

Article

Wind Tunnel Test of Sand Particle Size Distribution along Height in Blown Sand

Lifen Zhou ¹, Zhengnong Li ^{1,*}, Bin Huang ²  and Ou Pu ¹

¹ Key Laboratory of Building Safety and Energy Efficiency of the Ministry of Education, Hunan University, Changsha 410082, China; zhoulf88@hnu.edu.cn (L.Z.); puou666@hnu.edu.cn (O.P.)

² College of Civil Engineering and Architecture, Hainan University, Haikou 570228, China; huangbin@hainanu.edu.cn

* Correspondence: lizn@hnu.edu.cn

Abstract: In aeolian sand movement, the vertical distribution of sand particle size is intricately linked to sand flux, wind–sand flow field and dune development. In the present study, the distribution characteristics of sand grains in four particle size ranges at nine heights were investigated through sand blowing tests at five different reference wind speeds. The correlation between sand particle size and wind speed indicates that when the particle size was ≥ 0.35 mm, there was a linear variation of mass percentage with wind speed. When the particle size was < 0.35 mm, when $Z \leq 0.15$ m, a linear variation of mass percentage with wind speed was found; when $Z > 0.15$ m, an exponential modification in mass percentage with wind velocity was observed for sand grains falling within this specific range of particle sizes. The correlation between sand particle size and height indicates that when the reference wind speed was ≥ 15 m/s, the mass percentage of sand particles varied linearly with height. When the reference wind speed was ≤ 13.5 m/s, the mass percentage of sand grains with particle size in the 0.25–0.35 mm range increases first and then decreases with increasing height. The present results can provide a reference for subsequent research on the aerodynamic characteristics of wind–sand flow fields and on the mechanism of dune formation.

Keywords: aeolian sand movement; wind tunnel test; mass percentage; grain size distribution



Citation: Zhou, L.; Li, Z.; Huang, B.; Pu, O. Wind Tunnel Test of Sand Particle Size Distribution along Height in Blown Sand. *Sustainability* **2024**, *16*, 3914. <https://doi.org/10.3390/su16103914>

Academic Editor: Firoz Alam

Received: 14 March 2024

Revised: 25 April 2024

Accepted: 28 April 2024

Published: 7 May 2024



Copyright: © 2024 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

1. Introduction

In aeolian sand movement, the particle size of sand is a critical characteristic parameter which influences the sand flux, wind–sand flow field and dune development [1,2]. As such, the characteristics of the vertical distribution of sand particle size constitute a fundamental component in the investigation of the aerodynamic properties of wind–sand interactions.

At present, the focus of most domestic studies on wind-blown sand has been on the saltation of sand [3–5], lift-off speed and lift-off angular velocity [6–9], movement trajectory [10] and sand flux [11,12]. Additionally, the sand transport rate is the most direct representation of the strength of regional aeolian sand movement and a critical physical quantity in the research on wind-blown sand two-phase flow [13]. Dong et al. [14,15] and Tan et al. [16] conducted field observations and reported that the sand transport rate had an exponential distribution. In a wind tunnel test, Creyssels et al. [17] adopted particle image velocimetry (PIV) and particle tracking velocimetry (PTV) for analysis of saltated particles. Findings showed that the mass flux density of sand grains decreased exponentially with height. By conducting wind tunnel tests using sands of two mean sizes, Ni et al. [18] also concluded that sand flux decreased exponentially with height but found that the sand flux in near-ground areas deviated from the law of exponential distribution. The conclusion was that this phenomenon was caused by creep and spring-back of sands. However, as per the findings derived from the empirical study conducted by Mertie et al. [19] within the Thar Desert, the gradual decline in sand flux with increasing height was found to adhere more closely to a power function. There are many factors that lead to differences in sediment

transport rate along the height distribution. Obviously, the particle size distribution is one reason. The observed differences are influenced by a multitude of factors, and the distribution of particle grain sizes stands out as a prominent element among these factors.

Sand particle size serves as a primary determinant impacting sand concentration, velocity, momentum, as well as alterations in the wind–sand flow dynamics within the saltation layer caused by wind-driven sand movement. Additionally, it plays a pivotal role in shaping dune formation and migration [2,20,21]. Consequently, an increasing number of studies have been focusing on investigating the relationship between the distribution of sand particle sizes along the vertical axis and parameters such as sand flux, average wind speed, meteorological conditions and geographical features [22–24]. Despite such research efforts, there are limited studies on vertical sand grain size distribution. The characteristics of vertical sand particle size distribution directly influence sand flux and average wind speed, as well as others, and geographic features also influence the characteristics of vertical sand grain size distribution.

Recently, numerous scholars have conducted studies on the correlation between the particle size of sand on the bed and the average particle size of sand. Their conclusions can be classified into two main categories: Tan et al. [16], Lancaster et al. [25], Wang et al. [1] and Cheng et al. [26] expressed the belief that the average particle size of sand in the lower saltation layer was smaller than the average particle size of sand on the bed; however, after performing wind tunnel tests using four types of mixed sand, Xing et al. [27] identified that in specific wind field conditions and a predetermined sand particle size on the bed, the spatial distribution of sand grain sizes remained constant. With regard to the characteristics of particle size distribution of sand in the saltation layer, there are also two general opinions. One opinion is that above the sand bed, the average sand particle size decreases with increasing height [26,28]; the other opinion is that there exists a turning point for changes in the sand grain size 5–20 cm above the sand bed. Below this turning point, the average sand grain size diminishes, while above it, the average sand grain size increases [16,20,27,29]. The causes of these contradictions are not yet clear and there remains no consensus. Therefore, there is no effective support available for research on wind–sand flow dynamics and the acting force of wind-blown sand.

By combining previous research results, Yang et al. [30] conducted a study on the change in sand concentration at the vertical section at different wind speeds. Analysis was conducted on the change in concentration of coarse sand, medium-sized sand, fine sand and extra-fine sand with height at different wind speeds, and a correlation between the mass percentage of sand particle size and wind speed was observed. However, the correlation between sand grain mass percentage and wind speed at different heights was not analyzed. At the same time, there is an absence of comparative research between real-world wind field measurements and wind-tunnel-generated wind fields. There should be a great difference between the test result and change in sand particle size in actual wind–sand flow fields.

Based on the aforementioned research and by taking into account the unpredictability of sand storms, a wind-blown wind tunnel with sectional dimensions of 3 m × 2.5 m was adopted to simulate an actual measured wind field under the conditions in which an impurity-free wind field had been measured [31] (an impurity-free wind field is a wind field where sand on the ground is not blown or there is extra-low sand concentration in the air stream). Through this experiment, the influences of the movement of sand grains in the saltation layer and the sand particle size on sand concentration and wind–sand flow could be better understood. Further, the law of vertical sand particle size distribution was also investigated. Meanwhile, the relationship between the mass percentage of sand particle size and the wind speed in the same grain size range was analyzed, and the sand grain variation along the height in the same particle size range at different reference wind speeds was explored. The present study can serve as a reference for subsequent aerodynamic research pertaining to near-surface wind dynamics and wind-blown sand flow fields. Additionally, these outcomes establish a test basis for the development of dune morphology research.

2. Introduction of the Experiment

2.1. Simulation of Wind-Blown Sand Environment

In the natural world, the transport of wind-blown sand is a long-term, complex, large-scale process. Thus, since a complete simulation is difficult, an approximate simulation was performed. In the experiment, the dimensional method was adopted to establish similar criteria for wind tunnel testing of wind–sand flow dynamics [32,33]. In the wind tunnel, the simulation of wind-blown sand processes on a level and even sandy surface in a dynamically balanced state was achieved by employing isothermal conditions and the continuous movement of two phases of viscous incompressible fluid. Experiments have shown that the scheme can accurately simulate the corresponding proportion of wind–sand flow field [31].

The experiment was conducted in the DC low-speed boundary layer wind tunnel of the Institute of Electrical Engineering, Chinese Academy of Sciences, located in Dafutuo Village, Badaling Town, Yanqing County, Beijing. The wind tunnel consisted of a fan section, stable section, honeycomb section, contraction section, test section and divergent section. The working section of the tunnel was 3 m (W) × 2.5 m (H) × 20 m (L), and the wind velocity could be varied between 0 and 30 m/s. The wind tunnel structure diagram is shown in Figure 1. The wind tunnel had been altered to simulate a wind-blown sand environment prior to commencement of the project. The alterations involved a sand grain recovery device, an instrument coordinate frame, a sand protection wind profiler and a multiplex sand collector. A part of this device is shown in Figure 2.

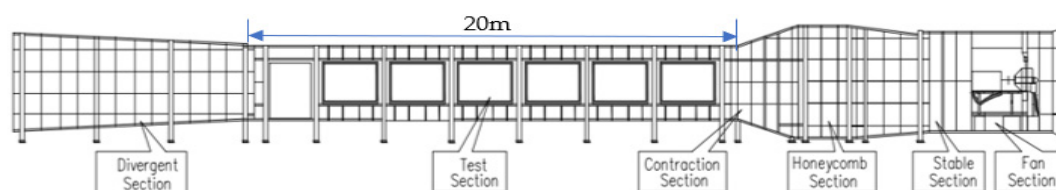


Figure 1. Structure of wind-blown sand wind tunnel.

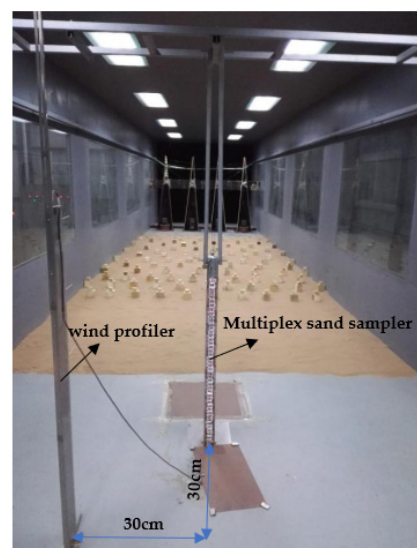


Figure 2. Multiplex sand sampler and wind profiler.

Figure 2 shows the relative positions of the multiplex sand sampler and wind profiler in the wind tunnel. The sand sampler and wind profiler were placed offset to reduce the interference of the sand sampler on the sampling results of the wind profiler in this experiment. The multiplex sand sampler was located on the central axis of the wind tunnel, with a vertical distance of about 1 m from the sand bed. The wind profiler deviated from

the centerline of the wind tunnel by 30 mm, with a vertical distance of 30 mm from the multiplex sand sampler and a vertical distance of about 1.3 m from the sand bed.

2.2. Device for Wind Tunnel Test of Wind-Blown Sand

The blown-sand experiment was conducted under normal windstorm conditions simulated by blowing the sand on the beds. The sand bed was positioned within the wind tunnel's test section. The geometric dimensions of the sand bed were 4 m long, 3 m wide and 0.15 m deep, which makes the spreading sand size fulfill the full development of particle motion [34]. The wind field layout is shown in Figure 3.

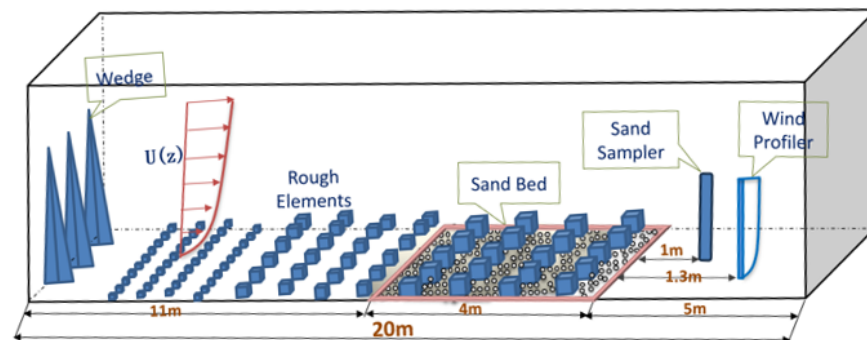


Figure 3. Wind field layout.

3. Experimental Results and Discussion

3.1. Wind Field Analysis of Wind Tunnel Test

According to the conditions of an impurity-free wind field measured in Ningxia Zhongwei Desert [31], impurity-free wind field commissioning was performed for the test before the wind-blown sand experiment. According to the measured sampling height, the wind tunnel sampling heights were 0.14 m, 0.28 m, 0.42 m, 0.56 m, 0.7 m, 0.84 m and 1 m. Data sampling was conducted, and the results of wind tunnel wind profile versus measured wind profile are shown in Figure 4.

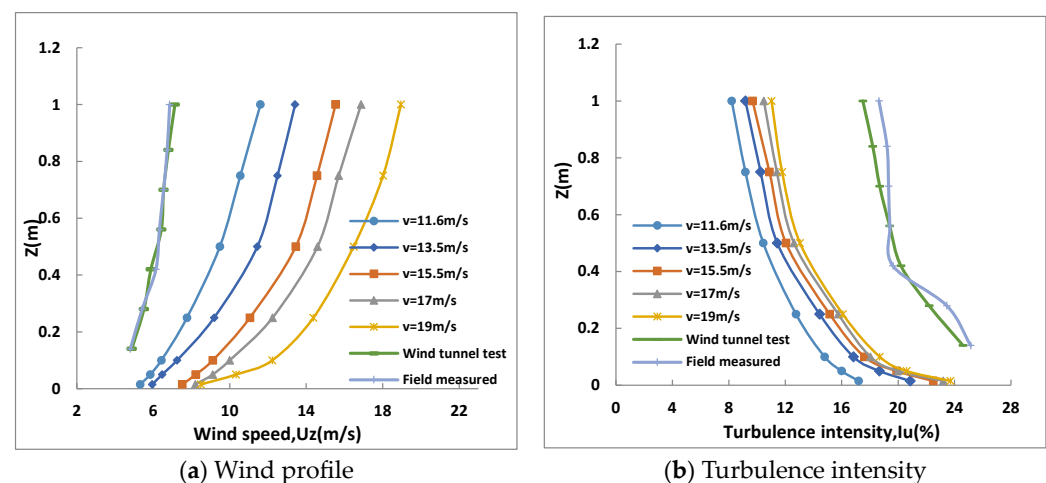


Figure 4. Wind tunnel test and field-measured wind profile and turbulence profile; wind profile and turbulence profiles under five reference wind speeds. Note: In the present study, the height of 1 m was the reference point and the reference wind speed was the wind speed at the height of 1 m.

As shown in Figure 4, the wind tunnel test and the wind profile and turbulence intensity measured on site were basically consistent, and the maximum deviation was at the height of 10 m. The velocity difference at 10 m of the gradient wind profile was 0.28 m/s. The deviation of turbulence at 10 m was 1.136%, thereby meeting the test requirements.

To better simulate turbulence, the wind spectrum had to reach a certain standard. Generally, a simulated wind spectrum should be close to the representative empirical spectra, such as “Davenport’s spectrum” or “von Karman’s spectrum” [33,35]. Based on Kolmogorov’s theory, these empirical spectra can be expressed in a unified form as indicated in Equation (1):

$$\frac{fS(z, f)}{u_*^2} = \frac{A\bar{f}^\gamma}{(1 + B\bar{f}^\alpha)^\beta} \quad (1)$$

where $S(z, f)$ is a function of fluctuation wind speed power spectrum density; f is frequency (Hz); u_* is the friction speed and $u_*^2 = \sigma_u^2/6$; A and B are constants; $\bar{f}$ is the Monin coordinates, and $\bar{f} = f \cdot z/U(z)$; and power exponents such as α , β and γ of spectrum satisfy $\gamma - \alpha\beta = -\frac{2}{3}$.

The fluctuation characteristics of wind affect the take-off and movement track of sand particles and also affect the particle size distribution characteristics of sand particles in the air. Therefore, the wind speed power spectrum at each measuring point was analyzed and then compared with classical wind speed spectra (Davenport spectrum and von Karman spectrum), as shown in Figure 5. The green solid line in this figure is the wind speed power spectrum at the reference height of the field-measured wind field.

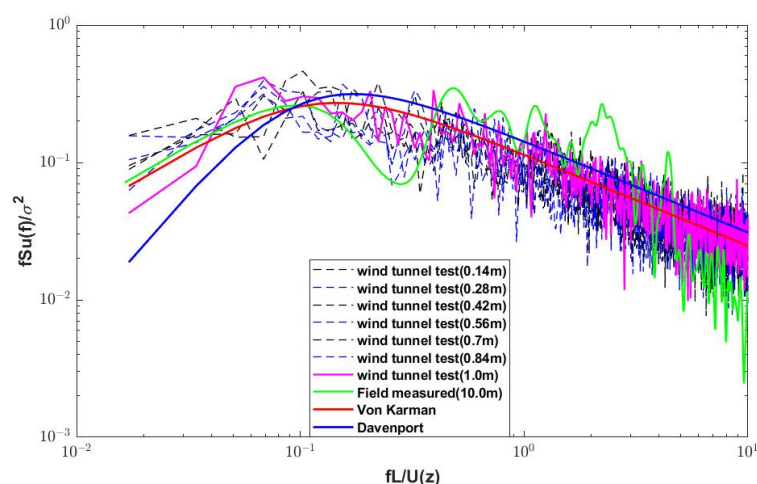


Figure 5. Comparison of field-measured power spectrum, wind tunnel power spectrum and classical spectra.

Figure 5 shows the 30 s wind speed data in the wind tunnel test. The power spectrum of downwind pulsating wind speed at each measurement point was normalized and then compared with both the Davenport spectrum and the von Karman spectrum. An observation can be made that within the 0.14–1 m height range, the peak value of the power spectrum was between 0.07 and 0.2. Within the range of $0.01 \leq f \cdot L/U(z) \leq 3$, the wind speed power spectrum at a height of 0.14–1 m was relatively close to the von Karman spectrum. The power spectrum, where $f \cdot L/U(z) > 3$ and at a height of 0.56–1 m, exhibited a tendency to align with the Davenport spectrum. However, within the height range of 0.14–1 m, spanning from low to high frequencies, the power spectrum was generally more in agreement with the von Karman spectrum. Such findings indicate that in this experiment, up to a height of 1 m above the ground, the von Karman spectrum provided a more accurate description of the distribution of fluctuating wind energy across different frequencies.

According to the described analysis results, the 10 min fluctuation wind data collected at a height of 10 m in the field, where wind speed and direction were stable, was chosen to serve as the power spectrum (Figure 5: the solid green line). This power spectrum was subsequently compared with the wind speed power spectrum at the reference point in this test, as well as the von Karman spectrum. We found that the wind speed power spectrum

of field measurements and wind tunnel tests is closer to the von Karman spectrum in the range of $f \cdot L/U(z) < 5$. The comparison results are shown in Figure 5.

Based on the aforementioned wind field test results in the wind tunnel, in this experiment, the wind and turbulence profiles at five reference wind speeds were obtained, as shown in Figure 4. The wind speed was determined by the sand protection wind profiler. The five reference wind speeds in Figure 4 are 11.6 m/s, 13.5 m/s, 15.5 m/s, 17 m/s and 19 m/s.

Figure 6 shows the comparison of the wind speed power spectrum at the reference point with the wind speed power spectrum at the reference point of the impurity-free wind field, as well as the von Karman spectrum and the Davenport spectrum, at five reference wind speeds. In the range of $f \cdot L/U(z) \leq 0.1$, the wind speed spectrum in the wind–sand flow field was between the Davenport spectrum and the von Karman spectrum, which was slightly different from the wind speed spectrum at the reference point in the impurity-free wind field. When $f \cdot L/U(z) > 0.1$, each wind speed spectrum was closer to the von Karman spectrum. Overall, the wind–sand flow field in this experiment was closer to the von Karman spectrum.

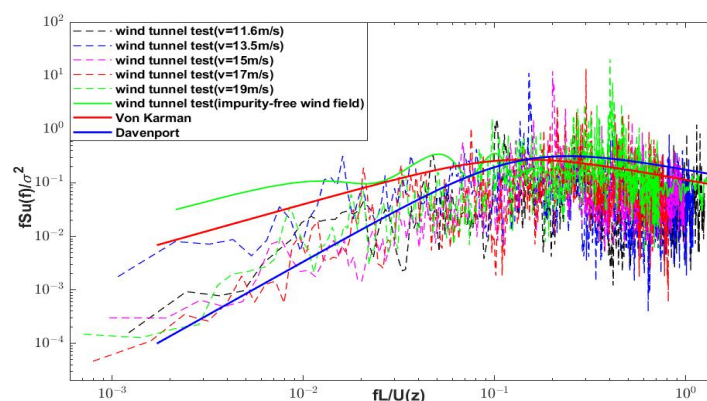


Figure 6. Comparison of the wind speed power spectrum and classical spectra.

3.2. Mass Percentage of Sand Grains on the Sand Bed

In the present experiment, sand was sourced from the Tengger Desert, and its range of grain size was 0.063–1 mm. The electronic scale used for weighing the sand was a high-precision electronic analytical scale with a measuring range of 100 g and an accuracy of 0.001 g. The sand on the bed was screened using circular screens with aperture sizes of 0.4 mm, 0.35 mm and 0.25 mm, respectively. The mass percentages of sand of different grain sizes were as follows.

Figure 7 is a histogram and probability cumulative curve of each sand particle size on the sand bed. Sand with a particle size over 0.4 mm accounted for 25.66% of the total mass; sand with a particle size of 0.35–0.4 mm accounted for 19.38% of the total mass; sand with a particle size of 0.25–0.35 accounted for 48% of the total mass; and sand with a particle size below 0.25 mm accounted for 6.96% of the total mass. In this experiment, the sand particle size was mainly 0.25–1 mm.

3.3. Gradient Change in Sand Transport Rate at Four Reference Wind Speeds

The sand was spread across the sand supply bed device. When the reference wind speed was too low during the test, sand collection was limited and difficult, resulting in significant test errors. Thus, the five reference wind speeds selected in the experiment were 11.6 m/s, 13.5 m/s, 15.5 m/s, 17 m/s and 19 m/s. In the process of blowing sand, the sand sampler would be covered with cardboard; when the wind speed was stable, the cardboard would be removed, and the sand sampler would be started. At reference wind speeds of 11.6 m/s and 13.5 m/s, the period of sand accumulation lasted for 1500 s. This duration was reduced to 900 s when associated with a wind speed of 15.5 m/s, further decreased to 300 s at 17 m/s and diminished to 180 s at a wind speed of 19 m/s. Once the designated

time elapsed, the sand sampler had to be immediately covered. Subsequently, the blowing of air was halted, and the collected sand was weighed and sieved. The sandbox had a square cross-section with a height of 0.02 m, an area of 0.0004 m² and a depth of 0.1 m. Based on the sand accumulation volume within the sand collection box during the test, sand collectors numbered 2, 5, 8, 11, 14, 17, 20, 23 and 26 were selected for weighing. The corresponding vertical coordinates for these box numbers were 0.03 m, 0.09 m, 0.15 m, 0.21 m, 0.27 m, 0.33 m, 0.39 m, 0.45 m and 0.51 m.

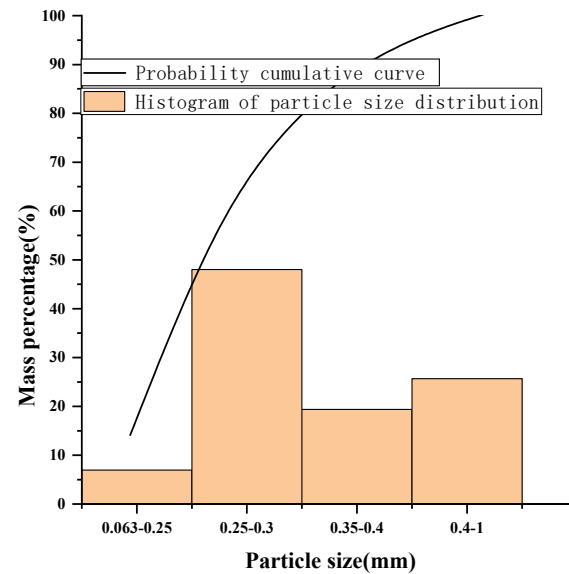


Figure 7. Mass percentage of each sand particle size and probability cumulative curve.

After normalizing the sand collection time to 300 s for the five reference wind speeds, the collected sand's weight at each reference wind speed is presented in Table 1 as follows.

Table 1. The mass of collected sand at different heights under five reference wind speeds Q_z .

Height	Wind Speeds 11.6 m/s	Wind Speeds 13.5 m/s	Wind Speeds 15.5 m/s	Wind Speeds 17 m/s	Wind Speeds 19 m/s
	Sand Collection (g)	Sand Collection (g)	Sand Collection (g)	Sand Collection (g)	Sand Collection (g)
0.51 m	-	0.019	0.038	0.220	0.401
0.45 m	-	0.022	0.083	0.441	0.674
0.39 m	-	0.036	0.270	0.495	1.069
0.33 m	-	0.074	0.330	0.965	1.800
0.27 m	0.062	0.164	0.633	1.685	2.817
0.21 m	0.436	0.639	1.839	4.033	8.193
0.15 m	0.950	2.020	5.382	10.408	19.409
0.09 m	3.369	8.087	18.482	33.069	55.784
0.03 m	8.823	27.911	58.662	88.172	147.150

Note: When the reference wind speed was 11.6 m/s, the total sand collection at height $Z \geq 0.33$ m was less than 0.1 g, and there was a large test error. Thus, the sand collection above this height was not recorded.

The sand transport rate is defined as the mass of sand entrained air flow that passes through a unit of area in a unit of time. The efficiency of the sand collection flux in the experiment was 90% [11]. The expression is:

$$q = \frac{Q_z}{A * T} \quad (2)$$

where q is the sand transport rate at any height of wind-blown sand flow; Q_z is the mass of collected sand at any height; A is the cross-sectional area of sand collection boxes; and T

is the duration of sand collection. The sand transport rates at the four different reference wind speeds are shown in Figure 8.

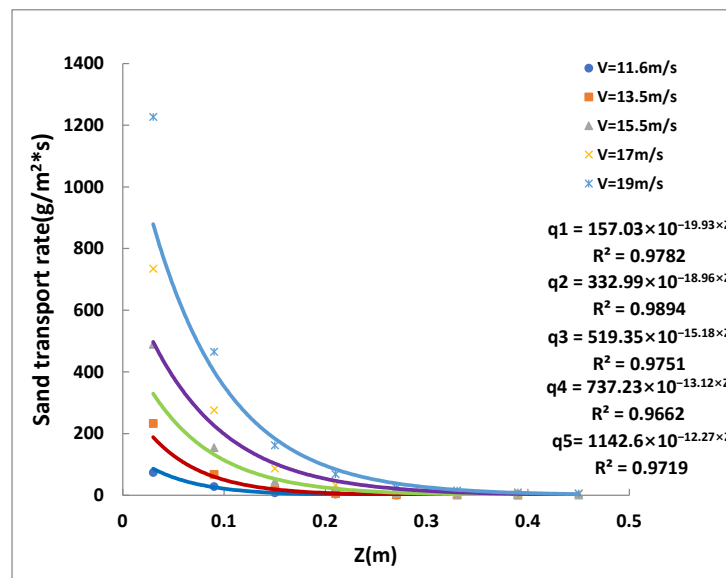


Figure 8. Sand transport rate along height direction. Note: In the above figure, q1–q5 are the fitted curves corresponding to the reference wind speeds at 11.6 m/s, 13.5 m/s, 15.5 m/s, 17 m/s and 19 m/s.

Figure 8 shows that below the height of 0.33 m, the greater the wind speed, the higher the content of coarse sand and the greater the sand transport rate. Conversely, when z was equal to or exceeded 0.33 m, the sand transport rate tended to approach zero. Such findings could potentially be attributed to variations in the mass percentage of sand grains with distinct particle sizes present on the sand bed. On the sand bed, coarse sand (≥ 0.35 mm) accounted for 45% and extra-fine sand (< 0.25 mm) accounted for less than 7%. With increasing height, the activity of larger-sized sand grains decreased. Although fine sand displayed greater mobility, its concentration was low, leading to challenges in effective collection. This resulted in a decreased sand transport rate at heights above $Z > 0.33$ m.

By analyzing the trend of the fitted curve for sand transport rate (with a correlation coefficient $R^2 > 0.96$), it was observed that the sand transport rate exhibited an exponential variation with respect to height. This result is consistent with those of Dong [15], Tan [16] and Creyssels [17].

3.4. Changes in Mass Percentage of Sand Grains with Height and Wind Speed in Each Particle Size Range

(1) Mass percentage of sand with different grain sizes at different heights

According to the weighing results of the sand content of the set collector, the collected sand at each height was screened. The mass percentage of sand grains within different size ranges at nine distinct heights for various reference wind speeds can be found in Tables S1–S5 in the Supplementary Materials.

An observation can be made from Tables S1–S4 that at the same height, for the same sand particle size, the higher the wind speed, the greater the mass percentage of sand with particle size ≥ 0.35 mm, and the mass percentage of sand with particle size < 0.35 mm was lower. Below the height of 0.09 m, at the four reference wind speeds, the mass percentage of sand grain size ≥ 0.4 mm was consistently higher than that of sand of grain size of 0.35–0.4 mm. Such results suggest that the initial distribution of sand grain sizes on the sand bed influenced the mass percentage of sand grains within the lower saltation layer. However, as revealed by the comparison of the mass percentages of sand in the bottom saltation layer in Tables S1–S4 and Figure 8, at a reference wind speed of 13.5 m/s, the

mass percentages of sand grains with the size of ≥ 0.35 mm were smaller than those on the original sand bed, and the mass percentages of sand with a particle size < 0.35 mm exceeded 52%. Obviously, the average particle size of the sand grains was smaller than that of the original sand bed. However, when the reference wind speed was ≥ 15.5 m/s and the height was $Z \leq 0.09$ m, the mass percentages of sand grains with a particle size of ≥ 0.35 mm exceeded 45.04%, and the mass percentages of sand with a particle size less than 0.35 mm exceeded 48%. As such, the average particle size of the sand grains was significantly larger than that of the sand bed. The described results are not consistent with the results of Lancaster [25], Wang [1], Tan [2], Cheng [26] and Xing [27]. It was also observed that at the reference wind speed > 13.5 m/s, at the height of $Z < 0.27$ m, the mass percentage of sand particles with size < 0.25 mm consistently remained lower than that on the sand bed. In addition, the greater the wind speed, the smaller the mass percentage of sand particles with a particle size of less than 0.25 mm at the same height. This trend could potentially be attributed to three factors: first, in comparison to larger sand grains, smaller sand grains were more susceptible to wind speed influences and exhibited greater activity at higher heights. Second, elevated reference wind speeds led to increased wind velocities near the bottom, enhancing the activity of coarser sand particles in that region. Hence, higher reference wind speeds corresponded to greater proportions of coarse sand and lower proportions of fine sand at the bottom. Third, fine sand was more susceptible to external environmental factors, introducing potential testing errors during the processes of sieving and weighing.

Notably, the effective height of sand collection was $Z = 0.27$ m at the reference wind speed of 11.6 m/s, and the characteristics of sand mass percentage distribution of each particle size at this reference wind speed were only for auxiliary reference analysis and were not compared with the sand mass percentage at other reference wind speeds.

(2) The relationship between the mass percentage of sand grains and reference wind speed

At identical heights, the correlation between the mass percentage (P_i) of sand particles with various grain sizes and the reference wind speed (V_{ref}) was established through the application of the least squares fitting method. The resulting relationships are depicted as follows: P1, P2, P3 and P4 in Figure 9 correspond to the fitted curves for particle size components 0.25 mm, 0.25–0.35 mm, 0.35–0.4 mm and > 0.4 mm, respectively.

As shown from the fitting curves of Figure 9a–c, at the height $Z \leq 0.15$ m, the mass percentage of each particle size had a linear relationship with the reference wind speed, and the correlation index R^2 was greater than 0.91.

In Figure 9d,e, specifically within the height range of 0.21 m to 0.27 m ($0.21 \text{ m} \leq Z \leq 0.27 \text{ m}$), two distinct trends were observed. The mass percentage of sand grains smaller than 0.35 mm exhibited an exponential decrease as wind speed increased (with a correlation coefficient $R^2 > 0.92$). In contrast, the mass percentage of sand grains with particle sizes ≥ 0.35 mm showed a linear increase with higher wind speeds (with a correlation coefficient $R^2 > 0.83$).

In Figure 9f–h, specifically within the height range of 0.33 m to 0.45 m ($0.33 \text{ m} \leq Z \leq 0.45 \text{ m}$), distinct patterns were observed. The relationship between the mass percentage of sand grains with particle sizes smaller than 0.35 mm and wind speed demonstrated a closer alignment with exponential change (with a correlation coefficient $R^2 > 0.75$). Conversely, the mass percentage of sand grains with particle sizes greater than or equal to 0.35 mm displayed a stronger conformity with linear behavior (with a correlation coefficient $R^2 > 0.79$).

In Figure 9i, when the height was $Z = 0.51$ m and the reference wind speeds were 13.5 m/s and 15.5 m/s, the mass of sand particles with a particle size of 0.35–0.4 mm was zero. Additionally, at the same height and reference wind speeds (13.5 m/s, 15.5 m/s and 17 m/s), the mass of sand particles with a particle size greater than 0.4 mm was also zero. Further, as the height Z exceeded 0.51 m, screening became challenging due to the limited amount of collected sand. Therefore, the relationship between the mass percentage of sand grains and the reference wind speed at this particular height was not analyzed.

Thus, within the height $Z \leq 0.45$ m, the relationship between the mass percentage of each particle size and the reference wind speed could be expressed in sections as follows:

① $Z \leq 0.15$ m,

$$P = \alpha \times V_{\text{ref}} + A \quad (3)$$

② $0.21 \text{ m} < Z \leq 0.45$ m,

$$\begin{cases} P = \beta \times V_{\text{ref}}^\varphi & \text{particle size} < 0.35 \text{ mm} \\ P = \alpha \times V_{\text{ref}} + A & \text{particle size} \geq 0.35 \text{ mm} \end{cases} \quad (4)$$

where P represents the mass percentage of sand grains; V_{ref} is the reference wind speed, m/s; and $\alpha, A, \beta, \varphi$ are fitting parameters.

The fitted curve in Figure 9 shows that the mass percentage of the sand grains decreased with increasing wind speed when the particle size was < 0.35 mm; when the particle size was ≥ 0.35 mm, the mass percentage of sand grains increased with increasing wind speed. Such results are similar to the wind tunnel test results of Yang et al. [30]. However, an observation was made that at any height, the average mass percentage of medium and coarse sands had a linear relationship with wind speed, whereas fine and ultra-fine sands had a power exponential relationship, which is inconsistent with the findings of the present study. Obviously, it is not appropriate to substitute the mass percentage at each height with the average mass percentage of sand grains.

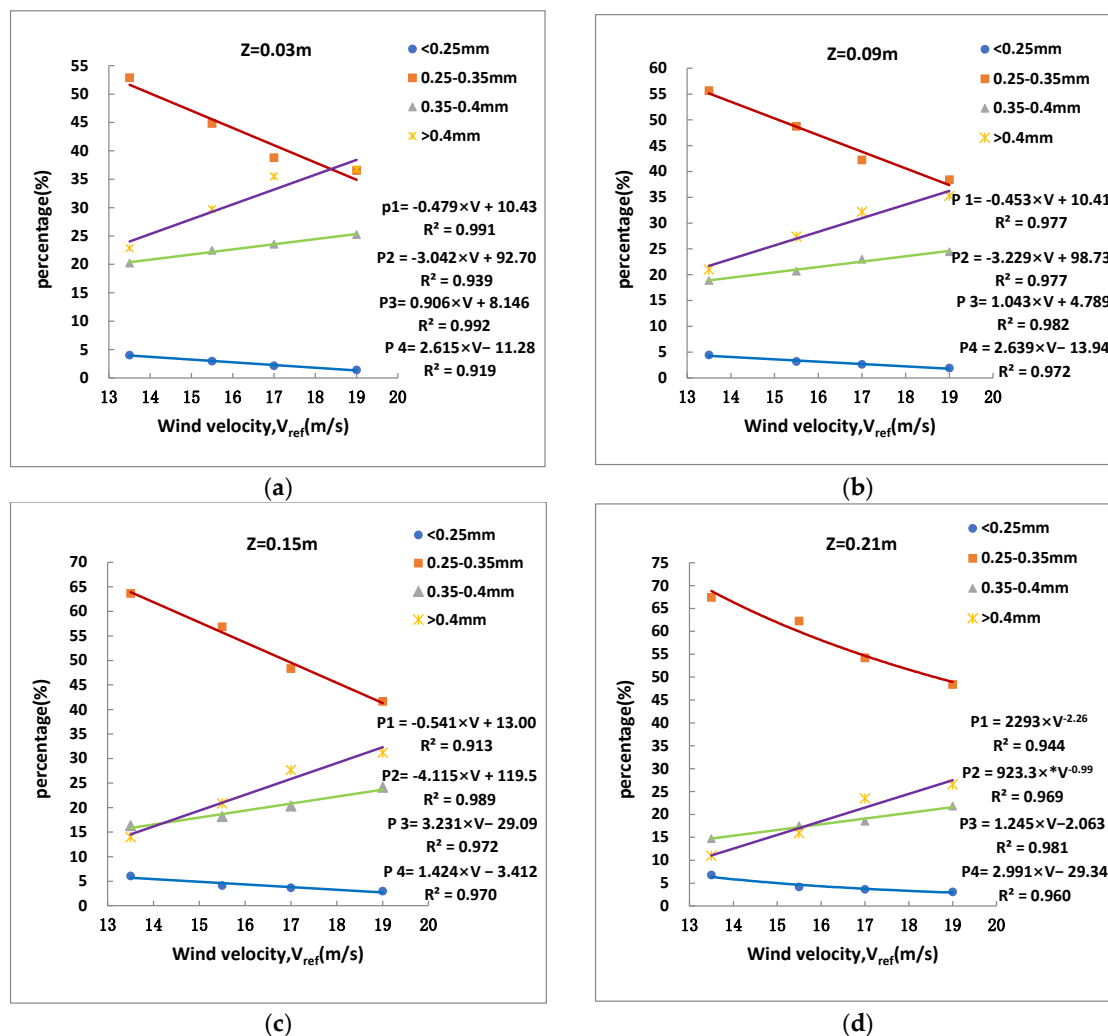


Figure 9. Cont.

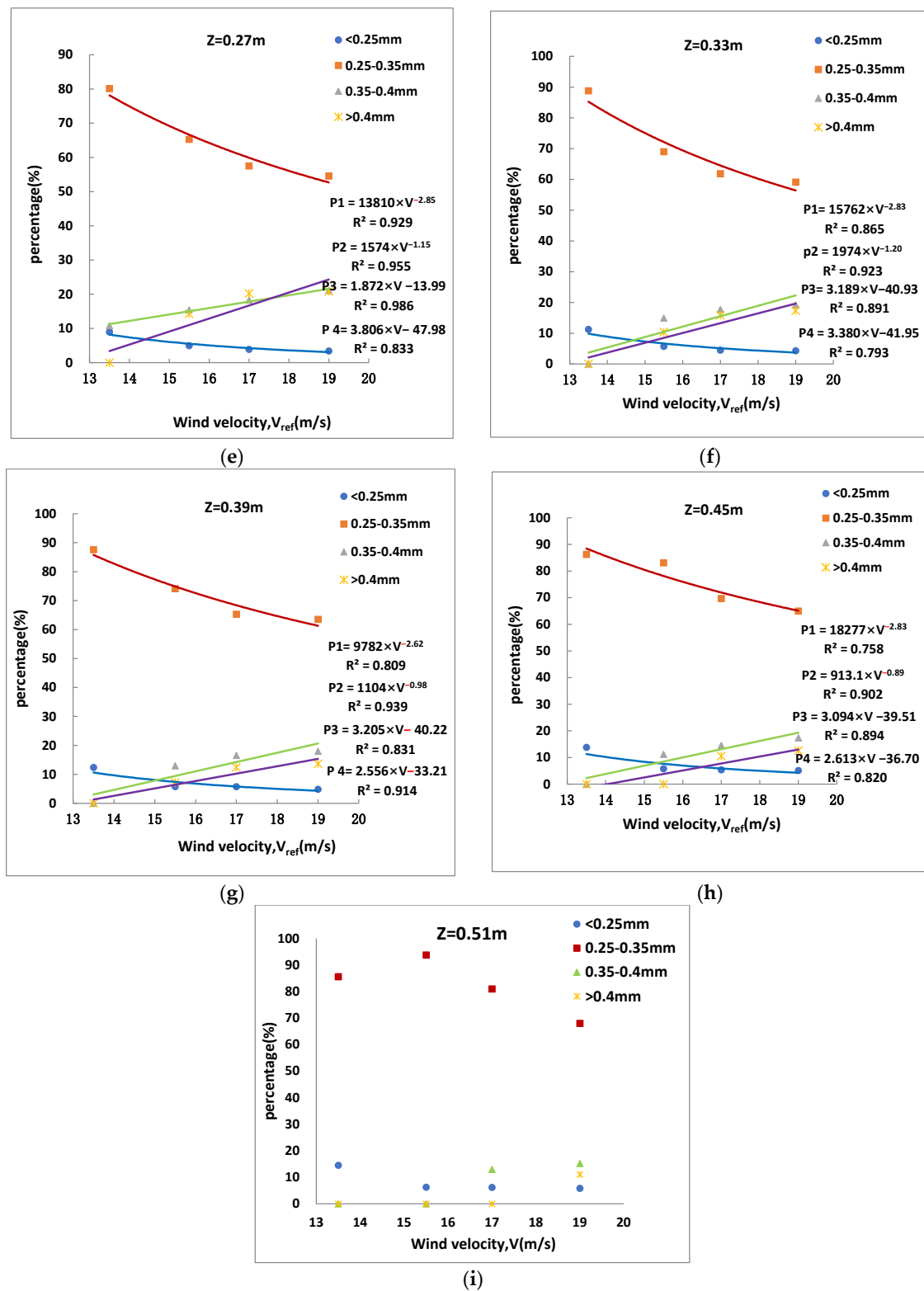


Figure 9. Relation between mass percentage of sand with the same range of particle size at each height and reference wind speed. (a) The relationship between the mass percentage of sand particles of various sizes and wind speed at a height of $Z = 0.03$ m; (b) The relationship between the mass percentage of sand particles of various sizes and wind speed at a height of $Z = 0.09$ m; (c) The relationship between the mass percentage of sand particles of various sizes and wind speed at a height of $Z = 0.15$ m; (d) The relationship between the mass percentage of sand particles of various sizes and wind speed at a height of $Z = 0.21$ m; (e) The relationship between the mass percentage of

sand particles of various sizes and wind speed at a height of $Z = 0.27$ m; (f) The relationship between the mass percentage of sand particles of various sizes and wind speed at a height of $Z = 0.33$ m; (g) The relationship between the mass percentage of sand particles of various sizes and wind speed at a height of $Z = 0.39$ m; (h) The relationship between the mass percentage of sand particles of various sizes and wind speed at a height of $Z = 0.45$ m; (i) The relationship between the mass percentage of sand particles of various sizes and wind speed at a height of $Z = 0.51$ m.

(3) Variation of mass percentage of sand grains along height

On the basis of the calculation results of Tables S1–S4 in the Supplementary Materials, the variation trend of the mass percentage of sand grains at the four reference wind speeds along the height is shown in Figure 10. (When the reference wind speed is ≤ 13.5 m/s, due to the significant difference between the change in the mass percentage of sand particles in each particle size range and other wind speeds, the variation of sand particle mass percentage in this reference wind speed will only analyze the trend and does not fit the curve. The analysis of mass percentage variation along the height of sand grains for each particle size will be separately addressed for the reference wind speeds of 11.6 m/s and 13.5 m/s in subsequent sections).

Figure 10a–d displays the mass percentage of sand grains within the four distinct particle size ranges across various heights and reference wind speeds. By observing the figure, it becomes evident that the mass percentage of sand particles with sizes ≥ 0.4 mm and 0.4–0.35 mm decreased with an increase in height, while the mass percentage of sand particles with sizes 0.25–0.35 mm and < 0.25 mm increased with height. The correlation index ($R^2 > 0.94$) obtained from the fitted curves in Figure 10a–d indicates that the mass percentage of sand grains within each particle size range exhibited a linear-like change along the vertical direction. This trend can be described as follows:

$$P = \mu * Z + \delta \quad (5)$$

where P follows Equations (3) and (4); μ, δ is the test fitting parameter; and Z is the height of sand collection, m.

According to the fitting curves of Figure 10a,b, when the particle size was ≥ 0.35 mm, the higher the reference wind speed, the larger the mass percentage of sand grains in the same particle size range. By analyzing the slopes of the fitting curves in both graphs, it becomes apparent that as the height increases, the mass percentage of sand grains within the particle size range of 0.35–0.4 mm experienced a notably slower reduction compared to sand grains with a particle size of ≥ 0.4 mm.

Figure 10c,d show that when the particle size was less than 0.35 mm and the higher the reference wind speed, the smaller the mass percentage of the sand grains in the same particle size range. According to the slopes of fitting curves in the two figures, the growth rate of the mass percentage of sand with particle size of 0.25–0.35 mm along the height direction was significantly higher than that of the sand with particle size < 0.25 mm. Figure 10d also shows that when the reference wind speed was 13.5 m/s, the mass percentage of the sand grains with particle size < 0.25 mm was much greater than that at other reference wind speeds.

Comparing Figure 10a–d, the variation of the mass percentage of each sand particle size along the height was relatively moderate (as shown in Figure 10a, the slope of P1–P3 was -59.76 , -62 and -64.42 , respectively; in Figure 10b, the slope of P1–P3 is -21.29 , -21.14 and -25.67 , respectively; in Figure 10c, the slope of P1–P3 is 72.13 , 81.19 and 94.4 , respectively; in Figure 10d, the slope of P1–P3 is 8.917 , 8.065 and 7.101 , respectively). The change in curves was close to parallel.

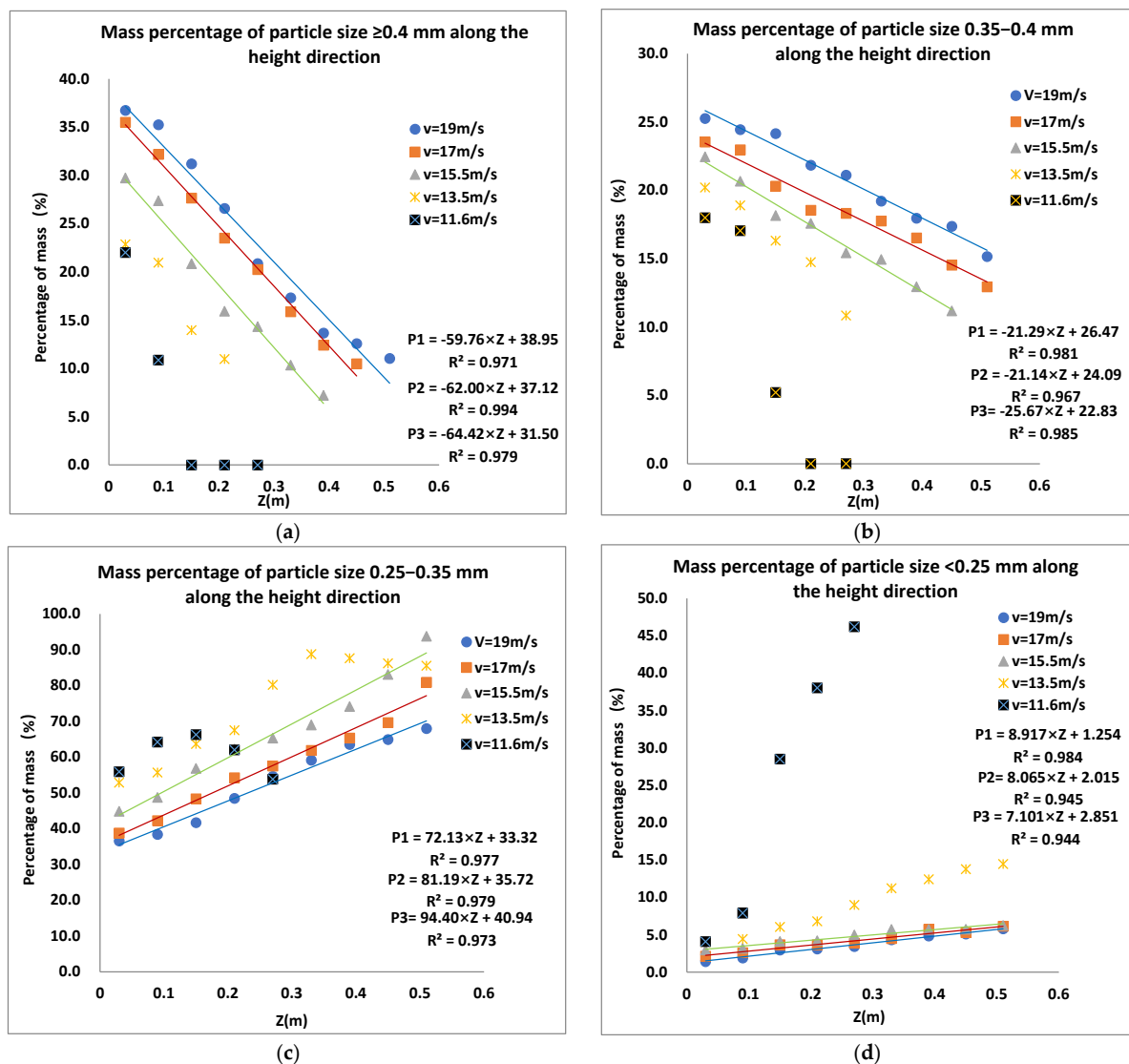


Figure 10. At five reference wind speeds, the change in the mass percentage of sand particles in each particle size range along the height. (a) Mass percentage of sand particle size ≥ 0.4 mm along the height direction; (b) Mass percentage of sand particle size of $0.35-0.4$ mm along the height direction; (c) Mass percentage of sand particle size of $0.25-0.35$ mm along the height direction; (d) Mass percentage of sand particle size < 0.25 mm along the height direction. Note: The fitting formula P1–P3 in the figure corresponds to the fitting curves at reference wind speeds of 19 m/s, 17 m/s and 15.5 m/s, respectively.

In Figure 10a–d, the relation between mass percentage of sand with each grain size and height at the reference wind speed of ≤ 13.5 m/s differed greatly compared to other reference wind speeds. This distinction is especially pronounced in Figure 10c,d. In Figure 10c (at particle size $0.25-0.35$ mm), when the reference wind speed is 11.6 m/s, at heights $Z < 0.21$ m, the mass percentage of sand grains increased with height. Conversely, at heights $Z \geq 0.21$ m, the mass percentage of sand grains decreased with height, and the height $Z = 0.21$ m marked the turning point. When the reference wind speed is 13.5 m/s, at heights $Z < 0.33$ m, the mass percentage of sand grains increased with height. Conversely, at heights $Z \geq 0.33$ m, the mass percentage of sand grains decreased with height, and the height $Z = 0.33$ m marked the turning point. In Figure 10d (at particle size < 0.25 mm), the curve depicting the relationship between mass percentage of sand grains along the height direction exhibited a significant deviation from the trends observed for sand grains at other reference wind speeds.

Such results could be ascribed to the fact that at low wind speeds, beyond a certain height, the sand particles primarily consisted of sizes < 0.35 mm. As the mass percentage of sand grains with a size smaller than 0.25 mm increased, a natural consequence was a reduction in the mass percentage of sand grains within the 0.25–0.35 mm size range. This phenomenon subsequently led to an initial increase followed by a decrease in the mass percentage of sand grains within the 0.25–0.35 mm size range along the height profile.

Obviously, when the reference wind speed was < 13.5 m/s, the mass percentage of sand with a particle size of 0.25–0.35 mm showed an inflection point at a certain height ($Z < 0.33$ m), and the mass percentage increased first and then decreased along the height. A prediction could be made that when the reference wind speed dropped to a certain value, the mass percentage of sand grains with particle size in the 0.25–0.35 mm range would decrease with the increase in height, which is similar to the change in sand particle size > 0.35 mm along the height when the wind speed was > 15.5 m/s.

4. Conclusions

In the present study, wind tunnel testing was conducted concerning the wind–sand flow field under wind-blown sand environment conditions based on the actual characteristics of wind fields in deserts. Analysis was performed with regard to the gradient of sand transport rate and the mass percentage of sand grains with four grain sizes at different heights under five different wind speeds. The present research achievements serve as a valuable foundation for testing the aerodynamic traits of wind-driven sand movement close to the ground and the formation of dunes. Additionally, they provide a point of reference for numerical modeling investigations focused on the attributes of wind-borne sand flow fields. The main conclusions can be summarized as follows:

(1) From the comparison of wind tunnel tests and field-measured wind speed spectra with Davenport spectra and von Karman spectra, an observation can be made that the flow field characteristics of wind tunnel tests were in good agreement with the measured wind field characteristics. Such findings demonstrate the feasibility and accuracy of wind tunnel testing and lay a foundation for subsequent research involving wind tunnel testing of wind–sand flow fields.

(2) In the experiment, the sand transport rate changed exponentially along the height direction. The characteristics of vertical distribution of mass percentage were as follows. The percentage of sand grains with diameter ≥ 0.35 mm increased with increasing reference wind speed and decreased with increasing height. The percentage of sand grains with diameters less than 0.35 mm decreased with increasing reference wind speed and increased with increasing height.

(3) The correlation between mass percentage of sand grains in the same range of particle size with reference wind speed was as follows. For heights $Z \leq 0.15$ m, it was observed that the mass percentage of sand grains with a diameter less than 0.35 mm exhibited a linear decrease as wind speed increased, while the mass percentage of sand grains with a diameter equal to or greater than 0.35 mm displayed a linear increase with escalating wind speed. On the other hand, at heights $Z \geq 0.21$ m, the relationship governing the mass percentage of sand grains with a diameter greater than 0.35 mm continued to conform to linear change in accordance with reference wind speed. However, the mass percentage of sand grains with a diameter less than 0.35 mm demonstrated an exponential decrease with the increase in wind speed.

(4) From the blowing sand test at five different reference wind speeds, findings showed that the distribution of sand grain sizes in the height direction was not consistent with the distribution of sand grain sizes on the bed. The fitting curve of the sand mass percentage along the height direction reveals that the mass percentage of the sand grains linearly changed with increasing height. When the reference wind speed was ≤ 13.5 m/s, the mass percentage of the sand particle size range of 0.25–0.35 mm initially increased and then decreased along the height direction, with a turning point in the trend.

We predict that as wind speed diminishes to a specific threshold, the mass percentage of sand particles with a particle size range of 0.25–0.35 mm is likely to decrease along the height. This emerging question could potentially serve as a focal point for future research endeavors.

(5) In the experiment, due to the difficulty of sand collection caused by low wind speed, further research should be conducted pertaining to the distribution of sand of different grain sizes at low wind speed. Meanwhile, the brief duration of sand collection could result in inadequate sand mass at significant heights ($Z > 0.51$ m), while excessively prolonged collection times might lead to an excessive accumulation of sediment at the bottom. As such, targeted research is needed to address the challenge of sand particle size distribution at elevated height ($Z > 0.51$ m). These will also become research topics in our subsequent research work.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/su16103914/s1>, Table S1: Mass percentage of each grain size at 9 heights under the reference wind speed of 13.5 m/s; Table S2: Mass percentage of each grain size at 9 heights under the reference wind speed of 15.5 m/s; Table S3: Mass percentage of each grain size at 9 heights under the reference wind speed of 17 m/s; Table S4: Mass percentage of each grain size at 9 heights under the reference wind speed of 19 m/s; Table S5: Mass percentage of each grain size at 5 heights under the reference wind speed of 11.6 m/s.

Author Contributions: Conceptualization, Z.L. and L.Z.; methodology, L.Z.; validation, L.Z., B.H. and O.P.; investigation, L.Z.; resources, Z.L.; data curation, L.Z.; writing—original draft preparation, L.Z.; writing—review and editing, L.Z.; supervision, B.H. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the National Natural Science Foundation of China grant number 51478179.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data are contained within the article and Supplementary Materials.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Wang, X.-M.; Dong, Z.-B.; Zhang, J.-W.; Zhao, A.-G. Relations between morphology, air flow, sand flux and particle size on transverse dunes, Taklimakan sand sea, China. *Earth Surf. Process. Landf.* **2002**, *27*, 515–526. [\[CrossRef\]](#)
2. Tan, L.-H.; Zhang, W.-M.; Qu, J.-J.; Du, J.; Yin, D.-Y.; An, Z.-S. Variation with height of aeolian mass flux density and grain size distribution over natural surface covered with coarse grains: A mobile wind tunnel study. *Aeolian Res.* **2014**, *15*, 345–352. [\[CrossRef\]](#)
3. Carneiro, M.-V.; Paehtz, T.; Herrmann, H.-J. Jump at the onset of saltation. *Phys. Rev. Lett.* **2011**, *107*, 098001. [\[CrossRef\]](#)
4. Li, W.-Q.; Zhou, Y.-H. Statistical behaviors of different-sized grains lifting off in stochastic collisions between mixed sand grains and the bed in aeolian saltation. *J. Geophys. Res. Atmos.* **2007**, *112*, D22106. [\[CrossRef\]](#)
5. Shao, Y.-P.; Li, A. Numerical modelling of saltation in the atmospheric surface layer. *Bound. Layer Meteorol.* **1999**, *91*, 199–225. [\[CrossRef\]](#)
6. Haff, P.-K.; Anderson, R.-S. Grain scale simulations of loose sedimentary beds: the example of grain-bed impacts in aeolian saltation. *Sedimentology* **1993**, *40*, 175–198. [\[CrossRef\]](#)
7. Zheng, X.-J.; Xie, L.; Zou, X.-Y. Theoretical prediction of lift off angular velocity distributions of sand particles in wind-blown sand flux. *J. Geophys. Res. Atmos.* **2006**, *111*, D11109. [\[CrossRef\]](#)
8. Xie, L.; Dong, Z.-B.; Zheng, X.-J. Experimental analysis of sand particles lift-off and incident velocities in wind-blown sand flux. *Acta Mech. Sin.* **2005**, *21*, 564–573. [\[CrossRef\]](#)
9. Bo, T.-L.; Zheng, X.-J.; Duan, S.-Z.; Liang, Y.-R. The influence of wind velocity and sand grain diameter on the falling velocities of sand particles. *Powder Technol.* **2013**, *241*, 158–165. [\[CrossRef\]](#)
10. Ho, T.-D.; Valance, A.; Dupont, P.; Ould, E.-I.; Moutar, A. Aeolian sand transport: Length and height distributions of saltation trajectories. *Aeolian Res.* **2014**, *12*, 65–74. [\[CrossRef\]](#)
11. Gillies, J.-A.; Etyemezian, V.; Nikolich, G.; Nickling, W.-G.; Kok, J.-F. Changes in the saltation flux following a step-change in macro-roughness. *Earth Surf. Process. Landf.* **2018**, *43*, 1871–1884. [\[CrossRef\]](#)

12. Zheng, X.-J.; He, L.-H.; Wu, J.-J. Vertical profiles of mass flux for windblown sand movement at steady state. *J. Geophys.-Solid Earth* **2004**, *109*, B01106. [\[CrossRef\]](#)
13. Butterfield, G.-R. Near-bed mass flux profiles in Aeolian sand transport, High-resolution measurements in a wind tunnel. *Earth Surf. Process. Landf.* **1999**, *24*, 393–412. [\[CrossRef\]](#)
14. Dong, Z.-B.; Wang, H.-T.; Wang, X.-M. A wind tunnel investigation of the influences of fetch length on the flux profile of a sand cloud blowing over a gravel surface. *Earth Surf. Process. Landf.* **2004**, *29*, 1613–1626. [\[CrossRef\]](#)
15. Dong, Z.-B.; Lu, J.-F.; Man, D.-Q.; Lv, P.; Qian, G.-Q.; Zhang, Z.-C.; Luo, W.-Y. Equations for the near-surface mass flux density profile of wind-blown sediments. *Earth Surf. Process. Landf.* **2011**, *36*, 1292–1299. [\[CrossRef\]](#)
16. Tan, L.-H.; Zhang, W.-M.; Qu, J.-J.; Wang, J.-Z. Aeolian sediment transport over gobi: Field studies atop the Mogao Grottoes, China. *Aeolian Res.* **2016**, *21*, 53–60. [\[CrossRef\]](#)
17. Creyssels, M.; Dupont, P.; Moctar, A.-E.; Valance, A.; Cantat, I.; Jenkins, J.-T.; Pasini, J.-M.; Rasmussen, K.-R. Saltating particles in a turbulent boundary layer: Experiment and theory. *J. Fluid Mech.* **2009**, *625*, 47–74. [\[CrossRef\]](#)
18. Ni, J.-R.; Li, Z.-S.; Mendoza, C. Vertical profiles of aeolian sand mass flux. *Geomorphology* **2002**, *49*, 205–218. [\[CrossRef\]](#)
19. Mertia, R.-S.; Priyabrata, S.; Kandpal, B.-K.; Prasad, R. Mass height profile and total mass transport of wind eroded aeolian sediments from rangelands of the Indian Thar Desert. *Aeolian Res.* **2010**, *2*, 135–142. [\[CrossRef\]](#)
20. Farrell, E.-J.; Sherman, D.-J.; Ellis, J.-T.; Li, B. Vertical distribution of grain size for wind blown sand. *Aeolian Res.* **2012**, *7*, 51–61. [\[CrossRef\]](#)
21. Bo, T.-L.; Zheng, X.-J.; Duan, S.-Z.; Liang, Y.-R. Analysis of sand particles lift-off and incident velocities in wind-blown sand flux. *Acta Mech. Sin.* **2013**, *29*, 158–165. [\[CrossRef\]](#)
22. Zhan, K.-J.; Liu, S.-Z.; Yang, Z.-H.; Fang, E.-T.; Zhou, L.-P.; Wang, Q.-Q.; Guo, S.-J.; Zhang, J.-H.; Huang, N. Suspended dust particle characteristics during an sandstorm on 29 February 2008 in Minqin area, China. *Aeolian Res.* **2017**, *25*, 79–86. [\[CrossRef\]](#)
23. Zhang, Z.-C.; Dong, Z.-B.; Qian, G.-Q. Field observations of the vertical distribution of sand transport characteristics over fine, medium and coarse sand surfaces. *Earth Surf. Process. Landf.* **2017**, *42*, 889–902. [\[CrossRef\]](#)
24. Liu, B.-L.; Qu, J.-J.; Ning, D.-H.; Guo, Y.-H.; Zu, R.-P.; An, Z.-S. Grain-size study of aeolian sediments found east of Kumtagh Desert. *Aeolian Res.* **2014**, *13*, 1–6. [\[CrossRef\]](#)
25. Lancaster, N.; Nickling, W.-G.; Neuman, M.-K. Particle size and sorting characteristics of sand in transport on the stoss slope of a small reversing dune. *Geomorphology* **2002**, *43*, 233–242. [\[CrossRef\]](#)
26. Cheng, H.; He, J.-J.; Zou, X.-Y.; Li, J.-F.; Liu, C.-C.; Liu, B.; Zhang, C.-L.; Wu, Y.-Q.; Kang, L.-Q. Characteristics of particle size for creeping and saltating sand grains in aeolian transport. *Sedimentology* **2015**, *62*, 1497–1511. [\[CrossRef\]](#)
27. Xing, M. The harmonious character in equilibrium aeolian transport on mixed sand bed. *Geomorphology* **2007**, *86*, 230–242. [\[CrossRef\]](#)
28. Namikas, S.-L. A conceptual model of energy partitioning in the collision of saltating grains with an unconsolidated sediment bed. *J. Coast. Res.* **2006**, *22*, 1250–1259. [\[CrossRef\]](#)
29. Arens, S.-M.; Boxel, J.-H.-V.; Abuodha, J.-O.-Z. Changes in grain size of sand in transport over a foredune. *Earth Surf. Process. Landf.* **2002**, *27*, 1163–1175. [\[CrossRef\]](#)
30. Yang, Y.-Y.; Liu, L.-Y.; Li, X.-Y.; Shi, P.; Zhang, G.-M.; Xiong, Y.-Y.; Lyu, Y.-L.; Guo, L.-L.; Liang, B.; Zhao, M.-D.; et al. Aerodynamic grain-size distribution of blown sand. *Sedimentology* **2019**, *66*, 590–603. [\[CrossRef\]](#)
31. Huang, B.; Li, Z.-N.; Zhao, Z.-F.; Wu, H.-H.; Zhou, H.-F.; Cong, S. Near-ground impurity-free wind and wind-driven sand of photovoltaic power stations in a desert area. *J. Wind. Eng. Ind. Aerodyn.* **2018**, *179*, 483–502. [\[CrossRef\]](#)
32. Wu, Y.; Sun, Y.; Zheng, C.-R.; Sun, X.-Y. (Eds.) *Wind Engineering and Structural Wind Resistance Design*; Harbin Institute of Technology Press: Harbin, China, 2014; pp. 34–37. (In Chinese)
33. Huang, B.-C.; Wang, C.-J. (Eds.) *Principle and Application of Structural Wind Resistance Analysis*; Tongji University Press: Shanghai, China, 2008; pp. 108–114. (In Chinese)
34. Dong, Z.-B.; Wang, H.-T.; Liu, X.-P.; Wang, X.-M. The blown sand flux over a sandy surface: A wind tunnel investigation on the fetch effect. *Geomorphology* **2004**, *57*, 117–127. [\[CrossRef\]](#)
35. ASCE. *ASCE Manual of Practice No.67 on Wind Tunnel Studies of Buildings and Other Structures*; ASCE: Reston, VA, USA, 2003.

Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.