Numerical Simulation of Wind-Sand Flow Field Around Highway Subgrade in Shifting Dune Areas and Formation Mechanism of Pavement Sand Hazards: Postprint

Authors: Xingxin Zhang

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Abstract

Based on CFD (Computational Fluid Dynamics) numerical simulation and taking Provincial Highway 303 at Zhongzaohuo in Qinghai Province as the study area, the wind-sand flow field around highway embankments in mobile dune areas was simulated and analyzed, revealing the formation mechanism of road pavement sand hazards in mobile dune areas, with the aim of providing a theoretical basis for the prevention and control of such hazards. Numerical simulation results indicate that when airflow passes over mobile dunes and embankments, the airflow velocity becomes zoned; when mobile dunes are present, the deceleration zone around the embankment increases significantly, with the embankment slopes and leeward slopes entirely within the low-velocity airflow region; above the dune height, airflow velocity increases sharply at the dune crest, and influenced by the shape of the obstacle itself, the wind speed distribution changes from an "Ω" shape to an "M" shape. When the original protection system on the dune surface is neglected in terms of maintenance and renewal, sand particles accumulate extensively near the dunes, the dunes gradually migrate along the prevailing wind direction, becoming a sand source that buries the embankment and forms sand hazards. The numerical simulation results are consistent with field observations, confirming the accuracy of the numerical simulation. For the prevention and control of sand hazards on highways in mobile dune areas, detailed investigation of local geomorphology and wind-sand flow movement patterns should be conducted, the original protection system should be regularly inspected and maintained, accumulated sand should be promptly removed, and it is necessary to both prevent wind-sand flow from supplying sand sources to the dunes and prevent the dunes themselves from becoming sand sources.

Full Text

Numerical Simulation of Wind-Blown Sand Flow Field and Formation Mechanism of Sand Damage on Road Surface in Shifting Dune Area

ZHANG Xingxin[1], ZHANG Kai[1], SHI Boyuan[2], CUI Baohong[3], ZHAO Liming[1]

[1]School of Civil Engineering, Lanzhou Jiaotong University, Lanzhou 730070, Gansu, China
[2]School of Innovation and Entrepreneurship, Lanzhou Jiaotong University, Lanzhou 730070, Gansu, China
[3]The 1st Construction Co., Ltd. of China Railway 15th Bureau Group, Xi' an 710018, Shaanxi, China

Abstract

Based on Computational Fluid Dynamics (CFD) numerical simulation, this study analyzes the wind-sand flow field around highway roadbeds in shifting dune areas, taking Provincial Highway 303 in Zhongzaohuo, Qinghai Province as the research area, to reveal the formation mechanism of pavement sand damage and provide a theoretical basis for prevention and control measures. Numerical simulation results demonstrate that when airflow passes over shifting dunes and roadbeds, the airflow velocity becomes partitioned into distinct zones. The presence of shifting dunes significantly expands the deceleration zone around the roadbed, with both the roadbed slope and leeward slope falling entirely within the low-velocity airflow region. Above the dune height, airflow velocity increases sharply at the dune crest, and influenced by the obstacle' s geometry, the wind speed profile transitions from an "Ω-shaped" to an "M-shaped" distribution. When the existing protection system on dune surfaces is neglected for maintenance and renewal, sand particles accumulate extensively near the dunes, causing them to gradually migrate along the prevailing wind direction and become a sand source that buries the roadbed, thereby creating sand damage. The numerical simulation results align well with field observations, confirming the accuracy of the simulation approach. For sand damage prevention in shifting dune areas, it is essential to thoroughly investigate local geomorphology and wind-sand flow patterns, conduct regular inspections and maintenance of existing protection systems, and promptly remove accumulated sand to both prevent wind-sand flow from supplying sand sources to dunes and stop the dunes themselves from becoming sand sources.

Keywords: shifting sand dunes; subgrade; numerical simulation; sand-flow field

1 Study Area and Methods

1.1 Study Area Overview

The study section is located on Provincial Highway 303 southeast of Zhongzaohuo in Wutumeiren Township, Qinghai Province, spanning kilometers 3–10. The area is characterized primarily by aeolian landforms with scattered dunes of various types. The climate is a plateau continental arid type with scarce precipitation, high evaporation, and deep groundwater tables. Vegetation is sparse, consisting mainly of natural plants such as *Calligonum* and *Tamarix*. Wind is strong, with an average annual wind speed of 5–6 $m \cdot s^{-1}$ and maximum instantaneous wind speeds reaching 30 $m \cdot s^{-1}$. The prevailing wind direction and primary sand-driving wind direction are both westerly. Sand sources are predominantly barchan mobile dunes with abundant supply. Numerous dunes are distributed along both sides of the highway. To prevent dune migration and roadbed burial, sand barrier fixation measures were previously implemented on dune surfaces. However, over time, the protection system has been neglected for maintenance and renewal. The windward slope barriers have suffered severe wind erosion, while sand has accumulated massively on the leeward slope, enabling dunes to gradually approach the roadbed and create sand damage on the pavement [FIGURE 1].

1.2 Computational Domain and Meshing

Considering the influence of dune shape on simulation results and modeling difficulty, the shifting dune was simplified as shown in FIGURE 2. Based on field investigations, the basic parameters of the shifting dune and highway roadbed are: sand dune height of 6 m, base width of 30 m, roadbed height of 3 m, and roadbed width of 12 m, with left-right symmetry. The shifting dune was positioned 50 m from the inlet boundary. The Gambit pre-processing software was used for mesh generation, with four boundary layers applied at the bottom wall surface. The first boundary layer height was set to 0.3 m with a growth rate of 1.2, resulting in a total of 200$\times$10^{4} grid cells across the computational domain. To ensure reliable results, the bottom grid was arranged within the range where the logarithmic distribution law holds valid, typically requiring 11.5 $< y^+ <$ 200–400. The maximum y^+ value in this simulation was 30, satisfying the requirement.

For boundary conditions, a velocity inlet and outflow condition were applied. The inlet wind speed profile followed a logarithmic distribution equation, with axis velocities set at 12 $m \cdot s^{-1}$, 18 $m \cdot s^{-1}$, 24 $m \cdot s^{-1}$, and 30 $m \cdot s^{-1}$. The shifting dune and roadbed were treated as wall boundaries [15].

1.3 Research Methods

The Eulerian two-fluid model was employed for transient simulation of wind-sand two-phase flow, treating each phase as a continuous medium filling the entire computational domain and undergoing complex coupled motion simultaneously. Temperature effects were neglected, treating the flow as adiabatic. Due to low Mach numbers at the inlet (maximum velocity of 30 $m \cdot s^{-1}$), air compressibility was considered to have negligible effect on flow characteristics, and the flow was treated as incompressible. The entire computational domain served as the solution domain, satisfying mass, momentum, and energy conservation throughout. Since the standard k- model was developed for high Reynolds number conditions but Reynolds numbers are low near wall surfaces, standard wall functions were applied in near-wall regions to ensure calculation accuracy. The Shear Stress Transport (SST) k-ω model was used for flow field calculations, with a second-order implicit method for time integration and the Phase Coupled SIMPLE algorithm for solution. Discretization of turbulence kinetic energy, momentum, and other parameters employed a second-order upwind scheme. Residuals were controlled at 10^{-5} during calculations to ensure convergence and simulation accuracy.

1.4 Calculation Parameters

Field investigations revealed that accumulated sand consists mainly of fine and very fine sand. The simulation set sand particle diameter d = 0.25 mm, sand phase density   = 2650 $kg \cdot m^{-3}$, air density   = 1.225 $kg \cdot m^{-3}$, and viscosity   = 1.79$×10^{-5}$ Pa · s. Pressure was set to atmospheric. Since the multiphase flow theory applies to dilute phases, sand particle volume fraction was set to 0.02. The friction viscosity used the Schaeffer model, while collision viscosity employed the Gidaspow model. Both lift and drag coefficients were set to 0.5, and the momentum exchange coefficient used the Syamlal-O' Brien model. The maximum sand bed packing rate was set to 0.63.

2 Results and Analysis

2.1 Distribution Characteristics of Simulated Wind-Sand Flow Field

FIGURE 3 shows the simulated wind-sand flow field distribution around shifting dunes and roadbeds at different wind speeds. The flow field distribution patterns are fundamentally consistent across different wind speeds. As wind-sand flow approaches the dune, it is obstructed, causing gradual velocity reduction and forming a significant airflow deceleration zone on the windward slope. The airflow then climbs along the slope, continuously converging at the dune crest to form an acceleration zone. Additionally, wind speed contours on the windward slope are essentially parallel to the slope gradient. As the airflow continues forward, a low-velocity zone forms near the leeward slope, roadbed surface, and leeward roadbed slope, gradually recovering to the incoming flow velocity after completely passing the obstacles.

FIGURE 4 illustrates the flow field distribution around the roadbed alone at different wind speeds. Comparing FIGURE 3 and FIGURE 4 reveals that the presence of shifting dunes significantly affects flow field distribution around the roadbed. Without dunes, the acceleration zone occurs at the road shoulder, with the roadbed slope in a low-velocity zone. With shifting dunes present, the dune's blocking and energy dissipation cause both the roadbed slope and leeward slope to fall entirely within the low-velocity zone, while the acceleration zone shifts to the dune crest. Furthermore, the deceleration zone around the roadbed expands noticeably. In both scenarios, differences in flow field distribution across wind speeds mainly manifest as variations in the size of velocity zones. Compared to V = 24 $m \cdot s^{-1}$, the deceleration and low-velocity zones decrease while the acceleration zone increases at V = 12 $m \cdot s^{-1}$.

2.2 Horizontal Wind Speed Distribution Characteristics

Wind-sand flow generally moves close to the surface, making near-surface wind speed significantly influential on sand particle movement. FIGURE 5 shows horizontal velocity distribution around the roadbed at different heights (0.3 m, 2.3 m, 5.3 m, and 6.0 m). Without shifting dunes, velocity suddenly increases at the road shoulder due to convergence effects, then decreases substantially on the roadbed slope, reaching a minimum at mid-slope. FIGURE 6 shows horizontal velocity distribution around both shifting dunes and roadbed at different heights. With dunes present, airflow velocity below dune height decreases sharply within 5-10 m ahead of the dune, drops rapidly to near zero upon encountering the obstacle, then begins increasing after passing it. On the leeward side of the roadbed, the road shoulder is 5.3 m above ground, and the influence of convergence effects diminishes, resulting in reduced airflow acceleration.

Above dune height, airflow velocity increases sharply at the dune crest. Influenced by the obstacle' s shape, the wind speed profile transitions from an "Ω-shaped" to an "M-shaped" distribution. FIGURE 7 shows that at the same height across different wind speeds, the velocity variation patterns are fundamentally consistent. At heights of 2.3 m, 5.3 m, and 6.0 m, maximum wind speeds reach 13.3 $m \cdot s^{-1}$, 20.2 $m \cdot s^{-1}$, and 27.0 $m \cdot s^{-1}$ respectively for initial wind speeds of 12 $m \cdot s^{-1}$, 18 $m \cdot s^{-1}$, and 24 $m \cdot s^{-1}$, representing 1.11, 1.12, and 1.13 times the initial velocities. As wind speed increases, the maximum wind speed above dune height gradually increases, though the magnitude of change is relatively small.

2.3 Sand Particle Volume Fraction Distribution

When wind speed reaches the critical threshold, surface sand particles begin to move, detach from the surface, and enter the airflow, forming wind-sand flow. As wind speed increases, sediment transport capacity increases, raising the maximum sand transport rate. FIGURE 8 shows sand particle volume fraction distribution around the roadbed at different wind speeds. Without shifting dunes, sand accumulation on the windward roadbed slope significantly exceeds that on the leeward slope. As wind speed increases, accumulation on the windward slope gradually decreases while leeward slope accumulation shows little change, consistent with findings by Shi et al. [19].

FIGURE 9 shows sand particle volume fraction distribution around both shifting dunes and roadbed. With shifting dunes present, sand accumulation occurs primarily at the windward dune toe, with minimal accumulation on the leeward dune slope and around the roadbed. As wind speed increases, accumulation at the windward toe decreases while accumulation on the leeward slope and around the roadbed tends to increase. Comparing FIGURE 8 and FIGURE 9 reveals that with shifting dunes, most sand accumulates on the windward dune slope, leaving minimal accumulation around the roadbed. Over time, however, sand accumulation near dunes increases. On one hand, the dune itself acts as a sand source, with wind removing surface sand particles from the windward slope that then fall onto the interface between dune and roadbed and onto the pavement. On the other hand, this causes dunes to slowly migrate along the prevailing wind direction, burying the roadbed and creating sand damage.

3 Discussion

Comparison of numerical simulation results with actual field sand accumulation (FIGURE 10) shows that simulated sand distribution aligns well with actual conditions, validating the simulation accuracy. Shifting dunes represent a critical factor that cannot be ignored in roadbed protection. Although dunes on both sides of highways crossing shifting dune areas have been stabilized with surface sand barriers, neglecting maintenance over time leads to extensive sand deposition near dunes. This enables shifting dunes to gradually approach the roadbed, creating pavement sand damage. Therefore, for highways passing through shifting dune areas, in addition to conventional protection measures such as straw checkerboard barriers, sand fences, and sand-retaining walls, it is essential to thoroughly investigate local geomorphology and wind-sand flow patterns. Regular cleaning of accumulated sand near dunes and timely inspection and renewal of existing protection systems are necessary to both prevent wind-sand flow from supplying sand to dunes and stop dunes themselves from becoming sand sources.

4 Conclusions

This study employed CFD numerical simulation to analyze wind-sand flow field variation patterns and sand accumulation characteristics around highway roadbeds in shifting dune areas at different wind speeds, yielding the following conclusions:

1) Airflow becomes partitioned into velocity zones near dunes and roadbeds. With shifting dunes present, the deceleration zone around the roadbed expands significantly, with both roadbed slope and leeward slope falling entirely within the low-velocity zone. The acceleration zone shifts to the dune crest.

2) With shifting dunes present, airflow velocity increases sharply at the dune crest, changing the wind speed profile from an "Ω-shaped" to an "M-

shaped" distribution. At the same height across different wind speeds, velocity variation patterns around dunes and roadbeds are fundamentally consistent. The maximum wind speed above dune height gradually increases with wind speed, though the magnitude of change is relatively small.

3) With shifting dunes present, sand accumulates primarily on the windward dune slope. On one hand, the dune itself serves as a sand source, with wind removing surface sand particles from the windward slope that scatter onto the pavement. On the other hand, this causes dunes to slowly migrate along the prevailing wind direction, burying the roadbed and creating sand damage.

4) For highways located in shifting dune areas, it is essential to thoroughly investigate local geomorphology and wind-sand flow patterns, conduct regular inspections and maintenance of existing protection systems, and promptly remove accumulated sand to both prevent wind-sand flow from supplying sand sources to dunes and stop dunes themselves from becoming sand sources.

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