Analysis of Optimal Spacing for High-Standing Reed Sand Barriers along Xinjiang S214 Provincial Highway (Postprint)

Authors: Chen Baiyu, Cheng Jianjun, Li Shengyu, Cheng Jianjun

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Abstract

Taking the sand hazard control section of Xinjiang Provincial Highway S214 as the study background, the wind-sand flow field around high-standing reed sand barriers was analyzed using CFD (computational fluid dynamics) numerical simulation. The results indicate that the flow field around high-standing reed sand barriers can be divided into a windward deceleration zone, an acceleration zone above, and a leeward recovery zone, with no obvious vortex zone generated on the leeward side. The reasonable spacing between sand barriers is negatively correlated with wind speed. The field layout pattern exhibits good protective effect against wind-sand flow at 20 $m \cdot s^{-1}$. When wind speed is lower than this value, the leeward side of the second sand barrier basically generates no recovery zone, while the windward sides of the subsequent two sand barriers accumulate more sand distributed close to the barriers, resulting in relatively rapid barrier burial. Optimizing sand barrier spacing through the adjacency principle can fully exploit the protective function of each barrier, effectively resist wind-sand flow erosion, and appropriately extend the service life of the sand barriers. Based on previous observation data, field surveys, and numerical simulation results, the recommended spacing for high-standing reed sand barriers in the study area is 20–25 m. These research results can provide a theoretical basis for the rational layout of high-standing reed sand barriers in the study area and also serve as a reference for the construction of other wind-sand protection projects.

Full Text

2 Methodology

This study employs computational fluid dynamics (CFD) numerical simulation to investigate wind-sand flow fields around high-parallel reed sand barriers along the Xinjiang S214 provincial highway. The simulation domain and sand barrier model are illustrated in [Figure 3: see original paper]. The calculation domain adopts a pressure-outlet boundary condition at the outlet and a velocity-inlet boundary condition at the inlet, with the inlet velocity profile defined by the logarithmic law:

$$V(y) = \frac{u_*}{k} \ln\left(\frac{y}{y_0}\right)$$

where $V(y)$ is the wind speed at height y, u_* is the friction velocity, k is the von Kármán constant (0.4), and y_0 is the aerodynamic roughness length. The barrier is modeled as a porous medium with a wall boundary condition applied to the surface.

Sand particle size ranges from 0.075–0.25 mm, with a median diameter of $d_s =$ 0.15 mm. The particles are treated as granular material with density $\rho_s =$ 2650 $\text{kg} \cdot \text{m}^{-3}$ and dynamic viscosity $\mu_s = 0.0047$ Pa · s. The fluid phase is air with density $\rho_k = 1.225$ $\text{kg} \cdot \text{m}^{-3}$ and viscosity $\mu_k = 1.789 \times 10^{-5}$ Pa · s. Simulations are conducted at three wind speeds: 10 $\text{m} \cdot \text{s}^{-1}$, 15 $\text{m} \cdot \text{s}^{-1}$, and 20 $\text{m} \cdot \text{s}^{-1}$.

The k- turbulence model is employed for closure, with the SIMPLEC algorithm used for pressure-velocity coupling. The convergence criterion is set to 10^{-6}. The QUICK scheme is applied for spatial discretization of momentum equations, and particle trajectories are calculated using the Lagrangian method with stochastic tracking [**?**].

3 Results and Analysis

3.1 Flow Field Characteristics

Numerical simulation results reveal that the flow field around high-parallel reed sand barriers can be divided into three distinct zones: a windward deceleration zone, an upper acceleration zone, and a leeward recovery zone. No obvious vortex formation is observed on the leeward side, which differs from solid barriers due to the permeable nature of the reed structure.

At a wind speed of 6 $\text{m} \cdot \text{s}^{-1}$, the barrier induces significant velocity reduction on the windward side, creating favorable conditions for sand deposition. The deceleration effect extends approximately 0.5 m upstream, with velocity reduction exceeding 91.5% within 3 m immediately behind the barrier [**?**]. As wind speed increases to 12 $\text{m} \cdot \text{s}^{-1}$, the flow separation becomes more pronounced, though the leeward recovery zone remains relatively stable without large-scale eddy formation.

When wind speed reaches 20 $\text{m} \cdot \text{s}^{-1}$, the upper acceleration zone exhibits maximum velocity enhancement of approximately 1.5 times the incoming flow speed. The leeward recovery zone extends 10–15 m downstream, beyond which the flow field gradually returns to undisturbed conditions. The absence of strong leeward vortices reduces the risk of localized scour behind the barriers.

3.2 Sand Accumulation Patterns

Sand accumulation primarily occurs on the windward side of the barriers, with deposition rates varying significantly with wind speed. At lower wind speeds (6-10 $m \cdot s^{-1}$), sand particles settle within 2-3 m upstream of the barrier, forming a gentle slope. At moderate speeds (12-15 $m \cdot s^{-1}$), deposition shifts closer to the barrier structure, with accumulation heights reaching 20-25 cm. Under high wind speeds (20 $m \cdot s^{-1}$), sand flux increases substantially, leading to more rapid barrier burial.

The numerical results indicate that the burial speed of barriers is negatively correlated with spacing distance. When barriers are spaced 20-25 m apart, each barrier maintains its protective function while allowing sufficient space for sand storage between structures. This spacing optimizes the balance between protection efficiency and material costs.

3.3 Optimization of Barrier Spacing

Based on the matching principle between barrier spacing and flow field recovery distance, reasonable spacing should be adjusted according to local wind regimes. For the S214 highway section studied, where prevailing wind speeds range from 10-20 $m \cdot s^{-1}$, a spacing of 20-25 m is recommended. This configuration ensures that the leeward recovery zone of the upstream barrier does not interfere with the windward deceleration zone of the downstream barrier, maintaining effective protection along the entire system.

Field observations confirm that barriers spaced at 20-25 m intervals exhibit slower burial rates and more uniform sand distribution compared to closer or wider spacings. At 30 m spacing, significant sand accumulation occurs between barriers, reducing overall system efficiency. At 15 m spacing, the flow field interaction between adjacent barriers creates complex velocity patterns that accelerate local erosion.

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Abstract: The CFD (computational fluid dynamics) numerical simulation method was used to study the wind-sand flow fields around the high-parallel reed sand barrier of the Xinjiang S214 provincial highway sand control section. The results showed that the flow field division around the high-parallel reed sand barrier can be divided into the windward side deceleration zone, the upper acceleration zone, and the leeward side recovery zone; no obvious vortex zone formation was observed on the leeward side. Reasonable spacing between sand barriers was found to be negatively correlated with wind speed. The field layout mode has a better protective effect on wind-sand flows of 20 $m \cdot s^{-1}$; when the wind velocity is lower, minimal eddy currents developed on the leeward side of the second sand barrier. More sand accumulated on the windward side of the latter two sand barriers and they are close to the distribution of sand barriers. The burial speed of sand barriers is also faster. Through optimizing the distance between sand barriers based on matching principles, the protection of each sand barrier can be maintained, effectively resisting the invasion of sand and prolonging the service life of the barriers. According to previous observational data, field investigation, and numerical simulation results, it is suggested that high-parallel reed sand barriers in the study area should be spaced by 20-25 m. The results of this research provide a theoretical basis for the reasonable spacing of high-parallel reed sand barriers along the Xinjiang S214 provincial highway, and also provide a reference for the construction of other wind-sand protection projects.

Keywords: high-parallel reed sand barrier; wind-sand flow fields; reasonable spacing; numerical simulation; Ruoqiang County

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