Seismic performance evaluation for super-long span cable-stayed bridges

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Abstract: Based on the capacity/demand (C/D) analysis of bridge components, and life cycle and performance based seismic design principles, a practical approach is developed for the seismic performance evaluation of super-long span cable-stayed bridges. According to the approach, the seismic performance evaluation of the Sutong Bridge, which is a cable-stayed bridge with a main span of 1 088 m, is completed, and the practicality of the approach is validated. The earthquake resistance level for super-long span cable-stayed bridges is discussed, including the earthquake level, its corresponding structural performance and check indices. And a set of formula for capacity/demand ratio calculation of bridge components is proposed.

Key words: super-long span cable-stayed bridges; seismic performance; capacity/demand analysis

1 Introduction

China suffers a lot from earthquake disasters, especially in recent years. Therefore, when constructing bridges across rivers and seas, how to ensure the seismic safety of them has become an important issue.

Super-long span cable-stayed bridges are competitive in the constructions of bridges across rivers and seas. Since the investment to construct super-long span cable-stayed bridges is enormous and these bridges always have great political and economic importance, the losses will be correspondingly huge if these bridges are destroyed in earthquakes. Thus, to ensure the seismic safety of bridge structures has great significance. The appropriate seismic countermeasure and effective seismic design are based on the seismic performance evaluation.

At present, there are two methods for seismic performance evaluation. One is the evaluation based on capacity/demand (C/D) analysis or push-over analysis; the other is based on seismic fragility curves. The first method is introduced by *Federal Highway Administration: Seismic Retrofitting Manual for Highway Bridges*[1], which is applied to ordinary steel and concrete bridges with a main span less than 150 m. The capacity/demand analysis is much easier than push-over analysis which at present is only appropriate for ordinary bridges. The difficulty of push-over analysis includes the confirmation of the load pattern and the simulation of the energy dissipation of complicated bridges. Seismic fragility curves describe the probability that the bridge fragility exceeds a certain state in the earthquake, and have been broadly paid close attention to in the past few years[2, 3]. However, it is so tedious to create a seismic fragility curve that present researches focus on the ordinary bridge whose seismic fragility curves are easier to attain and much more applied as well.

For the seismic performance evaluation of super-long span cable-stayed bridges, the capacity/demand analysis is more helpful for several reasons. Firstly, it is difficult to create seismic fragility curves because super-long span cable-stayed bridges are in the minority and they have complicated structure as well as perplexing responds in the earthquake. Secondly, each super-long span cable-stayed bridge has its unique earthquake response which can not be applied to any other bridges even if the seismic fragility curves are created with great cost and innumerable hardships. On the other hand, push-over analysis is only available for ordinary bridges. For super-long span cable-stayed bridges, push-over analysis absolutely fails to present an acceptable load pattern and fails to simulate the dynamic property of the damping devices such as viscous damper in the super-long span cable-stayed bridge. Besides, for the super-long span cable-stayed bridges, it would be required to perform elastically in the earthquake, for which the strength of bridge component is always more concerned with. Therefore, the capacity/demand analysis concerning components is much more

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feasible and more appropriate as well.

This paper will introduce a practical approach of the seismic performance evaluation based on the capacity/demand analysis for super-long span cable-stayed bridges. According to this approach, the paper takes Sutong Bridge for an example to evaluate the seismic performance of super-long span cable-stayed bridges.

2 A practical approach for the seismic performance evaluation

The key problem in the seismic performance evaluation based on the capacity/demand analysis for super-long span cable-stayed bridges is the calculation of the capacity/demand ratio of components. The calculation relates to seismic criterion and seismic effects. To make things worse, the complicated structure of super-long span cable-stayed bridges makes it even more difficult.

According to the practice of Chinese highway bridge construction as well as the guidelines for seismic design of highway bridges in current China, a practical approach of the seismic performance evaluation based on the capacity/demand analysis for super-long span cable-stayed bridges is proposed, as shown in Fig. 1. It is an approach that evaluates the seismic performance of the whole structure with the partial fragility analysis of the components.

The procedure involves several steps. First, determine an appropriate seismic criterion and the seismic input correspondingly. Second, select the vulnerable components of the bridge, and build appropriate finite element model for the time history analysis to calculate the capacity and demand of the vulnerable components. Finally, calculate the capacity/demand ratio of the components and evaluate the seismic performance of the whole bridge.

2.1 Seismic criterion and seismic input

The minimum seismic criterion of bridges is established by the government and is applied to the seismic design code of bridges. However, the seismic criterion for a certain major bridge should be higher than the minimum criterion. It is set down and applied by the proprietor considering the importance of the construction, the economy as well as the risk[4].

Prof. Fan Lichu, Tongji University, takes the lead in suggesting the seismic design principles based on the life cycle and performance for super-long span bridges[5], that is, decide the seismic performance requirements of the bridge to design with the consideration of the importance, repairability, replaceability, inspectability and retrofitability of the important components of the major bridges in the life cycle. In terms of the principles, the parameters of the seismic criterion should involve not only the earthquake level but also the corresponding structural performance and check indices. The different structural performance requirements and check indices require different seismic capacity of the bridge even though the earthquake level is the same.

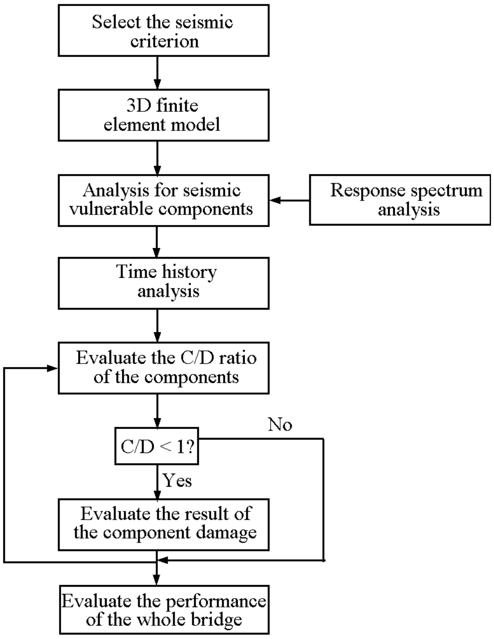


Fig. 1 A practical approach of the seismic performance evaluation for super-long span cable-stayed bridges

It is the first time that the seismic criterion is determined distinctly in the seismic performance research of Sutong Bridge[6]. Because the construction costs huge investment, locates at the rich province, Jiangsu, and is the hinge of the communication lines, it is significant both economically and politically. Therefore, the proprietor selects higher criterion with the consideration of the suggestion from researcher and designer, and correspondingly decides the earthquake level, structural performance requirements as well as check indices, as shown in Table 1 and Table 2.

According to the seismic criterion for super-long span cable-stayed bridges, the seismic input usually involves earthquake parameters in two different probabilities. The earthquake parameters provided by the seismic risk evaluation report of the bridge site usually include design acceleration response spectra and acceleration time histories. And at least 5 acceleration time histories are needed for each earthquake level.

Table 1 Seismic criterion for Sutong Bridge

Earthquake levels	Structural performance requirements
P1: return periods 1 000 years	Elastic structure in the earthquake; keep open to traffic without repair after the earthquake
P2: return periods 2 500 years	Tiny crack in the pylon needless to repair; partial damage in side piers; connection components such as bearings in working order, and all other components undamaged

Table 2 The performance check for the components of Sutong Bridge

Components	Earthquake levels	
	P1	P2
Cable, girder	/	Check the stress
Bearings	/	Check the shear of fixed bearings; check the displacement of free bearings
Side piers	Check stress	Check the strength capacity (considering force reduction)
Pile foundations, tower and pier	Check stress	Check the strength capacity
Expansion joints	/	Check the displacement

2.2 Seismic vulnerable components selection

Because of the structural complexity and the huge number of components of the super-long span cable-stayed bridges, it would be necessary to preliminarily screen out the vulnerable components and then carry out detail analyses for these components.

It is indicated by the earthquake damage data and the seismic performance study for many cable-stayed bridges[7], that the side piers, pile foundations, bearings and connections are the vulnerable components. For a super-long span cable-stayed bridge, the vulnerable parts of the towers and side piers lies on the structural form and the connection conditions, so they have to be preliminarily sifted by the seismic response analysis. It will be better to confirm the seismic vulnerable components of the superstructure such as the girder and the cable, although their responses are generally dominated by the static load.

It takes three steps to complete the preliminary filtration of the seismic vulnerable components. First, take response spectrum analysis. Second, envelop the earthquake response of the bridge structure. Finally, get the seismic vulnerable components in terms of the structural design data.

2.3 Component C/D ratio calculation and seismic performance evaluation

As mentioned above, the capacity/demand ratio is the key index for seismic performance evaluation of the super-long span cable-stayed bridge. Apparently, the calculation of the capacity and the demand will be indispensable to get the C/D ratio.

For the seismic response analysis of a super-long span cable-stayed bridge, response spectrum analysis method is not satisfying. In the seismic design codes in service home and abroad, time history analysis method is suggested to use to analyze the seismic response of a complicated bridge. Therefore, the nonlinear time history analysis method is used to compute the seismic demand of components, while the nominal strength, which is calculated in term of the bridge design codes in service but ignore the safety factor, is adopted as the seismic capacity of components. What to represent the capacity and the demand of the components depends on the structural performance requirements of the earthquake level in the seismic criterion. This paper takes the higher earthquake level for example to calculate the C/D ratio of the super-long span cable-stayed bridge. The formulas are shown in Table 3.

Table 3 C/D ratio formulas for components of super-long span cable-stayed bridges

Structure components	Response components	C/D ratio calculation	Explanations
Fixed bearings	Shear force	$r_{bf} = \dfrac{P_b(C)}{P_b(D)}$	$P_b(C)$ is bearing resistance; $P_b(D)$ is maximum shear demand, and capacity design principle is applied to the bearings on yielded piers.
Isolation bearings, expansion joints	Displacement	$r_{bd} = \dfrac{\Delta(C) - \Delta_t(D)}{\Delta_s(D)}$	$\Delta(C)$ is the displacement capacity; $\Delta_t(D)$ is the maximum displacement demand as a result of the other causes, for example, temperature; $\Delta_s(D)$ is the maximum displacement of the earthquake level.
Side piers	Bending moment	$r_{cm} = \mu \cdot \dfrac{M_c(C)}{M_c(D)}$	$M_c(C)$ is the nominal yielded strength; $M_c(D)$ is the maximum elastic response; μ is the available ductility coefficient of the column.
	Shear force	$r_{cf} = \dfrac{V_c(C)}{V_c(D)}$	$V_c(C)$ is the nominal shear strength; $V_c(D)$ is the maximum shear demand, capacity design principle is applied to the yielded pier.

cont.

Structure components	Force components	C/D ratio calculation	Explanations
Pylon	Bending moment	$r_{\mathrm{tm}}=\frac{M_{\mathrm{t}}(\mathrm{C})-M_{\mathrm{td}}(\mathrm{D})}{M_{\mathrm{t}}(\mathrm{D})}$	$M_{\mathrm{t}}(\mathrm{C})$ is the nominal yielded strength; $M_{\mathrm{td}}(\mathrm{D})$ is the bending moment caused by dead load; $M_{\mathrm{t}}(\mathrm{D})$ is the maximum elastic seismic response.
	Shear force	$r_{\mathrm{cf}}=\frac{V_{\mathrm{t}}(\mathrm{C})-V_{\mathrm{td}}(\mathrm{D})}{V_{\mathrm{t}}(\mathrm{D})}$	$V_{\mathrm{t}}(\mathrm{C})$ is the nominal shear strength; $V_{\mathrm{td}}(\mathrm{D})$ is the shear force caused by dead load; $V_{\mathrm{t}}(\mathrm{D})$ is the maximum shear demand of the earthquake level.
Pile foundations	Vertical capacity of single pile	$r_{\mathrm{pc}}=\frac{P_{\mathrm{p}}(\mathrm{C})-P_{\mathrm{d}}(\mathrm{D})}{P_{\mathrm{sc}}(\mathrm{D})}$	$P_{\mathrm{p}}(\mathrm{C})$ is the nominal vertical capacity; $P_{\mathrm{d}}(\mathrm{D})$ is the pressure of single pile caused by dead load; $P_{\mathrm{sc}}(\mathrm{D})$ is the maximum pressure of single pile of the earthquake level.
	Shear force of pile section	$r_{\mathrm{pf}}=\frac{V_{\mathrm{p}}(\mathrm{C})}{V_{\mathrm{p}}(\mathrm{D})}$	$V_{\mathrm{p}}(\mathrm{C})$ is the nominal shear strength; $V_{\mathrm{p}}(\mathrm{D})$ is the maximum elastic shear force of the earthquake level.
	Bending moment of pile section	$r_{\mathrm{pm}}=\frac{M_{\mathrm{p}}(\mathrm{C})}{M_{\mathrm{p}}(\mathrm{D})}$	$M_{\mathrm{p}}(\mathrm{C})$ is the nominal yielded strength; $M_{\mathrm{p}}(\mathrm{D})$ is the maximum elastic bending moment of the earthquake level.
Steel girder, cable	Stress of the cross section	$r_{\mathrm{s}\sigma}=\frac{\sigma_{\mathrm{s}}(\mathrm{C})-\sigma_{\mathrm{sd}}(\mathrm{D})}{\sigma_{\mathrm{ss}}(\mathrm{D})}$	$\sigma_{\mathrm{s}}(\mathrm{C})$ is the nominal strength of the cross section; $\sigma_{\mathrm{sd}}(\mathrm{D})$ is the dead stress of the section; $\sigma_{\mathrm{ss}}(\mathrm{D})$ is the maximum section stress of the earthquake level.

According to the formulas listed in Table 3, C/D ratios of all vulnerable components are calculated and listed in one table, then damage sequence of all components in the earthquake are analyzed, finally the seismic performance of the whole bridge are evaluated. C/D ratio represents the seismic performance of all components. If it is less than 1.0, the component may be damaged in the earthquake. For the seismic performance evaluation of the whole bridge, it is necessary to consider the result that the partial damages of the components weaken the stability of the whole structure and impact the normal operation of the bridge.

3 Seismic performance evaluation of Sutong Bridge

This paper takes the Sutong Bridge for example to evaluate the seismic performance of the super-long span cable-stayed bridge using the practical approach mentioned above, in order to validate the practicality of the approach. The bridge is a twin-tower cable-stayed bridge with a 1 088 m steel box girder span, and 40.6 m wide. It has inverted "Y" reinforced concrete pylon of 297.7 m high. Side piers include auxiliary piers near pylons, auxiliary piers far from pylons and the transition piers. The deck is supported by sliding spherical steel bearings sitting on top of each side pier which is the separate thin-wall hollow pier of 60 m high. Towers and piers are all founded on bored piles with elevated pile cap.

3.1 Dynamic analytical model of the bridge structure

It is a 3D finite element model, as shown in Fig. 2. The girders, pylons and side piers are simulated as beam elements taking the geometry stiffness caused by dead load into account. It is the master-slave connection between joints of the girder and the cable. The cable is simulated as frame element including the cable sag effect and the geometry stiffness change caused by the dead load.

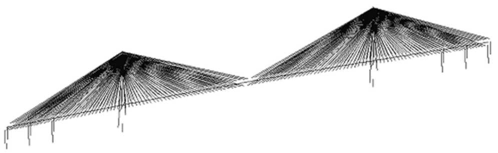


Fig. 2 Dynamic analytical model of Sutong Bridge

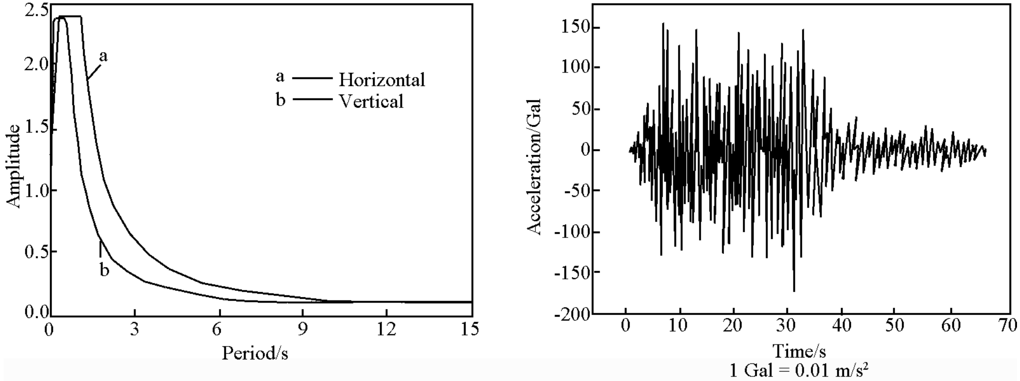
It is free between the pylon and the girder longitudinally but transversely master-slave connection. It is longitudinal free between girders and side piers during dynamic characteristic analysis and response spectrum analysis. During the time history analysis, however, the friction energy consumption effect is considered in the direction that is relatively free between girders and piers.

The pile group foundation is simulated as the piles are embedded under the scouring line at a certain depth which is determined by the equivalent horizontal stiffness of the single pile. And the earthquake parameters at the scouring line are applied to the seismic input.

The analysis of the dynamic characteristic shows that the super-long span cable-stayed bridge is a very long-period structure with its first longitudinal vibration period 15.4 s and the first lateral bending period 10 s.

3.2 Seismic input

The seismic parameters of the bridge were provided by the seismic engineering institute of Jiangsu Province. The parameters of 1 000 years and 2 500 years return period of the seismic input are applied to the seismic response analysis. Each of them includes seismic acceleration response spectrum and seismic acceleration time history with 10 curves each group. The seismic acceleration response spectrum and one of the horizontal seismic acceleration time history curves of 2 500 years return period are shown in Fig. 3.



(a) Acceleration response spectrum (b) Acceleration time history curve

Fig. 3 Seismic input (return period: 2 500 years)

3.3 Seismic vulnerable components selection

As mentioned above, pylons, piers, foundations, bearings and connections are apparently the seismic vulnerable components of the cable-stayed bridge. Therefore, the response spectrum analysis method is applied to the seismic response analysis of the bridge to calculate 400 vibration modes with combination of CQC (complete quadratic combination) method. Two direction combinations of the input depending on the SRSS (square root of the sum of the squares) method are "longitudinal plus vertical" and "transverse plus vertical". The seismic response envelope are drawn according to the result from the analysis. The result shows that the seismic response of the upper structure doesn't dominate the design, the vulnerable positions of the pylon are the bottom section and section over the beam or under the crossing point, and the vulnerable positions of side piers are the bottom section of them.

3.4 C/D ratio calculation of vulnerable components

The C/D ratio of the seismic vulnerable components mentioned above is representatively calculated in the earthquake level P2 with the return period 2 500 year according to structural system (Longitudinally: damper between pylons and girders, $C = 15\ 000$, $\alpha = 0.4$, whose corresponding unit of damping force is kN and of velocity is m/s; sliding bearing between side piers and girders. Transversely: master-slave connection between pylons and girder; master-slave connection between side piers and girders), which is recommended by the technical design phrase of Sutong Bridge[6,8].

Time history analysis method is applied to calculate the seismic response taking the energy consumption effect of the sliding bearings and dampers into account. The direction combinations of the input are also "longitudinal plus vertical" and "transverse plus vertical". All the 10 time history curves of the 2 500 years period are input and analyzed for the seismic response and the results are averaged.

The C/D ratios of bearings and expansion joints are shown in Table 4 and Table 5. Apparently, ratios of the bearings are a little more than 1.0 since the capacity of bearing shear is dominated by the seismic design. The ratios of the displacement of the connection device is 0.92 ~ 1.21 if it is a regular free floating system. However, the damper between pylons and girders can enhance the safety margin and the ratios will be 1.46 ~ 2.24.

Table 4 C/D ratio of the bearings

Bearing position	Transversal resisting force	Vertical tensile resistance	Longitudinal displacement	
			Free floating system	Damper between pylon and girder
Auxiliary pier near the north pylon	1.02	1.19	0.92	1.46
Auxiliary pier far from the north pylon	1.02	1.05	1.00	1.79
North transition pier	1.01	1.19	1.08	2.01
Auxiliary pier near the south pylon	1.18	1.25	1.02	1.84
Auxiliary pier far from the south pylon	1.01	1.05	1.02	1.73
South transition pier	1.09	1.30	1.07	2.00

Table 5 Longitudinal displacement C/D ratio of expansion joint

Expansion joint position	Free floating system	Damper between pylon and girder
North girder end	1.21	2.24
South girder end	1.09	1.85

C/D ratios of pylons, piers and foundations are shown in Table 6. The maximum bending moment of the pile belongs to the pile head section, because of the steel guard barrel under the pile cap of the bored piles in a quite long length with its wall thickness not less than 25 mm. The moment C/D ratio of the pile are calculated in two ways. One takes the transverse constraint effects of the steel guard barrel into account only. The other equivalently converts the steel guard barrel of 15 mm wall thickness into the longitudinal steel bars stressed with the bored pile.

Table 6 indicates that the minimum longitudinal bending moment C/D ratio 2.47 of pylons belongs to the bottom section of the north pylon, that minimum transverse bending moment C/D ratio 1.0 belongs to upper side of the cross beam of the north pylon, and that the minimum bending moment C/D ratio 1.06 and 1.35 without force reduction belongs to the side piers.

Table 6 C/D ratio of pylons, piers and foundations

Component position	Pylon and pier		Pile group foundation					
			Longitudinal input plus vertical input			Transverse input plus vertical input		
	Longitudinal	Transverse	Vertical	M1	M2	Vertical	M1	M2
North transition pier	1.79	1.73	2.29	1.28	2.59	2.31	1.16	2.36
Auxiliary pier far from the north pylon	1.59	1.98	2.59	1.38	2.71	3.21	1.30	2.47
Auxiliary pier near the north pylon	1.06	1.35	2.88	1.14	2.19	3.39	0.90	1.69
North pylon	2.47	1.00	5.26	1.31	2.24	3.15	1.12	2.00
South pylon	3.24	1.07	4.93	1.13	1.93	3.38	1.09	1.92
Auxiliary pier near the south pylon	1.56	1.51	4.47	1.29	2.38	4.49	1.15	2.12
Auxiliary pier far from the south pylon	1.59	2.03	2.67	1.34	2.66	3.02	1.13	2.19
South transition pier	2.09	1.91	2.25	1.34	2.64	3.05	1.72	3.24

Notes: M1 is the bending moment C/D ratio taking the transverse constraint effects of the steel guard barrel into account only. M2 is the bending moment C/D ratio with the consideration of the moment resistance of steel guard barrels.

Also, Table 6 shows other facts as follows. The vertical capacity of the pile is abundant because the C/D ratio is 2.25 ~ 5.26. The transverse bending moment C/D ratio of the most unfavorable pile of the auxiliary pier near the north pylon is the minimum 0.9, while that of the south transition pier is the maximum 1.72, and the others are all between 1.09 and 1.38. The foundation with high pile cap is much vulnerable in the earthquake. Thanks to the steel guard barrels, the moment C/D ratio of the most unfavorable pile of each foundation is apparently enhanced, with the minimum 1.69, the maximum 3.24.

3.5 Seismic performance evaluation of Sutong Bridge

Much clearer conclusion of the seismic performance of Sutong Bridge will be made, if the further comparison of the C/D ratios of all seismic vulnerable components is achieved.

The displacement C/D ratio of the sliding bearings on the auxiliary piers near the north pylon and the bending moment C/D ratio of the most unfavorable pile of each foundation will be less than 1.0, if only the transverse constraint effects of the steel guard barrels are taken into account and the completely free floating structural system is applied. That is, the corresponding siding bearings and the most unfavorable pile will be partial damaged most probably in the earthquake. Theoretically, if a much higher seismic acceleration peak is applied to the bridge, the destruction sequence of all seismic vulnerable components will be: firstly the auxiliary pier far from the north pylon and its foundation, secondly the bearings, thirdly the pylons and their pile group foundations, fourthly the expansion joints, fifthly the foundation of side piers except auxiliary piers, and finally the columns of side piers.

However, if it is a floating system with dampers between pylons and girders and the resistance of the steel guard barrels with 15 mm wall thickness is taken into consideration at the same time, the C/D ratio of each component will be not less than 1.0 and the seismic requirements are surely satisfied. In theory, if much higher seismic acceleration peak is applied to the structure with dampers, the destruction sequence of all seismic vulnerable components will be: firstly the pylon columns, secondly the bearings, thirdly the side pier columns, fourthly the expansion joints and finally the pile group foundations.

4 Conclusion

A practical approach of seismic performance evaluation based on the capacity/demand analysis for super-long span cable-stayed bridges is developed in this paper. The earthquake resistance level for super-long span cable-stayed bridges and the C/D ratio calculation of the components are emphatically studied. According to the procedure, the seismic performance evaluation of the Sutong Bridge, which is a cable-stayed bridge with a main span of 1 088 m, is completed, and the practicality of the procedure is validated.

The results show that the seismic vulnerable components of Sutong Bridge are bearings, expansion joints, pylons, side piers and their foundations. The displacement C/D ratio of the sliding bearings on the auxiliary piers near the north pylon and the bending moment C/D ratio of the most unfavorable pile of each foundation will be less than 1.0, if only the transverse constraint effects of the steel guard barrels are taken into account and the free floating structural system is applied. That is, the corresponding siding bearings and the most unfavorable pile will be partial damaged most probably in the earthquake. However, if it is a floating system with dampers between pylons and girders and the resistance of the steel guard barrels with 15 mm wall thickness is taken into consideration at the same time, the C/D ratio of each component will be not less than 1.0 and the seismic requirements are surely satisfied.

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