CFD evaluation of erosion rate around a bridge near a sand dune

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Abstract. This study performs a series of simulations through solving the Navier-Stokes equations and the RNG k-ε turbulence model to investigate the wind erosion rates around a bridge in a desert area with sand dunes. The digital elevation model of sand dunes and the bridge model are obtained respectively from hypsographic map and construction drawings. Through combining them into the CFD software of Fluent the simulation zone was formed. The data of wind speed obtained from field observation is fitted into a logarithm format, which was imported into Fluent model as a inlet wind speed condition. Then, the effect of Dun-Go railway on wind-blown sand movement of the neighbouring environment is simulated. The results exhibit that affected by both the sand dune and bridge, the flow field is in a complex condition. It is also shown that the bridge in upstream of the sand dune will not increase the sand transport rate intensively, but change both wind velocity gradient and turbulence kinetic energy over surface of sand dune. On the other hand, when the bridge is built downstream the sand dune, simulation results show that sand deposition rate would be decreased in reference region downstream the pier.

1. Introduction
Wind-blown sand transport over desert is an important subject in the multiphase fluid dynamic. In the December of 2012, a railway was announced to under construction in Northwestern China, between Golmud, Qinghai and Dunhuang, Gansu. Around Shashangou, between Dunhuang and the Altyn-Tagh-Qilian mountain system, the railway will have to cross the eastern edge of the Kumtag Desert. There was a concern that the sand dunes of this area may shift, and even bury the railway. So a 10.7-kilometer-long bridge will be built across a sand valley. The valley stretches itself in a “U” type among complex land forms including compound barchan chain, chain ridges and pyramid dunes. The construction will bring two problems: the effects of the bridge on the wind field and sand transport rate on sand dunes, and the effects of wind-blown sand movement on bridge piers and floor.

This study conducts full scale CFD simulation using the Reynolds averaged Navier-Stokes equations and the RNG k-ε turbulence model to investigate wind field on an area around the bridge. The validity of the simulation is confirmed by comparing the numerical results with the field experiment wind velocity data in same point in the model.

2. Model Description
2.1. Governing equation
To simulate the flow field of the region, the CFD software of fluent 14.0 assumed that a neutral atmosphere boundary layer existed and the 3-D Reynolds averaged N-S equation and the continuity equation should be satisfied. Moreover, the boundary conditions of bridge and sand dunes were set to be non-slip boundary and the flow was considered to be incompressible. The governing equations are listed in the help document of software.

Continuity equation:
\[
\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_i} (\rho u_i) = 0
\]
where \( \rho \) means the density of the air and \( u_i \) is the fluid velocity.

Momentum equation:
\[
\frac{\partial (\rho u_i)}{\partial t} + \frac{\partial}{\partial x_j} \left( \rho u_i u_j \right) = -\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j} \left( \mu \frac{\partial u_i}{\partial x_j} \right) + \frac{\partial}{\partial x_j} \left( -\rho u_i' u_j' \right)
\]
where \( p \) stands for the static pressure and \( -\rho u_i' u_j' \) is Reynolds stress.

The turbulence model of k-\( \varepsilon \) RNG was suggested to be applied when simulating complex flow field [1]. The k-\( \varepsilon \) RNG turbulence model is given as [2]:
\[
\frac{\partial (\rho k)}{\partial t} + u_i \frac{\partial (\rho k)}{\partial x_i} = \frac{\partial}{\partial x_i} \left( \mu \frac{\partial k}{\partial x_i} \right) + G - \rho \varepsilon
\]
\[
\frac{\partial (\rho \varepsilon)}{\partial t} + u_i \frac{\partial (\rho \varepsilon)}{\partial x_i} = \frac{\partial}{\partial x_i} \left( \mu_t \frac{\partial \varepsilon}{\partial x_i} \right) + C_{\mu} \frac{\varepsilon}{k} G - C_{\varepsilon} \rho \frac{\varepsilon^2}{k}
\]
\[
G = 2 \mu_S S_{ij} S_{ij}
\]
\[
C_{2e} = C_{2e} + C'_{2e}
\]
\[
C'_{2e} = C_{\mu} \rho \eta^3 \left( 1 - \eta \eta_0^2 \right) \frac{1 + \beta \eta^3}{1 + \beta \eta^3}
\]
\[
\mu_t = \rho C_{\mu} \frac{k^2}{\varepsilon}
\]
\[
\eta = S \frac{K}{\varepsilon}
\]
\[
S = \left( 2 S_{ij} S_{ij} \right)^{1/2}
\]
where \( k \) is the turbulence kinetic energy, \( \varepsilon \) is the kinetic energy dissipation rate, \( \sigma_k \) is the Prandtl number of kinetic dissipation rate, \( \sigma_\varepsilon \) is the Prandtl number of dissipation rate, \( S_{ij} \) is the shearing rate tensor, \( C_{\mu}=0.085 \), \( \sigma_k=0.719 \), \( \sigma_\varepsilon=0.719 \), \( C_{2e}=1.42 \), \( C_{2e}'=1.68 \), \( \beta=0.012 \), \( \eta=4.38 \).

2.2. Boundary condition

2.2.1. Atmospheric boundary condition. The profile of wind velocity and k-\( \varepsilon \) were defined as follows [3]:
\[
U(z) = \frac{u_*}{K} \ln \left( \frac{z}{z_0} \right)
\]
\[
k(z) = \frac{(u_*)^2}{\sqrt{4 \pi}}
\]
\[
\varepsilon(z) = \frac{(u_*)^3}{K(z+2z_0)}
\]
where \( U \) stands for velocity, \( u_* \) is friction velocity, \( K \) is von-Karman number , \( z \) is height and \( z_0 \) is roughness height, \( d/30 \), \( d \) is mean particle diameter of sand which is considered to be 250 \( \mu m \).

2.2.2. Simulating zone. Figure 1 presents a schematic description of the computational domain. At the inlet face, the wind velocity obtained from field observations is imposed. A free developing wind field condition is specified at outlet boundary. On the boundary at the top and the lateral, a zero-gradient for pressure normal to the boundary is supposed. For bridge and ground boundaries, a non-slip condition is set.

2.3. Mesh generation
The mesh is conducted based on non-uniform grid. All mesh edges were no more than 2-meter-long in domain and no more than 0.2-meter-long near surface of bridge and sand dune. The grid expansion ratio $\gamma < 1.5$ and 5 inflation layers on the solid boundary is set.

2.4. Numerical validation

To validate the numerical method we designed a field observation in this study. Figure 2 shows the layout of experiment. During a process of a 24 h-long sand storm, we obtained wind velocity data from the wind speed profile meter at A station (black points in figure 3(a)), and the data matched into logarithmic type (red line in figure 3(a)). This logarithmic wind speed profile is imposed as inlet wind condition. After a 2000-step iteration until flow field is stable. The simulated wind velocity data at position B can be obtained from CFD-post software and it matches well with wind velocity data obtained from experiment as shown in figure 3.

2.5. Evaluation of wind-blown sand movement

2.5.1. Simulating wind erosion potential on the sand dune. According to Yeh and Tsai [4], wind erosion potential, $P$, was offered in AP-42 Compilation of Air Pollutant Emission Factors published by U.S. Environmental Protection Agency(EPA):

$$ P = 58(u_* - u_{*t})^2 + 25(u_* - u_{*t}) $$

where $u_*$ is threshold friction velocity (m s$^{-1}$).

$$ P = 0(u_* \leq u_{*t}) $$

$$ u_* = \sqrt{\frac{\tau_w}{\rho}} $$

In this work, threshold friction velocity is regarded as 0 m/s, which will overstate sand transport rate. Thus, the equation we used to predict wind erosion rate can be written as:

$$ P_0 = 58u_*^2 + 25u_{*t} $$

2.5.2. Simulating sand depositing rate after the bier. First, to calculate the sand flux blown into controlling zone (figure 5), data of sand transport flux and wind speed is obtained from field observation by setting several sand samplers around pier. The relationship between sand mass concentration $C$ (kg m$^{-3}$) and wind speed $v$ (m s$^{-1}$) is parameterized (figure 4) and result comes out to be:

$$ C = 0.0136 \times e^{-\left(\frac{v}{1.38094}\right)} - 8.7 \times 10^{-5} $$

analyse every grid on boundary plane a, b, c, and d, the sand mass flux through each grid can be written as:

$$ Q_i = C \times v_i \times A_i $$

where $v_i$ is the wind velocity passing vertically through the grid and $A_i$ stands for the grid area. Sum $Q_i$ of all grids in the boundary planes of a, b, c and d in figure 5, we obtained sand mass flux transported into controlling zone: $Q_m = \sum Q_i$. 

Figure 1. Simulating zone

Figure 2. Arrangement of the experiment
Second, to evaluate the quantity of sand saltating from the land surface and leaving controlling zone, we bring in saltation flux equation of Owen in 1964 [5]:

$$Q_o = \frac{c_0 \rho g}{\rho} u^3 \left(1 - \frac{u^2}{u^*_t} \right)^2$$ (20)

According to simulation result, the value of $u_*$ and $u^*_t$ of every grid on land surface (shown in figure 5) are already known. Because the mean diameter of sand is considered to be 250 $\mu$m, $c_0$ is suggested to be 1.5. However, the dimension of $Q_m$ and $Q_0$ is disunity, we defined a new saltation flux variable $Q_s$ based on $Q_o$:

$$Q_s = Q_{0i} \times l_i \times u_{0i}$$ (21)

where $l_i$ (m) stands for grid length perpendicular to the $i$th direction and $u_{0i}$ (m s$^{-1}$) stands for wind velocity in the $i$th direction. Sum $Q_s$ of all grids on land surface shown in figure 5, we obtained sand quantity leaving controlling zone, indicate as $Q_{out} = \Sigma Q_s$.

3. Results and Discussion

3.1. The effect of bridge on the sand dune

Figure 6 presents the simulation results of wind speed (figure 6(a)) and wind erosion potential "$P_0$" (figure 6(b)) over the sand dune without bridge upstream. The results clearly show that the maximum value of "$P_0$" appears near the top of the sand dune, which indicate particles in this position will leave the ground more easily than other positions. According to the simulation results, the maximum wind erosion potential rate "$P_{0max}$" has a value of 17.89 and the maximum wind velocity occurs to be 8.2 m s$^{-1}$. Similar operations have been applied in cases of the bridge is 0 m~20 m from the root of the sand dune.
The values of concerned variables of $P_{\text{omax}}$ and velocity $u_{\text{max}}$ are listed in table 1. Where $S$ stands for distance between the bridge and the sand dune, $P_{\text{omax}}$ is the maximum wind erosion rate on sand dune, $d_u d_h^{-1}$ is velocity gradient and $k$ is turbulence kinetic energy.

Overall, the result shown in table 1 indicates that the difference between wind erosion potential rate with and without bridge is little. However, the wind speed has decreased from 8.2 m s$^{-1}$ to 6.2 m s$^{-1}$ with $S$ increased from 0 m to 20 m. At the same time, wind speed gradient which is related to viscous stress increased from 36.85 to 142.79. Whereas turbulence kinetic energy which is related to Reynolds stress decreased from 0.352 J kg$^{-1}$ to 0.213 J kg$^{-1}$. We know that shear stress is consists of viscous stress and Reynolds stress and thus, friction velocity $u_*$ is related to wind speed gradient and turbulence [6]. In this study, the reason that $P_{\text{omax}}$ did not change observably is determined by the action of velocity gradient and turbulence together.

### Table 1. Result of wind erosion potential rate on the top of sand dune

| $S$ (m) | $u_{\text{max}}$ (m s$^{-1}$) | $P_{\text{omax}}$ | $d_u d_h^{-1}$ | $k$ (J kg$^{-1}$) |
|--------|-----------------|------------------|----------------|-----------------|
| No bridge | 8.2 | 17.89 | 36.85 | 0.352 |
| 0 | 8.2 | 17.77 | 31.89 | 0.328 |
| 10 | 6.1 | 17.99 | 49.87 | 0.287 |
| 20 | 6.2 | 18.03 | 142.79 | 0.213 |

### 3.2. The effect the sand dune working on the bridge

We have calculated the quantities of sand deposition rate in computation domain at four circumstances: without the sand dune, the distance between the bridge and the sand dune is 1 m, 10 m, and 20 m respectively. Table 2 shows the sand mass flux in every controlling plane. It indicates that the quantity of sand deposition rate decreases when there is a sand dune upstream. With the distance $S$ increasing from 1 m to 20 m, the mass of sand accumulated behind the pier per second decreased about 10%. In another word, the sand deposition quantity around the pier will not be badly affected by the sand dune.

### Table 2. Results of sand deposition rate after the pier

| Distance (m) | $Q_{\text{in}}$ (kg s$^{-1}$) | $Q_{\text{out}}$ (kg s$^{-1}$) | $Q_{\text{surf}}$ (kg s$^{-1}$) | Sand deposition rate (kg s$^{-1}$) |
|-------------|----------------|----------------|----------------|-----------------|
| No sand dune | 2.889 | -0.181 | -0.091 | -0.033 | 2.584 |
| 1 | 2.412 | -0.261 | -0.102 | -0.021 | 2.028 |
| 10 | 1.894 | 0.117 | -0.097 | -0.011 | 1.903 |
| 20 | 2.143 | -0.272 | -0.022 | -0.028 | 1.821 |
4. Conclusions
Passing through the desert between Dunhuang and Golmud, the Dun-Go railway is destined to have an effect on neighbouring environment. Although many experiments have been performed to predict how the railway will affect the neighbouring environment, numerical calculation is still needed in consideration of its conveniences. From the consequences of the CFD simulation case in this study, we find out that the upstream bridge will not greatly affect the wind erosion rate on the surface of sand dune for the corporate actions of both wind speed gradient and turbulence make the friction velocity changes little. On the other hand, the sand deposition rate after the bier decreases because of the existence of the upstream sand dune. In a summary, the bridge will not affect wind erosion on this sand dune, and the sand dune will decrease sand deposition rate of the downstream pier.

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