Abrasion rates of ventifacts

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Abstract

Although ventifacts are often utilized to determine past and present wind directions and sediment mobilities in arid, coastal, and periglacial environments, their morphodynamics have not been well understood. In this study, based upon the principles of classical mechanics, the abrasion rate of ventifact is analytically expressed by the elastic properties of rock or mineral components and the mass flux density of sediment transported by wind. The unknown abrasion coefficient can be estimated via wind tunnel experiments. The practicability of this novel formula is shown by the calculation of short-term abrasion depth of ventifacts over a desert pavement. It is expected that the current work will improve the quantitative reconstruction of paleo-environments and paleo-climates using ventifacts.

Keywords Ventifact · Abrasion rate formula · Aeolian sediment transport

1 Introduction

Ventifacts are pebble- to boulder-sized rocks shaped by aeolian particles in arid, coastal, and periglacial environments [1–3]. Stone pavements cover more than 50% of terrestrial desert surfaces [4]. The ventifacts in the northern hemisphere midlatitudes are particularly reported in the literature [1]. Ventifacts are also widespread on Mars [5, 6], because of highly active aeolian sediment transport and abrasion processes. As a typical type of erosional landform as well as yardangs, they are significant in determining past and present wind direction and sediment mobility [1, 2]. Both morphological and morphodynamic studies on this landform have been performed frequently since 1855, in which two papers closely related with ventifacts were published [7]. Depending on wind conditions, small ventifacts might have one or more facets separated by sharp keels. There are Brazil-nut, pyramidal, and other shapes in plan view, and some distinctive surface features such as pits, flutes and grooves, see [3, 8, 9] for more detailed

morphological characteristics. Ventifact formation is influenced by factors similar to those of dunes [10]. Morphodynamic processes, abrasion in particular, can be investigated by means of field investigation [8, 11–14], numerical simulation [15, 16], laboratory simulation [17–25], and theoretical analysis [26, 27]. Field investigations are commonly time-consuming. A long-term field observation suggested that the abrasion of the ventifacts located at a small western Arctic coastal settlement had been virtually undetectable over 50 years [14]. As a comparison, the formation and development of facets and surface features by direct impacts of sand grains can be numerically modeled efficiently [15, 16]. But the principles of these numerical simulations are weakly supported by physical laws. As far as we know, more practical methods are abrasion experiments using the apparatuses specially designed [19–21] or various kinds of wind tunnels [17, 18, 24, 25]. Abrasion rate must be determined firstly, in order to quantitatively describe the morphodynamic processes of ventifacts. This variable is a function of wind velocity, particle supply,

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and the mechanical properties of rocks etc. For an impact, it is traditionally recognized that the mass lost is roughly proportional to the translational energy of the impacting particle [18, 20, 21, 26]. This empirical “abrasion law” can be reasonably expanded to include two common mechanical parameters of target materials by modeling the collision and break precesses [27]. Recently, A unified equation of the rate of bedrock erosion by sediment-laden fluid flows in fluvial, coastal, and aeolian environments was put forward [28], although the theoretical foundation is lacking. In the presented study, a mechanically-based novel expression of abrasion rate is derived according to the principles of classical mechanics and the abrasion model proposed by Wang et al. [27], and then field observation is performed to test the formula.

2 Methodology

2.1 Theoretical model

The volume of target material removed by an impact can be written as [27],

$$\frac{V}{d^3} \propto \frac{\rho_s u^2 E}{\sigma_s^2} \quad (1)$$

where V is the volume lost, ρ_s , d , and u are the density, diameter, and speed of the impacting particle, E and σ_s are Young's modulus and yield stress of the target, respectively.

Abrasion rate is often defined as the eroded depth of target materials per unit time. A basic fact is that the failure area of brittle materials generally increases with the increase of the size of impacting rigid grains. Therefore, the volume lost V per impact is,

$$V \propto h d^2 \quad (2)$$

where h is the eroded depth.

Given the mass flux density q , defined as the mass perpendicularly passing through an unit area per unit time, the mass transported by wind through an area of a grain in duration T is

$$\delta m = \frac{1}{4} q \pi d^2 T = \frac{1}{6} n \rho_s \pi d^3 \quad (3)$$

where the sand grain is assumed to be a perfect sphere, n is the grain number.

Hence, the impact times is,

$$n = \frac{3qT}{2\rho_s d} \quad (4)$$

The length of “sand column” through the area of a grain is,

$$l = \frac{\frac{1}{6} n \pi d^3}{\frac{1}{4} c \pi d^2} = \frac{2nd}{3c} \quad (5)$$

where c is the volume concentration of aeolian sand.

From Eqs. (4) and (5), the speed of a single impacting grain is,

$$u = \frac{l}{T} = \frac{q}{c \rho_s} \quad (6)$$

Combining Eqs. (1), (2), (4), and (6), the expression of abrasion rate is derived as,

$$v_a = \frac{nh}{T} = C_a \frac{q^3 E}{\rho_s^2 \sigma_s^2} \quad (7)$$

where the empirical constant C_a can be named as “abrasion coefficient”. The volume concentration c was assumed to be a constant, and has been contained in C_a . Hereinafter, the function form in the right side of (7) and the unknown abrasion coefficient C_a will be verified and determined by the previous experimental data.

2.2 Field observation

Given a ventifact, E and σ_s in (7) can be found from large numbers of materials handbooks, e.g. [29]. Table 1 lists these two mechanical parameters we adopted in this study. For a saturated aeolian transport, many mass flux expressions or numerical simulation procedures have been developed [30]. However, the granular material supply for wind-blown sediments shaping ventifacts is often limited in a natural environment. To determine the unsaturated mass flux density q and examine the practicability of the theoretical expression (7), we designed and performed a field observation over a

Table 1 Mechanical parameters of common rock or mineral components of ventifacts (No. 1–5) and the material used in the simulation experiments (No. 6)

No.	Rock/Mineral	E (GPa)	σ_s (MPa)
1	Basalt	72.0	343.0
2	Granite	54.0	204.0
3	Marble	48.5	145.0
4	Quartzite	67.5	288.8
5	Fused silica	72.0	1100.0
6	Sandstone (soft)	0.98	10.0

E and σ_s are Young's modulus and yield stress (compressive strength), respectively

desert pavement at the Dashagou gobi of the Kumtagh desert (China) in the spring of 2017. In this region, the prevailing wind direction is northwest (295°). The gravel cover and vegetation cover of the desert pavement are about 20–40% and 5–15%, respectively. The wind velocities at the heights of 0.5 m and 1.0 m above the surface were automatically and continuously recorded by two super sonic anemometers (Fig. 1a) with the sampling frequency of 20 Hz during March 22 to May 2. The near-surface mass flux was artificially and discontinuously measured by using a conventional sand collector (Fig. 1b) with the sampling efficiency larger than 90%. The mean grain size of aeolian sediment is about 200 μm . Meanwhile 15 soft sandstone blocks with the dimension of 20 cm $\times$ 10 cm $\times$ 10 cm or so were cut and smoothed from natural alluvial deposits, and then were placed at this ventifact site to observe the perceptible effects of abrasion by aeolian sand grains. Both the inlet of the sand collector and the front faces of sandstone blocks were perpendicular to the prevailing wind direction.

The natural process of aeolian sediment transport is highly intermittent [31–33]. Friction speed and duration are two dominating factors. Wind erosion events can be detected from the time series of wind speed in the prevailing wind direction. Here the minimal durations of erosion and non-erosion events are empirically set to be 0.5 min and 0.25 min. The friction speed u_* in a wind erosion event must be larger than the threshold friction speed u_{*t} (≈ 0.30 m/s). In the numerical program of data analysis, erosion and non-erosion events are not allowed to contain each other. The sediments transported by several to hundreds of wind erosion events were collected in one sampling time (10–60 min) of the sand collector. If the number of wind erosion events in one run for collecting aeolian sand, the friction speed and duration of the i -th event are denoted as N , u_{*i} , t_i , then the time-averaged friction speed u_* can be calculated by $\sum_{i=1}^N u_{*i} t_i / \sum_{i=1}^N t_i$.

Fig. 1 Two super sonic anemometers and one sand collector were utilized to measure wind velocity and mass flux density over a desert pavement. The super sonic anemometers were located at the height of 0.5 m and 1.0 m above the surface. The sand collector is 60 cm high

(a) Two super sonic anemometers.

(b) One sand collector.

3 Results and discussion

3.1 Function form

The abrasion law of (1) has been confirmed by the experimental data of [20, 22], see Fig. 7 in Ref. [27] for details. As a conclusion, the expression of abrasion rate (7) should be valid. Unfortunately, all variables and parameters in (7) are seldom measured simultaneously in existing abrasion experiments. We only found one experiment in which the strengths of rock specimens were tested [19]. Figure 2 shows that the relation between abrasion rate and the compression strength of sandstone can be well fitted by $v_a \propto \sigma_s^{-2}$ when sand flux is constant. This reconfirms that the function form of (7) is acceptable.

3.2 Abrasion coefficient

The empirical constant C_a in (7) can be estimated, according to the wind tunnel experiments conducted

Fig. 2 The relation between abrasion rate and compression strength for sandstone can be well fitted by $v_a \propto \sigma_s^{-2}$ when sand flux keeps constant. This reconfirms that the function structure of (7) is acceptable. The experimental data denoted by “•” are sourced from Ref. [19]

by Bridges et al [24]. Most extant ventifacts are igneous or metamorphic [34]. Since the short-term, e.g. quarterly or annual, abrasion rates of nature rocks and mineral of ventifacts, such as basalt, chert, and quartz, are too small or unnoticeable, the materials with much lower strength are widely served as targets in abrasion experiments. The material of soft sandstone was successfully simulated by a mosaic of water, gypsum and sand in their wind tunnel experiments [24]. The sandstone simulatant target with flat sides and the front face angled at different degrees relative to the tunnel floor was abraded by sand flux in the wind tunnel. The target losses mass and forms the ventifact-like surface features during this abrasion process. The change of target weight was recorded in each experiment run. Totally, nine abrasion rates for the front face of three targets perpendicular to the wind direction were obtained under the condition of a constant sand flux of 0.4 kg/min. Aeolian sediment transport mainly occurs in the near-bed flow region. An optical measurement in a wind tunnel with the cross-section of 0.3 m × 0.3 m indicates that the region above 19 mm from the bed generally makes only 20% contribution to total mass flux [35]. Note that the dimensions of the wind tunnel

are larger and the wind speed is higher in the experiments of Bridges et al [24], we assume that the mass flux contribution in the region of abrasion targets is 50%. Consequently, the mass flux density q is computed to be 0.056 kg/m². The typical values of Young's modulus E and yield stress σ_s of soft sandstone are listed in Table 1. Substituting q , E , σ_s , ρ_s ($\approx 2.65 \times 10^3 \text{ kg/m}^3$), and the measured v_a into (7), it is found that the abrasion coefficient C_a ranges from 1.79×10^8 to 5.36×10^9 , and the mean value is 3.00×10^9 .

3.3 Morphological change

Although ventifact-like shapes did not develop owing to the relative short observation period, the windward surface of sandstone block was morphologically changed by the abrasion of aeolian sand grains. As shown in Fig. 3, depending on the mechanical properties of targets, typical impact features like individual depressions of sand grains, small flutes, and grooves might emerge on the original smooth surfaces. The maximum abrasion depth is about 4.0 mm.

Fig. 3 Morphological change of the windward surface of sandstone block caused by the abrasion of aeolian sand grains

(a) the original surface is smooth.

(b) individual depressions of impinging grains appear and the surface becomes slightly rough.

(c) small flutes emerge and the surface becomes severely rough.

(d) grooves occur and abrasion depths are measurable.

Fig. 4 Variation of the near-surface mass flux density q with friction speed. The measured data of unsaturated mass flux density are too discrete to find a suitable polynomial function as done in the saturated aeolian sediment transport. Therefore, q was fitted by a piecewise linear function of u_*

3.4 Aeolian sediment transport and abrasion depths

The variation of the mean mass flux density q of the 0–10 cm height with friction speed u_* is plotted in Fig. 4. The saturated mass flux is the low-order polynomial function of u_* [36]. But the data of unsaturated mass flux density are too discrete to find a suitable polynomial function. We choose a piecewise linear function of u_* to fit q ,

$$q = \begin{cases} 0 & \text{if } u_* \leq 0.30 \\ 0.0304 & \text{if } 0.30 < u_* \leq 0.35 \\ 0.2149 & \text{if } 0.35 < u_* \leq 0.40 \\ 0.6709 & \text{if } 0.40 < u_* \leq 0.45 \\ 0.9254 & \text{if } 0.45 < u_* \leq 0.50 \\ 8.4675 & \text{if } 0.50 < u_* \leq 0.55 \\ q_{max} = 30.9378 & \text{if } u_* > 0.55 \end{cases} \quad (8)$$

where the units of q and u_* are $\text{g/m}^2\text{s}$ and m/s , q_{max} is the maximum value of q we obtained.

There are 2988 wind erosion events from March 22 to May 2, see Fig. 5 for the time series. They are discontinuously and almost uniformly distributed in the observation time. Some strong wind erosion events ($u_* > 0.6 \text{ m/s}$) intensively happen in the afternoons of March 22, April 18 and May 1. As shown in Fig. 6, the statistical characteristics of wind speed and duration indicate that most events occur when wind speed is slightly larger than threshold friction speed, and only last dozens of seconds. The accumulative effective abrasion duration is 36 h. For the common rock or mineral components of vitrification in Table 1, the abrasion depths are calculated to be 0.101 mm, 0.214 mm, 0.381 mm, 0.134 mm, 0.010 mm, and 1.619 mm respectively, when $C_a = 3.00 \times 10^9$. Because the computed abrasion depth of soft sandstone (1.619 mm) is in

Fig. 5 Time series of wind erosion events during March 22–May 2

Fig. 6 The statistical characteristic of wind erosion events. Most events occur when wind speed is slightly larger than threshold friction speed, and last dozens of seconds

the range of the in-situ values (≤ 4.0 mm) we measured, the expression of abrasion rate (7) is practicable.

In addition to determining abrasion rate and then describing the morphodynamic evolution process, physically-based models could provide some insights on dating the ventifacts composed of two or more minerals. Different from many previous studies, the short-term abrasion depths are tightly related with rock or mineral mechanical properties in the current model. It is difficult to determine the age of most ventifacts [9, 37], partly because their primary morphology is unknown. Since many ventifacts are heterogeneous, see Fig. A22 in Ref. [38] for a vivid example of quartz veins in a basalt rock-type ventifact, it is probable to estimate the time taken to form ventifacts by the different abrasion depths of rock components using (7), if local wind conditions are well understood.

4 Conclusions

In this study, an analytical expression for the abrasion rate of ventifact is derived, and then the abrasion coefficient is obtained from a previous wind tunnel experiment. The agreement of abrasion depth between theoretical prediction and field measurement indicates that the novel formula seems satisfactory. It is expected that the abrasion coefficient will be measured more accurately, and that such a physically-based model will be helpful for the studies on the morphodynamic evolution and chronology of ventifacts.

Acknowledgements We are grateful to Hui-Zhong Chen, Zong-Hu Hou, Chun-Lai Zhang, Feng Zhang, Xue-Yong Zou for assistance with the field measurements. The reviewer and editor offered insightful comments and suggestions for improving the quality of this manuscript.

Funding This research was supported by Natural Science Foundation of China projects (Nos. 41630747 and 41571006).

Compliance with ethical standards

Conflicts of interest The authors declare that there have no conflict of interest.

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