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Numerical simulation of sand load applied on high-speed train in sand environment

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Abstract: High-speed train running in the sand environment is different from the general environment. In the former situation, there will be sand load applied on high-speed train(SLAHT) caused by sand particles hitting train surface. This will have a great impact on the train stability, running drag and surface corrosion. Numerical simulation method of SLAHT in sand environment is studied. The velocity and mass flow rate models of saltation and suspension sand particles and the calculation model of SLAHT caused by sand particles hitting train surface are established. The discrete phase method is adopted for numerical simulating the process of saltation and suspension sand particles moving to train surface and generating sand load. By comparison with the field tests, the numerical simulation reliability is analysed. The theoretical formula of SLAHT changing with cross-wind and train speed is proposed. SLAHT changing law is analyzed. Research results indicate that SLAHT changing with cross-wind and train speed is a quadratic relationship. When train speed is constant, SLAHT increases quadratically with cross-wind speed improvement. When cross-wind speed is constant, SLAHT increases quadratically with train speed improvement.

Key words: sand environment; train; saltation; suspension; sand load; numerical simulation

1 Introduction

Sand environment has great impact on railway traffic safety. When the sand particles hit train surface, it will cause a large SLAHT. On the one hand, it will affect train stability, even leads to rollover accident. On the other hand, it will hit train surface, leads to corrosion and other damage. Therefore, the research on SLAHT in sand environment is the basis of train sand problem. For example, in China Lan-xin Railway Bali Wind Zone, as the railway basically located next to the Tianshan Mountains, both sides of the railway are Gobi Desert. Because of the Siberian cold and Tianshan Pass “wind speed growth in narrow tube” effect [1], the wind blows strongly and frequently in this region [2]. As a result, Gobi Desert sand flow is formed. It makes the Lan-Xin Railway sand disasters extremely serious. Similarly, sand problem along the railway is extremely serious in many countries, such as Russia and Australia. So, the research on SLAHT in sand environment has important engineering significance.

Field observation, wind tunnel experiment and numerical simulation are the main means for sand problem research. Based on field observation and wind tunnel experiment, a series of studies on wind-blown sand are obtained [3]. With the development of numerical simulation method and the improvement of computing performance, numerical simulation study becomes more and more important in sand problem research.

LI et al [4] used two-phase fluid-structure interaction method to study SLAHT under sanstorm environment. ZHENG et al [5] studied motion trajectory of sand particles around railway by using random walk model method. Both two methods mentioned above can not calculate the drag force. As a result, the two methods only apply to small diameter sand particles which have good following performance.

In this work, the discrete phase method is adopted for numerical simulating the process of saltation and suspension sand particles moving to train surface and generating sand load. As a result, sand particles with any diameter can be simulated. The theoretical formula of SLAHT changing with cross-wind and train speed is proposed in this paper. As a result, it can give clear quantitative guidance in engineering application.

2 Numerical simulation method of SLAHT

For the research on sand load generated by sand particles hitting train surface, the discrete phase [6]

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method is adopted. Firstly, flow field around the train [7] is in demand. Then, the initial states including saltation and suspension sand particles are needed to set. That is to say, sand particles saltation and suspension model are needed to establish. Then, the movement of sand particles from initial states to the train surface is simulated. Finally, SLAHT generated by sand particles hitting train surface is calculated according to sand particles impact model.

2.1 Sand particles saltation model

Sand saltation is the process by which sand grains are propelled by the wind in short hopping trajectories close to the ground [8]. When environmental wind speed reaches critical starting wind speed, sand particles “jump” into the air by wind and then transport to upper air [9]. This phenomenon is called sand particles saltation process. Sand saltation motion usually plays the key role in the wind-erosion process [10]. Sand saltation movement generates approximately 75% of the sand transport flux [11, 12]. Sand particles saltation model includes sand particles saltation velocity model and sand particles saltation mass flow rate model.

2.1.1 Sand particles saltation velocity model

Distribution Eqs. (1)–(2) of mixed particle size sand flow saltation velocity probability density is proposed in Ref. [6]. In order to facilitate discussion, equations are listed below.

$$f(v_{\mathrm{E}} \mid U, D)=\frac{\mathrm{e}^{\frac{-v_{\mathrm{E}}}{0.00027\mathrm{e}^{0.2U}D^{-0.1}+0.12}}}{0.00027\mathrm{e}^{0.2U}D^{-0.1}+0.12} \tag{1}$$

$$f(u_{\mathrm{E}} \mid U, D)=\frac{\mathrm{e}^{-\frac{(u_{\mathrm{E}}-0.1\mathrm{e}^{0.1U}D^{0.05}-0.15)^2}{2(0.09\mathrm{e}^{0.03U}D^{-0.1}+0.2)^2}}}{\sqrt{2\pi}(0.09\mathrm{e}^{0.03U}D^{-0.1}+0.2)} \tag{2}$$

where D represents sand particle diameter (m); U represents environmental wind speed (m/s); v_{E} and u_{E} respectively represent vertical component and horizontal component of sand particle saltation velocity (m/s); f represents sand particles velocity probability density.

Sand particles saltation velocity probability distribution is calculated through Eqs. (1)–(2), and it is used to simulate sand particles saltation velocity distribution. According to the distribution, sand particles saltation velocity model is established.

2.1.2 Sand particles saltation mass flow rate model

As it is difficult to directly observe wind-blown sand quantity or quality, the cross-sectional structure of sand flow is measured in existing field observation and laboratory experiment. Thereby, sand flow mass flow rate distribution along the height is obtmined [13]. Integrating horizontal sand flow mass flow rate per unit area along the height [14], the sand transport rate per unit width in wind-blown sand physics [15] is obtained. Its definition formula is shown as [16]

$$Q=C\sqrt{\frac{D}{D_0}}\frac{\rho_g}{g}u_*^3 \tag{3}$$

where Q represents sand transport rate per unit width (kg/(m·s)); C represents empirical coefficient; D_0=2.5×10^{-4} m, represents standard sand particle diameter; g represents acceleration of gravity; ρ_{g} represents sand particles density (kg/m^3); u_* represents friction velocity (m/s). The definition formula of friction velocity [17] is shown as

$$u_*=(U_0-b_1)/b_2 \tag{4}$$

where U_0 represents wind speed at 10 m height (m/s); b_1 and b_2 represent empirical coefficients.

In order to establish the sand particles saltation mass flow rate model, sand particles saltation mass flow rate per unit area is assumed as G firstly. Then, sand particles saltation velocity is obtained according to Eqs. (1)–(2). Thereby, the assumed initial state of sand particles saltation is given as $k(G, U, D)$. Sand particle is assumed as a sphere and only effected by gravity and air resistance during the movement in the air. Then the status of sand particles in any moment during the movement in the air can be calculated.

The horizontal sand flow mass flow rate per unit area at a height h can be obtained by accumulating all the sand mass flow passing through a cross-section l at height h.

$$q(U,G,z)=\sum m\big(k(G,U,D),x,z\big) \tag{5}$$

where x represents horizontal distance between sand particle saltation position and the cross-section l, (m); z represents distance between ground and height h, (m); $m(k(G, U, D), x, z)$ represents sand particles mass flow rate per unit area of sand particles saltating from the saltation position and moving through cross-section l at height h (kg/(m^2·s)); $q(U, G, z)$ represents horizontal sand flow mass flow rate per unit area at a height h (kg/m^2·s)).

Integrating $q(U, G, z)$ along the height and multiplying unit width, the assumed sand transport rate per unit width Q_1 is obtained.

$$Q_1=\int_0^\infty q(U,G,z)\,\mathrm{d}z=\int_0^\infty \sum m\big(k(G,U,D),x,z\big)\mathrm{d}z \tag{6}$$

Combining Eqs. (3)–(4), relationship between sand transport rate per unit width and sand particle diameter, wind speed is obtained as

$$Q_2=C\sqrt{\frac{D}{D_0}}\frac{\rho_g}{g}(U_0-b_1)^3/b_2^3 \tag{7}$$

For Gobi Desert conditions of the Lan-Xin Railway in this study, empirical coefficient C is set as 1.6 and b_1

and b_2 are set as –1.6 and 21.6 separately.

Make the assumed value Q_1 equal theoretical value Q_2. Then G is obtained. That is to say, sand particles saltation mass flow rate model is established.

2.2 Sand particles suspension model

Sand particles suspension model includes sand particles suspension velocity model and sand particles suspension mass flow rate model. Sand particles suspension velocity distribution is given by cross-wind velocity profile distribution. Sand particles suspension mass flow rate is determined according to the field observation data of the Shisanjianfang Area in the Lan-xin Railway Bali Wind Zone. The data can get from Reference 1.

2.3 SLAHT model

After initial state, sand particles finally hit train surface through the movement in the air. It can be got from Ref. [18], according to impact speed, elastic modulus of sand particle, sand particle diameter and sand particle mass, it will generate two types collision between sand particles and train surface: elastic and plastic collision.

The normal direction contact force of single sand particle hitting train surface with elastic collision [18] is shown as

$$F_i = \frac{4}{3}E\frac{a^3}{R} \tag{8}$$

where $F_{\rm i}$ represents single sand particle normal direction contact force (N); E represents single sand particle elastic modulus (Pa); a represents the contact surface radius (m); R represents single sand particle radius (m).

The normal direction contact force of single sand particle hitting train surface with plastic collision[17] is shown as

$$F_i = \pi p_y\left[a^2 - \frac{1}{12}\left(\frac{\pi p_y R}{E}\right)^2\right] \tag{9}$$

where $p_{\rm y}$ represents yield limit of single sand particle (Pa).

The normal direction contact force in each time can be obtained by the theorem of momentum. Integrating it over time and dividing by the total contact time, the time mean normal direction contact force by single sand particle hitting train surface is obtained.

$$F = \frac{1}{t}\int_o^t F_i \mathrm{d}t \tag{10}$$

where F represents time mean normal direction contact force of single sand particle (N); t represents total contact time (s).

Because the impact time of single sand particle hitting train surface is less than 1 ms [18], it is feasible to use the time mean normal direction contact force as the normal direction contact force.

After getting the equation of normal direction contact force generating by single sand particle hitting train surface, SLAHT is got by accumulating all sand particles normal direction contact force.

$$P = \sum_1^n F_j \tag{11}$$

where n represents the total number of sand particles; P represents SLAHT (N); F_j represents time mean normal direction contact force of each sand particle.

Overall, SLAHT model is established.

3 Reliability analysis of SLAHT numerical simulation

In order to analyze the reliability of numerical simulation, numerical calculation results are comprised with field observation tests data under same state. Numerical calculation is got according to the numerical simulation method of SLAHT in sand environment proposed in section 2. The movement of sand particles from initial states to observation position is simulated. Sand pressure generating by sand particles impact train surface is calculated. The Field observation tests data is adopted according to the data of the Shisanjianfang Area in the Lan-Xin Railway Bali Wind Zone in Ref. [1]. The cross-wind speed is 53 m/s. The observation and calculation value of sand pressure are 136.99 Pa and 140.17 Pa, separately. And the difference between numerical calculation result and field observation tests data is 3.07%. It means the numerical simulation method of SLAHT in sand environment established in this paper is credible. The method can accurately simulate the process of saltation and suspension sand particles moving to train surface and generating sand pressure by hitting.

4 Proposing theoretical equation of SLAHT

Numerical simulation of SLAHT in different cross-wind speeds and train speeds is studied by using method proposed above.

4.1 Flow field computation grid and computation conditions for SLAHT

China's CRH380 high-speed train is chosen for study. The roadbed is modeled after simplification. Because bottom flow field of train has small effect on sand load, the bogies are neglected.

The midpoint of train's center section is selected as coordinate origin. X axis is along the length of the train and the positive direction of X axis is the reverse direction of train moving direction. Y axis is along horizontal direction. Z axis is perpendicular to the ground and the positive direction of Z axis is upward direction. Calculation area is set as follows: -780 m$<x<$100 m, -150 m$<y<$50 m, -0.896 m$<z<$50 m.

Structural grid is used to partition the whole calculation area and the total grid number is 6.7 million. The first mesh length around train surface is 1×10^{-7} m. 3D sand flow field calculation model is established and the head surface mesh is shown in Fig. 1.

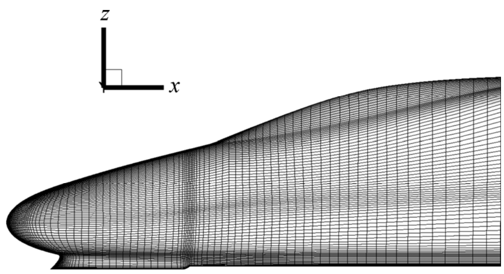

Fig. 1 Head surface mesh of China's CRH380 high-speed train 3D sand flow field calculation model

As the cross-wind speed is relatively small, the incompressible RANS equation is solved by a double precision solver in the commercial software Fluent. The atmospheric pressure is set to 101325 Pa, and the temperature of atmosphere is set to 288.15 K. In order to simulate the turbulence, the SST k–ω model is utilized. The boundary conditions of the computational domain are set as following:

1) The domains on the X and Y axes negative direction are given as the velocity inlet boundary. The velocity in X axis direction is given as train speed. The velocity in Y axis direction is given as cross-wind speed. The velocity in Z axis direction is set to 0.

2) The domains on the X and Y axes positive direction are given as the outlet boundary condition.

3) The domains on the Z axis positive direction is given as symmetric boundary condition.

4) The surfaces of the train are given as non-slip boundary condition.

5) The roadbed and the ground are given as moving wall boundary condition and the velocity is set as train speed in X axis direction.

For the trajectory calculation, the surface of the train, roadbed, ground and the outlet boundary are all set as escape boundary condition, where the trajectory calculation are terminated when the sand particles reach these boundaries.

There are 240 kinds of computation conditions. Three kinds of environmental cross-wind speeds are selected: 35 m/s, 41 m/s, 50 m/s. Train speeds are selected 8 kinds in 0–500 km/h. Sand particle diameters are selected 10 kinds in 0.075–6 mm.

4.2 SLAHT numerical simulation

SLAHT in different cross-wind speeds and train speeds is calculated according to the numerical simulation method proposed above. The calculation results of SLAHT changing with 8 kinds of train speeds is plotted in Fig. 2.

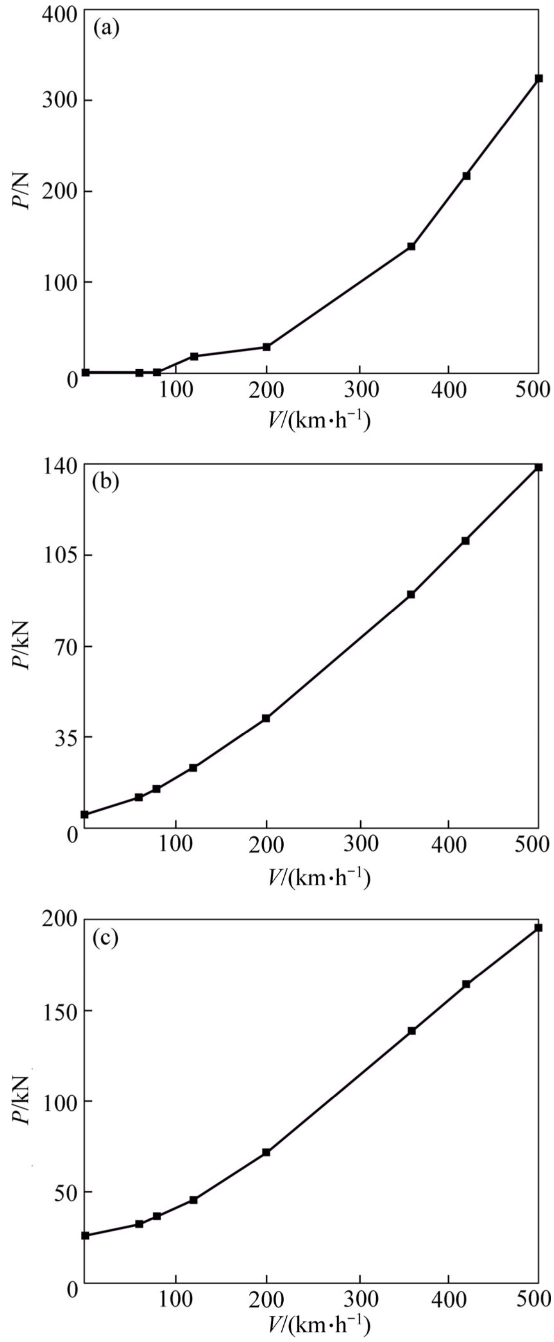

Fig. 2 SLAHT changing with train speed in different cross-wind speeds: (a) Cross-wind speed 35 m/s; (b) Cross-wind speed 41 m/s; (c) Cross-wind speed 50 m/s

4.3 Proposing theoretical equation of SLAHT changing with cross-wind and train speed

It can be got from Fig. 2, both cross-wind speed and train speed have a significant influence on SLAHT. To facilitate discussion, the law of SLAHT changing with cross-wind speed fits firstly. Because there are only 3 kinds of cross-wind speeds, binomial model is selected for fitting. Binomial structure is shown in Eq. (12).

$$P = A_1U^2 + A_2U + A_3 \tag{12}$$

where A_1, A_2 and A_3 represent coefficients related to train speed respectively.

Adaptation range of Eq. (12) is analyzed. A certain wind speed is required for sand particles saltation. And for sand particals, a certain saltation height is needed to hit train surface. In this paper, cross-wind speed for starting generating SLAHT is defined as critical speed U_{Critical}.

When $U<=U_{\text{Critical}}$, $P=0$. Thus, adaptation range of Eq. (12) is $U>U_{\text{Critical}}$.

Next, coefficients related to train speed A_1, A_2 and A_3 is determined. The related data in Fig. 2 is put into Eq. (12), A_1, A_2 and A_3 results corresponding to train speed are got. The calculation results show that A_1, A_2 and A_3 are changed with changes of train speed separately. That is to say, coefficients A_1, A_2 and A_3 are functions of train speed respectively. Coefficients A_1, A_2 and A_3 are shown in Eqs. (13)–(15), respectively.

$$A_1 = -0.00257V^2 - 1.13334V + 93.2118,\quad R^2=1 \tag{13}$$

$$A_2 = 0.23977V^2 + 109.55669V - 6534.36404,\quad R^2=1 \tag{14}$$

$$A_3 = -5.24181V^2 - 2446.36857V + 114525.227,\quad R^2=1 \tag{15}$$

Putting Eqs. (13)–(15) into Eq. (12), theoretical equation of SLAHT changing with cross-wind and train speed is proposed.

$$P = (-0.00257V^2 - 1.13334V + 93.2118)U^2 + (0.23977V^2 + 109.55669V - 6534.36404)U + (-5.24181V^2 - 2446.36857V + 114525.227) \tag{16}$$

where U represents environmental cross-wind speed (m/s); V represents train speed (km/h); P represents SLAHT (N).

Equation (16) is written as general formula in Eq. (17).

$$P = a_1U^2V^2 + a_2U^2V + a_3UV^2 + a_4UV + a_5U^2 + a_6V^2 + a_7U + a_8V + a_9 \tag{17}$$

where a_1, a_2, a_3, a_4, a_5, a_6, a_7, a_8 and a_9 are coefficients with units.

When $U<=U_{\text{Critical}}$, $P=0$. And when $U>U_{\text{Critical}}$, $P>0$. Thus, adaptation range of Eq. (17) is $U>U_{\text{Critical}}$ and $V\geq 0$.

Putting $U=35$ m/s, 41 m/s, 50 m/s into Eq. (16), Eqs. (18), (19) and (20) are got.

When $U=35$m/s, P is shown in Eq. (18).

$$P = 1.88\times10^{-3}V^2 - 0.226V + 6.93 \tag{18}$$

When $U=41$ m/s, P is shown in Eq. (19).

$$P = 0.269V^2 + 140V + 3.30\times10^3 \tag{19}$$

When $U=50$ m/s, P is shown in Eq. (20).

$$P = 0.322V^2 + 198V + 2.08\times10^4 \tag{20}$$

Equations (18)–(20) are written as general formula in Eq. (21).

$$P = B_1\text{V}^2 + B_2V + B_3 \tag{21}$$

where B_1, B_2 and B_3 represent coefficients related to cross-wind speed respectively.

4.4 SLAHT changing law analysis

It can be got from Eq. (16), SLAHT changing with cross-wind and train speed is a quadratic relationship.

When train speed $V>0=$constant, it is the results of Eq. (12). SLAHT increases quadratically with cross-wind speed improvement.

When cross-wind speed $U>U_{\text{Critical}}=$constant, it is the results of Eq. (21). SLAHT increases quadratically with train speed improvement.

5 Conclusions

1) The velocity and mass flow rate models of saltation and suspension sand particles and the calculation model of SLAHT are established.

2) Theoretical equation of SLAHT in sand environment is proposed. SLAHT changing with cross-wind and train speed is a quadratic relationship separately.

3) When train speed $V>0=$ constant, SLAHT increases quadratically with cross-wind speed improvement.

4) When cross-wind speed $U>U_{\text{Critical}}=$constant, SLAHT increases quadratically with train speed improvement.

For engineering application, a maximum operating train speed can be given according to the maximum allowed SLAHT for each environmental wind speed.

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