Sand Erosion of Steel-Concrete Composite Girder Cable-Stayed Bridge Is Considered Time-Varying Seismic Vulnerability Analysis

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Abstract. The main disasters in this research project are sandstorm and frost, and the number of sandstorm days accounts for 63% of the total number of days in the whole year. Therefore, in order to study the influence of wind-sand erosion and seismic action on the seismic performance of concrete cable tower columns of steel-concrete composite girder cable-stayed bridge, the cable tower columns of steel-concrete composite girder cable-stayed bridge consolidated by pier and tower beams of a highway in Qinghai province were taken as the research object. After being eroded by wind-sand for 0, 20, 40, 60, 80 and 100 years, they were divided into 6 working conditions. Based on the IDA analysis method, the reasonable damage index was selected as the damage index of the structure, and the seismic vulnerability analysis of the cable tower column of the steel-concrete composite beam cable-stayed bridge under time-varying earthquake was carried out. The analysis results show that the failure probability along the bridge and across the bridge will increase, but the failure probability along the bridge is much higher than the failure probability along the transverse bridge. After 100 years, when PGA= 0.5g, the failure probability along the bridge is 12 times that of the transverse bridge. Therefore, the concrete pylons are not easy to be damaged in the transverse bridge direction.

Keywords: Steel-concrete composite girder cable-stayed bridge; Erosion by wind and sand; Incremental dynamic analysis procedure; Seismic fragility

1 Introduction

Bridges in the hub of transportation, but in the process of use by the impact of bad conditions is serious, such as sand erosion, chloride ions corrosion of steel and so on. Especially for steel-hybrid combination girder cable-stayed bridges, the wind and sand erosion leads to the shedding of concrete from the tower columns, which thins the protective layer of the tower column concrete, and the strength of the tower column concrete is discounted [1], resulting in a reduction in the cross-sectional area of

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the structure [2], and reduces the strength and ductility of the material [3], which then causes the structure to undergo premature damage, resulting in a reduction in the seismic performance of the structure [4], and even makes it impossible to meet the design period of normal use and the structural reliability requirements. There are most sandstorms in north and northwest areas of our country, and the bridge structure is in the severe environment of strong sandstorm, which seriously affects its safety and durability [5]. However, earthquake is another important factor affecting the damage of bridge structure. Therefore, it is very important to correctly evaluate the bridge structure under both wind-sand erosion and seismic action for the full cycle safety of the bridge.

The probability of various failure states of bridge structure under different earthquake intensity is different. In recent years, with the concept of full-cycle durability, the seismic susceptibility of structures affected by bad condition factors has been emphasized by scholars at home and abroad. For example, Jion [6] concluded that the fragility zones of inverted "Y"-shaped towers of cable-stayed bridges tend to appear at the bottom, middle and top of the tower under the excitation of seismic waves at 20 Class III sites. zhong [7] used numerical simulation to derive the limit state of the cables, towers and columns to obtain an accurate estimation of the fragility of the cable-stayed bridge system. Ghosh [8] analyzed the seismic vulnerability of rusted-out reinforced concrete bridge structure, and showed that the seismic performance of the whole structure and key components of the bridge would be attenuated by the corrosion of steel bars, and the failure probability of the structure would be increased. Dai Kuangyu [9] Steel corrosion is an important factor affecting the durability of reinforced concrete structures, which can lead to the extension of natural vibration period of structures, the change of earthquake demand and the attenuation of earthquake resistance.

Therefore, this paper takes the bridge tower of the steel-hybrid composite beam cable-stayed bridge as the research object, considers the influence of wind-sand erosion and seismic action on the time-varying vulnerability, and uses the IDA method to carry out a large number of nonlinear time history calculations to analyze the seismic vulnerability of the steel-hybrid composite beam cable-stayed bridge tower, and discusses the influence of structural seismic capacity changes caused by wind-sand erosion on the structural seismic vulnerability analysis results.

2 Finite Element Calculation Model

2.1 Engineering Background

This bridge is a highway bridge in Qinghai, the main bridge span 155+296+155=606m double-tower double cable-stayed steel-hybrid combination girder cable-stayed bridge, the bridge width is 36.6m, and the main girder adopts bilateral I-beam combination girder. Cable-stayed cables are made of φ7mm high-strength galvanized parallel steel wires with standard strength of 1770MPa, and the cables are protected by double-layer PE sheaths. The main tower is a reinforced concrete structure H-type bridge tower with octagonal cross-section, the main tower is made of C50 concrete, and the height of No.16 and No.17 towers is 113 m. The characteristic period of response spectrum is 0.45 s. The site category is Class II, and the design seismic grouping is the third group.

2.2 Seismic Wave Selection

Based on the U.S. Pacific Earthquake Research Center database, the peak ground acceleration (PGA) is used as an indicator of ground shaking intensity, and 12 seismic waves that meet the characteristics of the site are selected, and the specification and the average response spectrum are shown in Figure 1.

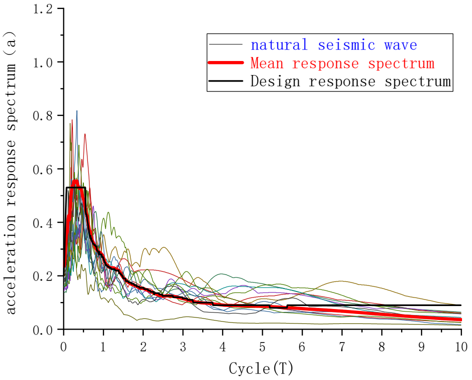


Fig. 1. Responses pectrum graph of 12 seismic waves (5% damping)

2.3 Finite Element Simulation

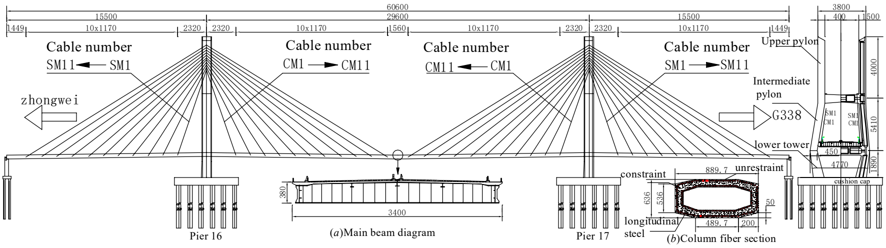


Fig. 2. Bridge layout (unit /cm)

Finite element software is used to establish the finite element model of the whole bridge. The main girder is in elastic state under seismic action, so it is simulated by elastic beam-column unit; the bridge tower columns are simulated by fiber section plastic hinge model, the fiber section is made of concrete fiber and steel fiber, the concrete fiber is constrained (unconstrained) by the concrete, the concrete eigenstructure is made of Concrete02, and the nonlinearity is based on Kent-Scott-Park eigenstructure model, and the reinforcement eigenstructure is made of Steel02, and the eigenstructure is made of Menegottto-Pinto-Filippou model. Steel02, the ontological relationship is Menegottto-Pinto -Filippou model; the diagonal cable is simulated by truss unit, and the material is elastic, and the initial stress of the diagonal cable is simulated by initializing the stress material, as shown in Fig. 2.

3 Variation of Wind and Sand Erosion Parameters

The project is located in the arid climate zone of the mesothermal zone, and the main disasters are gale, sandstorm, drought, frost, hail, etc. The wind is mostly concentrated in January-April, accounting for 63% of the annual gale days. High winds are mostly concentrated in January-April, accounting for 63% of the annual number of days of high winds, sandstorms occur mostly in April and May, the average wind speed of 3.2m/s over the years, and the maximum wind speed is 20.7m/s. The project is located in the mid-temperate arid climate zone, and the main disasters are wind, sand erosion, drought, frost and hail.

In order to study the effect of wind and sand erosion on concrete materials, three 150(mm) x 150(mm) x 150(mm) concrete specimens were subjected to erosion experiments based on the maximum wind speed at the project site, which was then combined with the erosion wear formula [10-11]. According to the erosion time, the erosion amount and folding area of this tower column with time were calculated as shown in Table 1.

Table 1. Relation between aeolian sand erosion quality and C50 concrete strength and time varying age

Time	20a	40a	60a	80a	100a
weight eroded(kg)	$4.09\text{x}10^{-5}$	$8.17\text{x}10^{-5}$	$1.23\text{x}10^{-4}$	$1.63\text{x}10^{-4}$	$2.04\text{x}10^{-4}$
Reduction of area(m^2)	$2.86\text{x}10^{-2}$	$5.72\text{x}10^{-2}$	$8.58\text{x}10^{-2}$	$1.14\text{x}10^{-1}$	$1.43\text{x}10^{-1}$

4 Seismic Vulnerability Analysis

4.1 Seismic Susceptibility Calculation Formula

The seismic vulnerability of a structure is defined as the conditional probability that the structure reaches or exceeds a certain limit state for a given level of seismic intensity: this is called the seismic vulnerability function [11].

$$F_{\phi}(X) = P[T \geq R | IM = x] = \Phi[\frac{\ln m_{T|IM} - \ln m_R}{\sqrt{\eta_T^2 + \eta_R^2}}] \tag{1}$$

$$\ln m_{T|IM} = \lambda_0 + \lambda_1 \ln(IM = PGA) \tag{2}$$

Formulas containing: $\Phi[\bullet]$ is the distribution function under the standard orthotropic; IM is the ground vibration intensity parameter; $T \ge R$ Indicates that the structure has reached or exceeded a certain limit state, T for seismic response. R For seismic capacity m_T is the median value of the seismic response of the structure; m_R is the median value of the seismic capacity of the structure; η_T is the log standard deviation of the seismic response; η_R is the log standard deviation of the seismic capacity of the structure; Parameters λ_0 and λ_1 can be obtained by log-linear regression of the results of the nonlinear time course analysis.

According to the empirical value provided by HAZUS99, when IM takes the ground Peak Acceleration (PGA) as the independent variable, $\sqrt{\eta_R^2+\eta_T^2}$ is set to 0.5[12].

4.2 Definition of Damage Limit States of Cable Tower Columns

High pier (tower) large-span bridge pier top displacement and the curvature of the control section does not appear synchronously, material damage and deformation is not a one-to-one correspondence between the relationship [13]. Therefore, the bending moment-curvature analysis of the control section is performed, and the curvature is used as the basis for judging the damage of piers and columns, and the tower columns are divided into four damage states [14], and the damage states are described in Table 2.

The lower section of the tower column in the left tower of Pier 17 was identified as vulnerable section under 12 natural seismic waves. Each condition corresponds to a maximum axial force under 12 seismic waves, and then use XTRACT section analysis software to analyze the bending moment curvature of the lower section of the middle tower column of the left tower of Pier 17 under the maximum axial force, and get the limit values of damage indicators corresponding to different damage states, as in Table 3.

Table 2. Description of damage state of cable tower column[14]

Faulted condition	Slight failure	Moderate failure	Serious failure	Complete failure
Damagecharacteristics	Have a slight crack	Outer edge steel yield	Appearance of plastic hinge	The core concrete is crushed
damage criterion	$\varphi \le \varphi'$	$\varphi' < \varphi \le \varphi_y$	$\varphi_y < \varphi \le \varphi_u$	$\varphi > \varphi_u$

(Note: φ' is the curvature of the longitudinal bar at first yield, φ_y is the equivalent yield curvature, and φ_u is the curvature of the core concrete at crushing.)

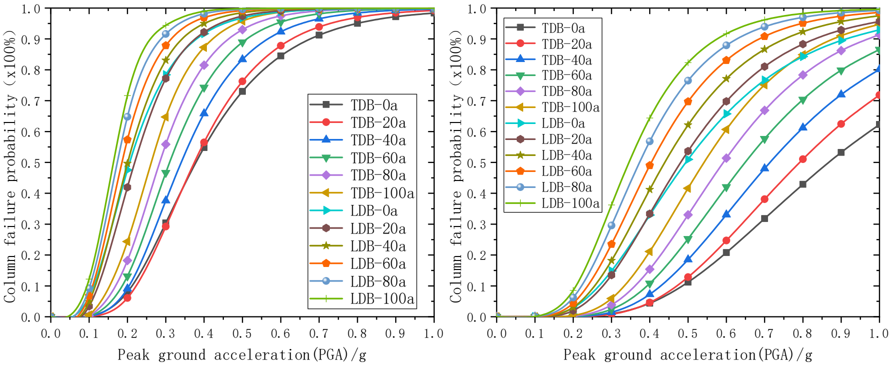
Table 3. Relation table of section curvature (x1000/m) at the lower end of the left tower column of Pier 17

Control cross section	Faulted condition	0a	20a	40a	60a	80a	100a
Section of the lower end of the middle tower of the left tower on Pier 17	Slight failure	0.275434	0.275449	0.275465	0.275539	0.275675	0.275885
	Moderate failure	0.686977	0.694083	0.699707	0.708726	0.718354	0.728139
	Serious failure	0.924435	0.934364	0.941314	0.954869	0.967447	0.981302
	Complete failure	1.574782	1.571404	1.566838	1.562622	1.561471	1.543113

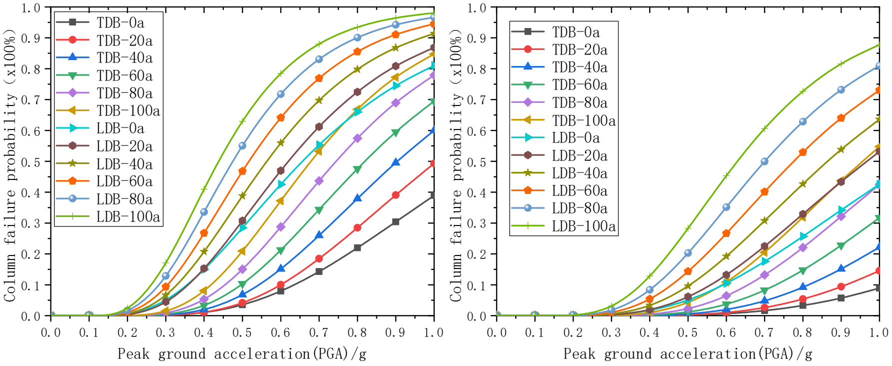
4.3 IDA-Based Paracross-Bridge Tower Susceptibility Curves

Incremental Dynamic Analysis. Incremental dynamic analysis method (IDA) is to adjust the 12 seismic waves that have been selected to conform to the engineering background site category to ten different intensity levels of 0.1g~1.0g according to the equal step, so that a total of 120 waves can be adjusted to observe the change of the seismic response of the structure, so as to analyze the change of the structural linear.

The Vulnerability Curve Is Established. The seismic response of the cable-stayed tower column towers under 120 seismic loads is characterized by curvature logarithmization, and the two coefficients λ_0 and λ_1 of Eq. (2) are obtained by linear fitting, as shown in Table 4 below. Then combined with Eq. (1) for the seismic susceptibility analysis of each damage state, and finally fitted the time-varying seismic susceptibility curve of the wind-sand erosion cable-stayed bridge, and the fitted curve of the seismic susceptibility of the cable-stayed tower columns is shown in Fig. 3.



(a) Slight failure **(b)** Moderate failure



(c) Serious failure **(d)** Complete failure

(transverse direction of bridge-TDB; Longitudinal direction of bridge-LDB)

Fig. 3. Seismic vulnerability curves of tower under different time and age

Table 4. The linear fitting parameters of column curvature and ground peak acceleration (PGA)

Fitting Parameters		0a	20a	40a	60a	80a	100a
Longitudinal direction of bridge	λ_0	1.0444	1.1697	1.1906	1.2115	1.2324	1.2533
	λ_1	-6.5471	-6.4162	-6.2852	-6.1543	-6.0233	-5.8924
transverse direction of bridge	λ_0	1.1023	1.2346	1.2566	1.2786	1.3007	1.3228
	λ_1	-7.1267	-6.9842	-6.8416	-6.6991	-6.5565	-6.4140

From Fig. 3, it is known that the failure probability of both the crosstower columns in the cis-bridge direction and the transverse direction under the same seismic intensity increases with the increase of time; moreover, the failure probability of the crosstower columns decreases with the improvement of the damage index, and the failure probability increases with the increase of the seismic intensity, which is consistent with the damage law of the crosstower columns under the seismic action.

Taking the 0-year working condition as an example, when PGA=0.4g, the probability of slight damage in the downward direction of the bridge is 91.72%, the probability of moderate damage is 32.93%, the probability of severe damage is 15.02%, and the probability of complete damage is 1.78%; whereas, the probability of slight damage in the transverse direction of the bridge is 54.81%, the probability of moderate damage is 4.39%, and the probability of severe damage is 1.07%. The probability of complete damage hardly occurs.

5 Conclusion

The following conclusions are obtained through the analysis of steel-hybrid combined girder cable-stayed bridge under the action of wind-sand erosion:

(1) The failure probability of cable-stayed tower columns in the down-bridge direction increases with time-variation and with the increase of seismic intensity, while the cross-bridge direction also shows the same law, indicating that the failure probability of cable-stayed tower columns is affected by wind and sand.

(2) The failure probability of the single column of the cable tower column is larger than that of the transverse bridge although the stiffness is larger than that of the transverse bridge in the cis-bridge direction because the transverse bridge direction is a similar quilted structure formed by the double tower columns and the tie beams, so it is not suitable to be damaged.

(3) The vulnerability analysis of the cable-stayed tower columns did not consider restorative maintenance, and the purpose of the study is to analyze the seismic vulnerability of the main components of cable-stayed bridges under the natural action of erosion, and the results of the study also show that, in order to ensure the safety of the bridge, it is necessary to regularly inspect the bridge during the life cycle of the bridge and maintain it in due time.

(4) This study only considers the influence of wind-sand erosion on the concrete structure, but does not take into account the influence factors such as temperature and frost on the structure. In the future, these factors can be coupled as a reference for the structure design in extreme environments.

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