Experimental study on the seismic damage behavior of aeolian sand concrete columns
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ABSTRACT
In order to promote the application of aeolian sand in concrete frame structures, it is necessary to study the seismic damage performance of aeolian sand concrete columns. In this paper, 4 concrete column specimens with different replacement percentages of aeolian sand were tested under lateral cyclic loading. The 4 replacement percentages of aeolian sand were 0%, 10%, 20%, and 30%. The seismic damage process of the specimens was studied by comparing the seismic indexes exhibited in the test. Then, the damage model of the specimens was studied. The results showed that the specimen whose replacement percentage of aeolian sand reached 30% had superior seismic damage performance. Its degree of damage was smaller than that of the other specimens under the same conditions. Its seismic indexes, including the bearing capacity, ductility, stiffness degradation, and energy dissipation capacity, performed much better than those of the other specimens. Besides, this paper proposes a damage model of an aeolian sand concrete column based on current results. This model can be used to evaluate the damage degree of this kind of column.

1. Introduction
In the modern world, sand has been extensively exploited from rivers and mountains in the process of urbanization. This use has led to considerable damage to the protozoan habitat and has depleted many natural resources (Padmalal et al. 2008). Furthermore, the ecological environments of arid and semiarid regions are seriously threatened by desertification, which results in aeolian sand (Zhang et al. 2010). Hence, the application of aeolian sand in concrete structures has great potential to promote the harmonious coexistence of man and nature. This application can leverage the process of desertification into a kind of valuable resource. Moreover, the replacement of sand with aeolian sand will reduce the production cost of concrete.

Many scholars are committed to promoting the development of aeolian sand concrete. Sonbul et al. (2016) studied desert sand in some areas of Saudi Arabia. The results showed that these superfine particles could be used in concrete and cement mortar. However, when the replacement percentage of desert sand reaches 50%, the strength of concrete or mortar is reduced. Taryal and Chowdhury (2012) studied the water-binder ratio, compressive strength and shrinkage performance of concrete specimens mixed with desert sand. The results showed that the water consumption of concrete increases because of the addition of desert sand. Besides, the compressive strength of concrete does not decrease when the replacement percentage of desert sand is controlled within 40%. R’Mili and Ouezdou (2012) carried out experimental research on self-compacting concrete mixed with desert sand. The results showed that the working parameters of self-compacting concrete are improved when the replacement percentage of desert
sand is less than 30%. Chen et al. (2014) analyzed the influence of the water-binder ratio, the content offly ash and the desert sand replacement percentage on the compressive strength of high-strength concrete. The experimental results showed that it is feasible to use desert sand to mix and make high-strength concrete in which the optimum replacement percentage of desert sand is 30%. Dong et al. (2016) conducted a freeze-thaw cyclic test of concrete specimens mixed with aeolian sand and lightweight aggregates. The results show that the incorporation of aeolian sand can reduce the freeze-thaw damage of the concrete. This method can achieve the best effect when the replacement percentage of aeolian sand is 20–30%. Yang et al. (2014) conducted a mechanical property test of high-strength concrete mixed with desert sand. The test results showed that it is feasible to use desert sand instead of ordinary engineering sand. A reasonable replacement percentage of desert sand is from 0% to 40%.

Throughout the current study results, there are few reports about the seismic behavior of aeolian-sand-containing structural members. Concrete frame structures are widely used all over the world. Therefore, it is significant to promote the application of aeolian sand in this kind of structure. This paper studied the seismic damage performance of aeolian sand concrete columns, which are the essential lateral resistance members in aeolian sand concrete frame structures. Four concrete column specimens with different replacement percentages of aeolian sand were designed, constructed, and then tested under lateral cyclic loading. The seismic damage process of the specimens was studied by comparing the seismic indexes exhibited in the test. Besides, the damage model of the specimens was also studied.

### 2. Materials and methods

#### 2.1. Materials and testing program

The properties of the fine aggregate used in this experiment are given in Table 1. The fineness modulus of river sand is 2.9, which belongs to medium sand. Aeolian sand is collected from kubuqi desert, which belongs to ultra-fine sand (The fineness modulus is between 0.7–1.5).

Figure 1 shows the voidage of fine aggregate under three aeolian sand replacement rates used in this study. Table 2 shows the mix ratio and the compressive strength of concrete with different aeolian sand replacement.

When specimens are poured, three cubic concrete blocks with 150 mm side length are reserved for each batch of concrete. These reserved concrete blocks are cured under the same conditions as the specimens. The cubic compressive strength of concrete in Table 2 was obtained by a standard pressure test machine. The surface of the pressure test machine has been cleaned up before testing. Loads are applied at an increasing nominal rate of 0.5 MPa/s until concrete cubes cannot bear larger loads. Then, the maximum load is recorded. All the reinforcements in this experiment are rebars. Table 3 shows the material properties of the reinforcements. The ultimate strength and yield strength of the steel bars were measured by a tensile strength test machine. The tensile speed is maintained at 10 MPa/s until the steel bars yield. After the steel is yielded, the strain rate before drawing is greater than or equal to 0.008/s.

### 2.2. Specimen design

The four columns have the same geometric size. The column width is 250 mm, and the calculated column height is 805 mm, the shear span ratio (the ratio of height to width of a column) is 3.5. PC1, SC1, SC2 and SC3 are the ID numbers of the four specimens. Among them, PC1 is an ordinary concrete column specimen, and SC1, SC2, and SC3 are the aeolian sand concrete column specimens whose replacement percentages of aeolian sand are 0%, 10%, 20%, and 30%, respectively. Table 1 shows the concrete mix ratio of the specimens. The size and internal details of the specimen are shown in Figure 2. Except that the replacement percentages of eolian sand is different, other characteristics of the specimens are the same.

#### 2.3. Specimen loading

The experiment was carried out in the Key Laboratory of Civil Engineering Structure and Mechanics of the Inner Mongolia University of Technology. The test equipment is shown in Figure 3. The foundation beam of the specimen was firmly fixed in steel through which the loading rack was fastened by bolts. The vertical actuator first applies an axial force to the specimens, and the axial pressure ratio remained at 0.2 during the test. The calculated vertical loads on PC1–SC3 columns are 446.25 kN, 460 kN, 478.75 kN, and 490 kN, respectively. Then, the horizontal actuator applies a lateral load to the top of the column, and the load applied point was 875 mm from the upper surface of the foundation beam. While the actuator is elongated, it is regarded as the positive direction of the load. While the actuator is shortened, it is regarded as the negative direction of

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Table 1. Properties of fine aggregate.

| Fine aggregate | Bulk density (kg/m³) | Apparent density (kg/m³) | Particle size (mm) |
|----------------|----------------------|--------------------------|-------------------|
| River sand     | 1697                 | 2597                     | <0.16            |
| Aeolian sand   | 1654                 | 2630                     | 0.16–0.315       |
|                |                      |                          | 0.315–0.63       |
|                |                      |                          | 0.63–1.25        |
|                |                      |                          | 1.25–2.5         |
|                |                      |                          | 2.5–5            |
|                |                      |                          | >5               |

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the load. In this experiment, 3 electronic displacement meters were used to measure the displacement of the corresponding positions of the column.

A loading method based on force-displacement compound control was adopted in this test. Before the structure entered the plastic yielding stage, the lateral loading was controlled by force. The load was a multiple of 10 kN. When the longitudinal steel bars yield, the yielding plastic stage was defined, and the displacement control loading was adopted. The values of the controlled displacement are obtained by integer multiples of the yield displacement $\Delta y$. When the horizontal load drops to 85% of the peak load, the experiment is terminated.

### Table 2. Concrete mix proportion.

| Specimens ID | Replacement percentage of aeolian sand | Water (kg/m$^3$) | Stone (kg/m$^3$) | Aeolian sand (kg/m$^3$) | Sand (kg/m$^3$) | Cement (kg/m$^3$) | Fly ash (kg/m$^3$) | Water-reducing admixture (kg/m$^3$) | Compressive strength (MPa) |
|--------------|----------------------------------------|-----------------|-----------------|-------------------------|----------------|------------------|----------------|-----------------------------------|--------------------------|
| PC1          | 0%                                     | 205             | 1266.36         | 0                       | 492.47         | 389.28           | 43.62           | 3.27                             | 35.7                     |
| SC1          | 10%                                    | 205             | 1266.36         | 49.25                   | 443.22         | 389.28           | 43.62           | 3.27                             | 36.8                     |
| SC2          | 20%                                    | 205             | 1266.36         | 98.49                   | 393.98         | 389.28           | 43.62           | 3.27                             | 38.3                     |
| SC3          | 30%                                    | 205             | 1266.36         | 147.74                  | 344.73         | 389.28           | 43.62           | 3.27                             | 39.2                     |

### Table 3. Steel properties.

| Types       | Yield strength (MPa) | Ultimate strength (MPa) |
|-------------|----------------------|-------------------------|
| Steel bar D6 | 412.5                | 542.6                   |
| Steel bar D16 | 403.1               | 534.7                   |

3. Results and discussion

3.1. Test phenomenon

All of the specimens used in the tests showed typical bending failure characteristics.

During the loading process of ordinary concrete column PC1, cracks first appeared in the tension zone, which distributed in the range of 100–200 mm at the bottom of the column. At this time, the displacement angle was about 1/337. After that, as the experiment continued, horizontal cracks continue to expand and extended, and the number of cracks increased. When the displacement angle reached about 1/87, the development of cracks accelerated obviously, and some cracks intersected to previous cracks. The longitudinal bars yield at this time. Then the force-controlled loading mode was changed into the displacement-controlled mode. When the displacement angle was about 1/43, the cracks expanded more. Much oblique cracks and a few vertical cracks appeared on the side of the column.
The sound of crushed concrete can be heard. As the test came to the later stage, massive concrete peeled. The buckled longitudinal reinforcement can be observed from the outside simultaneously. The failure process of the aeolian sand concrete columns was similar to the ordinary column. The cracking displacement angle of the former was bigger, which were 1/320, 1/318 and 1/306 when the replacement percentages of aeolian sand are 10%, 20%, and 30%, respectively. The cracks of the former grew more slightly compared with the latter. As a whole, the damage degree of the former was smaller than that of the latter when the specimens were at the same displacement angle. Besides, the displacement angle of the former corresponding to the yield point was more significant than that of the latter. The above phenomena became evident with the increase of the replacement percentages of aeolian sand. In the failure stage, a large number of concrete peeled off from the plastic hinge. Besides, buckling longitudinal reinforcement and deformed stirrups can be clearly observed from the outside simultaneously. Figure 4 shows the final states of the 4 specimens.

3.2. Hysteretic performance and skeleton curves

The hysteresis curves of the column specimens are shown in Figure 5. The shapes of the hysteresis loops of PC1, SC1, SC2, and SC3 are relatively similar. At the initial stage of cyclic loading, the curves are close to a straight line. This result indicates that the specimens are in an elastic state and that there is no residual
deformation. The slope of the hysteresis loops shows a gradual decrease with increasing cyclic loading. This result indicates that the stiffness of specimens is degrading and gradually entering an elastoplastic state. In the whole process of cyclic loading, the hysteresis curve becomes increasingly wide. When the pinching effect appears, it indicates that the reinforcement is undergoing slip. As the test continues, the damage accumulates gradually. In the later stage of lateral loading, and the area of a single hysteretic loop increased obviously, which indicated that the specimen had a large energy consumption and residual deformation. When the bearing capacity of the specimen is less than 85% of the maximum lateral load, the severely damaged specimens were considered to be failed. The area and fullness of the hysteretic loop reflect the energy consumption of the structure. Through the comparison of four hysteretic curves, we can observe that the hysteresis curve of SC3 is slightly fuller than that of PC1, SC1 and SC2. The specific values
of such difference will be discussed detailedly in Section 3.4.

The skeleton curves of the column specimens are shown in Figure 6. Scholars have proposed many methods to define yield point. The yield points in this paper were defined by the energy equivalence method (Mahin and Bertero 1976). From Figure 6, we can observe that the carrying capacity of the specimen is improved with increasing replacement percentage of aeolian sand. The skeleton curves can be roughly divided into 4 stages: the elastic stage at the initial stage of the test, the yielding stage, the strengthening stage, and the failure stage. All specimens have similar performance in the elastic stage. It should be pointed out that the yield force of the specimens gradually increases from PC1 to SC1, SC2, and SC3. Besides, the strength of the specimens also decreases successively more slowly from PC1 to SC1, SC2, and SC3. It can be concluded that the resistance capacity to lateral cyclic loading of the specimens is gradually improved with increasing replacement percentage of aeolian sand.

3.3. Feature points of specimens

The feature points of the specimens are shown in Table 4. Among them, $F_{cr}$ and $Δ_{cr}$ are the load and the displacement when the first crack appeared of the specimens. $F_y$ and $Δ_y$ are the load and the displacement when the column yields. $F_{max}$ is the maximum lateral load, and the corresponding displacement is $Δ_{max}$. When the bearing capacity in the test is less than 85% of the maximum lateral load, the column is considered to be failed. $F_u$ is the failure load of the column, and $Δ_u$ is the displacement when the column fails.

The displacement ductility coefficients (the ratio of $Δ_u$ to $Δ_y$) of the specimens measured from the test results are shown in Table 5.

Tables 4 and 5 show that the load-carrying and deformation capacities of PC1-SC3 present a gradually increasing trend with increasing replacement percentage of aeolian sand. SC3 had the most significant improvement compared with PC1. The maximum bearing capacity and ductility coefficients of SC3 are increased by 17.4% and 13.5%, respectively, compared to those of PC1. With increasing aeolian sand content, the cracking load tends to increase. The reason is that the tensile strength of concrete can be improved by replacing aeolian sand with river sand in a specific range. In other words, the concrete in the tension zone of the column is more difficult to crack. It can be concluded that the use of aeolian sand in the range of 0–30% replacement percentage can improve the seismic behavior of specimens to a certain extent.

3.4. Energy dissipation

The energy dissipation is defined as the area enclosed by the hysteresis loops. Figure 7 shows the accumulative hysteretic energy curves of the specimens. The energy dissipation capacity gradually increases with increasing displacement. Besides, with the increasing

![Figure 6. Skeleton curves.](image-url)
of replacement percentage of aeolian sand, the energy dissipation capacity of the 4 column specimens gradually increases at each stage of the test.

The total energy dissipation and the equivalent viscous damping coefficients \( h_e \) of different stages of this test are shown in Table 6. Specimen SC3 has a better performance than the other 3 specimens. The total energy dissipation of specimen SC3 is 1.35 times that of specimen PC1, 1.21 times that of specimen SC1, and 1.10 times that of SC2 in the failure stage. The \( h_e \) of the specimens also tend to increase with the increase of the replacement rate of aeolian sand. These results show that the use of aeolian sand in the range of 0–30% replacement percentage can improve the energy dissipation capacity of specimens to a certain extent.

### Table 4. Feature points of columns.

| Specimen ID | \( F_{cr} \) (kN) | \( \Delta_{cr} \) (mm) | \( F_y \) (kN) | \( \Delta_y \) (mm) | \( F_{max} \) (kN) | \( \Delta_{max} \) (mm) | \( F_u \) (kN) | \( \Delta_u \) (mm) |
|-------------|-------------------|-----------------------|-------------|-------------------|-----------------|-------------------|-------------|-------------------|
| PC1         | 21.1              | 1.61                  | 61.4        | 8.75              | 70.1            | 18.58             | 59.5        | 34.20             |
| SC1         | 21.6              | 1.51                  | 63.8        | 9.25              | 74.8            | 19.12             | 63.6        | 36.73             |
| SC2         | 23.2              | 1.64                  | 67.6        | 9.43              | 79.8            | 19.71             | 68.2        | 39.10             |
| SC3         | 24.7              | 1.58                  | 69.4        | 9.64              | 82.3            | 19.94             | 69.9        | 42.80             |

### Table 5. Displacement ductility coefficients.

| Specimen ID | Value of ductility coefficient | Ultimate drift |
|-------------|--------------------------------|----------------|
| PC1         | 3.91                           | 0.039          |
| SC1         | 3.97                           | 0.042          |
| SC2         | 4.14                           | 0.0445         |
| SC3         | 4.44                           | 0.0489         |

### 3.5. Stiffness degradation

Stiffness degradation is a phenomenon that the stiffness of specimens decreases with the increase of loading cycles. Through comparative analysis of the stiffness degradation, the difference of specimens’ seismic performance can be observed. In Figure 8, the drift is determined by dividing the displacement of peak point in each loading cycle by the height of specimens. The secant stiffness degradation coefficient curve of specimens is obtained by taking the drift as abscissa and the equivalent stiffness degradation coefficient as ordinate.

The stiffness degradation curves of PC1-SC3 have a similar shape as a whole. The stiffness decreases with the increased displacement and loading cycles. It is difficult to tell the difference between the 4 specimens on the graph before the drift is approximately 0.005. The gap of the descending speed gradually widens after the drift is 0.005. From the general trend, it can be observed that the stiffness degradation of the specimens is gradually slower with an increasing replacement percentage of aeolian sand. The stiffness degradation of specimen SC3 is the most subtle among the 4 specimens. It shows that the use of aeolian sand in the range of 0–30% replacement percentage can postpone stiffness degradation of the specimens, especially when the replacement percentage is 30%.

### 3.6. Internal causes

Existing studies have shown that the gradation of aggregates affects the mechanical properties of the
resulting concrete. The voidage can be reduced by improving the gradation, and the force transfer can be more productive, the strength and durability of concrete can be improved. Such a change can be further reflected in the seismic behavior of structural components. Essentially, replacing river sand with aeolian sand is a kind of change of fine aggregates in this paper, it is necessary to proceed with the analysis from this angle. Therefore, the Funk and Dinger (1992a, 1992b, 1992c, 1993, 1994a, 1994b) equation was used to calculate the fine aggregate with a range of 0.075~4.75 mm. Then, the calculation results were compared with the experimental aggregate gradation used in the test.

\[ U(G) = \frac{100 \times (G_l - G_s)}{G_l - G_s} \]  

In Equation (1), \( U(G) \) is the percentage content of particles with particle size less than \( G \). \( G_l \) is the largest particle size, and \( G_s \) is the smallest particle size. The value \( j \) is the distribution modulus. Some studies have shown that the range of \( j \) values for fine particles is relatively small. In view of the influence of aeolian sand studied in this paper, the \( j \) value is taken as 0.28 (Brouwers 2008).

Figures 9 and 10 show the gradation of the fine aggregates. Among the samples, PC1~SC3 are measured in the experiment, and DF is derived from the Dinger-Funk equation. It is easy to observe that with increasing replacement percentage of aeolian sand, the proportion of fine aggregates between 0.075 mm and 0.15 mm grows quickly. The curves PC1~SC2 are closer to curve DF, which indicates that the replacement of river sand by aeolian sand do improve the gradation of fine aggregates in this test. This finding is also consistent with many existing research results of aeolian sand concrete (Dong, Liu, and Xue 2018; Jiang et al. 2018; Li et al. 2017; Bao et al. 2016). However, when the replacement percentage of aeolian sand reached 30%, the previous trend was broken. The corresponding seismic behavior was not weakened as expected when the gradation gap of curve SC3 and curve DF began to increase. In order to show this phenomenon more clearly, the reduction rate of voidage of each group of fine aggregates in Figure 1 above is used as a criterion to describe the improvement of gradation. It is compared with the change rate of some leading performance indicators of the specimens in Figure 11, which is given below.

When the replacement rate exceeds 20%, the voidage of fine aggregate increases, which was 4.3% higher than that when the replacement rate of aeolian sand is 10%, though the growth rate of maximum bearing capacity decreases, the ductility of it are still increasing.

### Table 6. Energy consumption in different stage.

| Specimen ID | Yielding | | | Limit stage | | | Failure stage | |
|-------------|----------|----------|----------|------------|----------|----------|------------|----------|
| PC1         | 894.2    | 0.0291   | 2443.1   | 0.102      | 7037.64  | 0.313    |
| SC1         | 986.7    | 0.0312   | 2571.5   | 0.111      | 7830.93  | 0.327    |
| SC2         | 1136.3   | 0.0328   | 2884.2   | 0.127      | 8635.46  | 0.345    |
| SC3         | 1201.4   | 0.0335   | 3011.2   | 0.139      | 9528.24  | 0.357    |

**Figure 8. Stiffness degradation coefficient curves.**

**Figure 9** and **10** show the gradation of the fine aggregates. Among the samples, PC1~SC3 are measured in the experiment, and DF is derived from the Dinger-Funk equation. It is easy to observe that with increasing replacement percentage of aeolian sand, the proportion of fine aggregates between 0.075 mm and 0.15 mm grows quickly. The curves PC1~SC2 are closer to curve DF, which indicates that the replacement of river sand by aeolian sand do improve the gradation of fine aggregates in this test. This finding is also consistent with many existing research results of aeolian sand concrete (Dong, Liu, and Xue 2018; Jiang et al. 2018; Li et al. 2017; Bao et al. 2016). However, when the replacement percentage of aeolian sand reached 30%, the previous trend was broken. The corresponding seismic behavior was not weakened as expected when the gradation gap of curve SC3 and curve DF began to increase. In order to show this phenomenon more clearly, the reduction rate of voidage of each group of fine aggregates in Figure 1 above is used as a criterion to describe the improvement of gradation. It is compared with the change rate of some leading performance indicators of the specimens in Figure 11, which is given below.

When the replacement rate exceeds 20%, the voidage of fine aggregate increases, which was 4.3% higher than that when the replacement rate of aeolian sand is 10%, though the growth rate of maximum bearing capacity decreases, the ductility of it are still increasing,
which indicates that the filling effect of aeolian sand on river sand is not the only reason for the improvement of seismic performance of the column.

Some studies have shown that aeolian sand contains a large amount of amorphous silica and has a specific pozzolanic activity. Its application can improve the internal structure of the mortar and reduce the porosity of the mortar. Taken as small particles whose size is less than 0.15 mm, the dispersion of aeolian sand in the cement matrix can provide abundant space for various hydration reactions. This configuration can optimize the distribution of hydrated products of cement stone and produce a large amount of H-C-S (hydrated calcium silicate) and other gels. The formation of H-C-S not only improves the cementing material in cement but also improves the behavior of the interface between cement and aggregate (He, Shen, and Dong 2015; Dong and Shen 2013), which may explain why the ductile growth rate of the column is still improved when the aggregate gradation is fully satisfied.

Figure 9. Gradation of fine aggregates.

Figure 10. Particle size distribution of fine aggregate.
The correlation analysis of the curves shows that the filling effect of aeolian sand has an influence on both kinds of seismic performance of the column. The filling effect of aeolian sand has a higher correlation with the increase of the ultimate bearing capacity of the column, whose Pearson correlation coefficient is 0.9495, and has a lower correlation with the increase of the column’s ductile bearing capacity, whose Pearson correlation coefficient is 0.7261. In contrast, the activity effect of aeolian sand may have a more significant correlation with the improvement of ductility of the concrete column and a lower correlation with the improvement of the ultimate bearing capacity of concrete. The quantitative impact of these reactions remains to be further studied.

4. Damage analysis

To study the seismic damage behavior of aeolian sand concrete columns more comprehensively, it is necessary to analyze the damage evolution process of aeolian sand concrete columns. To date, many scholars worldwide have conducted many studies in this area and have proposed some damage models. In this paper, two models are selected to analyze the whole damage process of aeolian sand concrete column specimens under low-cycle repeated load tests: the stiffness-based damage model proposed by Roufaiel and Meyer, the deformation and energy dissipation based model proposed by Park & Ang.

4.1. Damage analysis based on stiffness

A stiffness-based damage model was revised by American scholars Roufaiel and Meyer (1987):

\[
D = \frac{k_{x,i} - k_y}{k_m - k_y}
\]  

(2)

In Equation (2), \(D\) is the damage coefficient of the specimen, \(k_{x,i}\) is the secant stiffness at the maximum displacement of each circle, \(k_m\) is the secant stiffness at the failure point of the specimen, and \(k_y\) is the secant stiffness at the yielding point of the specimen. Equation (2) shows that the value of yield point has a significant influence on this model. In this model, when the specimens did not reach the yield point, it was considered that the specimens were not damaged, this suggests that \(D = 0\). When \(D = 1\), it indicates that the specimen had failed entirely. The calculation results are shown in Figure 12.

Although the Roufaiel damage model is simple in the calculation, and the damage curves obtained from it can roughly show the difference between the specimens, its assumption that the damage condition before yield is zero does not agree with the actual situation. Many cracks can be observed distinctly before the specimen yield. Therefore, the two-parameter model is used to analyze the specimens as follows.
4.2. Damage analysis based on Park & Ang model

Through the analysis of a large number of test results of reinforced concrete beam and concrete column specimens, Park & Ang proposed a two-parameter damage model of reinforced concrete structures (Park and Ang 1985). The cumulative damage is considered in this model, and it is widely used in the research field of seismic engineering. The mathematical expressions are as follows.

\[ D = \frac{X_m}{X_u} + \beta \frac{E_h}{F_y X_u} \]  

(3)

\[ \beta = (-0.447 + 0.073 \lambda + 0.24n + 0.314 \rho_s) \times 0.7^{\rho_w} \]  

(4)

In Equations (3) and (4), \( D \) is the damage coefficient of the specimen; \( \rho_l \) and \( \rho_w \) are the ratios of longitudinal reinforcement and transverse reinforcement; \( n \) is the axial load; \( \lambda \) is the shear span ratio; \( X_u \) is the ultimate displacement of the specimens; \( X_m \) is the maximum displacement; \( F_y \) is the yield force of the specimens; \( E_h \) is accumulated hysteretic energy of the column in the cycle loading.

The value of \( \beta \) is in this model is based on the regression of the measured data of ordinary reinforced concrete beams and columns. To make the model more accurate for describing the damage process of the aeolian sand concrete column, the experimental data of the complete failure point at 85% of the maximum bearing capacity of the columns are brought into the formula (3), the value of damage index \( D \) at this time is determined to be 1. This point is used to deduce the \( \beta \) coefficient. The adjusted \( \beta \) coefficient is as follows:

\[ \beta = k(-0.447 + 0.073 \lambda + 0.24n + 0.314 \rho_s) \times 0.7^{\rho_w} \]  

(5)

\[ k = 1 - 0.0335\alpha - 1.725\alpha^2 \]  

(6)

In Equation (5), symbol \( k \) is the correction coefficient of \( \beta \), which is obtained by fitting the difference curve of \( \beta \) coefficient between SC1~SC3 and PC1. The correlation coefficient of \( k \) is 0.923, which is within an acceptable range. In Equation (6), symbol \( \alpha \) is the replacement percentage of aeolian sand. The calculation results of the damage coefficient of the specimens are shown in Figure 13.

From Figure 13, it can be observed that the damage index \( D \) of specimens reduces with increasing replacement percentage of aeolian sand under the same displacement. This result indicates that the use of aeolian sand in the range of 0–30% replacement percentage can suppress the failure process of aeolian sand concrete columns. By synthesizing many research results, Wang (1999) gave evaluation criteria for different damage levels in the form of defining index range. Table 7 shows the details.

From Table 7, Figures 12 and 13, it can be observed that, compared with the stiffness-based damage model, the damage curve of the Park & Ang model

![Figure 12. Damage ratio.](image-url)
revised in this paper is more appropriate to show the damage process of aeolian sand concrete.

5. Conclusions

This paper researched the seismic damage behavior of aeolian sand concrete columns. Four column specimens in the range of 0–30% replacement percentage of aeolian sand were tested under lateral cyclic loading. Through the analysis of the test results, the seismic damage process and damage model of the specimens were studied. Major conclusions can be drawn as follows:

(1) The use of aeolian sand as fine aggregate can reduce the damage degree of the specimens, particularly when the replacement percentage is 30%.

(2) The seismic indexes, including the bearing capacity, ductility, stiffness degradation, and energy dissipation capacity, perform much better with increasing replacement percentage of aeolian sand.

(3) The increase of the ultimate bearing capacity of the column has a greater correlation with the filling effect of aeolian sand. Besides, the improvement of ductility of the column has a greater correlation with the active effect of aeolian sand.

(4) It is feasible to use the Park & Ang model as revised in this paper to analyze the whole damage process of aeolian sand concrete column specimens.

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