Damage Assessment of Concrete under Wind-Sand Load

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Abstract. In this paper, a numerical model of wind-sand flow is established to explore the influence of wind-sand flow parameters on the stress state of the concrete. According to the contact mechanics theory, the wind erosion critical pressure of concrete members and the corresponding stress state of concrete are analyzed. A wind erosion damage assessment index based on stress fatigue theory is proposed.

1. Introduction
The erosion wear of wind on solid surface is called wind erosion. Long-term wind erosion will accelerate the durability of concrete damage, and reduce service life, which result in reduced structural safety. Many scholars have studied the material abrasion behavior under wind erosion through wind erosion tests [1–5] and numerical models [6–10] to explore the mechanism of wind erosion. However, there are few studies on material stress under wind-sand load. In this paper, the stress state of concrete under wind-sand load is analyzed and studied by numerical model, and a wind erosion damage evaluation index based on fatigue theory is proposed, which provides a reference for the design of concrete structure in dust storm areas.

2. Numerical Model
The concrete model is a cube with side length of 150mm, and the calculation domain size is 150m x 150m x 150mm(X x Y x Z). Considering the gravity of sand particles, the inlet boundary condition is velocity inlet, the outlet boundary condition is pressure outlet, the side and top of the calculation domain are symmetrical boundary conditions, and the bottom of the calculation domain and the wall of the concrete model are non-slip wall. Numerical calculation uses standard k-ε model, turbulent kinetic energy k and dissipation rate ε equations are shown as in equation (1) and equation (2). The coupling algorithm of pressure and velocity is Phase Coupled SIMPLE. The numerical model was used to simulate the Han’s test [5], and the numerical results were consistent with the experimental results, which verified the accuracy of the model.

\[
\rho \frac{dk}{dt} = \frac{\partial}{\partial x_i} \left[ \left( \mu + \frac{\mu_t}{\sigma_k} \right) \frac{\partial k}{\partial x_i} \right] + G_k + G_h - \rho \varepsilon - Y_m \tag{1}
\]

\[
\rho \frac{d\varepsilon}{dt} = \frac{\partial}{\partial x_i} \left[ \left( \mu + \frac{\mu_t}{\sigma_\varepsilon} \right) \frac{\partial \varepsilon}{\partial x_i} \right] + C_{1\varepsilon} \frac{\varepsilon}{k} \left( G_k + C_{2\varepsilon} G_h \right) - C_{2\varepsilon} \frac{\varepsilon^2}{k} \tag{2}
\]
Where, $G_k, G_b$ are the turbulent kinetic energy caused by the average velocity gradient and buoyancy respectively; $Y_M$ is the effect of pulsation expansion of compressible turbulence on total dissipation rate; $\mu$ is the eddy viscosity; adjustable constants $C_{1e} = 1.44, C_{2e} = 1.92, C_{3e} = 0.09, \sigma_k = 1.0, \sigma_z = 1.3$.

3. Stress Analysis of Concrete Under Wind-Sand Load

Wind erosion is related to wind-sand parameters such as wind-sand velocity, sand content and sand particle size. In order to explore the influence of wind-sand parameters on wind erosion, this paper mainly studies and analyzes the variation law of principal stress of concrete under different sand wind velocities. The working conditions of wind-sand velocities are set as follows: $18 \, \text{m/s}, 22 \, \text{m/s}, 26 \, \text{m/s}, 30 \, \text{m/s}$.

3.1. Critical Principal Stress Analysis of Concrete Wind Erosion

When the concrete just happens wind erosion, the corresponding wind-sand velocity is called the critical wind speed of wind erosion. As Han’s test shown, wind erosion on concrete happens when sand wind continuous action for 3min with sand content of 2% and sand particle size of 0.3mm. The corresponding wind erosion critical wind speed is $13.78 \, \text{m/s}$. In order to explore the stress state of concrete under different wind-sand loads, it is necessary to analyze and study the critical principal stress of concrete under the wind-erosion critical wind-sand load.

The load of wind-sand flow on the structure can be regarded as the net wind pressure caused by wind with sand and the impact pressure of sand particles on the surface of the object [11]. According to Load Code for Building Structures (GB50009-2012) and contact mechanics theory, the net wind pressure on the windward surface and the sand impact pressure are calculated under the wind erosion critical wind speed of $13.78 \, \text{m/s}$, respectively. The sum of the two can be regarded as wind-sand load, which is 2879Pa. However, this method of calculation does not fully consider the parameters such as wind vibration coefficient, body shape coefficient and the coupling between wind and sand at all times. In the calculation process, the sand impact pressure and net wind pressure are both average pressure. In this paper, the numerical model adopts the fluid-solid coupling method to obtain the distribution of wind-blown sand pressure at the critical wind-sand velocity of wind erosion, $13.78 \, \text{m/s}$.

As shown in figure 1, the maximum wind-sand pressure appears in the center area of the concrete specimen, which is 3.4kPa, and the distribution is that the wind-sand pressure decreases from the inside...
to the outside, which is more in line with the actual situation. It is of certain reference significance to
give the maximum wind-sand pressure by using the numerical simulation method.

The stress state of concrete under critical wind erosion pressure is further analyzed, and three paths are selected (shown in figure 2) to study the change of principal stress along the path: path 1 is the surface of the concrete windward surface, path 2 is located in the range of 0-0.08m from the surface of windward surface, and path 3 is located in the range of 0.08m-0.1m from the surface of windward surface. As shown in figure 3, the stress elements on paths 1 and 2 are in the state of tension-tension-compression stress. The elements on both sides of path 3 are in the state of tension-tension-compression stress, and the intermediate element is in the state of three-dimensional tension.

![Figure 3. Principal stress history of different path.](image)

3.2. Stress Analysis of Concrete Under Wind-Sand Load

The stress of concrete structure in wind-sand environment is complex, and the concrete units are in three-dimensional stress state. The principal stress value of the maximum tensile stress unit on the windward surface is extracted from the numerical model when the sand content is 2 %, the sand particle size is 0.3mm, and the wind-sand flow velocity is different (shown in table 1). The unit on the windward surface is in the three-dimensional stress state of tension-tension-compression, which is prone to damage. The maximum value of the first principal stress on the windward surface of the concrete increases with the increase of wind-sand velocity.

| Wind-sand flow parameters | \( \sigma_1 \) (Pa) | \( \sigma_2 \) (Pa) | \( \sigma_3 \) (Pa) | \( |\sigma_1 / \sigma_2| \) |
|---------------------------|-------------------|-------------------|-------------------|-------------------|
| Velocity                  |                   |                   |                   |                   |
| 18m/s                     | 8210.3            | 3918.8            | -2256.8           | 2.12              |
| 22m/s                     | 11983.0           | 5293.5            | -3245.4           | 2.26              |
| 26m/s                     | 17033.0           | 8047.5            | -3847.7           | 2.12              |
| 30m/s                     | 22733.0           | 10738             | -5132.6           | 2.12              |

4. Damage Analysis of Concrete Under Wind-Sand Load

High-cycle stress fatigue generally occurs in the concrete under wind-sand load [12]. With the increase of load, the cracks generated by sand particles impacting on the concrete surface expand and develop from the contact area to the interior in a tortuous path. With the generation of radial cracks, serious damage occurs in the contact area. All cracks interact with each other in an unsteady state to produce a sub-surface of the material. When the crack reaches a certain position, the expansion path turns upward. When the crack reaches the surface of the material, material spalling occurs around the damage area.
4.1. Wind Erosion Damage Criterion

Combined with Miner linear criterion, the damage of concrete model in wind erosion fatigue process is defined as damage variable, shown as equation (3), which is used as the judgment basis of fatigue damage of concrete model in wind and sand environment.

\[ D = 1 - \frac{p}{p_0} = \frac{n}{N} \]  

(3)

Where, \( p \) is the residual strength of concrete after wind erosion; \( p_0 \) is the initial strength of concrete; \( n \) is the number of cycles corresponding to the stress amplitude, \( N \) is the number of cycles corresponding to the fatigue life of the concrete, \( N = 2 \times 10^6 \); Damage factor \( D \) is a variable to measure the degree of material damage: \( D = 1 \) indicates that the material has been destroyed; \( 0 < D < 1 \) indicates that the material has different degrees of damage, the smaller the \( D \) value is, the less the material damage is.

About the fatigue theory, Wholer equation gives the relationship between stress level \( S \) and fatigue life or cycle number \( N \):

\[ S = A - B \log N \]  

(4)

The current \( S-N \) relationship is essentially determined by the uniaxial fatigue test. However, in the actual analysis of wind erosion damage of the concrete, the randomness of wind load and the stability of wind speed distribution in the whole year are considered, and the concrete model is in a multi-axial stress state. Therefore, in the analysis of wind erosion fatigue damage of concrete model, the wholer formula needs to be modified. According to the numerical simulation results, the maximum and minimum stress amplitude of the wind-sand load of the concrete is determined according to Equation (5), so as to calculate the coefficients \( A \) and \( B \) related to the stress ratio and loading mode, and give the modified \( S-N \) curve of concrete wind erosion.

\[ S_{max} = \frac{\sigma_{max}}{f_t} \]  

(5)

Where: \( S_{max} \) — maximum stress level; 
\( f_t \) — tensile strength of concrete, unit is MPa; 
\( \sigma_{max} \) — maximum stress of structural section in fatigue analysis.

In this paper, tensile strength design value 1.71MPa is adopted in all relative calculations. According to the wind erosion test of the concrete, the wind erosion phenomenon of the concrete specimen occurs when the wind-sand with velocity of \( 14m \cdot s^{-1} \) sustains for 3 min. The wind-sand with velocity of \( 26m \cdot s^{-1} \) sustains 1 min, and the wind erosion occurred on the concrete specimens. The strength loss rates were 0.01 and 0.06, respectively. The number of wind-sand loads corresponding to the velocity of wind-sand can be obtained from equation 3. In the numerical simulation results, the maximum cyclic stress \( \sigma_{max} \) is 1.7kPa at \( 26m \cdot s^{-1} \), and the maximum cyclic stress \( \sigma_{max} \) is 6.3kPa at \( 14m \cdot s^{-1} \). Taking the maximum stress amplitude into equation 5, it can be determined that the correlation coefficient \( A \) of the modified \( S-N \) curve is 0.0502, and \( B \) is 0.007.

Based on the modified \( S-N \) relationship, the damage of the windward surface of the concrete model under wind-sand loads with different wind-sand velocities is studied. The relationship curve between the wind-erosion fatigue life and the velocity is shown in the figure 4. The natural logarithm of the wind-erosion fatigue life and the velocity are in line with the linear relationship.
4.2. Wind Erosion Damage Analysis

If the long-term cyclic loading of wind-sand will lead to wind-induced fatigue, long-term cumulative fatigue damage will degrade the performance of components. In order to improve the safety of structural design, it is necessary to carry out quantitative research on material performance degradation of concrete materials during the whole life.

According to Miner linear criterion and damage mechanics theory, the concrete damage model is obtained, such as equation (6):

\[
\begin{align*}
E_D &= \left(1 - \sum_i^n D_i\right)E \\
f_{tD} &= \left(1 - \sum_i^n D_i\right)f_t \\
f_{cD} &= \left(1 - \sum_i^n D_i\right)f_c
\end{align*}
\]

Where, \(E, E_D\) are the initial elastic modulus of concrete and the elastic modulus after \(n\) years, unit is GPa; \(f_t, f_c, f_{tD}, f_{cD}\) are the initial tensile strength, compressive strength, tensile strength after \(n\) year and compressive strength after \(n\) year respectively, unit is GPa; \(D_i\) is the loss variable in year \(i\), \(D_i = d_i \times n \times f\left(v_i\right)\); \(d_i\) is the cumulative damage value in year \(i\); \(f\left(v_i\right)\) is the probability density function of wind velocity at 90° wind attack angle.

According to the measured data of Zha Xiaopeng [13] and equation (5), it is calculated that the elastic modulus of the concrete decreases to 30.1GPa, the tensile strength decreases to 1.58MPa, and the compressive strength decreases to 17.6MPa after 50 years, which have a certain degree of stiffness degradation. Therefore, the wind erosion fatigue should be considered in the structural design process to improve the safety of the structure.

5. Conclusion

This paper studies the mechanism of wind erosion of the concrete under wind-sand load through numerical simulation analysis based on the existing test data, and the results are as follows:

1) When the wind-sand velocity is greater than the critical wind speed, the windward surface element of the concrete is in the tension-tension-compression three-dimensional stress state. The maximum
The value of the first principal stress increases with the increase of wind sand velocity, which is easy to damage.

2) The wind erosion damage is essentially a kind of fatigue damage, and the occurrence of fatigue damage can be judged by the damage factor $D$. The natural logarithm of the wind erosion fatigue life satisfies a linear relationship with the wind-sand velocity.

3) Under the long-term action of wind-sand load, the elastic modulus, tensile strength, and the compressive strength dissipate, and a certain degree of stiffness degradation occurs. A stiffness degradation calculation model is proposed, which provides a reference for the structural design in dust storm areas.

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References

[1] Yunhong H, Yongming X and Shiting Y. 2010 Tribology 30 26-31.
[2] Chi L and Yu G. 2011 Rock and Soil Mechanics 32 33-38.
[3] Yujian F. 2015 the Study of Damage Mechanism and Evaluation of Concrete Under the Erosion of Wind-blown Sand Environment (Hohhot: Hohhot Inner Mongolia University of Technology).
[4] Xiaofei F. 2019 Wind Tunnel Test Study on Wind-sand Flow Field and Wind-sand Resistance of buildings (Changsha: Hunan University).
[5] Chaochao H 2020 Experimental Research on Wind-sand Load and Wind Erosion of Concrete in Aeolian Environment (Beijing: Beijing Jiaotong University).
[6] Xin L. 2013 Experimental Research on Transmission Line Wron in Wind-sand Two-phase Flow (Baodong: North China Electric Power University).
[7] Lin Y C. 2015 Research on LGJ-400/50 ACSR Surface Erosion Characteristics in Wind Sand Environment (Baodong: North China Electric Power University).
[8] Chaochao H. Experimental Research on Wind-sand Load and Wind Erosion of Concrete in Aeolian Environment (Beijing: Beijing Jiaotong University).
[9] LI S, Zheng S. 2017 Aerodynamic performance analysis of wind-sand flow on riding-type hangers of suspension bridges Journal of Vibroengineering 19.
[10] Mei Z. 2019 Wind-blown Sand Load and Wind Erosion of Bridge Under Air-borne Sand Environment (Beijing: Beijing Jiaotong University).
[11] Cheng Z. 2019 Research on Coupled Fluid-Solid Theorem and Dynamic Damage Mechanism of Wind Turbine Based on Data Exchange Methods (Baodong: North China Electric Power University).
[12] Yingjian T. 2020 the Analysis Method of Wind-induced Fatigue of High-rise Reinforced concrete Structure in the life cycle (Dalia: Dalian University of Technology).
[13] Xiaopeng Z. 2008 Theory and Method of Wind-induced Fatigue Safety Prewarning for High-rise Structure (Wuhan: Wuhan University of Technology).