

Research on Seismic Response Analysis of High Pier Cable-stayed Bridges

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Abstract. In mountainous areas with complex terrain, high pier cable-stayed Bridges are often used. The pier height and stiffness of the high-pier structure vary greatly, and the earthquake response and failure mode are different. Therefore, the earthquake will have a negative effect on the high pier cable-stayed bridge. This paper firstly introduces the seismic response of cable-stayed Bridges with high pier, including seismic analysis methods and dynamic characteristics analysis. Then, taking Wangheng Beipanjiang Bridge as an example, the seismic response of high pier cable-stayed bridge is studied in detail. The influence of earthquake on bridge pier, bridge span, cross bar and cable is analyzed, and the seismic response and safety measures are further analyzed. Through response spectrum analysis, it is found that earthquake affects the vertical and vertical response of high pier cable-stayed bridges, and the use of oil dampers can significantly reduce this effect. This paper can be an effective reference for seismic response analysis and aseismic research of high pier cable-stayed Bridges.

Keywords: High Pier Cable-stayed Bridge; seismic response analysis; Wangheng Beipanjiang River Bridge; safety measures.

1. Introduction

Cable-stayed bridge became prevalent in the end of the 20th century, as more new materials were introduced, and this bridge is optimal for a span longer than the Suspension bridge and has a greater stiffness compared to suspension bridge. The diagonal separation of cables and the symmetrical shape contribute to these advantages while enhancing the aesthetic appearance of the bridge as well. Especially for bridges in mountainous areas, the demand for high pier cable-stayed Bridges is on the rise, both to meet the high stiffness requirements and to overcome the height drop from the mountain top to the valley. However, frequent seismic activities in mountainous areas bring some hidden dangers to the cable-stayed Bridges with high piers.

Earthquakes have already brought severe impacts on some high pier cable-stayed bridges, like the Taiwan Jilu cable-stayed bridge in Nantou County. A 7.3 magnitude earthquake in Nantou County, Taiwan, on 21 September 1999 led to the failure of the anchorage of the cable-stayed cables of the Jilu Bridge, which led to the collapse of the bridge and caused some economic losses. As the high pier would lead to a reduction in the vertical stiffness of the bridge, the design should be considered more carefully on other parts, such as the height difference between piers, pier connection, span, crossbar and cables. After then, seismic analyses can be applied in details to reduce the impact of large earthquakes, which can also help to avoid accidents like the Jilu Bridge, thus improving the seismic rating of high-pier cable-stayed bridges.

This paper focuses on the seismic responses for these high pier cable-stayed bridges using the Wangheng Beipanjiang River Bridge as an example, and explores certain safety measures that would reduce the influence of earthquakes on high pier cable-stayed bridges.

2. Seismic Influence of High Pier Cable-stayed Bridges

2.1. Seismic Analysis Methods

There are two main seismic analytic methods, which include reaction spectrum method and time course analysis. Both two methods are widely used for the current seismic response studies, but they

are applied in different scenarios, as shown in Table 1. For reaction spectrum analysis, its computational principle can be elucidated using the equations of vibrational equilibrium of a single-mass viscous spring oscillator, which contains a linear relationship. Therefore, it's only applied on simple bridges as it could not predict the dynamic characteristics in a plastic state, despite its simplicity when considering a suitable seismic design code [1].

On the other hand, structures generally tend to experience large displacements under seismic action and will enter an elastic-plastic phase, at which point the response spectrum method, which is only used for the elastic phase and cannot be used for nonlinear analysis, becomes inapplicable. The dynamic time course analysis method is for the seismic effects of the need for more accurate seismic response data, and with the increase in the number of records of strong earthquakes and the refinement of the finite element calculation, it is recognized worldwide as the most accurate analytical method.

Table 1. Comparison of seismic analysis methods [2].

Analysis method	Pros	Cons	Scope of application
Reaction spectrum analysis	Accurate and easier to understand	(1) No reflect the element of holding time; (2) Ignore The random nature of the seismic action and the phenomenon of redistribution of the internal forces of the structure as it enters plasticity; (3) Assume that the ground vibrations at all supports of the structure are identical	Structural dynamic response analysis of complex and simple bridges in the linear elastic phase
Time course analysis	(1) Consider the redistribution of internal forces as the structure enters plasticity: (2) Record the entire process of structural response	(1) Complex and cumbersome calculations; (2) Require detailed and targeted site information	Elastic, plastic analysis of important, complex, and long-span bridges

2.2. Dynamic Characterization Effect

2.2.1. Effect on piers

(1) Tower pier height

The effect of tower pier height could be analyzed under the conditions of constant pier height difference and changing pier height difference. For constant pier height difference, when the overall pier height decreases, the stiffness of the bridge increases. Therefore, the frequency increases and the period of oscillation falls, and this change is more significant in the direction of the bridge. Due to the increase in strength of diagonal cables as the pier height falls, the stiffness of the bridge rises, which enhances the constraints on the main girder by the diagonal cables [3].

On the other hand, the effect on first-order vibration transverse to the direction of the bridge is smaller. For transverse oscillation, the bridge towers and transition piers provide the majority of lateral constraints, so an increasing strength of diagonal cables do not have a great impact on the frequency of oscillation [2].

It is worth to mention that both changes are not linear, as the rate of change of both vibrations falls when the pier height decreases, which could be described as an exponential recession for the change in period. For a decreasing pier height difference, the period of both oscillation falls, even though the change in transverse first-order vibration is more significant. The change in period of transverse oscillation contributes majorly to the height in high pier: as the height difference increases, the transverse stiffness of the bridge falls and the bridge becomes less stable. Therefore, in order to reach a safe design, the height difference between the piers should be hold constant [4].

(2) Pier connection

The period of oscillation could also be influenced by the choice of fixed support. Choosing the lower pier, the higher pier or both piers as the fixed support could have a huge impact on the frequency of oscillation, especially for the first-order vibration in the direction of the bridge. As the fixed support

is linked to the crossbeam of the main tower, which already has transverse restraint, the addition of fixed support does not affect the transverse stiffness, thus the transverse vibration will not be altered. Nevertheless, using fixed support greatly increases the stiffness in the vertical direction, and the period of the vertical vibration falls. Comparatively, adding fixed supports to both piers is more advantageous, because the asymmetry of the stiffness will lead to a smaller change in period [2].

2.2.2. Effect on span

Taking Hangzhou-Changsha Passenger Dedicated Railway Changsha Hub South West Upward Liaison Line Single Tower Cable-stayed Bridge as an example, the longer the span, the lower the stiffness of the bridge, thus the frequency of oscillation increases [5]. This could be shown on the first and third span of the bridge, as the first span is the largest and has the lowest stiffness, with a fundamental frequency of only 0.981 Hz, while the third span is the smallest and has a larger stiffness, with a fundamental frequency of 6.70 Hz. Also, the vertical stiffness is lower than the horizontal stiffness of this bridge.

2.2.3. Effect on crossbar

The position of crossbars alters both types of vibrations. When the crossbars are closer to the main beam, the transverse stiffness of the bridge increases, and the period of transverse oscillation decreases. Furthermore, when adding the crossbar at the lower tower pillar, the stiffness is higher compared to that when adding the crossbar at the middle tower pillar, while the stiffness falls when the crossbar is added at the upper tower pillar. This trend is also true for the first-order vibration at the direction of the bridge, even though adding crossbars does not affect the vertical stiffness. It shows that the influence of beam weight on the first order vibration along the bridge is the main factor: the influence of beam weight on the period is greater than that of increasing the longitudinal stiffness [2].

2.2.4. Effect on cables

Overall, earthquakes do not have a large impact on cables. As the tension difference in the same position is small, the height difference of piers does not have an impact on the response of tension to earthquakes. Due to the symmetrical shape of the bridge, and the cables transmit most of the vertical forces of the crossbar, the tension difference is insignificant [2].

3. Seismic Analysis of Beipanjiang Bridge

3.1. Project Overview

The controlling project of Wangmu-Anlong section of Yuqing-Anlong Expressway is Wangheng Beipanjiang Bridge, the superstructure of which is 3X30m pre-stressed concrete box girder (150+328+150m) pre-stressed concrete cable-stayed bridge + 3X30m pre-stressed concrete box girder; the starting pile number is K20+090.000, and the ending pile number is K20+907.500, and the centre of the main bridge is K20+500.000, and the total length of the bridge is 817.5m. The starting pile number is K20+090.000, the ending pile number is K20+907.500, the centre of main bridge is K20+500.000, the total length of the bridge is 817.5 m. The main tower of the lower structure adopts thin-walled hollow core folded H-type cable-stayed tower with group pile foundation; the No.3 and No.6 transition piers are thin-walled hollow core portal frame piers with group pile foundation; the approach bridges are double-column type piers, all of which are pile foundation; the abutment of the Wangmu Bank is gravity u platform with group pile foundation; the Anlong Bank is piled column type bridge platform with pile foundation [6].

3.2. Seismic Response

3.2.1. Dynamic characterization

By using finite element analysis method used in Seismic Performance Study of Wangheng Beipanjiang Bridge, the first ten vibration patterns (Table 2) have shown a reduction in the period by

86.5%, which is accompanied by a more asymmetric torsion and vibration of this bridge when the number of vibration patterns increases [7]. This response is majorly an exponential decrease, as the greatest fall is between the first two vibration patterns when the period falls from 10.00 to 3.98s, which is approximately a 60% reduction.

Table 2. Dynamic characteristics [7]

Order number	Period (s)	Vibration characteristics
1	10.00	Main beam longitudinal drift + vertical bending
2	3.98	First-order symmetrical vertical bending of main beam
3	2.81	First-order asymmetrical vertical bending of main beam
4	2.46	First-order lateral bending + torsion of main beam
5	2.09	Lateral bending of the main tower
6	1.83	First-order symmetric torsion of main beams
7	1.56	First-order symmetrical vertical bending of main beam
8	1.43	Main girder lateral bending + main tower lateral bending
9	1.35	Anti-symmetric torsion of main beams
10	1.35	Anti-symmetric lateral bending of the main beam

3.2.2. Reaction spectrum analysis

Even though this bridge is thought to be symmetric due to the similarity in height of piers and the position of the two piers, there is still disparity when analyzing the torque, axial force and displacement in different directions. The direction of seismic input of this bridge is adopted as transverse + vertical and longitudinal + vertical [8].

(1) Horizontal response

Overall, the displacement in the horizontal direction is less significant despite the greater axial force and torque that are applied. The results of internal forces in cross sections of reaction spectrum parts are shown in Table 3. The main girder main span mid-span transverse displacement is 26.9cm, which is about 37.1% of the longitudinal displacement. However, for the torque at pier 4, pier 5 and the main girder main span, the torque is exceptionally higher than that in the longitudinal direction: taking the torque at the main girder as an example, the transverse torque is 2256% of the longitudinal torque. Furthermore, the transverse axial force at bottom of pier 4 and pier 5 is greater than that in the longitudinal direction, as the transverse axial force is 175% and 261% of the longitudinal force at these two positions respectively. This effect contributes to the horizontal constraints well-established at the lower position of the two piers, which greatly enhances the stiffness in the transverse direction and reduces the displacement as the axial force and torque rise [8].

Table 3. Results of internal forces in cross sections of reaction spectrum parts [8]

Cross-section position	Longitudinal+vertical		Transverse+vertical	
	Torque (kN m)	Axial force (kN)	Torque (kN m)	Axial force (kN)
Pier 4 tower bottom	245780.0	16805.0	352120.0	29408.0
Pier 4 pier bottom	1118700.0	62241.0	2697900.0	62310.0
Pier 5 tower bottom	253950.0	11510.0	328760.0	30024.0
Pier 5 pier bottom	1449600.0	62126.0	2472900.0	61555.0
Main girder main span mid-span	18862.0	3430.9	425590.0	2875.5

(2) Longitudinal response

Compared to the axial force and torque experienced in the horizontal direction, this bridge has a weak carrying capacity in the longitudinal direction. Although most of the force and torque are smaller in the longitudinal direction, the displacement in the main girder is 72.6 cm, while the displacement is only 26.9cm in the horizontal direction, as shown in Table 4. This is largely a result of the longitudinal floating system applied, which reduces the amount of strength to resist the axial force and torque, so the displacement will be more significant.

Table 4. Cross-section displacement results for part of the reaction spectrum (cm) [8].

Cross-section position	Longitudinal+vertical	Transverse+vertical
Main girder main span mid-span displacement	72.6	26.9

Moreover, the height difference between pier 4 and 5 (even though not obvious) still contributes to a change in torque in the longitudinal direction, which is the direction along the bridge. The pier height of pier 4 and 5 is 190.4 and 187.9m respectively, and the torque on the pier 4 is 3.22% lower than that in pier 5. This is due to the increase in longitudinal stiffness as the height of the pier falls, which increases the amount of torque it could withstand. However, the axial force applied to both piers does not fulfil this conclusion, as the axial force on pier 4 is 31.5% smaller. Therefore, whether this conclusion meets the standards in the predicted dynamic characterizations needs to be examined more carefully [2].

3.3. Safety Measures

3.3.1. Elastic cord

Even though the anti-seismic effect of elastic cord is not as outstanding as that of the damper, it could still improve the impact of forces on the bottom of the main tower and the main tower pile driver within a given range of tension. There are four phases included when altering the tension of the elastic cord.

In the first phase, the stiffness of the elastic cord is between $0 \sim 1 \times 10^4$ kN/m. In this stage, elastic cord separates part of the inertial force on the bridge deck to the lower pylon. As the moment arm of the lower pylon is relatively short, the stiffness of the elastic cord rises, so more inertial force is transmitted by the elastic cord. Therefore, the tower bottom bending moment reaches its lowest point in this stage.

In the second phase, the stiffness of the elastic cord is between $1 \times 10^4 \sim 6 \times 10^4$ kN/m. Although the transmission paths don't change much, the forces of inertia caused by the increased frequency of the whole system increase very quickly. Therefore, the shear forces and bending moments at the bottom of the tower rise steadily.

Then, when the stiffness is between $6 \times 10^4 \sim 2 \times 10^5$ kN/m, the change in dynamic characteristics leads to a change in structural response. As it is in the first order vertical bending vibration pattern, peak shear and bending moments at the top of the pile are reached.

At last, when the stiffness is between $2 \times 10^5 \sim 1 \times 10^6$ kN/m, the order of vibration increases and contributes to a rise in the bending of the main tower. This high-order vibration will increase the tower bottom bending moment and reduce the shear force and bending moment at the top of the tower. The use of the 1×10^4 kN/m elastic cable is the most appropriate, considering the forces at the bottom of the tower section and the displacement requirements at the top of the tower and at the girder end, as well as the forces in the monopile section [9].

3.3.2. Damper

Taking oil damper as the damper used in "Seismic Performance Study of Wangheng Beipanjiang Special Bridge", the damping force is the smallest when the deformation of the bridge is the greatest, as the force approaches to zero [8]. When the damping force of the oil damper is the greatest, the deformation of the bridge is the smallest as well as the elastic force. Therefore, a phase difference of 90 degrees exists between the damping force of the oil damper and the elastic force of the structure. Overall, this does not increase the resultant force exerted on the bridge, which is a great advantage of using an oil damper. When the damping force is not proportional to the relative velocity, the relationship between the force and the velocity could be described as:

$$F = C v \alpha \quad (1)$$

Where F is the damping force, C is the damping coefficient, v is the velocity and α is the velocity index. For this specific bridge, the most suitable oil damper has a C of 3000 and α of 0.2 as the best

parameter, as the maximum longitudinal displacement at mid-span of main girder is only 0.3567m in this case, as shown in Table 5.

Table 5. The maximum longitudinal displacement at mid-span of main girder [8].

Number of dampers	Damping coefficient of a single damper (kNs/m)	Velocity index	Maximum longitudinal displacement at mid-span of main girder (m)
4	1000	0.2	0.5965
4	2000	0.2	0.4617
4	3000	0.2	0.3567

3.3.3. Combination of elastic cord and damper

It is clearly shown by Table 6 that the combination of damper and elastic cord does not lead to an improvement in reducing longitudinal displacements, as the displacement of the combination is 270% and 151% for the north beam end, and 203% and 164% for the north top of the tower compared to the displacements of the solidification system and the damper respectively. This combination does not provide the ideal situation where the elastic cords improve the forces at the base of the structural tower and the dampers control the displacements; due to the combined involvement of the structural elastic cords to improve and the dampers in the forces, the response of the individual cross-sections is more unfavorable than if the dampers were applied individually. In this circumstance, the complexity of the parameters does not elucidate the most important variable in changing the structural response. Therefore, using the damper directly is the best choice in reducing the seismic impact [9].

Table 6. Comparison of longitudinal seismic displacements (m) [9].

Position	Semi-floating	Flexible connection	Solidification system	Damper	Combination of damper and elastic cord
North beam end	1.043	0.568	0.107	0.192	0.289
North top of the tower	1.073	0.597	0.172	0.214	0.350

4. Conclusion

This paper discusses the seismic effects of high pier cable-stayed Bridges, and analyzes the seismic effects of Wangheng Beipanjiang Bridge as an example. In the seismic analysis of the high pier cable-stayed bridge, two kinds of seismic analysis methods are introduced first, and then the effects of pier and platform connection, span, beam and cable are demonstrated and explained. Then, an overview of the Wangheng Beipanjiang Bridge is given, and the seismic responses of the bridge and the safety measures to minimize these reactions in the event of an earthquake are introduced. Overall, this paper draws several important conclusions:

(1) When the pier height difference of the high pier cable-stayed bridge is small, the fixed support is small, the span is small, and the lower column and beam are added, the stiffness is usually high and the vibration period is reduced.

(2) The response spectrum analysis shows that the transverse and vertical responses of the high pier cable-stayed bridge are more significant than those of the longitudinal and vertical responses, and elastic cables and dampers should be used to minimize the seismic effect.

(3) The horizontal and longitudinal responses of Wangheng Beipanjiang Bridge do not represent all high pier cable-stayed Bridges, and the trends shown in Table 3 and Table 4 are not absolute. For other Beipanjiang Bridges, such as the Beipanjiang Bridge in Duge Town, more investigations should be conducted, which will support the conclusions about Wangheng Beipanjiang Bridge.

(4) The seismic effects of high pier cable-stayed Bridges should be further analyzed based on the relevant information of seismic zones in the region. Because the occurrence of earthquakes is closely related to the geological background, the study of seismic effects of high pier cable-stayed Bridges can be concentrated in the areas with high seismic activity frequency.

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