roughness elements were conducted. The main findings are: i) the effective bed roughness of crushed gravel, oblate shingle and cobblestone is related to largest diameter (d_{max}); ii) the roughness increases for increasing percentage of cover; iii) the shape of the roughness elements has not much effect on bed roughness.

Dong et al. (2002) performed wind tunnel experiments to determine the aerodynamic roughness length of spherical roughness elements of different size and cover at free-stream wind velocities in the range of 4 to 22 m/s. The aerodynamic roughness was found to increase with increasing cover values of 1% to 50 % and was about constant for cover values > 50%. If only a few isolated gravel particles are present (cover< 1%), the measured bed roughness is almost completely determined by the roughness of the surrounding bottom (cement floor).

Zhang et al. (2004) studied the surface roughness of cultivated soil by performing wind tunnel tests with five artificially prepared soil surfaces. Soil samples were taken from farmland in the semi-arid region of northwest China. The soil characteristics are: 36% sand, 53% silt and 11% clay. Five surface soil samples with depth of 15 cm were taken in tray-type sample boxes (50 cm × 30 cm × 15 cm). The diameters of the largest clods (D_{max}) were in the range of 1.5 to 50 mm. The effective roughness of a flat bed with about 20% to 40% of large clods was found to be in the range of 0.4 to 1.3 D_{max} .

Summarizing the results of Xian et al. (2002), Dong et al. (2002) and Zhang et al. (2004), it can be concluded that the static bed roughness of a flat, horizontal bed is related to the largest diameters of the roughness elements (pebbles, gravel, sand) on the surface. In the case of a flat sandy surface, the d_{90} is a good measure to represent the roughness of the surface. This is also valid for a subaqueous sand surface (Van Rijn 1993). A few isolated extremely large roughness elements (cover < 1%) have almost no effect on the overall bed roughness.

3.3 Bed irregularities and bed forms

Owen (1964) has found that the effective bed roughness of natural sandy surfaces with small-scale bed irregularities can be represented by:

$$z_o = \alpha_o u_*^2 / 2g \text{ and } k_s = 30z_o = 30\alpha_o u_*^2 / 2g \quad (3.1)$$

with: α_o = coefficient (≈ 0.01). Thus, the bed roughness increases for increasing bed-shear velocity, either due to the increasing dynamic grain roughness (more saltating grains) and/or due to increasing bed forms (growing ripples). At very high wind velocities, the ripples will most likely disappear again (Belly, 1964).

Hsu (1974) analyzed various field data sets from a variety of environments with particles sizes between 0.2 and 0.3 mm, including those over beaches, tidal flats, and small dune fields in Barbados, Ecuador, Florida, and Texas and in the Libyan desert. Based on these results, he proposed:

$$u_* = 0.037 U_{10m} \text{ and } u_* = 0.044 U_{2m} \quad (3.2)$$

with: U_{2m} = wind velocity at $z=2$ m above bed and U_{10m} = wind velocity at $z=10$ m above bed.

Using: $U_{wind,z} = (u_*/\kappa) \ln(z/z_o)$ with $\kappa=0.4$ and $z=2$ m yields $U_{2m}/u_* = (1/\kappa) \ln(2/z_o)$ which is equivalent to

$$z_o = 2/\exp(\kappa U_{2m}/u_*) \text{ or } k_s = 30z_o = 60/\exp(\kappa U_{2m}/u_*). \quad (3.3)$$

This gives: $k_s = 0.0067$ m (6.7 mm) for $u_* = 0.044 U_{2m}$ and $\kappa=0.4$. This roughness height of $k_s=6.7$ mm is much larger than the grain size of the beaches involved and is a measure of the thickness of the layer with intense sand transport producing roughness. As bed form data are not reported by Hsu, it is not clear whether the effect of bed forms on the bed roughness is very small or that bed forms were just absent.

Sherman (1982) and Sherman and Farrell (2008) proposed the following equation for natural sandy beds in wind tunnel and field conditions:

$$z_{o,dynamic} = z_{o,static} + (C_m/g)(u_* - u_{*,th})^2 \text{ and } k_{s,dynamic} = k_{s,static} + (30C_m/g)(u_* - u_{*,th})^2 \quad (3.4)$$

with: C_m = coefficient and $k_{s,static} = 2d_{50}$. They found $C_m \approx 0.012$ for wind tunnel data sets and $C_m \approx 0.13$ for field data sets. Limiting the maximum shear velocity u_* to less than 1.0 m/s, they found $C_m = 0.023$ for the wind tunnel data sets and $C_m \approx 0.15$ for the field data sets. Thus, the field and wind tunnel values are significantly different from each other by an order of magnitude. Field and Pelletier (2018) found $C_m=0.063$ based on their field data. Using: $C_m \approx 0.1$ for field sites, $u_*=0.5$ m/s and $u_{*,cr}=0.25$ m/s, it is found that $k_{s,dynamic} \approx 150$ mm, which is so high that it can only be caused by form-related roughness. The precise types of beds are not described but most likely, the grain-related bed roughness is dominant in wind tunnel experiments, whereas the bed roughness in field conditions is dominated by small-scale bed forms (ripples).

Strypsteen et al. (2017) and Strypsteen (2019) measured wind velocities (8 points up to 2.5 m above the bed) in 2016 at two Belgian beaches Mariakerke and Koksijde with sand in the range of 0.2 to 0.35 mm. The beach of Mariakerke ($d_{50}=0.31$ mm) is somewhat flatter and contains some shell fragments due to regular nourishments, but the measurements were performed in the dry upper beach zone with minor shells. The bed roughness derived from the velocity profile data is relatively small < 10 mm, as bed ripples were not present. The beach of Koksijde consists of sand ($d_{50}=0.21$ mm) with small-scale bed irregularities (ripples) and many shell hash and fragments with height of the order of 30 mm. The bed roughness is relatively high with values up to 100 mm due to the presence of bed ripples and patches of shells.

Lancaster and Baas (1998) measured the bed roughness of a smooth, bare, wind-rippled sand surface at the western part of the former delta of the Owen River in eastern California, USA. The surface sand at this site is coarse (median particle size of 500 to 1000 μ m). The largest relief is of the order of 150 mm. Bed form dimensions are not given, but most likely the ripple heights are in the range of 50 to 100 mm. It was found that: $k_s = 27$ mm for wind conditions below the threshold condition (no sand transport) and $k_s = 38$ mm for wind

conditions with sand transport (saltating grains). These relatively large roughness values are most likely caused by the presence of bed forms.

Pelletier and Field (2016) studied the roughness length of the microtopography of desert-type surface (sites in southwestern US, 2015). The roughness length scale was quantified by the H_{RMSE} , the root-mean-squared values of the surface elevations, which varied in the range of 0.55 to 36 mm. The dominant wave lengths (0.03 to 3 m) were also measured and the average slope S_{av} was computed over a horizontal scale of 0.01 m. The surfaces (30x30 m) studied were predominantly crusted and devoid of vegetation. No sediment transport was present, not even during fast winds. Wind speeds were measured to determine the u_* and z_o -values. Herein, it is assumed that the height (Δ_{ib} =crest to trough height) of the dominant bed irregularities is about $3 H_{RMSE}$. Using $\Delta_{ib}=3H_{RMSE}$, the ratio k_s/Δ_{ib} is found to be in the range of 0.04 to 7 depending on the bed slope/steepness. The effective bed roughness $k_{s,ib}$ of the irregular bed elevations can be represented by simple expressions, as follows:

$$\text{Linear slope effect:} \quad k_{s,ib} = 20 \Delta_{ib} S \quad (3.5a)$$

$$\text{Quadratic slope effect:} \quad k_{s,ib} = 150 \Delta_{ib} S^2 \quad (3.5b)$$

with: Δ_{ib} = height of dominant bed irregularities; S = slope/steepness of dominant bed irregularities ($S \equiv \Delta_{ib}/\lambda_{ib}$); λ_{ib} = length of dominant bed irregularities.

Equations (3.5a,b) are shown in **Figure 3.2**. As can be seen, the effective bed roughness of the irregular bed elevations is strongly dependent on the bed slope. For steep bed slopes of about 0.15, the effective bed roughness is of the order $k_{s,ib} \approx 5\Delta_{ib}$. Equation (3.5a) is the same as that for the flow of water over a rippled bed (see Van Rijn 1993).

Figure 3.2 Ratio of $k_{s,ib}/\Delta_{ib}$ as function of the bed slope S ; data of Pelletier and Field (2016)

Field and Pelletier (2018) studied the contributing effects of micro-morphology (ripples) and saltation-related grain roughness to the overall bed roughness. They report field measurements of z_o -values derived from velocity profiles measured over evolving sand ripples in field conditions (Salton Sea dune field near Salton City, California, USA). The ripple field had a bimodal grain-size distribution with the fine fraction ranging from 0.05 to 0.2 mm and the coarse fraction ranging from 0.5 to 1 mm. Wind speeds were close to or exceeded the saltation threshold during the three monitoring periods. The sand ripple height (Δ) and length (λ) were in the range $\Delta \approx 0.01$ -0.015 m; $\lambda \approx 0.15$ -0.35 m for smaller shear velocities of 0.2 to 0.3 m/s increasing to $\Delta \approx 0.015$ -0.03 m; $\lambda \approx 0.3$ -0.5 m for larger shear velocities of 0.3 to 0.6 m/s. The observations indicate that at low shear velocity ripples can maintain a fairly constant height and spacing while migrating downwind without further growth. The overall k_s -values derived from the data are roughly:

- $k_s = 0.5$ to 5 mm for $u_* < 0.2$ m/s (during conditions with static sand ripples and no saltation);
- $k_s = 1.5$ to 15 mm for $u_* = 0.2$ to 0.4 m/s (during conditions with saltation and evolving sand ripples);
- $k_s = 5$ to 50 mm for $u_* = 0.4$ to 0.6 m/s (during conditions with saltation and evolving sand ripples).

The roughness height during periods without saltation ($u_* < 0.2$ m/s;) represents the static grain roughness plus the form roughness of the fairly regular and smooth sand ripples resulting in small roughness values. The measurements indicate that the k_s -values during periods of saltation are much greater (factor 3 or more) than the values derived for conditions without saltation (static sand ripples). The maximum roughness values at the

site with regular ripples of Field and Pelletier (2018) are up to 50 mm, where those of Pelletier and Field (2016) are up to 700 mm for a site with irregular bed forms. Hence, the form roughness of irregular bed forms may be substantially higher (**Figure 3.2**).

3.4 General roughness prediction model

The effective grain roughness of a flat (static) sand bed without any grain movement is related to the size of the largest particles (d_{90}). Van Rijn (1982) studied the effective roughness of flat sand beds in flumes and rivers. The effective bed roughness was found to be in the range of $k_{s, \text{grain}} = 1$ to $10 d_{90}$ with a mean value of $3d_{90}$. The relatively large experimental range expresses the effect of small irregularities related to preparation of laboratory beds. A perfectly flat bed in field conditions does hardly occur. Observations of flat beds often show the presence of small irregularities, isolated larger roughness elements (shells, stones, pebbles, cobbles, vegetation) or the presence of patches with finer and coarser materials in conditions with graded sediments. Based on the available data (Xian et al. 2002; Dong et al. 2002; Zhang et al. 2004; van Rijn 1993), it is proposed to use $k_s = 3d_{90}$ for static grain roughness of relatively fine sands (< 0.5 mm) and $k_s = 1d_{90}$ for coarse sand (> 0.5 mm) and gravels.

The effective grain roughness of a flat, dynamic sand bed with significant sand transport as sheet flow is related to the thickness of the saltation or sheet flow layer, which increases for increasing wind velocities. Observations show that the transport layer is as high as about 0.5 m above the sand surface. However, most of the sand transport occurs in a layer with a thickness of about 50 mm (Yang et al. 2019). The effective roughness of a flat sand surface during conditions with intense sand transport in the upper wind regime is not precisely known, as no field data for this regime are available, but most likely the roughness will be related to the thickness of the saltation layer (10 to 50 mm). Winterwerp et al. (1990) studied the dynamic grain roughness in the upper flow regime with a plane fine sand bed in a water flume and flow velocities up to 2 m/s resulting in a dynamic grain roughness of about 10 mm ($\approx 30 d_{90}$). Similar experiments have not yet been done for aeolian transport. Therefore, generally accepted relationships to describe the effective bed roughness of a flat dynamic sand bed in the upper transport regime are not yet available.

Small-scale bed forms (ripples) or bed irregularities with height scales of 0.01 to 0.1 m and length scales of 0.1 to 1 m are mostly generated in the lower wind regime (< 10 m/s) and are gradually smoothed out in the transitional (10 to 15 m/s) and upper wind regimes (> 15 m/s; Belly 1964). When ripples are present, the effective bed roughness (form roughness) increases significantly, depending on the height and steepness of the ripples. The maximum effective bed roughness was found to be of the order of 5 times the bed form height (Pelletier and Field 2016). However, the data of Field and Pelletier (2018) show that the effect of form roughness is very minor with effective bed roughness values up to 50 mm. Based on the work of Owen (1964), Sherman and Farrell (2008) and Strypsteen (2019), the effective bed roughness (k_s) is in the range of 10 to 100 mm. As bed form information is lacking, it is not clear whether these roughness values are caused by the drag of saltating particles, the form drag of the bed forms or both. The form roughness of ripples leads to: i) smaller wind velocities in the near-bed layer, ii) larger shear velocities and iii) more turbulence (larger fluctuations). Larger shear velocities and more turbulence most likely lead to more saltating particles (larger concentrations), but smaller velocities lead to smaller transport rates. Overall, the sand transport may be slightly increased by the effect of form roughness (presence of ripples). Wind-driven sand transport is more intensively related to shear stresses acting on the static and dynamic grains and to lesser extent related to form drag, similar as in water flow (Van Rijn 1993).

A major drawback of the roughness predictors proposed by Owen (1964) and Sherman and Farrell (2008) is that the bed roughness (k_s) is related to the overall bed-shear velocity u_* , which depends on the bed roughness (k_s) itself. Hence, an iterative method is required to determine the k_s -value.

Herein, a simple and straightforward roughness predictor is proposed which primarily depends on the static and dynamic grain roughness parameters. Various transport regimes with different roughness parameters are distinguished based on the transport stage parameter T which is defined (see Van Rijn 1984, 1993) as the grain-

related bed-shear stress minus the threshold bed-shear stress divided by the threshold bed-shear stress: $T = (\tau_{\text{grain}} - \tau_{\text{th}}) / \tau_{\text{th}}$. The transport regimes and associated bed roughness parameters are:

- Premature transport stage with rolling, sliding and hopping particles ($T < 0.5$): mostly static grain roughness related to the larger particles (d_{90}) of the sand surface;
- Lower transport stage with saltating particles and evolving bed ripples ($0.5 < T < 1$): dynamic grain roughness produced by small-scale vortices in the lee of the saltating particles due to the wind-particle velocity differences;
- Transitional transport stage with saltating particles and smoothed-out ripples ($1 < T < 5$): dynamic grain roughness in combination with gradually disappearing form-related roughness;
- Upper transport regime with a thin sheet flow layer of saltating particles in contact with the surface and suspended transport layer ($T > 5$): dynamic grain roughness.

It is proposed to represent the effective bed roughness for sand transport in the lower, transitional and upper regime by the following expressions.

$$k_s = k_{s,ir} + k_{s,grain,st} + k_{s,grain,dyn} \quad (3.6a)$$

$$k_s = k_{s,ir} + d_{90} + \alpha_1 \gamma_r d_{50} T^{\alpha_2} \quad (3.6b)$$

$$T = [(u_{*,grain,st})^2 - (u_{*,cr})^2] / (u_{*,cr})^2 \quad (3.6c)$$

$$u_{*,grain,st} = \kappa U_{w,z} / (\ln(30z_w/d_{90})) \quad (3.6d)$$

$$u_* = \alpha_{veg} \alpha_{slope} \kappa U_{w,z} / (\ln(30z_w/k_s)) \quad (3.6e)$$

with: $k_{s,ir}$ = roughness due to irregularities (shells, stones, etc) producing additional turbulence (m); T = transport stage parameter (-); $k_{s,grain,st}$ = bed roughness height due to static grains (m); $k_{s,grain,dyn}$ = bed roughness height due to dynamic grains (m); d_{90} = grain diameter (90% smaller); $\kappa=0.4$; α_1 and α_2 = coefficients; $\gamma_r = 1+1/T$ = ripple enhancement coefficient for the lower wind transport regime with values between 1 and 3 depending on the ripple steepness (-). The γ_r -coefficient is related to the T -parameter in a way that the effect reduces for increasing T -values as the ripples are gradually smoothed out. The default coefficients α_1 and α_2 are found to be $\alpha_1 = 15$ and $\alpha_2 = 1$ for the data sets of Han et al. (2011) and Yang et al. (2019), see Section 4.3.

The d_{90} is roughly equal to $d_{90}=2$ to $3d_{50}$ for fairly uniform (narrow-graded) sand and may be as large as about $d_{90}=10d_{50}$ for very wide-graded sand mixtures. When relatively large shells and other roughness elements are present on a flat sand bed, the effective roughness will increase considerably due to generation of extra turbulence depending on the size and cover of the roughness elements resulting in an increase of the sand transport capacity. The static roughness of shells may be in the range of 1 to 5 mm for small to large shells with a cover percentage of 5% to 10% (McKenna et al., 2012). The roughness of shells can be neglected for cover percentages < 5% (see Dong et al., 2002; McKenna et al., 2012). The bed roughness related to irregularities is most likely somewhat larger for coarse sand surfaces than for fine sand surfaces. Equation (3.6) produces dynamic grain roughness values in the range of 5 to 10 mm for wind speeds of 10 to 15 m/s, which is of the right order of magnitude compared to the field data of Davidson-Arnott et al. (2005) and Strypsteen (2019) for a flat bed without much irregularities (no shells, no ripples). Equation (3.6) is a first attempt to better describe the dynamic grain roughness related to the saltation process. Detailed experiments in wind tunnels are highly recommended to improve the coefficients involved. It is noted that the bed roughness for sand transport may be substantially smaller than the bed roughness for the large-scale wind flow which is dominantly affected by macro-scale bed features (dunes, objects, etc.).

4. Sand transport for saturated conditions based on predicted shear velocity

4.1 Roughness predictor

To compute the sand transport rate (Equation 2.1), the bed shear velocity (u_*) and thus the bed roughness height (k_s) are required as input parameters. If measured velocity profile data are available, these parameters can be derived from the measured data. However, the shear velocity derived from the slope of the measured velocity profile is not representative for sand transport if bed forms are present.

If only one wind velocity from a nearby weather station is available, the bed roughness parameter (k_s) and hence the effective shear velocity for sand transport must be predicted. Various expressions are available to predict the k_s -value (Equations 3.2 to 3.4). A major drawback of these equations is that the bed roughness (k_s) is related to u_* , which depends on the bed roughness (k_s) itself. Hence, an iterative method is required to determine the k_s -value. A non-iterative prediction method is given by Equation (3.6).

4.2 Data sets used

Various data sets (see **Table 4.1**) from wind tunnel experiments and field sites have been used for calibration and verification of the predictive model. Only data sets with fully-developed sand transport and shear velocities which are more than 5% larger than the threshold shear velocity have been selected ($u_* > 1.05 u_{*,th}$). The data sets of Mariakerke contain some shell (< 5%), but this is neglected.

Data set	Number of data points	Wind velocity (m/s)	Grain size		Roughness of irregularities $k_{s,ir}$ (mm)
			d_{50} (mm)	d_{90} (mm)	
Wind tunnel experiments (Belly 1964)	36	5-12 z=0.3 m	0.44, 0.3, 0.145	$3d_{50}$	0
Wind tunnel experiments (Han et al. 2011)	6	10-20 z=0.6 m	0.203	$2d_{50}$	0
Wind tunnel experiments (Yang et al. 2019)	8	8-22 z=0.3 m	0.455	$2d_{50}$	0
Inch spit beach, Ireland (Sherman et al. 1998, 2013)	17	5-10 z=2 m	0.17	$3d_{50}$	1 (minor shell < 2%)
Esposende site, North Portugal (Sherman et al., 2013)	12	10-14 z=2 m	0.27-0.35	$3d_{50}$	2
Jericoacoara site, 500 m from shoreline, north-eastern coast of Brazil (Sherman et al., 2013)	15	13-17 z=2 m	0.22-0.44	$3d_{50}$	2
Mariakerke beach Belgium (Strypsteen et al., 2019)	14	6-11 z=2 m	0.31	$3d_{50}$	2 (some shell < 5%)
Koksijde beach Belgium (Strypsteen et al., 2019)	11	8-12 z=2 m	0.22	$3d_{50}$	15 (many patches of shells and shell hash; 10%-15%)

Table 4.1 Grain size and roughness input parameters of calibration and verification data

Wind tunnel experiments USA by Belly (1964)

Belly (1964) has performed detailed wind tunnel experiments with sand diameters of 0.44, 0.3 and 0.145 mm. Sand transport rates were measured in tests with and without sand feed. The wind velocity was measured by a pitot tube mounted in the wind tunnel (length=30 m; width=1.2 m; height=0.8 m). The wind tunnel had a sand feed system at the entrance. The sand bed had a length of 20 m and thickness of about 0.05 m. Sand transport was measured by a trap sampler at the end of the sand bed. The sand transport data of Belly are given in tables for 0.44 mm-sand (26 data points) and 0.145 mm-sand (15 data points). The plots of Belly for 0.44 m-sand only shows 13 data points, which are herein used (extracted from the plots). The data for 0.3 mm-sand were also

extracted from plots (11 data points) given by Belly. The measured wind velocities for 0.3-mm sand are not given by Belly (1964), and have therefore been derived by the authors from the plot of u_* against $u_{\text{wind,at 1 foot}}$ using the data of 0.455 mm-sand. Ripples were observed for wind velocities in the range of 7 to 10 m/s. Ripples were smoothed out for velocities > 10 m/s. The measured wind velocity at 0.3 m above the surface was used as input data for the Bagnold-equation.

Wind tunnel experiments China by Han et al. (2011)

Han et al. (2011) studied the effect of moisture content on sand transport in a wind tunnel (length=37m, width=1.2m, height=1.2 m). Sand trap measurements were done at the end of a sand tray with length of 4 m. The bed consisted of sand with $d_{50}=0.203$ mm. The sand trap (efficiency of 90% for particles >0.1 mm) had a height of 0.6 m and was sectionalized in 60 openings with height of 10 mm and width of 5 mm. The lowest opening was flush with the sand surface. The wind velocity was measured at $z=0.6$ m above the flat sand surface using a Pitot-tube method. The moisture content (ratio of mass of water and mass of dry sand $\times 100\%$) of the sand bed was varied in the range of 0.14% to 2.7%. The moisture content of the sand bed was prepared just before the experiment using distilled water. Each experiment was run over only 90 s to prevent a change of the moisture content. Five bed surface samples were taken after each experiment to determine the moisture content again. The measured results show that most of the sand transport is taken place in a layer with height of about 0.2 to 0.5 m above the sand surface depending on the wind velocity (10 to 20 m/s). The moisture content (w) has almost no effect on the height of the transport layer. The sand transport rate is not affected by moisture for $w < 0.25\%$. These values for $w < 0.25\%$ are used by the authors.

Wind tunnel experiments China by Yang et al. (2019)

Yang et al. (2019) studied the grain size distribution of the saltating particles for wind velocities in the range of 8 to 22 m/s. The sand used was typical dune sand collected from the southern margin of the Tengger Desert in China. The mean sand grain size is 0.455 mm. Before performing the wind-blown sand experiments, free-stream wind velocities were determined at a height of 0.3 m above the center line of the working section of the wind tunnel using a pitot tube. The sand beds were 1 m wide, 0.1 m deep and 8 m long, and this ensured that the sand flux was close to the saturation state at all measured wind velocities. The sand in the bed was replaced for each experiment. A segmented sand trap with height of 0.5 m was used to collect the sand grains in the saltation layer and was located on the center line at 12 m downward from the entrance of the working section of the tunnel. The duration of each experiment was in the range of 480 to 10 sec for the wind velocity range of 8 to 22 m/s.

Field experiments at Inch Spit beach in Ireland, Sherman et al. (1998)

The Inch Spit data were obtained along the beach and back beach profile seaward of the foredune in April 1994. The Inch site is part of a morphodynamically dissipative system in Dingle Bay, on the south-western coast of Ireland. Fetch distances perpendicular to the shoreline varied from 100 to almost 250 m, depending on the tide and wave conditions. Blowing sand was captured using Leatherman/Rosen type cylindrical traps with openings 40 mm wide and 450 mm high, and the bottom of the opening flush with the sand surface. The data used herein refer to the mean values of tower 1 and 2 (situated in the upper beach area with relatively dry sand without vegetation).

Field experiments at three sites of Sherman et al. (2013)

Data were obtained from field experiments conducted at three sites (Inch Spit, Ireland, Esposende, Portugal and Jericoacoara, Brazil). The Inch site (April 1994) is part of a morphodynamically dissipative beach system in Dingle Bay, on the south-western coast of Ireland. The field site at Esposende, along the northern coast of Portugal, was near the downwind end of a parabolic dune trough (May and June 2006). The upwind surface was flat and unobstructed and almost horizontal near the sand traps. During the experiments the sand surface was dry, and winds blew parallel to the trough with a fetch of approximately 80 m. Blowing sand was trapped using vertical arrays of hose-type traps. Samples for grain size analyses were obtained from sand caught in the traps.

Located on the north-eastern coast of Brazil, the Jericoacoara site was also near the downwind end of a parabolic dune trough, but at a location approximately 500 m from the shoreline. The upwind surface was flat and unobstructed, with a fetch of approximately 100 m, and the surface was almost horizontal near the traps. During the experiments, the wind blew parallel to the trough and the surface sediments were dry. Sand transport rates were measured with vertical hose-type trap arrays and grain size samples were obtained from the trapped sands. In order to estimate shear velocity using the cup anemometer data, wind speeds were averaged over time intervals coincident with those for sand trap data. The number of data was reduced to 32 data sets (5 for Inch Spit; 12 for Esposende and 15 for Jericoacoara) by selecting: i) only those wind profiles with a best-fit line R^2 exceeding 98%, ii) only those data for which the sand moisture content was less than 2% and iii) data sets with sand transport rates larger than about 0.3 g/m/s (1 kg/m/hour).

Field experiments Koksijde and Mariakerke beaches 2016-2018, Belgium

Strypsteen (2019) and Strypsteen et al. (2019) conducted field experiments at the beaches of Mariakerke and Koksijde in Belgium. The beach of Mariakerke ($d_{50}=0.31$ mm) is fairly flat and contains some shell fragments due to regular nourishments. The measurements were performed in the dry upper beach zone without much shells. The bed roughness (k_s) is smaller than 10 mm. The beach of Koksijde consists of sand ($d_{50}=0.21$ mm) with small-scale bed irregularities (ripples) and many shell fragments with height of the order of 30 mm. The bed roughness (k_s) is relatively high with values up to 45 mm. Wind-induced sand transport was measured by using MWAC-sand traps and streamer type traps on top of each other.

4.3 Model calibration

Basically, the calibration of the α_1 and α_2 coefficient of Equation (3.6) require measured data of bed roughness and sand transport for a flat sand bed under controlled conditions. The best data sets available are those of Han et al. (2011) and Yang et al. (2019), although only measured data of wind velocities and sand transport rates are given. Measured shear velocity values are not reported in their papers. Using Equation (3.6) with $\gamma_r = 1$ (no bed forms and $d_{90}=2d_{50}$ in combination with Equation (2.2), the coefficients α_1 and α_2 of Equation (3.6) are found to be $\alpha_1=15$ and $\alpha_2=1$, giving the best overall agreement between measured and predicted sand transport rates.

Figure 4.1 Comparison of measured and computed sand transport; $\alpha_B=2$; $\alpha_{th}=0.11$; $d_{90}=2d_{50}$ data of Han et al. (2018) and Yang et al. (2019)

The sand transport rates for 0.2 mm-sand of Han et al. (2011) are very well represented by the model, but the transport rates for the 0.455 mm-sand of Yang et al. (2019) are systematically overpredicted by a factor of 2 (**Figure 4.1**). The predicted grain roughness values are in the range of 3 to 20 mm depending on the wind velocity between 8 and 22 m/s. These values cannot be checked as measured values of the roughness are not given by Han et al. (2011) and Yang et al. (2019). However, the computed roughness values are of the right order of magnitude compared to the range of 1 to 10 mm found by Strypsteen et al. (2019) for the fairly flat beach of Mariakerke (Belgium). More experimental research with flat sand beds in wind tunnels are highly recommended, so that the grain-related roughness can be better determined.

4.4 Model verification

The predictive model consisting of Equations (2.1, 2.2, 2.3, 3.6) has been verified using the data sets of Belly (1964), Sherman et al. (1998, 2013) and Strypsteen et al. (2019). In all, 105 high-quality data sets have been used. The input data are the measured wind velocity at $z=2$ m, the d_{50} and d_{90} -values, see **Table 4.1**. For all field data, it is assumed that $d_{90}=3d_{50}$. The roughness related to background irregularities is varied between 1 and 15 mm depending on the presence of shells and other irregularities. No information is available for the field sites of Portugal and Brazil. As relatively coarse sand is present at these sites, the background roughness is set to 2 mm. The background roughness is set to 2 mm for the data of Mariakerke beach where minor shells and other irregularities were observed and to 15 mm for the data of Koksijde beach where large patches of shells and shell fragments/hash were observed. McKenna et al. (2012) found k_s -values in the range of 1 to 6 mm for a surface with many shells in a wind tunnel. In field conditions these values will somewhat larger due the presence of shell clusters.

The computation procedure of the predictive model for dry sand is as follows: 1) specify wind velocity u_w at one height; 2) specify d_{50} and d_{90} of sand; 3) specify background roughness of irregularities $k_{s,ir}$ (if present); 4) compute static grain roughness by Eq. (3.6d); 5) compute threshold shear velocity by Eq. (2.2); 6) compute T-parameter by Eq. (3.6c); 7) compute bed roughness k_s by Eq. (3.6b), 8) compute shear velocity u_* by Eq. (3.6e); 9) compute sand transport by Eq.(2.1). Other parameters are: $\kappa=0.4$; $\rho_{air}=1.2$ kg/m³; $\rho_{sand}=2650$ kg/m³; $\alpha_B=2$; $\alpha_{cr}=0.11$; $d_{50,ref}=0.00025$ m.

Figure 4.2 (right) shows a plot of measured and computed transport rates for all available 105 data points. The computed transport rates are based on the measured shear velocities. About 58% of the predicted data are within a factor of 2 of the measured values. The measured transport rates are significantly overpredicted for the field data of Sherman et al. (1998, 2013). The measured wind tunnel data of Belly (1964) show considerable scatter (over- and underprediction).

Figure 4.2 (left) shows a similar plot of measured and computed sand transport rates, but now the predictive model is used. Most (72%) of the predicted data are within a factor of 2 of the measured values. The overprediction is substantially reduced and the scatter within the data of Belly (1964) is also reduced. Similar scores were obtained by Van Rijn (1984; 2007) for sand transport by water flow. Given all variabilities and non-uniformities involved and the problem of measuring under extreme wind conditions, it may be almost impossible to predict the sand transport rate with a score of 100% within a factor of 2. The predicted values are sometimes much too large at conditions near the threshold value, which is an inherent effect of a deterministic approach. This is, however, not so important for engineering practice as the transport rates involved are very small. The predicted values are somewhat too small for higher wind velocities. The model underprediction may be related to the underprediction of the dynamic grain roughness ($k_{s,grain,dyn}$), as only a few laboratory data of Han et al. (2011) and Yang et al. (2019) were used to calibrate the dynamic grain roughness (Equation 3.6). This can be improved by using results from new wind tunnel tests with flat mobile beds (future research). According to Sherman et al. (2013), the measured transport rates at their field sites may be slightly too small, as minor moisture may have been present in the sand surface raising the threshold values slightly. Most likely, measured transport in field conditions are somewhat too small rather than too large given the relatively low efficiencies of most trap samplers. Sherman et al. (2013) noticed significant overprediction (factor 2 to 3) of the original

Bagnold-equation with measured shear velocities as input ($\kappa=0.4$). The overprediction is substantially reduced by using smaller bed-shear velocities taking only grain-related roughness into account (Equation 3.6).

Figure 4.2 Comparison of measured and computed sand transport;
Left: based on predicted shear velocities; Right: based on measured shear velocities

5. Other effects

5.1 General

A fully predictive model must include the effects of sloping surfaces, varying moisture contents, vegetation and shells. Herein, it is proposed to represent these effects by simple coefficients acting on the bed-shear velocity, the threshold velocity or on the sand transport rate. The proposed coefficients are derived from reliable data in the opinion of the authors and can be seen as a first estimate for engineering purposes. Further research is required to improve and extend the knowledge. Some processes can be studied in wind tunnels (effect of bed slope, moisture and shells), but other processes can be better studied at field sites (vegetation, saturation). Given time and budget, the proposed coefficients can be gradually improved as more data become available.

5.2 Moisture content

Wind-induced sand transport is strongly affected (reduction factor of 2 to 10) by moisture content and related cohesion/adhesion effects, particularly for lower wind velocities < 20 m/s (Hotta et al., 1984). Moisture contents up to 8% had much less effect ($< \text{factor } 2$) for high wind velocities in the range of 20 to 30 m/s in a wind tunnel (Hotta et al., 1984).

Cohesion and adhesion between particles increase the surface resistance against erosion (threshold shear velocity). Cohesion and adhesion effects may result from the presence of moisture, salt, algae, clay, organic matter and calcareous materials. Even low levels of moisture may effectively reduce the transport rate of dry sand. However, intensive rainfall may also increase the sand transport rate by splash effects promoting saltation

processes. Moisture content (w) may be the direct result of precipitation, water spray, wave uprush near the water line or capillary action (adhesive forces; surface tension forces).

Moisture fraction is generally defined as: $w = \text{mass water of sample} / \text{mass dry sand of sample}$ (moisture content is moisture fraction $\times 100\%$). Moisture content of a saturated sample can be computed by the expression $w_{\text{saturated}} = [\varepsilon / (1 - \varepsilon)] [\rho / \rho_s] \times 100\%$ with $\varepsilon =$ porosity factor (0.35-0.45 for sand); $\rho =$ water density ($\cong 1000 \text{ kg/m}^3$); $\rho_s =$ sand density ($\cong 2650 \text{ kg/m}^3$), yielding $w_{\text{saturated}} = 20\%-30\%$. Generally, moisture contents are in the range of 0 to 10%, as the pores are not fully saturated with water.

Let us assume that a sand particle with diameter D is covered by a thin water film with thickness δ except at the particle contact points; any other pore water is absent.

The volume of the water film is: $V_{\text{wf}} = 1.33\pi [(0.5D + \delta)^3 - (0.5D)^3]$ and the mass is: $M_{\text{wf}} = \rho V_{\text{wf}}$.

The volume of the sand particle is: $V_{\text{sand}} = 1.33\pi (0.5D)^3$ and the mass is $M_{\text{sand}} = \rho_s V_{\text{sand}}$.

The mass ratio of water and dry sand defined as the moisture fraction is:

$$w = M_{\text{wf}} / M_{\text{sand}} = \rho [(0.5D + \delta)^3 - (0.5D)^3] / [\rho_s (0.5D)^3].$$

Using: $D = 200 \mu\text{m}$ for sand, $\delta = 0.01D = 2 \mu\text{m}$, it follows that: $w \cong 0.025$ (2.5%).

Thus, a thin water film with thickness equal to $2 \mu\text{m}$ surrounding a sand particle of $200 \mu\text{m}$ yields a moisture content of about 2.5%. A water film of $1 \mu\text{m}$ yields a moisture content of 1%. Dry sand has a moisture content $< 0.25\%$ (Han et al., 2011). In conditions with a moisture content $> 2.5\%$, the sand transport rate is strongly reduced to a very small value. In conditions with $w = 10\%$ (near the water line), the surface is so saturated that aeolian transport reduces to almost zero even under very strong winds.

Various authors have studied the influence of moisture on the threshold shear velocity of sand particles by wind in wind tunnel conditions (Chepil, 1956; Belly, 1964; Hotta et al., 1984; Saleh and Fryrear, 1995; Cornelis and Gabriels, 2003 and Han et al., 2011) and in field conditions (Davidson-Arnott et al., 2005, 2008; Udo et al., 2008).

Figure 5.1 Threshold shear velocity as function of particle diameter and moisture content; laboratory data (Han et al. 2011; Cornelis and Gabriels 2008; Belly 1964) and field data (Davidson-Arnott et al. 2008)

Available laboratory data of Belly (1964), Hotta et al. (1984), Cornelis and Gabriels (2003) and Han et al. (2011) are shown in **Figure 5.1**. The effect of moisture is negligibly small for moisture content $< 0.25\%$ (Han et al. 2011). The threshold shear velocity increases for increasing moisture content. Sand with $w = 0.5\%$ has a significant higher threshold shear velocity (factor 1.5 to 2) than that of dry sand. The scatter and error ranges are relatively large, which is most likely caused by the different definitions and measuring method used by the various researchers. The wind tunnel data of Belly refer to the upper 1 mm of the surface, as he used a moist air flow. The wind tunnel data

of Hotta et al. refer to a layer of 5 mm as samples with thickness of 5 mm were taken from the surface. The wind tunnel data of Cornelis and Gabriels and Han et al. refer to a layer of 1 to 3 mm. A basic problem is the rapid decrease of the moisture content due to the blowing wind, even for very short run times (< 2 min, Cornelis and Gabriels, 2003). Davidson-Arnott et al. (2008) report an increase of the threshold wind speed and shear velocity of only 20% for 0.26 mm-sand in the case of an increase of the moisture content from 1 to 4% in field conditions, see Figure 5.1. Udo et al. (2008) found an increase of a factor of 2 for 0.18 mm-sand in the case of an increase of the moisture content from 0 to 10%. The field results show a large discrepancy compared to those for wind tunnel conditions. Most likely, this is caused by the thickness of the top layer in which the moisture content is measured. The field data are valid for a top layer with a thickness of about 20 mm, whereas the laboratory data refer to the topmost layer of 1 to 5 mm. The moisture content of the thin top layer of 1 to 5 mm in field conditions will be much lower than the average value over a layer of 20 mm. The field experiments (Davidson-Arnott, 2008) also show that the moisture content at a certain location and thus the critical shear velocity can change rapidly over a period of minutes to hours due to drainage and/or drying by wind and sun. Large variations of the critical wind speeds were observed: $u_{w,min} = 5$ m/s (lowest wind speed with sediment transport) and $u_{w,max} = 9$ m/s (highest wind speed without sediment transport) mainly due to variations of the moisture content. Based on this, the wind-driven sediment transport is highly variable in space and usually intermittent in time. Delgado-Fernandez (2011) found that the moisture conditions of natural beaches can be crudely classified into three categories: a) dry with $w_{20mm} < 2\%$ and a fully developed saltation system; b) medium with $w_{20mm} = 2$ to 10% and restricted sand transport and c) wet with $w_{20mm} > 10\%$ and sand transport is completely prevented.

The effect of the moisture content on the threshold shear velocity is herein represented by: $u_{*,th,wet} = \alpha_w u_{*,th,B}$ with

$$\alpha_{w,2mm} = 1 + 2 \tanh(w_{2mm}) \quad (3.7a)$$

$$\alpha_{w,5mm} = 1 + 0.25 w_{5mm} \quad (3.7b)$$

$$\alpha_{w,20mm} = 1 + 0.1 w_{20mm} \quad (3.7c)$$

with: w_{2mm} = moisture content in upper 2 mm of surface (in %), w_{5mm} = moisture content in upper 5 mm of surface and w_{20mm} = moisture content in upper 20 mm of surface. Equations (3.7a,b,c) and that of Belly are shown in **Figure 5.1**. Equation (3.7a) and that of Belly (1964) are both in reasonable agreement with the laboratory results, but largely overpredict for field conditions. Equation (3.7b) is very close to the data and the empirical equation of Hotta et al. (1984). Equation (3.7c) represents the field data of Davidson-Arnott (2008) and is advised for field conditions provided that the moisture content of the topmost 20 mm is measured (input value). Application of Equation (3.7c) requires input data of the moisture content of the topmost 20 mm of the sand bed, either from measurements or from a prediction model for the moisture content. Brakenhoff et al. (2019) have studied the moisture content in cross-shore direction from the low tide water line to the upper dry beach and developed a prediction model for the surface moisture content calibrated with data from a mesotidal beach in The Netherlands. The length of the intertidal beach was about 60 m. Their results show that the lower 30% of the intertidal beach is always saturated with water and $w_{20mm} > 20\%$. Higher up the tidal beach up to the high tide line, the moisture content is between 5% and 20% depending on the tidal stage; drying rates were found to be 50% in 2.5 hours. Above the high tide line, the moisture content decreased from about 5% at the high tide line to about 2% at about 30 m beyond the high tide line in conditions without rainfall. This latter zone is the transition zone to the dry beach, where the moisture content solely depends on precipitation (rainfall). In the Netherlands, there is a total rainfall time of about 500 hours or about 20 days per year in which windblown transport in the 'dry' beach zone is almost absent (wet conditions $w_{20mm} > 10\%$), about 45 days with restricted conditions (medium $w_{20mm} = 2\%$ to 10%) and 300 days with dry conditions ($w_{20mm} < 2\%$). Drying times of the topmost layer of 3 mm after rainfall are found to be fairly short (< 3 hours, Hotta et al., 1984). This means that effect of precipitation on wind transport in the dry beach zone is meaningful, but not dominant. Most of the time (at least 80%), the dry beach zone is really dry.

De Vries et al. (2014) have found that the transition zone of about 30 m seaward and landward of the high tide line in which the moisture content reduces from about 5% to 2% is an important source of sand for the gradual pickup (entrainment) of sand, as other supply-limiting factors (shells, vegetation) are absent in that zone. The

pickup process will continue in the dry beach zone if supply-limiting factors are absent (shell lag deposits, vegetation).

5.3 Shells

Shells (calcium carbonate) can protect the beach surface against erosion of the sand particles. Large percentages of shell are mostly found on the upper part of natural beaches outside the wave action zone and on beaches with nourished sand. Literature on this topic is rather scarce and mostly qualitative. The two main effects of shells on the sand transport process are: i) shells cover a certain area of the bed which is not available for sand particle erosion and ii) sand particles in the direct vicinity of shells are less exposed to the wind forces (hiding effect). Observations in wind tunnels and field conditions show that shells of different sizes tend to interlock and form clusters (spatial organization; McKenna et al., 2012; Strypsteen 2019). At the Dutch sand motor site (see Section 6.1) with shell cover values up to 20%, sufficient sand particles were winnowed from the shelly bed to give appreciable erosion and deposition volumes of sand. Based on these observations, it is herein assumed that the effects of shells on the sand transport process can be best represented for engineering purposes by a simple reduction coefficient acting on the transport rate. This coefficient is derived from the experiments in wind tunnels (Van der Wal, 1999 and McKenna et al. 2012). It is realized that this approach only gives the transport-limiting effect.

Van der Wal (1999) studied the effect of shells on the wind-induced transport rate of beach sand. Beach sand samples were taken from 5 sites along the Dutch coast and tested in a wind tunnel. The d_{50} varied in the range of 0.21 to 0.35 mm. The percentage of shells (> 2 mm) varied in the range 1 to 30%. A tray with (length=1.22m; width=0.33 m; height=0.03m) was filled with weighed oven-dried sand and placed in the middle of the test section. The sample surface was smoothed and levelled to the tray edges. The wind speed was gradually increased over one minute to about 11 m/s and kept at this speed for another minute. Then, the wind speed was gradually returned to zero over one minute. After the experiment, the sand was reweighed. The percentage of sand blown off during the test was calculated for each of the experiments. The transport rate was reduced by a factor of 1.5 for samples with a percentage of shells of 10% and by a factor of 3 for samples with a percentage of shells of 20% to 30%. Shell pavements were formed during the wind tunnel experiments with shell-rich beach samples.

McKenna et al. (2012) conducted a wind tunnel study on the effect of various types of shells on the erosion of a sand bed with a total area of about 10 m². Wind velocities were in the lower range of 8 to 12 m/s ($BF < 7$). Three types of shells were used: crushed shells with cover percentages between 12% and 22% (heights 1.1 to 1.6 mm); small shells < 12.7 mm with cover percentages between 17% and 43% (height 2.6 to 5.7 mm) and large shells > 12.7 mm with cover percentages between 14% and 30% (heights 7 to 9.2 mm). The freestream velocity was gradually increased until the cumulative number of particle counts recorded by a piezoelectric impact sensing device began to increase continuously. A sediment trap at the downwind end was used to collect sand particles eroded from between the shells. The test was terminated when the transport rate dropped to a negligible value (< 0.05 g/cm/s). It was observed that the shells were organized into chains and clusters with the long axis of many of the shells appearing to be aligned with the wind flow. The threshold wind velocity and shear velocity were found to increase by about 15% to 25% for a cover of 15% and about 35% to 45% for a cover of 43%. The amount of erosion after the test (in kg/m²) was recorded showing almost no erosion for the largest cover values of 40% both for small and large shells. Erosion is reduced by a factor of 5 to 10 by increasing the cover of shell from about 15% to about 30-40%. Crushed shells are less effective than small/large shells. The sand transport is estimated to be reduced by about 40% for a cover of 15% and about 95% for a cover of 40%.

Important parameters appear to be the fetch length and the uniformity of the shell cover. In wind tunnel experiments, the fetch length is relatively small (1 to 8 m in the studies discussed herein) and the initial shell cover is quite uniform in space. In field conditions, the fetch length is often larger than 50 m and the shells are not uniformly distributed over the beach surface. Shell clusters are pronounced features at natural beaches (Strypsteen 2019). McKenna et al. (2012) have observed in their wind tunnel experiments that the shells are not operating independently, but rather display some degree of spatial organization resulting in shell clusters of partly interlocking shells of different sizes. Shells are sometimes rolling coming to rest against others downwind

resulting in clusters. Corridors of lower shell coverage are generated at the sand surface. This justifies the use of a simple transport limiting coefficient for engineering practices. Herein, the reduction effects based on the tests of Van der Wal (1999) and McKenna et al. (2012) are simply represented in Equation (2.1) by a reduction factor acting on the transport rate:

$$\alpha_{\text{shell}} = (1 - 2p_{\text{shell}}/100)^2 \quad (3.8)$$

with p_{shell} = percentage of shell (<30%). The sand transport rate as affected by shells was not measured directly in the studies considered herein (van der Wal, 1999; McKenna et al., 2012; Hoonhout and De Vries, 2017) and thus Equation (3.8) could not be tested against measured transport rates. Equation (3.8), which is only valid for a shell cover < 30%, is herein used as a transport-limiting factor acting on the sand transport rate to obtain a quick engineering scan of the effect of shells in reducing sand transport on nourished shelly beaches. The gradual development of an armor layer in time cannot be represented in this way, as it requires a more detailed approach. Basically, the simulation of sand transport in conditions with a relatively wide grain size distribution ($d_{90}/d_{10} > 10$) and significant shell cover values (10% to 30%) requires an approach with multiple fractions including a book-keeping process for each grid cell and vertical sand layer. Hiding and exposure effects must be included as well as roughness variation effects (Raupach 1992; Van Rijn 2007). The present model can be extended to a fractional approach (Van Rijn 2007). Using such an approach, the changes in surface conditions can be simulated both in space and time. Hoonhout and De Vries (2017) used a fractional model to study the windblown sand transport at a large-scale mega-nourishment (sand motor in The Netherlands). They found that the intertidal zone and the transition zone where shells were absent were the dominant sources of sand for windblown sand. The dry beach plain with abundant shell cover (5% to 15%) developed a beach armor layer suppressing the pickup of sand particles to some degree. However, such an approach is far more complex with many coefficients and calibrations involved and may be a bridge too far for engineering purposes (see detailed discussion by McKenna et al., 2012). In section 6.1 it is shown that Equation (3.8) predicts meaningful results for the Dutch sand motor site which is a shelly beach plain/nourishment site. Model improvements based on detailed research in wind tunnels and at field sites focusing on the sand transport processes with wide grain size distributions including/excluding shells are highly recommended.

5.4 Vegetation

Wind-blown sand transport is substantially reduced if numerous roughness elements are present on a sand surface, as shown in a fundamental study by Gillies et al. (2006). Sand transport was measured between plastic buckets (4 different configurations) resting on a flat horizontal sand surface. Results of these tests indicate that sediment transport rates through patches of roughness are controlled by the roughness density depending on the dimensions (width, height) and number of elements. Sand transport reductions based on comparison with upwind trap results were as large as 90%.

The effects of vegetation on wind-blown sand can be described as (Wolfe and Nickling 1993): i) vegetation extracts momentum from the air flow resulting in larger roughness; ii) vegetation elements are obstacles for saltating sand grains and iii) vegetation reduces part of the surface where sand transport takes place. Vegetation is herein identified as grass-type plants with a maximum height of about 0.5 m. The shear velocity can be determined from wind velocity measurements outside the roughness layer (say 2 times the plant height) to eliminate the local velocity variations occurring between the plants. Both the shear velocity and the overall effective bed roughness will increase due to the presence of the vegetation.

Two approaches are possible to account for the effect of vegetation on the sand transport rate by : i) increase of the threshold value as the sand grains are hiding between the vegetation and the application of the total bed-shear velocity for sand transport (Musick and Gillette, 1990; Raupach et al., 1993; Musick et al., 1996;) and ii) reduction of bed-shear velocity acting on the sand grains between the vegetation and the application of the standard threshold shear velocity (Raupach 1992).

The latter approach requires partitioning of the bed shear stress ($\tau = \tau' + \tau''$) into a component related to grain roughness (τ') and another component related to form drag of the vegetation (τ''). The stress component τ'

represents the averaged stress on the exposed grain surface. This approach has been formulated and tested in great detail by Raupach (1992), Brown et al. (2008), Shao et al. (2015). Raupach assumed that the surface consists of randomly distributed cylinders uniform in size, each having a frontal area of a_f and n is the number density (number unit area) of the roughness elements (roughness). The frontal area index of the roughness elements is $\lambda = n a_f$. The ratio of roughness basal area to frontal area is $\sigma = a_b/a_f$ and the exposed percentage of the surface subject to wind velocity is $p_s = (1 - \sigma\lambda)100$ and the cover percentage $p_v = \sigma\lambda 100$. The shear stress on the exposed surface can be expressed as: $\tau/\tau_0 = [1 - \sigma\lambda]^{-1} [1 + \beta\lambda]^{-1}$ with $\beta = C_r/C_s$ and $C_s =$ frictional drag coefficient and $C_r =$ pressure drag coefficient. Raupach et al. (1993) formulated a correction factor for the threshold friction velocity in the presence of roughness elements: $u_{*,cr} = u_{*,cr,0} [(1 - m\sigma\lambda)(1 + m\beta\lambda)]^{0.5}$ with $m =$ coefficient ≈ 0.5 .

The approach of Raupach is most scientific, but it contains many coefficients and parameter to be specified as the vegetation roughness is of complex nature with many influential parameters (stem diameter, stem height, number of stems per bundle or plant; bundle porosity, bundle configuration, heterogenous clustering, etc.). Herein, a simpler approach is proposed for engineering practices by using a correction coefficient (α_v) based on percentage of cover and the vegetation height and acting on the shear velocity (see Equation 2.3).

Various researchers have studied the effect of vegetation on wind-blown sand transport in wind tunnels (Buckley, 1987; Burri et al., 2011; Youssef et al., 2012; Hesp et al., 2019) and at field sites (Wasson and Nanninga, 1985; Lancaster and Baas 1998; Arens et al., 2001; Hupy 2003; Hesse and Simpson, 2006; Davidson-Arnott et al., 2012). Buckley (1987) studied the effect of sparse vegetation on wind-blown dune sand (0.15 mm) in a wind tunnel. Three plant types (F,G,R) with heights of the order of 10 cm were used, corresponding to characteristic shapes of common small herbaceous dune plants. Cover percentages were in the range of 0 to 20%. Sand transport was measured with three vertical profile traps 50 cm downstream of the vegetated area.

The reduction of sand transport rate at constant wind velocity of 10 to 15 m/s for plant type F was as large as 90% for a cover of 20%, see **Figure 5.2**.

Lancaster and Baas (1998) studied the effect of vegetation on the bed roughness and the sand transport process at the western part of the former delta of the Owen River in eastern California, USA. The surface sand at the site is coarse (median particle size of 0.5 to 1 mm). The sand sheets are vegetated with salt grass with a cover that ranges from zero to about 30 per cent and which increases northwards. The sand flux measured at 0.1 to 0.2 m above the bed was largest at the sites A and B with a vegetation cover < 5%. The sand flux strongly decreases for increasing values of the vegetation cover. **Figure 5.2** shows the normalized sand flux values (ratio of local transport and upwind transport) for increasing cover values. A vegetation cover of 10% already gives a reduction of 50%. The reduction is about 90% for a cover of about 25%.

Arens et al. (2001) studied the effect of vegetation density on aeolian sediment transport and deposition in the area of foredunes (12 m high) at the Holland coast near the Hague. The seaward front of the foredune was partitioned into three plots, each 100 m long along the foredune and 10 m wide over the cross-shore. The plots were planted with 4, 2 and 1 bundles of reed stems per m^2 . Each bundle consisted of 15 stems; bundle diameter is 0.17 m; porosity of bundle is about 50%. The number of bundles is 1 per m^2 at distance of 1 m (plot N1), 2 per m^2 at distance of 0.7 m (plot N2) and 4 per m^2 at distance of 0.5 m (Plot N4). The height of the stems was approximately 0.5 m immediately after planting and gradually decreased due to sand burial. Analysis of all sand trap data (wind velocity between 10 and 12 m/s) shows sand transport reductions from 40% to almost 100%, see **Figure 5.2**. Also noticed was gradual deposition starting at the first row of the reed bundles and slowly evolving into bed forms as a result of the reduction of sand transport within the vegetated area. This was also observed by Hesp et al. (2019) with artificial plants ($h=22$ cm) in a wind tunnel and at field sites. Bed form heights were largest for the highest cover value of 40-50%.

Burri et al. (2011) performed a wind tunnel study of wind-blown sand with live plant canopies: three canopy densities (cover 4%, 16% and 47%) of Perennial Ryegrass ($h=6$ cm) and bare sand surfaces ($d_{50} \approx 0.6$ mm). The sand transport decreased by about 90% for cover of 16% and by about 100% for cover of 47%, see **Figure 5.2**. The sand transport increased by about 20% for the lowest cover of 4%, which is attributed to the increase of local shear stress due to flow acceleration around the plants and due to extra lee turbulence produced by the plants. Furthermore, the grasses were observed to trigger erosion by oscillating movements at the sand surface.

Davidson-Arnott et al. (2012) reported a 99%-reduction of sand transport at a vegetated foredune (stations 6 and 10) with cover percentages of 15 to 25% compared with sand transport at the beach (stations 1, 3, 4; $d_{50}=0.26$ mm) during an event with wind velocities of about 10 to 11 m/s. Sand transport reduced from about 50 ± 30 kg/m/hr to about 0.35 ± 0.25 kg/m/hr. These results are in line with the values presented in **Figure 5.2**.

All available data are shown in **Figure 5.2**. It can be clearly seen that high reed bundles ($h=50$ cm) of Arens et al. (2001) have a greater reducing effect on the sand transport rate than the lower plants ($h=10$ cm) used by Buckley (1987) and Lancaster and Baas (1998). Hupy (2003) found that sand transport was much larger in areas of loose sand and at sites directly downwind from loose sand than in areas containing heavy crusting, gravel, or a forb/grass cover. Differences between sites with gravel surfaces and those with forb/grass cover were, however, insignificant. Thus, the cover percentage seems to be the dominant factor rather than the type of cover. Hesse and Simpson (2006) also conclude that sand movement along desert dunes is primarily controlled by vegetation cover. Sand movement responds to short-term variations in vegetation cover (including crust). A simple threshold of vegetation cover below which sand transport begins was not found.

The data of **Figure 5.2** can be crudely represented by an engineering expression:

$$\alpha_{veg} = [1 - (\Delta_v / \Delta_{v, minimum})^{0.5} p_{veg} / 100]^2 \quad (3.9)$$

with: p_{veg} = percentage of vegetation cover (<30%); Δ_{veg} = height of vegetation which is of order of 0.1 to 0.5 m; $\Delta_{veg, minimum}$ = minimum height of vegetation (about 0.1 m). Equation (3.9) valid for wind velocities up to about 15 m/s (measured at about 1 to 4 m above surface) shows reasonable agreement with the available data with vegetation cover up to 30%. The agreement is not perfect, but the general trends are well represented. During extreme wind velocities in the range of 15 to 30 m/s, other effects come into play (destruction of vegetation, exposed root systems), which are herein neglected. More field research is required to extend the knowledge of the vegetation effects, particularly for higher wind velocities.

Figure 5.2 Normalized sand flux as function of vegetation cover based on various field data

6. Example applications of the predictive sand transport model

The proposed model can be applied in a rather straightforward way for loose, dry sand without shells and vegetation. For moist beach and dune systems including shells and vegetation, the estimation of these parameters requires detailed attention. The percentage of shells can be determined from samples taken over the upper 20 cm of the sand surface at the site or from samples taken at the offshore borrow (source) area in the case of beach nourishment. Vegetation height and cover can be estimated from sites similar to the site studied. Guidelines for the estimation of moisture can be given by distinguishing three ranges (Delgado-

Fernandez, 2011): i) almost dry sand for moisture values $w_{20\text{mm}} < 2\%$ during 70% to 80 % of the time, ii) transition range with a drying sand surface and $w_{20\text{mm}} = 2\%$ to 10% during 3 hours after each rainfall event and iii) wet sand for $w_{20\text{mm}} > 10\%$ during rainfall conditions preventing sand transport.

Two example cases are studied: i) sand transport at a horizontal beach parallel to the shoreline with effects of moisture and vegetation and ii) sand transport from the beach normal to the dune crest.

6.1 Sand transport at beach parallel to shoreline

The predictive model for wind-blown sand transport has been used to predict the sand transport rate for a range of conditions. **Figure 6.1** shows computed values for dry sand with $d_{50} = 0.3$ mm and $d_{90} = 0.5$ mm. The predicted transport rates for dry sand (solid bold curve) show a continuously increasing transport rate for increasing wind velocity. The effects of moisture (Equation 3.7c) and vegetation cover (Equation 3.9) are also shown. The moisture content increases the threshold shear velocity significantly and reduces the dynamic grain roughness (smaller T-parameter and thus smaller $k_{s,\text{grain}}$), resulting in almost zero transport for a wind velocity of 8.5 to 14.5 m/s for $w_{20\text{mm}}$ -values of 2% to 10% of the topmost 20 mm of the beach sand surface.

Figure 6.1 Wind transport of sand based on predictive model (modified Bagnold-equation) ($d_{50} = 0.3$ mm; $d_{90} = 0.5$ mm; $\alpha_B = 2$; $\alpha_{th} = 0.11$)

Once, the threshold value is exceeded the transport rate is much smaller. The reduction effects are largest for wind velocities < 18 m/s. The reduction effect diminishes for higher wind velocities further away from the threshold value. For a high wind velocity of 30 m/s (Beaufort scale 11), the reduction effect is about 20% for $w_{20\text{mm}} = 2\%$ to about 50% for $w_{20\text{mm}} = 10\%$.

Vegetation (plant height = 0.3 m) with covers of 5% to 15% reduces the effective shear velocity of the wind resulting in almost zero transport for wind velocities smaller than 6.5 to 8.5 m/s. Vegetation has a strong effect on the sand transport rate for wind velocities < 12 m/s. A vegetation cover of 15% consisting of plants of 0.3 m high reduces the sand transport rates by a factor of 2 to 3 for wind velocities > 12 m/s.

A very interesting test case for the predictive model is the windblown sand transport at the Dutch sand motor site, which is a mega-nourishment of about 21 Mm³ (De Vries and Hoonhout, 2018; Hoonhout and De Vries 2019). The dominant wind direction is parallel to the fore dunes. Measured deposition/erosion volumes are $300,000 \pm 100,000$ m³ for a period of 4 years (2011-2015) in the windblown beach plain area. Based on this, the annual-mean sand transport is about $75,000 \pm 25,000$ m³/year. The beach width normal to the coast is about 750 m in the middle zone of the site resulting in an annual-mean sand transport rate per unit width of about 100 ± 35

$\text{m}^3/\text{m}/\text{year}$ passing from the updrift half on the southwest side to the downwind half on the northeast side of the beach plain area. The large beach plain at a level of 5 m above mean sea level consists of shelly sand with $d_{50}=0.335$ mm and a shell cover in the range of 5% to 15%. The tidal range is about 2 m. The dominant wind direction is from southwest approximately parallel to the foredune row. During about 30% of the time, the wind speeds are below 8 m/s (BF3) without transport. During 70% of the time, the annual-mean wind speed representative for sand transport is about 10 to 11 m/s (BF5) at a height of 10 m above the beach surface. Table 6.1 shows measured and computed annual-mean transport values for three cases. The computed value is about 50% too large for ideal conditions with dry sand, no shells and no moisture. Fairly accurate results are obtained for a shell cover of 10% and minor moisture of 1% to 2% (supply limiting factors). Most likely, shells are more important than moisture effects, as the beach plain is very flat and infiltration of rainfall is rapid due to the relatively high beach level. Hoonhout and De Vries (2019) have used a much more complex sand transport model (Aeolis) including beach armoring due to presence of shells and a beach drying model in the intertidal zone. Detailed model calibration was required to represent the measured erosion and deposition patterns in the windblown zone. They used the term $(u_* - u_{*,th})^3$ in the Bagnold-equation, which yields much too small transport rates (Strypsteen 2019; Strypsteen et al. 2019). As windblown transport rates were not successfully measured by mechanical traps at the sand motor site, the coefficients of the transport model could not be calibrated separately. The transport model and the detailed beach armoring model were all calibrated in one procedure, which may easily obscure the deficiencies of each component. It is concluded that the sand motor data with a shell cover < 15% and mostly dry sand can be represented by a fairly simple model approach as proposed in this paper.

Table 6.1 Measured and computed sand transport rates; sand motor site The Netherlands

Cases	Computed annual-mean sand transport ($\text{m}^3/\text{m}/\text{year}$)	Measured annual-mean sand transport ($\text{m}^3/\text{m}/\text{year}$)
1. Wind speed= 10-11 m/s; dry sand $d_{50}=0.335\text{mm}$; $d_{90}=1-3$ mm; no shells; no moisture	140 ± 70	100 ± 35
2. Wind speed= 11 m/s dry sand $d_{50}=0.335\text{mm}$; $d_{90}=2$ mm; shells=5%-15%; no moisture	130 ± 30	
3. Wind speed= 10-11 m/s; moist sand $d_{50}=0.335\text{mm}$; $d_{90}=2$ mm; shells=10%; moisture $w_{20\text{mm}}=1\%-2\%$	60 ± 30	

6.2 Sand transport normal to dune

Wind flow from the beach across the foredune profile involves acceleration and deceleration effects over a varying sand surface, see **Figure 6.2**. If vegetation is present along part of the dune front, the surface roughness may also vary horizontally (non-uniform roughness). The wind speed at the sloping dune surface can be determined by various methods: i) measurements at the sloping surface (wind speed masts); ii) wind flow computations using a mathematical model (open foam CFD-model) and iii) empirical coefficients relating the local wind speed to the upwind velocity ($u_{w,local} = \alpha_{local} u_{w,0}$). Wind normal to the beach accelerates along the slope of the foredune and is maximum at the dune crest level (Arens et al., 1995; Wiggs et al. 1996 and Smyth and Hesp, 2015). The sand transport at the sloping surface of the dune front is affected in various ways: i) increase of the wind velocity enhancing the sand transport rate, ii) increase of the threshold shear velocity for upsloping wind flow reducing the sand transport rate and iii) decrease of the particle velocity during upward part of the saltation trajectory related to the counteracting gravity component reducing the transport rate. Another effect is the generation of upward wind velocities enhancing suspension processes. During strong onshore winds, the upward wind velocities may exceed the fall velocity of grains of 0.2 to 0.3 mm (0.8 to 1.5 m/s). Suspension effects are herein neglected. It is assumed that saltation is the dominant mode of transport.

Figure 6.2 Wind flow normal to dune

Arens et al. (1995) studied the wind speedup effects at the front of the foredune at three coastal sites (sand of 0.17 to 0.26 mm) in the Netherlands. The dune height was in the range of 6 to 23 m. The beach width was in the range of 80 to 600 m. Three to five masts with cup-anemometers were placed at the beach, in the dune zone (corner zone) and at the dune crest. Wind deceleration occurs in the dune toe zone (corner zone), where the wind speed is reduced by about 10%-20% for small dunes < 10 m high to about 50% for a large dune with height of about 20 m. Wind acceleration is most strong at near the dune crest, where the wind speed is increased by 10% for small dunes up to 50% for larger dunes (20 m). An increase in foredune height up to 10 m leads to an increase of the speed-up near the dune crest of about 50% during onshore wind, but a further increase of foredune height from 10 to 20 m was found to have little effect.

Wiggs et al. (1996) studied the wind velocity distribution across an unvegetated desert dune (10 m high; 100 m long) in Oman and across an artificial dune in a wind tunnel. Both the field and wind tunnel data demonstrate similar patterns of wind and shear velocity over the dune, confirming significant flow deceleration upwind of and at the toe of the dune, acceleration of flow up the windward slope. The field data showed a decrease of the shear velocity at the dune toe, but this was not observed in the wind tunnel based on shear velocity data derived from turbulence measurements. Wind tunnel measurements using a special high-frequency wire probe suggests that the field method of shear velocity derivation is inadequate. The wind tunnel results exhibit no reduction in shear velocity upwind of or at the toe of the dune. Evidence provided by measured Reynolds stress profiles and turbulence intensities measured in the wind tunnel suggest that this maintenance of upwind shear stress may be the result of slightly diverging streamline curvature producing additional turbulence, which are not recorded by the traditional techniques used in the field measurements.

Smyth and Hesp (2015) studied the wind flow over a small artificial dune of sand (0.25 mm) with trapezoidal cross-section made at the landward end of a beach. The dune height is 3 m; the length of the dune front is 4 m; the dune front slope is 1 to 1.5 (angle=34°). A computational fluid dynamic model (CFD) was used to compute the wind flow across the dune and the shear velocity along the surface for an onshore wind velocity of 8 m/s at $z=1$ m above the beach surface (inlet $x=0$). The results show a strong reduction (factor 2) in shear velocity at the toe of the dune. The wind velocity strongly (factor 1.5 to 1.7) increases at the crest. The wind velocity and shear velocity decrease again beyond the dune crest. The deceleration and acceleration effects at the toe and near the crest computed by Smyth and Hesp (2015) are much stronger than the effects measured by Arens et al. (1995) and Wiggs et al. (1996), which is most likely caused by the sharp transitions in the profile of the artificial dune. In field conditions these transitions will be smoother resulting in less strong deceleration/acceleration effects. Furthermore, additional turbulence (slightly diverging streamlines) is produced in the corner zone enhancing the shear stresses.

Given the available information on the velocity distribution along the dune front, the predictive modified Bagnold-equation has been used to compute the sand transport rates at the beach and across the dune front up the crest for wind flow normal to the dune. The upwind velocity is defined at 1 m above the beach level and varied in the range of 7 to 30 m/s. The dune dimensions are taken from the data of Davidson-Arnott et al. (2012). The dune height is 10 m above the beach level; the slope angle in the dune toe zone is about 12° and the slope

angle of the dune front is about 22° . The beach and dune sand have $d_{50}=0.26$ mm; d_{90} is set to 0.5 mm and the angle of repose is set to 35° . The beach width is 30 to 40 m, which may give supply-limited effects for onshore winds. The threshold shear velocity of 0.26 mm-sand is 0.26 m/s at the horizontal beach, 0.29 m/s in the dune toe zone and 0.29 m/s in the crest zone based on Equation (2.2) including slope effect for upsloping flow. It is assumed that the median grain size is about constant along the beach and dune faces based on the detailed sampling analysis work of Hallin et al. (2019) for beaches in Sweden. The sand transport is computed at levels of 2 m and 3 m in the dune toe zone, at 5 m (mid-front), and at the dune crest of 10 m above the beach level. The wind speed modification across the dune profile is derived from the available field and wind tunnel data (Arens et al., 1995; Wiggs et al., 1996) resulting: $u_{wind,local}=\alpha_{local} u_{w,o}$ with $\alpha_{2m}\cong 1$ (lower toe zone), $\alpha_{3m}=1.2$ (upper toe zone), $\alpha_{5m}=1.3$ (mid-front) and $\alpha_{10m}=1.5$ (crest).

Figure 6.3 *Aeolian sand transport at beach level and at higher levels along dune front; dry sand $d_{50}=0.26$ mm; including effects of wind modification, slope on threshold shear velocity and vegetation*

Figure 6.3 shows the computed aeolian sand transport rates at 4 levels for conditions with wind flow normal to the dune front. Supply-limitation effects are neglected. The wind velocity at the horizontal axis is defined at the beach. The sand transport rates (dry sand) at level of 2 m in the dune toe zone is about the same as that on the beach except for relatively small wind speeds < 10 m/s. The sand transport rates at levels of 3 and 5 m are larger (factor 1.5 to 3) than those at level of 2 m. The sand transport rates at level of 10 m (crest) are a factor of 5 larger than those at level of 2 m. The increase of the sand transport rates between levels of 2 and 10 m will lead to erosion if vegetation is absent. The sand transport rates are also computed for conditions with vegetation (plant height=0.3 m; cover=15%) resulting in a significant reduction (factor of 10). These computed results are compared to the measured results of Davidson-Arnott et al. (2012). They report measured transport rates of about 0.0055 kg/m/s at a level of 2 m and 0.02 (± 0.005) kg/m/s at levels of 3 to 5 m during oblique onshore winds of about 10 to 11 m/s at dune crest (storm 3-4 May 2010; fairly dry sand as rainfall only occurred on the evening of 3 May). Assuming a smaller wind velocity of about 8 to 9 m/s at the beach, the predicted sand transport rates are of the order of 0.003 to 0.01 kg/m/s at the beach and about 0.02 to 0.04 kg/m/s at levels of 3 to 5 m, see **Figure 6.3**. These computed values are in very reasonable agreement with the measured values. The measured transport rates at levels of 3 to 5 m are somewhat underpredicted by the model, which may be related to moisture effects (rainfall) and supply-limited effects reducing the (measured) transport rates. Sand transport rates in crest zone with vegetation were also measured by Davidson-Arnott et al. (2012). The vegetation cover of marram grass was highly variable, ranging from about 20% near the crest to about 9% to 40% at a level of about 5 m. The measured sand transport rates in the crest zone (levels of 9 to 10 m) are almost zero

(smaller than 0.00015 kg/m/s; factor 50 smaller than at level of 2 m). The model predicts zero transport for a vegetation cover of 15% (plant height=0.3 m) for wind velocities < 11.5 m/s.

The application of the present model to cross-shore windblown sand transport for a beach-dune system is a first and crude attempt to see whether the model predicts meaningful results. Ideally, the model should be coupled to a cross-shore sand transport model for the water system in a time loop-procedure so that the bed morphology from deep water to the foredune row can be simulated in one model. Cohn et al. (2018) have proposed such a coupled model, but our knowledge of shallow-water marine and aeolian processes including precipitation and vegetation needs to be much improved to obtain really accurate morphodynamic predictions. A somewhat different modelling approach at a higher level of aggregation is that of Delgado-Fernandez (2011) and Hallin et al. (2019) which are developed to model the sediment supply and supply limiting conditions from the beach to the dune over longer time scales (months to years). The present model can be easily included in such an approach.

7. Conclusions and recommendations

A fully predictive model for loose, dry sand is proposed, which only requires input from the wind velocity at one height above the surface and characteristic sand diameters (d_{50} , d_{90}). The model is based on the modification of the well-known Bagnold equation by including the threshold shear velocity, which is slightly adjusted to ensure a smoother transition from the non-transport regime to the transport regime. The sand transport rate is related to the static and dynamic grain roughness by using a semi-empirical roughness predictor, which is calibrated based on sand transport data from wind tunnel experiments with a flat mobile sand surface. Analysis of transport data from wind tunnel experiments shows that: 1) the cubic relationship between the transport rate and the shear velocity is a very reasonable approach and 2) the transport decreases for smaller diameters at higher shear velocities (upper regime), but increases slightly for smaller diameters at low shear velocities. This effect is to some extent represented by the modified Bagnold-equation due to the inclusion of a threshold shear velocity. However, the transport of fine sand (0.15 mm) is overpredicted by the Bagnold equation, if the measured shear velocity is used. In all, 105 high-quality data sets of wind tunnel and field experiments have been used for verification of the proposed predictive model. About 73% of the predicted values are within a factor of 2 of measured values of the transport rate. A higher score is hardly possible, given all variabilities and non-uniformities involved (wind field, sand composition, bed relief, surface roughness). The example application related to wind flow and sand transport normal to a foredune shows that the predictive model produces very reasonable results compared to measured sand transport rates across the dune front based on the field data of Davidson-Arnott et al. (2012).

The effects of moisture, vegetation and shells on the sand transport process are included by fairly simple expressions which are acting on the shear velocity, the threshold value and the transport rate. The coefficients were derived from available experiments in wind tunnels and at field sites. Sand transport reduces to almost zero for a moisture content of the topmost 20 mm of the surface exceeding 10%. Similarly, the sand transport is almost completely suppressed for a vegetation cover of about 20% to 30%. Even so, a shell cover of 30% to 40% reduces the sand transport to almost nil. Available data shows that the type of cover is less important.

Sand transport by wind can be compared to that by water by using the T-parameter (Eq. 3.6c). Using $T \approx 5$ (upper transport regime) and $d_{50} = 0.2$ mm, the sand transport rate by wind is about 0.1 kg/m/s whereas that by water flow is of the order of 1 kg/m/s. Suspended sand transport is dominant in water flow whereas, saltation transport is dominant in air flow.

To extend the knowledge of the bed roughness and sand transport of sandy beaches, wind tunnel and field experiments are highly recommended. There is pressing need for detailed, short-duration experiments in wind tunnels with a flat, mobile sand surface in the upper transport regime to study the dynamic grain roughness. The effective roughness of a flat sand with and without shells (cover percentage of 3 to 30%) can also be studied in a wind tunnel at low wind velocities without sand transport. The form drag of artificially prepared ripples can also be determined in a wind tunnel. Special field studies focusing on the effect of ripples and shells on sand transport are also highly recommended.

8. References

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Conflicts of interest

None

Journal Pre-proof

Highlights of Paper: a fully predictive model for aeolian sand transport

1. fully predictive model for aeolian sand transport
2. development of roughness predictor model
3. verification using 105 high-quality data sets
4. inclusion of effects of moisture, vegetation and shells
5. two practical applications of the model and comparison to measured field data