Large scale sand saltation over hard surface: a controlled experiment in still air (Postprint)

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Abstract

Saltation is the major particle movement type in wind erosion process. Saltating sand grains can rebound up to tens of times larger in length and height over hard surface (such as gravel surface) than over loose sand surface. Gravels usually have different faces, causing distinct response of the impacting grains, but the effects of the grain and gravel-surface contact angle on grain rebound are not yet well quantified. We performed full-range controlled experiments of grain saltation using different contact angles, grain sizes and impact speeds in still air, to show that contact angle increases the height of representative saltation path but decreases particle travel length. The results were compared with outputs from the COMprehensive numerical model of SALTation (COMSALT). Large saltation height of 4.8 m and length of 9.0 m were recorded. The maximum and representative saltation height over the gravel surface were found to be about 4.9 times and 12.8 times those over the loose sandy surface, respectively. The maximum saltation length may be reduced by 58% and the representative saltation height may be increased by 77% as contact angle increases from 20° to 40°. We further showed that the collision inertia contributes 60% of the saltation length, and wind contributes to the other 40%. These quantitative findings have important implications for modeling saltation trajectory over gravel surface.

Full Text

Preamble

Large-scale sand saltation over hard surface: a controlled experiment in still air

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Abstract

Saltation is the dominant mode of particle movement during wind erosion processes. Saltating sand grains can rebound to heights and lengths tens of times greater over hard surfaces (such as gravel surfaces) than over loose sand surfaces. Gravels typically possess multiple faces with distinct orientations, causing varied responses in impacting grains, yet the effects of the contact angle between grains and gravel surfaces on rebound characteristics remain poorly quantified.

We conducted full-range controlled experiments of grain saltation using different contact angles, grain sizes, and impact speeds in still air to demonstrate that contact angle increases the height of representative saltation paths while decreasing particle travel length. Results were compared with outputs from the COMprehensive numerical model of SALTation (COMSALT). Saltation heights of 4.8 m and lengths of 9.0 m were recorded. Maximum and representative saltation heights over gravel surfaces were approximately 4.9 times and 12.8 times those over loose sandy surfaces, respectively. Maximum saltation length may be reduced by 58% and representative saltation height increased by 77% as contact angle increases from 20° to 40°. We further demonstrated that collision inertia contributes 60% of saltation length, with wind contributing the remaining 40%. These quantitative findings have important implications for modeling saltation trajectories over gravel surfaces.

Keywords: sand saltation; trajectory; gravel surface; contact angle; full-scale experiment

1. Introduction

Saltation represents the primary mode of aeolian sand transport during wind erosion processes in planetary environments (Shao et al., 1993; Ayoub et al., 2014; Burr et al., 2015). Saltation trajectory may be one of the main factors influencing the initial size of aeolian dunes (Pähtz et al., 2015; Lämmel and Kroy, 2017) and thus deserves the most research consideration (Li et al., 2020). The characteristic length and height of saltation trajectories over loose sand surfaces are on the order of 10^{-3} to 10^{-2} m (Williams and Leer, 1995; Hagen et al., 2010), and the rebound of particles over massive particles in a heterogeneous surface travels higher than that in a homogeneous surface with the same grain size (Bagnold, 1973). In blown sand conditions, smaller particles saltate higher or become suspended in air because drag force varies with the square of particle diameter while weight varies with the cube (Lorenz and Zimbelman, 2014).

However, over immobile hard surfaces such as gravel (stony) Gobi desert—which covers an area of 1.3×10^{6} km^{2} in Central Asia—saltation can be remarkably different, exhibiting much longer and higher trajectories that demonstrate the effect of particle rebound from hard surfaces. This phenomenon was recognized long ago, as Bagnold (1941) noted that "the sand movement over a rough immobile or partially immobile surface differs in this important respect from that over a surface of dune sand⋯" because in this case grains impact the surface by bouncing rather than splashing, thereby retaining more saltation kinetic energy. Over a granular sandy surface, most grains are ejected with low energy (Ammi et al., 2009), whereas the majority of particles can be rebounded by rigid gravel surfaces. Consequently, sand flux over gravel surfaces under extremely strong wind conditions (gust wind speeds exceeding 40 m/s) may be greatest in the layer tens of centimeters above the ground surface [Figure 1: see original paper], and sand grains jumping up to 10 m high have been observed (Yin, 1989; Cheng et al., 2016; Tan et al., 2020).

[Figure 1: see original paper] Evidence of large-scale saltation over gravel surface. (a) Serious sand abrasion of a wood pole on the windward side from about 0.1 m to more than 1.5 m in a Gobi area of Xinjiang, but the bottom part below 0.1 m is less damaged; (b) abrasion of a concrete bridge pier (indicated by the ellipse) shows the strongest abrasion at about 0.8 m high; (c) sand deposited behind a 3.3 m high wall as wind breaker at a section of the Lanzhou-Xinjiang high-speed railway; and (d) grain-size distribution of five samples from the site shown in (c). At the three sites of (a)-(c), wind is almost unidirectional, with sand blowing toward the abrasion side in (a) and (b) but the other side of the wall in (c).

Most studies on sand movement over gravel surfaces employ the same approach as those over sandy surfaces, examining aerodynamic roughness length and wind velocity profile (Dong et al., 2002a, b; Zhang et al., 2008). A turning point was observed in sand concentration profiles due to sand-gravel collision, differing from concentration profiles over sand surfaces (Zhang et al., 2008). Particles of different sizes may also respond diversely during collision with the surface. Although Bagnold (1941) noted that the size and spacing of pebbles affect particle movement, few studies have focused on how pebble characteristics influence grain movement. Hardly any such studies have been conducted at large scales due to practical difficulties; for example, saltation height could exceed wind tunnel upper boundaries, preventing measurement of actual heights. In field conditions, grain size and gravel characteristics remain difficult to measure and parameterize because separating the effects of gravels with different shapes, sizes, and surface angles on saltation particles is not feasible. Consequently, new experimental methods are needed to study the effect of gravel surfaces on particle saltation.

Suppose a group of grains with identical properties and trajectories (i.e., with the same impact velocity and angle) impacts a gravel surface. The rebound would substantially affect the subsequent trajectories of these grains. A natural gravel surface can be considered to be composed of many surfaces with different reflection angles. If the effect of the contact angle between the impacting grain and gravel surface is known, the complicated trajectories of sand grains observed in wind-tunnel and/or field experiments can be decoded by considering the probability distribution of reflection angles of the gravel surface. We can then better predict grain trajectories and sand transport flux, increasing our knowledge of the wavelength of incipient ripples or dunes in hard surface areas, which is of great importance for understanding gravel surface formation and evolution.

To obtain saltation trajectories that may be unattainable through traditional wind tunnel experiments and field measurements, we designed equipment to capture the full-scale saltation range of sand particles and performed controlled experiments to measure the concentration of saltation particles and grain saltation length at sequential locations. We obtained details of saltation trajectories in still air to demonstrate how the contact angle of gravel surfaces influences sand saltation trajectories for different grain sizes and impact speeds. By analyzing trajectory characteristics, we distinguished the contributions of grain inertia and fluid momentum to sand saltation. Results were then compared with simulations for sandy surfaces from the COMprehensive numerical model of SALTation (COMSALT), a physically based saltation model capable of switching off turbulent air effects to generate results comparable to our tests (Kok and Renno, 2009).

2.1 Blasting equipment

We designed equipment that can control blasting air speed and contact angle while collecting impacted particles at various horizontal and vertical locations [Figure 2: see original paper]. The system consisted of: an air compressor to generate high-speed airflow; a pressure valve to control air pressure; an electromagnetic valve with timer to control blasting duration; a sand-blasting gun with a 0.5 cm diameter round opening to feed and eject sand particles; a hard smooth slate with adjustable angles on a platform to simulate gravel surfaces; a series of square plastic bins (10.0 cm length and 30.0 cm depth) along the blasting center to collect horizontally settled particles; and a stack of removable steel bins (each 5.5 cm height, 5.0 cm width, 20.0 cm length, 25° uptilt, with a porous air outlet at the end) on a portable frame to collect saltation sand profiles at different distances.

Air speed was calibrated at 15.0 cm from the sand-blasting gun opening (the location of the proposed contact center). A pilot tube measured wind speed changes with controlled air pressure to establish their relationship. Pressure was increased from 1.0×10^{5} Pa at 0.5×10^{5} Pa intervals with three replications. A good linear relationship was determined [Figure 2d: see original paper]; however, above 3.5×10^{5} Pa pressure (approximately 56.0 m/s air speed), the relationship tended to degrade. In fact, the pilot tube failed to reflect any air speed changes above 4.0×10^{5} Pa pressure because measured static pressure also increased in the violent airflow. Therefore, only four reference air speeds from 20.0 to 50.0 m/s at 10.0 m/s intervals were used. These selected speeds may be apparently higher than those in typical blown sand experiments, especially in wind tunnels, but are frequently encountered in Gobi areas. Particles traveled a short distance (15.0 cm) in the same direction as the high-pressure jet air stream, so we can assume they followed the air speed before collision with little damping during the transient traveling period (<0.0075 s at 20.0 m/s air speed).

Vertical bins were arranged with their openings on a vertical plane, with the lower edge of the lowest bin set at the same height as the contact center. The contacting slate dimensions were chosen to ensure no particles could fly directly over but had to collide with the slate under the three angle conditions (Section 2.3). Trial tests were conducted before each speed, angle, and particle size experiment to determine the number of bins needed in both directions. For each scenario with a specific contact angle, speed, and particle size, the horizontal test was performed first, followed by the vertical test with the frame positioned from the slate margin (0.0 cm) and moved back every 30.0 cm to obtain trajectories. Bins were removed starting from the top, and sand particles in each bin were weighed using a balance with 0.1 mg resolution. If particles weighed less than the balance' s maximum resolution, their numbers were counted and weights estimated based on quartz density and average volume (assuming spherical shape) of the size group. Three replications were performed for each test scenario.

All tests and weighing were conducted in an indoor environment with still air. During each test, a cloth sheet was laid on the floor to recycle the remaining blasted sand and prevent secondary saltation.

2.2 Contact angle at gravel surface

In Gobi areas, gravels on the underlying surface exhibit different coverage, sizes, orientation, and roundness. Gravel shapes can be highly irregular, with each gravel possessing several faces.

The inclination angle (0° for horizontal) of each face that may encounter a saltating sand grain defines the contact angle ; the rebound liftoff angle (α) will then be the sum of 2 and β, where β is the blasting angle of the particle (downward positive). In our equipment, β was set to 0° (horizontal sand stream) for simplification, so $\alpha = 2$.

We randomly selected over 300 gravels from the Gobi in the eastern Kumtag

Desert, Northwest China, and manually measured their faces. Besides the underside face touching the ground, each gravel typically had 3-4 faces that could encounter saltating sands. The face inclination angles (0° level with ground, 90° vertical) distributed over a large range from nearly 0° to over 90° [Figure 2e: see original paper]. However, for all steep gravel face angles larger than 50°, grains would rebound vertically or even backward upward, making their forward velocity and subsequent travel paths unmeasurable. For gentle angles smaller than 10°, saltation conditions would be similar to those over a level surface, and grains might not develop full trajectories before hitting the ground. Consequently, we only considered gravel inclination angles of 20°, 30°, and 40°, which were also the most frequently measured angles and resulted in α values of 40°, 60°, and 80°, respectively, assuming elastic collision. Air from the nozzle may diffuse at about 13° and cause errors (Reichardt, 1941), but sand particles have much larger inertia, resulting in less dispersed α than the air.

2.3 Sand

Aeolian sands were collected from the Mingsha Megadune east of the Kumtag Desert, Northwest China. These quartz sands were screened to form three size groups: 0.10-0.25 mm (fine sand), 0.25-0.50 mm (medium sand), and 0.50-1.00 mm (coarse sand).

A total of 36 experimental groups were conducted, each involving removal and reloading of tens of horizontal bins once and vertical bins 6 times (shortest measured distance: 1.8 m) to 27 times (longest measured distance: 8.1 m).

2.4 COMSALT simulation

Experimental results on saltation with different values were compared with simulations from COMSALT (Kok and Renno, 2009). This model simulates particle saltation due to gravity, fluid drag, fluid shear, turbulent air, and various other processes. It does not consider collisions between saltation particles and can turn off turbulent air effects, making it comparable to our still-air experiments. Many fluid forces such as the Saffman force from shearing flow and the Magnus force from particle rotation were experienced in both experiments and COMSALT. The model reports two-dimensional steady-state results, meaning particle-surface and particle-wind interactions are averaged over many iterations to reach dynamic equilibrium.

COMSALT assumes a flat surface and estimates a mean rebound angle α of 40°, which matches our = 20° experiments. Therefore, the comparison reveals differences between saltation over gravel surfaces (our tests) and flat surfaces (COMSALT simulation). However, it is worth noting that other ejection angle ranges have also been recommended, for example 60° (Ammi et al., 2009).

COMSALT uses the log-law wind profile to estimate clear-wind shear velocity:

$$u = \frac{u_*}{k} \ln \frac{z}{z_0}$$

where u is air speed (m/s); u_* is shear velocity; z is height (m); $z_0 \approx D/30$ is surface roughness based on particle size D (m); and k is the von Kármán constant set to 0.4. Details about particle trajectory, collision process, and wind profile readjustment can be found in the model documentation (Kok and Renno, 2009).

3.1 Distribution of saltation sands

Since sand flux was measured continuously, we plotted concentration contours of saltation sands, which also represent the probability density of sand grains for given size, impact speed, and conditions. For all conditions, sand grains tended to concentrate in a narrow trajectory range, indicating the existence of a dominant saltation trajectory where particle concentration can be hundreds of times greater than in marginal areas. However, the scatter range of particle saltation (light gray areas in Figs. 3–5) was obviously large because the saltation process is highly stochastic, and particles are unlikely to travel in a single path even with identical internal and environmental factors.

As increased, particles moved more upward but settled at shorter distances, resulting in larger saltation ranges after collision and more upright (higher) but narrower (shorter) profiles, as shown in Figure 3a [Figure 3: see original paper] at 20° versus Figure 3c at 40°, for example. Additionally, the peak concentration of the particle cloud was reduced more quickly with , although total flux remained the same with identical air speed (same injection speed and duration), e.g., from 88.2 g/min in Figure 3g at 20° to 7.1 g/min in Figure 3i at 40°. This occurs because a shallow horizontal yields small α, causing particle streams to concentrate in narrow paths with small .

As impact speed increased, both saltation height and length increased. Maximum saltation height (H_m) and maximum saltation length (L_m) at 50 m/s impact speed for the three size groups were 2.8 and 2.7 times those at 20 m/s wind speed. Larger particle sizes rebounded higher and saltated longer, so saltation space followed the sequence: coarse sand [Figure 5: see original paper] > medium sand [Figure 4: see original paper] > fine sand [Figure 3: see original paper]. We found that coarse sands (0.50–1.00 mm) rebounded farthest when = 20°, while the highest rebounds occurred at = 40° under 50 m/s impact speed.

3.2 Representative trajectory and maximum height profile

The height of maximum saltation sand concentration (H_c) at each horizontal location was extracted to form the representative trajectory (characteristic grain path) of sand particles for different sizes, contact angles, and impact speeds [Figure 6: see original paper]. The outer boundaries of Figures 3–5 were extracted to create a group of H_m profiles representing the upper limit positions of grains along travel paths.

H_m profiles bounded by the highest particles were remarkably larger than H_c profiles representing average particle features. Peak heights on H_m profiles were about 3.5, 2.7, and 2.3 times those on H_c profiles when equaled 20°, 30°, and 40°, respectively. Therefore, considering only a representative height on a theoretical trajectory may substantially underestimate the potential sand saltation height. Results also showed that representative saltation paths have elliptical shapes and long tails with downward settling angles smaller than liftoff angles (Bagnold, 1941; Ho et al., 2014), and that H_c height increases with wind speed (Zheng et al., 2004).

3.3 Characteristic values of the trajectories

Peak L_m, H_c, and H_m values in the saltation spaces were extracted to show their relationships with [Figure 7: see original paper]. On average, L_m increased with particle size and decreased with for a given flow speed [FIGURE:7a–c], reduced by 12% as increased from 20° to 30° and by another 24% as increased from 30° to 40°. H_c increased with particle size and , except for the case of 50 m/s impact speed with = 30° [FIGURE:7d–f]. H_m also increased with particle size and speed; however, its relationship with was not strong [FIGURE:7g–i].

Within a size and impact speed group, accounted for 58% (40%–98%) of variance in L_m, 77% (29%–97%) of variance in H_c, but only 21% (8%–39%) of change in H_m. This indicates that H_m is less impacted by contact angle, so particles in all size groups can reach high elevations after collision.

Changes in L_m, H_c, and H_m values with impact speed were generally monotonic for any particle size and α, allowing linear relationships to be established with v. Regression coefficients a and b, together with their R^2 values, are given in Table 1 to quantitatively show these changes. For instance, decreasing coefficient a values with increasing α for L_m indicate that trajectory length is reduced at higher contact surface angles.

3.4 Relationships of α with L_m/H_c and L_m/H_m

A good linear relationship between L_m/H_c and α was found in previous wind tunnel experiments on blown sand, showing that representative saltation length can be 10.0 times the height (Ling and Wu, 1980), at least when $30° < \alpha < 90°$ (Zou et al., 1999), which covers our current α range. The average L_m/H_c value across four speeds at three α conditions in our experiments was 40% ± 5% less than its blown-sand counterpart, but still followed a linear pattern [Figure 8: see original paper]. This suggests that L_m under field blown-sand conditions may be about 1.7 times (1.0/0.6) larger than our measured values.

Because H_m is clearly larger than H_c, the ratio L_m/H_m is smaller compared to L_m/H_c, even after adjusting L_m by 1.7 times. The scatters of L_m/H_c and L_m/H_m generally distribute in separate areas [Figure 8: see original paper]. However, because H_m is difficult to obtain in field measurements or wind tunnel experiments, this L_m/H_m versus α relationship is less valuable than the L_m/H_c versus α relationship, though L_m/H_m also follows a linear pattern with α.

These relationships between α and both L_m/H_c and L_m/H_m are generally independent of wind speed, as shown in Table 1 and Figure 8, indicating that at least within the tested liftoff angle range, grain trajectory shapes under different winds remain similar.

3.5 Comparison with COMSALT-simulated saltation over flat sandy surface

COMSALT simulation results agreed well with $= 20°$ tests on L_m for fine sand at lower impact speeds (<40 m/s), but agreement decreased for larger particle sizes (discrepancy about 60% for medium sand and 100% for coarse sand) although similar trends persisted [Figure 9a: see original paper]. A possible explanation is that COMSALT may overestimate L_m for large particles with high shear velocity (u_* ranged from 0.63 to 1.78 m/s), or that our tests failed to collect all saltation particles at downstream ends where mass flux was very low.

However, COMSALT clearly underestimated saltation height over hard surfaces for both maximum height (H_m) [Figure 9b: see original paper] and representative height (H_c) [Figure 9c: see original paper]. Here, we used the height of z_{50} (the saltation layer height below which half of horizontal mass flux occurs, representing the typical height of most saltation particles) from COMSALT output as our H_c counterpart. Test results for H_m were 4.9 times COMSALT simulation results, and H_c results were 12.8 times greater. These differences are similar to those between COMSALT-referenced experiments over flat sandy surfaces with centimeter-level saltation heights and hyper saltation over Gobi areas with meter-level heights shown in Figure 1. This indicates that saltation height over gravel surfaces is clearly higher than over sandy surfaces despite similar rebound angles, and additional parameters are needed to reflect saltation over gravel surfaces.

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4. Discussion

The previous section clearly demonstrated the effects of grain size and impact speed on saltation, showing that trajectory height and length increase with these variables. This section focuses on the effect of contact angle and the contribution of particle inertia to saltation, which are not usually accessible through common saltation research methods.

4.1 Effect of contact angle on saltation

Direct measurement of full-scale grain trajectories over gravel surfaces has not been performed previously. Sand transport above certain heights (e.g., 0.6 m) is usually considered negligible due to its trace rate (Dong and Qian, 2007). Average saltation height is often expressed in terms of grain size and wind velocity. While saltation density does reduce quickly with height above the representative trajectory, as shown in Figures 3-5, both L_m and H_c are affected by contact and rebound angles. For example, L_m decreased by about 58% when contact angle changed from 20° to 40°, while H_c increased by about 77% with similar contact angle changes. Both increased with impact speed in quiescent air tests, as in windy conditions (Ho et al., 2011).

The decrease of L with   in still air can be easily imagined, and results prove the reliability of our equipment and method. Results reveal that H_m is less sensitive to contact angle, so almost all particle size groups can reach high elevations under the same wind condition (more than 2-3 times H_c), although density or probability is hundreds of times lower. Fine sand can saltate over 3.0 m high, and coarse sand almost 5.0 m high in our test scenarios—more than 10.0 times typical saltation heights over flat surfaces. Given that natural winds may be more violent than test conditions and areas are large with unlimited sediment sources, it is unsurprising that aeolian sand can deposit on trails behind 3.3-m high windbreak walls in Gobi areas of Northwest China, and that all size groups were found similar to other normal aeolian sands [Figure 1d: see original paper]. This explains why sand control measures that usually work in sandy deserts fail in some Gobi areas with strong winds.

These findings differ from common blown-sand trajectories, where grains rebounding at larger angles may rise higher and travel longer due to greater transferred momentum. Therefore, contributions to the whole particle trajectory can be divided into two parts: that from inertia after collision and that from wind energy. We can now separate these contributions quantitatively.

4.2 Contribution of particle inertia to trajectory

Blown sands are supported by both inertia after surface collision and energy from wind. To date, available saltation models typically adopt forces in horizontal and vertical directions to solve trajectories, mixing the effects of inertia and wind energy.

In our tests, all sand momentum came from inertia, and horizontal velocity increase by wind was not included under still-air conditions, allowing us to identify the influences of inertia and wind energy in shaping saltation trajectories.

The linear relationships between L_m/H_c and α in Figure 8 are independent of impact speed, reflecting the saltation mechanism. The travel distance gap between blown sand and still-air sand results from momentum transfer from wind. There was no wind force to create acceleration in the still-air case, but particles still traveled long distances due to inertia and followed the linear relationship between trajectory characteristic values and α. Based on the offset of L_m/H_c values in Figure 8, we deduce that during hyper saltation after collision with a hard surface, 60% of the travel path is accomplished by inertia after collision, and wind energy contributes the other 40%. The total L_m for tested sands under natural wind would be about 1.7 times our measured values.

The finding that inertia contributes 60% of the saltation trajectory can be used to validate available trajectory models in the literature, such as distributions of lift grains and inertia contributions. Models can incorporate the linear L_m/H_c versus α relationship by first reflecting inertia after collision, then adding wind effects. This approach can simulate saltation processes in quiescent air (windless cases) or strong wind over hard surfaces, as well as dynamic changes in saltation trajectories when wind speed varies.

The additional increase in saltation height and length from Magnus force due to particle spin could range from 10% to about 50% (Zou et al., 2007). Consequently, our test results may still be conservative in projecting saltation length of sand grains over gravel surfaces.

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5. Conclusions

Full-scale indoor experiments were performed on sand particle saltation over hard surfaces with different contact angles in still air. We demonstrated that all sand size groups can rebound to several meters high, leading to surprisingly strong abrasion at high positions and deposition behind high sand barriers in Gobi areas, with larger particles tending to rebound higher over longer distances. When contact angles ( ) were 40° and 20°, measured saltation heights and lengths reached 4.8 m and 9.0 m, respectively, for coarse sand at 50 m/s test impact speed [Figure 7: see original paper]. Maximum saltation length (L_m) may be reduced by 58% and representative saltation height (H_c) increased by 77% when surface contact angle changes from 20° to 40°. Collision inertia with hard surfaces contributes 60% of saltation length, with wind contributing 40%, so actual saltation lengths and heights under field conditions are about 1.7 times larger than measured values.

Linear relationships were established for estimating trajectory characteristics of saltating sands with different impact speeds and contact angles over gravels in still air (Table 1).

Results were compared with COMSALT simulations, which showed that saltation over hard surfaces clearly differs from that over sandy surfaces given otherwise similar factors. Maximum saltation height (H_m) and H_c over hard surfaces might be 4.9 times and 12.8 times those over sandy surfaces. These findings are unattainable in current wind tunnel experiments or field measurements and can serve as a first step toward understanding the effect of surface elements (gravel shape, orientation, etc.) on sand saltation. New parameters and modules can be added to current saltation models based on these findings, enabling physically based parameterization of particle movement over different surfaces (sandy and gravel). Additionally, advanced testing technologies such as particle tracking velocimetry (Jiang et al., 2017) might work together with the sand-blasting method to measure velocity fields of saltating sand.

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Note: Figure translations are in progress. See original paper for figures.