Study on the Applicability of Boundary Layer Displacement Thickness for Evaluating Sand Barrier Windbreak Effectiveness: A Case Study of Polylactic Acid (PLA) Sand Barriers Postprint

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Abstract

Surface roughness, as a traditional indicator commonly employed in wind erosion protection, has played a significant role in evaluating the protective effectiveness of engineering measures such as shelterbelts and sand barriers. However, phenomena of incomplete accuracy have been observed for surface roughness in practical applications. To address this issue, a new reference indicator—boundary layer displacement thickness—was introduced. Through wind tunnel simulation experiments, the accuracy of these two indicators (surface roughness and boundary layer displacement thickness) was verified by measuring wind speed frequency, fitting wind speed flow fields, and calculating windbreak effectiveness in polylactic acid (PLA) sandbag sand barriers of varying side lengths. The results demonstrate that with increasing barrier grid side length of the PLA sandbag sand barriers, average wind speed exhibits an upward trend, wherein the average wind speeds within barriers with side lengths of 1.5 m and 2.0 m are 1.13 and 1.24 times that of the 1.0 m barrier, respectively; windbreak effectiveness exhibits a decreasing trend, wherein all locations within the 1.0 m barrier exceed 0.6, all locations within the 1.5 m barrier exceed 0.5, and all locations within the 2.0 m barrier exceed 0.4; and the area of high-speed regions in the wind speed flow field shows an increasing trend. This indicates that the protective function of sand barriers gradually decreases as their barrier grid side length increases. Concurrently, with increasing barrier grid side length, boundary layer displacement thickness shows a decreasing trend, whereas surface roughness shows a trend of first decreasing then increasing. In summary, boundary layer displacement thickness demonstrates higher accuracy in evaluating the protective effectiveness of sand barriers and can serve as a new supplementary reference indicator.

Full Text

Applicability Study of Boundary Layer Displacement Thickness for Evaluating Windbreak Benefits of Sand Barriers: A Case Study of Polylactic Acid (PLA) Sand Barriers

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Abstract

Surface roughness, a conventional index widely applied in wind erosion protection, plays a crucial role in evaluating the effectiveness of engineering measures such as shelterbelts and sand barriers. Despite its prevalent use, practical applications reveal limitations in its accuracy. To address this issue, we introduce a novel reference index termed “boundary layer displacement thickness.” Through wind tunnel simulation experiments, we measured wind speed frequency distributions, fitted wind velocity flow fields, and calculated wind prevention efficiency across polylactic acid (PLA) sandbag barriers of varying grid sizes to validate the accuracy of both surface roughness and boundary layer displacement thickness. The results demonstrate that as the grid side length of PLA sandbag barriers increases, the average wind speed exhibits an upward trend. Specifically, the average wind speeds within 1.5 m and 2.0 m barriers are 1.13 and 1.24 times that of the 1.0 m barrier, respectively. Concurrently, wind prevention efficiency shows a declining trend, with values exceeding 0.6, 0.5, and 0.4 for the 1.0 m, 1.5 m, and 2.0 m barriers, respectively. The high-velocity zone area in the wind flow field displays an expanding pattern, indicating that protective effectiveness diminishes as barrier grid size increases. Meanwhile, boundary layer displacement thickness shows a consistent decreasing trend with increasing grid side length, whereas surface roughness exhibits an anomalous pattern of initial decrease followed by increase. In summary, boundary layer displacement thickness demonstrates higher accuracy in evaluating sand barrier protection effectiveness and can serve as a valuable supplementary reference index.

Keywords: boundary layer displacement thickness; wind erosion evaluation; wind tunnel simulation; polylactic acid sand barrier

1. Introduction

Wind erosion refers to the process where soil and sand particles detach from the surface under airflow impact, become transported, and subsequently deposited. This phenomenon causes severe natural disasters and environmental problems, particularly in arid and semi-arid regions where it often becomes the dominant factor constraining agricultural production and environmental deterioration, thereby affecting resource development and sustainable socioeconomic progress in these areas. To effectively mitigate wind-sand disasters, researchers have investigated various wind erosion protection measures, including shelterbelts, biological soil crusts, sand-fixation agents, and sand barriers. Among these, sand barriers have become an important engineering measure in China's sand control efforts due to their simple deployment, effective protection, and long service life.

In evaluating the protective benefits of wind erosion control measures, surface roughness has been widely applied due to its high sensitivity to changes in underlying surfaces. However, over recent decades, most researchers have simply adopted this parameter without deeper investigation. Some scholars have even suggested that existing calculation methods only provide estimates of roughness, with results that are not entirely accurate. Analysis of the roughness calculation formula reveals that roughness is derived from wind speeds at two different heights, and different height combinations yield different values. Consequently, roughness values lack uniqueness and are only applicable to individual experiments, making them unsuitable for comparative analysis across multiple experiments. In reality, surface roughness is not constant under specific underlying surface conditions but varies significantly with wind speed. Given the complex nature of airflow changes in field conditions, calculating roughness using only two height data points introduces substantial errors.

Through investigation of wind speed profiles, this study proposes utilizing boundary layer displacement thickness to evaluate protective effectiveness. The boundary layer refers to the near-surface flow region where airflow viscosity cannot be neglected. Boundary layer displacement thickness is defined as the additional thickness required for a channel to allow viscous fluid to pass through in the same time and volume compared to a smooth channel. This parameter represents the energy consumption of airflow by rough surfaces. By integrating the wind speed profile and calculating the area between the function curve and coordinate axes, the length of a rectangle with equivalent area represents the boundary layer displacement thickness. The calculation formula is:

$$\delta = \frac{\int_0^h f(x)dx}{U}$$

where δ is the boundary layer displacement thickness, $f(x)$ is the wind speed profile function, and U is the ideal wind speed value.

Polylactic acid (PLA) sandbag barriers represent a new material barrier increasingly used in recent years, offering advantages such as green biodegradability, long protection duration, low cost, and simple deployment. These barriers embody the concept of using sand to control sand and play an important role in wind-sand management. Therefore, this study employs PLA sandbag barriers as the research object to analyze the accuracy of surface roughness and boundary layer displacement thickness in evaluating protective measure effectiveness.

2. Materials and Methods

2.1 Wind Tunnel

The wind tunnel simulation system used in this study is a direct-current wind tunnel. The total length is approximately 24.3 m, with a test section cross-sectional area of 0.6 m × 0.6 m and a length of 11.0 m. The power section, 1.5 m long, provides airflow; the stabilization section, 1.48 m long, contains a honeycomb mesh that breaks up large air masses into fine streams; and the contraction section, 1.5 m long, accelerates airflow through rapid cross-sectional reduction. Together, these components provide stable airflow with continuously adjustable wind speeds ranging from 3–40 $\mathrm{m \cdot s^{-1}}$. During experiments, we used roughness elements (4 cm × 5 cm × 6 cm) to fit wind speed profiles. The Reynolds number was calculated using:

$$Re = \frac{ud}{v}$$

where u is flow velocity ($\mathrm{m \cdot s^{-1}}$), d is characteristic length (m), and v is air kinematic viscosity coefficient ($\mathrm{m^2 \cdot s^{-1}}$). Based on field meteorological data, the experimental wind speed was set at 8 $\mathrm{m \cdot s^{-1}}$ (at 20 cm height), yielding a Reynolds number of 3.2×10^5.

To accurately measure wind speeds at different positions, we employed a three-dimensional mobile measurement system in the test section with a precision of 0.01 $\mathrm{m \cdot s^{-1}}$. The measurement devices included hot-film anemometers (IFA300) and hot-wire anemometers (VT-200).

2.2 Model Construction

PLA sandbag barriers typically have a barrier height of 20 cm. This study used PLA material filled with sand to construct models at a 1:5 scale, with corresponding grid side lengths of 1.0 m, 1.5 m, and 2.0 m (actual model dimensions: 20 cm, 30 cm, and 40 cm). To approximate natural surface conditions, a layer of sand particles was adhered to the test section floor.

Wind tunnel measurement point distribution is shown in [Figure 4: see original paper]. Along the wind direction, measurement points were arranged along the centerline of the middle grid, starting 20 cm upwind of the barrier. Horizontal point spacing was set at one-tenth of the grid dimension, while vertical measurement ranged from 1–20 cm. Wind speeds were measured within different grids until values stabilized, followed by horizontal cross-section measurements. Horizontal cross-section points were arranged in 10 rows and columns at heights of 10 cm (below barrier height), 20 cm (at barrier height), and 30 cm (above barrier height).

2.3 Wind Speed Frequency Statistics

Wind speed frequency statistics were analyzed after stabilization within barrier grids, examining minimum, maximum, mean, standard deviation, kurtosis, skewness, and coefficient of variation. Kurtosis characterizes the peakedness of the probability density distribution relative to a normal distribution, with positive values indicating more values near the mean and negative values indicating more dispersed distributions:

$$K = \frac{n(n+1)}{(n-1)(n-2)(n-3)} \sum \left(\frac{x_i - \bar{x}}{s} \right)^4 - \frac{3(n-1)^2}{(n-2)(n-3)}$$

where K is kurtosis, x_i is the ith statistical value, $\bar{x}$ is the sample mean, and n is sample size.

Skewness describes the symmetry of the probability density distribution relative to a normal curve. Positive skewness indicates more data on the left side (median < mean), while negative skewness indicates more data on the right side (median > mean):

$$S = \frac{n}{(n-1)(n-2)} \sum \left(\frac{x_i - \bar{x}}{s} \right)^3$$

where S is skewness.

The coefficient of variation analyzes sample dispersion, with values >0.15 generally indicating high variability and poor data reliability:

$$v = \frac{sd}{\bar{x}}$$

where v is the coefficient of variation, sd is standard deviation, and $\bar{x}$ is the mean.

2.4 Spatial Correlation

Spatial autocorrelation statistics measure the fundamental property of spatial data interdependence between locations. The model includes nugget, sill, and range parameters. The range represents the maximum distance at which two locations exhibit spatial correlation. The ratio of nugget to sill defines spatial correlation degree, with values of 0–0.25 indicating extremely strong correlation, 0.25–0.75 moderate correlation, and >0.75 weak correlation.

2.5 Wind Prevention Efficiency

Wind prevention efficiency quantifies the degree of wind speed reduction after passing through protective measures:

$$a = \frac{v_0 - v}{v_0}$$

where a is wind prevention efficiency, v_0 is original wind speed ($\mathrm{m \cdot s^{-1}}$), and v is wind speed after protection ($\mathrm{m \cdot s^{-1}}$).

3. Results

3.1 Surface Roughness and Boundary Layer Displacement Thickness

By measuring stable wind speeds at different heights within barrier grids, wind speed profiles were fitted for various barrier sizes [Figure 5: see original paper]. All profiles were well-fitted by natural exponential functions with determination coefficients (R^2) > 0.95. Surface roughness and boundary layer displacement thickness were calculated from these profiles . For surface roughness calculations, wind speeds at actual heights of 5 cm and 20 cm were used. Surface roughness showed a decreasing-then-increasing trend with increasing grid side length, peaking for the 1.0 m barrier. In contrast, boundary layer displacement thickness consistently decreased with increasing grid side length, being 1.13 and 1.24 times smaller for 1.5 m and 2.0 m barriers compared to the 1.0 m barrier, respectively.

3.2 Wind Speed Frequency Statistics

Statistical analysis of stabilized wind speed frequencies within different barrier grids reveals that mean wind speed at all heights increases with grid side length. At 10 cm height, mean speeds are 1.86, 2.39, and 3.15 $\mathrm{m \cdot s^{-1}}$ for 1.0 m, 1.5 m, and 2.0 m barriers, respectively; at 20 cm height, values are 3.62, 4.13, and 4.33 $\mathrm{m \cdot s^{-1}}$; and at 30 cm height, values are 4.89, 5.20, and 5.42 $\mathrm{m \cdot s^{-1}}$. However, large standard deviations indicate that means are significantly affected by extreme values. Kurtosis and skewness values show substantial dispersion in wind speed frequency distributions, reflecting intense and complex wind speed variations within barrier grids. Additionally, nearly half the samples have coefficients of variation >0.15, confirming that mean values are heavily influenced by extremes and require further processing.

3.3 Spatial Autocorrelation

To investigate the relationship between barrier protective effectiveness and grid size, wind flow fields within grids were fitted. Prior to fitting, spatial autocorrelation analysis was performed on wind speed frequencies using geostatistical methods . Results show that wind speed frequencies in all barrier grids can be fitted with Gaussian models, with spatial correlation degrees <0.25, indicating extremely strong spatial correlation among measurement points. This confirms high reliability and accuracy of the wind tunnel simulation data.

3.4 Wind Flow Field

Numerical simulations of stabilized flow fields within different grids are shown in [Figure 6: see original paper]. At 10 cm measurement height, the 1.0 m barrier creates two blue deceleration zones behind the barrier with a yellow acceleration zone in the center and orange core areas; the 1.5 m barrier forms a large blue low-speed zone that gradually recovers, creating an orange acceleration region in the rear half; the 2.0 m barrier shows similar structure but with lighter colors. At 20 cm height, all barriers exhibit post-barrier wind speed reduction, with larger grid sizes showing higher wind speeds. At 30 cm height, the 1.0 m barrier shows two orange acceleration zones at the sides with faster side velocity reduction; the 1.5 m barrier forms a central low-speed structure that increases toward the sides; and the 2.0 m barrier shows similar patterns to the 1.5 m barrier but with reduced intensity.

3.5 Wind Prevention Efficiency

Analysis of wind prevention efficiency within different barrier grids [Figure 7: see original paper] shows that all grid sizes achieve efficiency values <1.0, indicating effective protection. At 10 cm height, the 1.0 m barrier maintains efficiency >0.6, the 1.5 m barrier >0.5, and the 2.0 m barrier >0.4. Efficiency decreases uniformly with increasing grid size for the 1.0 m barrier, while the 1.5 m barrier shows sharp efficiency decline in the 0.4–0.6 range, and the 2.0 m barrier exhibits poor wind erosion prevention capability with high internal wind speeds.

3.6 Correlation Analysis

Correlation analysis between surface roughness, boundary layer displacement thickness, and various indicators [Figure 8: see original paper] reveals that surface roughness shows negative correlations with grid side length and wind speed, and positive correlation with wind prevention efficiency, but these correlations are not statistically significant. In contrast, boundary layer displacement thickness shows significant negative correlations with grid side length and wind speed, and significant positive correlation with wind prevention efficiency, with correlation coefficients >0.8.

4. Discussion

4.1 Accuracy of Surface Roughness

The results demonstrate that PLA sandbag barriers provide effective wind protection that diminishes with increasing barrier size. Boundary layer displacement thickness accurately reflects this protective pattern, whereas surface roughness yields inconsistent results. Correlation analysis confirms that surface roughness shows weaker correlations with parameters than boundary layer displacement thickness. To verify surface roughness applicability, wind speeds at multiple heights were used to calculate roughness values . Results show that when calculation heights fall within the 15–20 cm range where airflow changes dramatically, surface roughness values are anomalous, while other height combinations yield more indicative results.

Longitudinal cross-section flow fields along the wind direction [Figure 9: see original paper] reveal significant airflow uplift and acceleration above the barrier, with intense wind speed variations in this zone. Above the uplift region, airflow stabilizes again. The anomalous surface roughness values correspond to heights within this dramatic airflow change zone, indicating that intense airflow variations are the primary cause of inaccurate surface roughness calculations.

4.2 Applicability of Boundary Layer Displacement Thickness

In practice, the surface boundary layer height far exceeds the effective protection height of barriers, and boundary layer displacement thickness also exceeds the measurement range of this study, requiring methodological adaptation. In the calculation formula, ideal wind speed values cannot be measured directly; however, selecting wind speeds beyond the effective protection height suffices. As shown in [Figure 5: see original paper], actual wind speeds at heights >0.5 m approach original wind speeds, suggesting that 0.5 m can serve as the calculation height for evaluating sand barrier effectiveness. This approach can be adjusted accordingly when evaluating other protective measures like shelterbelts and biological soil crusts.

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5. Conclusions

1. PLA sandbag barriers demonstrate effective wind prevention, with protective effectiveness decreasing as barrier size increases.
2. Surface roughness is calculated from wind speeds at two different heights. When selected heights fall within zones of dramatic wind speed change, the calculated surface roughness shows poor accuracy. Therefore, airflow structural characteristics must be considered during application.
3. Boundary layer displacement thickness is calculated from wind speed profiles within the effective protection height, compensating for impacts from

intense airflow variations in specific zones. This index shows higher accuracy in evaluating protective measure effectiveness and can serve as a valuable supplementary reference to surface roughness.

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