Postprint: Aerodynamic Parameters of Typical Underlying Surfaces in the Aeolian Sand Area of the Middle Reaches of the Yarlung Tsangpo River

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Abstract

Near-surface aerodynamic parameters are important components of aeolian sand research. The middle reaches of the Yarlung Tsangpo River (hereinafter referred to as the Yarlung Tsangpo) are one of the areas most severely affected by wind-sand disasters in the Tibet region, where floodplains and piedmont sand flow areas constitute the primary source regions for wind-sand disasters in the middle reaches. Research on their near-surface aerodynamic parameters facilitates the assessment of wind-sand disasters and the forecasting and early warning of sandstorms in this region. Three types of underlying surfaces were selected: floodplain vegetated areas (vegetation coverage >20%), anthropogenically disturbed areas (vegetation coverage <20%), and sand flow areas (without any vegetation). The friction velocity (u*) and aerodynamic roughness length (z0) were calculated using the wind speed profile method. The results indicate: (1) The near-surface wind speed reduction follows the order vegetated areas > anthropogenically disturbed areas > sand flow areas, with the wind speed reduction in vegetated areas being approximately twice that in sand flow areas. (2) The near-surface wind speed profiles for different underlying surfaces can all be expressed as logarithmic linear functions (uz=bln(z)+a), but with different fitting parameters. (3) The average u* values for vegetated areas, anthropogenically disturbed areas, and sand flow areas are 0.73 m·s-1, 0.59 m·s-1, and 0.36 m·s-1, respectively, while the average z0 values are 7.1×10^{-2} m, 3.7×10^{-2} m, and 4.7×10^{-4} m, respectively. The u* and z0 in vegetated areas are approximately 2 times and 150 times those in sand flow areas, respectively. (4) The u* in vegetated areas, anthropogenically disturbed areas, and sand flow areas all increase with increasing mean wind speed, with the magnitude of increase following the order vegetated areas > anthropogenically disturbed areas > sand flow areas. (5) The response patterns of z0 to mean wind speed differ between vegetated areas and sand flow areas: z0 in vegetated areas increases slowly with increasing wind speed, whereas z0 in sand flow areas shows a decreasing trend at low wind

speeds and begins to increase when the wind speed exceeds a threshold value (6.5 m · s-1).

Full Text

Aerodynamic Parameters of Typical Underlying Surfaces in an Aeolian Region in the Middle Reaches of the Yarlung Zangbo River

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Abstract

Aerodynamic parameters in the near-surface layer constitute a critical component of aeolian research. The middle reaches of the Yarlung Zangbo River (hereinafter referred to as the Yarlung River) represent one of the most severely wind-sand affected regions in Tibet. River floodplains and piedmont shifting sand areas serve as the primary source zones for aeolian disasters in this region. Investigating their near-surface aerodynamic parameters facilitates the assessment of wind-sand hazards and the forecasting of sandstorms. This study examined three typical underlying surfaces: a river floodplain vegetation area (vegetation coverage > 20%), an anthropogenically disturbed area (vegetation coverage < 20%), and a shifting sand area (without any vegetation). Using the wind speed profile method, we calculated friction wind speed (u*) and aerodynamic roughness length (z_0). The results demonstrate that: (1) The amplitude of wind speed reduction in the near-surface layer follows the order: vegetation area > disturbed area > shifting sand area, with the vegetation area exhibiting nearly twice the reduction magnitude of the shifting sand area. (2) Although near-surface wind speed profiles across different underlying surfaces can be expressed as log-linear functions (uz = b ln(z) + a), the fitting parameters differ significantly. (3) The average u* values for the vegetation area, disturbed area, and shifting sand area are 0.73, 0.59, and 0.36 $m \cdot s^{-1}$, respectively, while the average z_0 values are 7.1×10^{-2}, 3.7×10^{-2}, and 4.7×10^{-4} m, respectively. The u* and z_0 of the vegetation area are approximately 2 times and 150 times those of the shifting sand area, respectively. (4) The u* values for all three surfaces increase with increasing average wind speed, with the rate of increase following the order: vegetation area > disturbed area > shifting sand area. (5) The responses of z_0 to average wind speed differ markedly between the vegetation area and the shifting sand area. The z_0 of the vegetation area increases slowly with wind speed, whereas the z_0 of the shifting sand area shows a decreasing trend at low wind speeds but begins to increase when wind speed exceeds a threshold value of 6.5 $m \cdot s^{-1}$.

Keywords: Yarlung Zangbo River; wind speed profile; friction velocity; aerodynamics; roughness length

Introduction

Aeolian processes represent a primary factor affecting ecological environments and sustainable socio-economic development in arid and semi-arid regions of northwestern China [1-3]. The Tibetan Plateau also experiences significant aeolian activity, with processes that differ markedly from low-altitude regions of northwestern China due to the high-altitude, low-pressure atmospheric environment [4-6]. Aerodynamic parameters—specifically friction wind speed (u*) and aerodynamic roughness length (z_0)—constitute essential elements in aeolian research [7-9]. Accurate calculation of u* and z_0 facilitates the prediction and quantification of sediment transport rates and dust fluxes [10-12] and serves as an important metric for evaluating sand control engineering effectiveness [13-15]. The friction wind speed reflects the shear stress exerted by airflow on the surface; when u* exceeds the threshold friction velocity, surface particles detach and become airborne, initiating wind erosion [16-18]. The roughness length represents the height at which wind speed theoretically reaches zero and is a commonly used parameter in atmospheric boundary layer turbulence flux parameterization schemes [19-21]. It is highly sensitive to changes in surface roughness elements, reflecting the attenuating effect of roughness elements on wind speed [22-24] and is significantly influenced by underlying surface properties.

Previous studies on aerodynamic parameters have primarily focused on low-altitude aeolian regions, revealing that u* and z_0 vary considerably across different underlying surfaces. For instance, research on the Taklimakan Desert has shown that u* on dune surfaces correlates closely with surface undulation [25], while studies on the Gobi Desert indicate that z_0 is minimal and that u* relates to both surface biomass and topographic relief [26]. Investigations of the Cele oasis-desert ecotone have demonstrated that u* and z_0 differ significantly among mobile dunes, semi-mobile dunes, and fixed dunes [27]. These studies underscore the substantial differences in aerodynamic properties across various underlying surfaces, highlighting the importance of observing and calculating near-surface airflow dynamic parameters to understand energy conversion between roughness elements and wind dynamics, assess regional aeolian activity intensity, and estimate dust emissions.

However, most existing research has concentrated on low-altitude aeolian regions. Air density at high altitudes (approximately 0.81 $kg \cdot m^{-3}$) is lower than at low altitudes (approximately 1.23 $kg \cdot m^{-3}$), and aeolian sediments on the Tibetan Plateau are rich in silt and clay (5.8% ± 7.2%), significantly exceeding the content in low-altitude regions [28]. Calculations using sand-driving wind formulas indicate that the initiation process of sand particles differs between high- and low-altitude regions [29]. Unfortunately, field measurements in high-altitude areas remain scarce, limiting our understanding of aeolian disaster formation mechanisms in these environments.

The middle reaches of the Yarlung River experience intense aeolian activity [30-32] and represent an important dust source region outside China' s northern deserts [33-35]. The region' s climate features concurrent wind and dry seasons [36], with abundant loose sediments [37] and anthropogenic destruction of surface vegetation and soil structure [38], resulting in severe wind-sand disasters. However, research on aeolian processes in this region remains relatively limited [39]. Previous studies have focused primarily on dust source provenance [40-42], aeolian geomorphology [43-45], desertification processes [46-48], and sediment transport characteristics [49-51], but have inadequately elucidated dust movement mechanisms across different surfaces due to insufficient investigation of their aerodynamic properties. Therefore, this study calculates aerodynamic parameters for vegetation areas, disturbed areas, and shifting sand areas based on field-measured wind profile data, providing a reference for regional sediment transport calculations, dust flux estimation, and aeolian disaster assessment.

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1. Study Area Overview

The study area is located in the Shannan section of the middle Yarlung River basin, extending from Gongga County in the west to Naidong District in the east (90°30 -92°40 E, 29°10 -29°30 N), at elevations above 3,550 m. The Nyenchen Thanglha Mountains lie to the north and the Himalayas to the south. The region has a mean annual temperature of 8.7 °C and mean annual precipitation of 372 mm, with a unimodal distribution curve and distinct dry (winter and spring) and rainy (summer) seasons. The mean annual relative humidity is 51%, higher in summer and lower in winter. The mean annual wind speed is 2.6 $m \cdot s^{-1}$, stronger in winter and spring and weaker in summer and autumn. Wind direction is complex and significantly influenced by topography, with westerly winds prevailing [52].

The Yarlung River' s middle reaches feature a braided river system. Seasonal variations in runoff expose large areas of river islands and floodplains during low-water periods in winter and spring [53]. The dry, loose surface sediments are transported northward to piedmont areas and even slopes under strong airflow, resulting in frequent aeolian activity [54]. Research suggests that aeolian disasters in this region may have originated during historical periods of highland barley cultivation and have intensified with increasing human development; the frequency of aeolian activity has shown an increasing trend in recent years [55].

2. Methods

2.1 Field Measurements

Aeolian activity in the study area occurs frequently in winter and spring, particularly severe after noon. Therefore, measurements were conducted between 12:35–15:34 and 14:35–18:04 at the Semburi floodplain in Gongga County and near Changguo in Shannan City (Fig. 1 [Figure 1: see original paper]), respectively. Two-dimensional ultrasonic anemometers (wind speed range: 0–30 $\mathrm{m \cdot s^{-1}}$, resolution: 0.01 $\mathrm{m \cdot s^{-1}}$; wind direction range: 0–359°, resolution: 1°) were used to observe wind speeds at different heights, with a data recording frequency of 1 min. During the observation period, distinct sand-laden airflow formed at both sites.

The wind direction was $240° \pm 14°$ and wind speed $\geq 4\ \mathrm{m \cdot s^{-1}}$ at both sites. The surface undulation was minor at both locations. The Semburi site had vegetation cover dominated by reeds (*Phragmites australis*) with heights of 20–40 cm and coverage of 10%–30%. The Changguo site consisted of loose aeolian deposits without vegetation cover (Fig. 1 [Figure 1: see original paper]). At Semburi, measurements were conducted over three underlying surfaces: vegetation area (vegetation coverage $> 20\%$), disturbed area (vegetation coverage $< 20\%$), and shifting sand area (no vegetation). The wind sensor installation heights were 20, 40, 90, 180, and 200 cm above ground level. Although the surface properties at Changguo were similar, measurements were also taken at 30, 80, 170, and 200 cm for comparative purposes. The reference wind speed sensors at both sites were installed at 200 cm height. Semburi and Changguo recorded 1,440 and 1,380 data points, respectively.

2.2 Data Analysis

Under high wind speed conditions, atmospheric stratification tends to be neutral [56]. Under neutral stratification, the near-surface wind profile equation can be expressed as [57]:

$$u_z = \frac{u_*}{k} \ln\left(\frac{z}{z_0}\right)$$

where u_z is the wind speed at height z ($\mathrm{m \cdot s^{-1}}$), u_* is the friction wind speed ($\mathrm{m \cdot s^{-1}}$), z is the height (m), k is the von Kármán constant ($k = 0.4$), and z_0 is the aerodynamic roughness length (m). The relationship between wind speed and height can be expressed as [58]:

$$u_z = b \ln(z) + a$$

where a and b are fitting coefficients. The parameters u_* and z_0 can be calculated as:

$$u_* = bk$$

$$z_0 = \exp\left(-\frac{a}{b}\right)$$

To ensure data quality when calculating parameters using the wind profile equation, we selected data within the wind speed range of $\geq 4\ \mathrm{m \cdot s^{-1}}$ and wind direction range of 200°–290° (shaded area in Fig. 2 [Figure 2: see original paper]). Semburi had 1,080 wind speed records $\geq 4\ \mathrm{m \cdot s^{-1}}$ (mean wind speed: $7.20 \pm 2.17\ \mathrm{m \cdot s^{-1}}$, main wind direction: 248° ± 21°), while Changguo had 1,020 records $\geq 4\ \mathrm{m \cdot s^{-1}}$ (mean wind speed: $7.98 \pm 1.56\ \mathrm{m \cdot s^{-1}}$, main wind direction: 240° ± 14°).

To compare wind profiles across different underlying surfaces, wind speeds at various heights were normalized using the highest measurement point:

$$u_i' = \frac{u_i}{u_f}$$

where i represents the i-th layer from lowest to highest, u_i' is the dimensionless normalized wind speed at layer i, and u_f is the reference wind speed at the highest layer.

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3. Results

3.1 Wind Profile Characteristics

Wind speed decreases with height in both vegetation and sand areas, but the reduction amplitude differs significantly (Table 1). The wind speed reductions are: vegetation area 40% ± 19%, disturbed area 18% ± 12%, and shifting sand area 18% ± 13%. The wind speed profiles for all three underlying surfaces follow a log-linear function relationship [59], with fitting parameters evaluated using the least squares method. The coefficient of determination (R^2) and root mean square error (RMSE) were introduced to assess goodness-of-fit.

The slope of the wind profile indicates the magnitude of wind speed reduction with height. The vegetation area, with relatively tall vegetation and high coverage, exhibits the largest slope, followed by the disturbed area, with the sand area showing the smallest slope (Fig. 3 [Figure 3: see original paper]). The Changguo site has uniform shifting sand, so the slopes at the two measurement points are similar (0.41–0.52). Normalized wind profiles show similar patterns: higher vegetation with greater coverage yields larger slopes. The slope values are 0.41–

0.52 for the vegetation area, 0.18-0.20 for the disturbed area, and 0.18-0.19 for the sand area, demonstrating reproducibility and confirming that differences in profile coefficients result from varying surface properties.

3.2 Aerodynamic Parameter Characteristics

Surface properties significantly influence u_* and z_0. The u_* values differ markedly among surfaces: vegetation area > disturbed area > shifting sand area (Fig. 4 [Figure 4: see original paper]). The average u_* in the vegetation area is 2.0 times that of the disturbed area and 2.0 times that of the shifting sand area. The u_* distribution in the vegetation area is broad and unimodal with a coarse tail, with minimum, average, and maximum values of 0.20, 0.73, and 1.76 $m \cdot s^{-1}$, respectively. The u_* distribution in the disturbed area is narrower than in the vegetation area, with minimum, average, and maximum values of 0.19, 0.59, and 1.54 $m \cdot s^{-1}$, respectively. The u_* distribution in the shifting sand area is concentrated and approximately unimodal, with minimum, average, and maximum values of 0.19, 0.36, and 0.69 $m \cdot s^{-1}$, respectively.

The z_0 values also differ significantly among surfaces: vegetation area > disturbed area > shifting sand area (Fig. 4 [Figure 4: see original paper]). The average z_0 in the vegetation area is 1.9 times that of the disturbed area and 151 times that of the shifting sand area. The z_0 distribution in the vegetation area has a large variation range with a fine tail in the probability density curve, ranging from 0.5×10^{-2} to 13.1×10^{-2} m with an average of 7.1×10^{-2} m. The z_0 variation range in the disturbed area is smaller than in the vegetation area, ranging from 1.1×10^{-2} to 10.4×10^{-2} m with an average of 3.7×10^{-2} m. The z_0 distribution in the shifting sand area is more concentrated than in the vegetation area, approximately unimodal, ranging from 1.2×10^{-4} to 39.3×10^{-4} m with an average of 4.7×10^{-4} m.

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4. Discussion

4.1 Relationship Between Aerodynamic Parameters and Surface Properties

Aerodynamic parameters are jointly influenced by surface attributes and airflow conditions, with their variation representing the result of interactions between roughness elements and airflow [60-62]. Although we strictly controlled wind speed and direction ranges (Fig. 2 [Figure 2: see original paper]) and normalized wind speeds (Fig. 3 [Figure 3: see original paper]), significant differences in aerodynamic parameters persist between vegetation and sand areas ($P < 0.05$), reflecting the substantial influence of surface properties on airflow conditions. The primary differences between vegetation and sand areas lie in vegetation coverage and height: the vegetation area has coverage > 20% with heights of 20-40 cm, while the disturbed area has coverage of 10%-30%. These differences essentially reflect variations in surface roughness elements.

Lettau [63] suggested that while factors affecting surface aerodynamic parameters are complex, the most critical determinant is surface roughness elements. Li et al. [64] reached similar conclusions, identifying surface roughness elements as the key factor influencing aerodynamic parameters, with larger roughness elements yielding greater z_0 values. Vegetation increases surface roughness elements, enhances near-surface Reynolds shear stress, and creates a zero-plane displacement height [65-67], resulting in u_* and z_0 values in the vegetation area significantly greater than those in the sand area. For instance, the average z_0 values are 7.1×10^{-2} m in the vegetation area and 4.7×10^{-4} m in the sand area. The wind speed reduction between the top and bottom measurement layers reaches 40% in the vegetation area but only 18% in the sand area. This difference leads to significantly higher u_* in the vegetation area (average 0.73 $m \cdot s^{-1}$) compared to the sand area (average 0.36 $m \cdot s^{-1}$). Zhang et al. [68] attributed such differences to flexible vegetation' s ability to alter its structure and morphology, thereby consuming more near-surface airflow energy and reducing energy reaching the surface, which increases near-surface wind speed reduction and enhances turbulence intensity—the primary cause of increased surface friction wind speed. On the same surface, near-surface turbulence intensity increases with wind speed, leading to increased u_* and demonstrating that u_* increases with wind speed.

4.2 Relationship Between Aerodynamic Parameters and Average Wind Speed

4.2.1 Relationship Between Friction Wind Speed and Average Wind Speed Both vegetation and sand areas show significant positive linear correlations between u_* and average wind speed (Fig. 5 [Figure 5: see original paper]), consistent with previous research [69-71]. However, the rate of increase differs: the vegetation area shows a slightly greater increase than the disturbed area, while the sand area exhibits the smallest increase (Fig. 5 [Figure 5: see original paper]). The u_* increase rate in the vegetation area is 1.2 times that in the sand area. Additionally, the u_* increase rates at Semburi and Changguo are similar because both surfaces consist of flat sand. This indicates that the u_* increase rate is closely related to surface type: vegetated surfaces show greater u_* increase with wind speed than sand surfaces because rougher vegetation enhances near-surface turbulence intensity, which strengthens with increasing wind speed.

4.2.2 Relationship Between Aerodynamic Roughness Length and Average Wind Speed The relationship between z_0 and average wind speed differs markedly between vegetation and sand areas (Fig. 6 [Figure 6: see original paper]). In the vegetation area, z_0 increases slowly with wind speed (Fig. 6 [Figure 6: see original paper]). In the sand area, z_0 initially decreases slowly with increasing wind speed but increases rapidly when wind speed exceeds a threshold of 6.5 $m \cdot s^{-1}$ (Fig. 6 [Figure 6: see original paper]).

Previous research has shown that near-surface wind speed can alter the structure and morphology of flexible roughness elements, thereby changing z_0 [72-74]. Studies in the Taklimakan Desert transition zone have demonstrated that z_0 is larger at low wind speeds and smaller at high wind speeds on surfaces without sand transport [75]. Observations at the southeastern edge of the Tengger Desert indicate that z_0 for straw checkerboard-covered surfaces increases rapidly with wind speed at low velocities ($< 6\ \mathrm{m \cdot s^{-1}}$) but increases slowly at high velocities ($> 8\ \mathrm{m \cdot s^{-1}}$), while z_0 for sand surfaces increases slowly at low wind speeds ($< 8\ \mathrm{m \cdot s^{-1}}$) but increases rapidly at high wind speeds ($> 6\ \mathrm{m \cdot s^{-1}}$) [76]. Wind tunnel experiments comparing aeolian sand flow and clean wind fields have shown that z_0 is larger in sand flow conditions than in clean wind and increases with wind speed in sand flow conditions [77-78].

We propose that: (1) The z_0 in the vegetation area results from the combined effects of sand flow and vegetation; (2) The presence or absence of sand flow significantly affects calculated z_0 values for sand surfaces. Without sand flow, calculated z_0 may be overestimated, whereas with sand flow, z_0 increases exponentially with wind speed. The threshold value ($6.5\ \mathrm{m \cdot s^{-1}}$) indicates the threshold wind speed, similar to the calculated threshold sand-driving wind speed. During the observation period, the mean air pressure was 650 hPa, mean temperature was 10.1 °C, and calculated air density was approximately $0.81\ \mathrm{kg \cdot m^{-3}}$. Using the sand-driving wind formula [79] and the mean particle diameter of the sand surface (292.81 m), the threshold wind speed at 200 cm height is $6.6\ \mathrm{m \cdot s^{-1}}$.

4.3 Effect of Altitude on Wind Profiles

To elucidate the relationship between altitude and near-surface wind speed, we normalized field measurement data from shifting sand surfaces in different regions using the normalization formula. The normalized wind profiles of shifting sand surfaces in the study area (Changguo) and those from Tazhong [80], Kubuqi Wind Farm [81], Guazihu in the Badain Jaran Desert [82], and the Zhongwei Aeolian Observation Station [83] all follow log-linear relationships ($R^2 > 0.98$) (Fig. 7 [Figure 7: see original paper]):

$$u' = c \ln(z) + d$$

where c and d are normalized wind profile fitting coefficients (Table 2). Parameter c decreases exponentially with increasing altitude, while d increases exponentially, revealing differences in how near-surface wind speed changes with altitude (Fig. 7 [Figure 7: see original paper]). Larger c values (and smaller d values) indicate faster wind speed reduction, and vice versa. This demonstrates that compared to low-altitude areas, high-altitude regions have lower air density and viscosity, resulting in less energy consumption as airflow energy is transferred downward. According to the Reynolds number formula, high-altitude regions are more prone to turbulence. This indicates that airflow in high-altitude areas changes more slowly with height, consuming less energy and causing aeolian sediments to move higher and farther than in low-altitude areas [84-86].

In summary, u_* and z_0 differ significantly between Semburi and Changguo, with distinctly different relationships to average wind speed. Although both surfaces may experience wind erosion under high wind speeds, analysis of u_* indicates that Changguo' s sand surface has greater wind erosion potential. Considering the spatial-temporal variation characteristics of surface types in the study area, where large areas of river islands and floodplains are exposed during winter and spring [87], we recommend focusing sand disaster prevention efforts on these river islands and floodplains.

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5. Conclusions

This study yields the following conclusions:

1. The wind speed reduction amplitude in the near-surface layer follows the order: vegetation area > disturbed area > shifting sand area, demonstrating vegetation' s role in reducing near-surface wind speed and thereby mitigating soil wind erosion.
2. The average u_* values for vegetation area, disturbed area, and shifting sand area are 0.73, 0.59, and 0.36 $m \cdot s^{-1}$, respectively, corresponding to average z_0 values of 7.1×10^{-2}, 3.7×10^{-2}, and 4.7×10^{-4} m, respectively. The u_* and z_0 of the vegetation area are approximately 2 times and 150 times those of the shifting sand area, respectively. Based on these results, sand disaster prevention should prioritize river islands and floodplains.
3. Both vegetation and shifting sand areas show significant linear relationships between u_* and average wind speed, with u_* increasing as average wind speed increases, but the rate of increase is greater in the vegetation area than in the shifting sand area.
4. The responses of z_0 to average wind speed differ between vegetation and shifting sand areas, closely related to the properties of surface roughness elements and the presence of sand flow.

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