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# SEISMIC DESIGN OF HIGH PIERS FOR MOUNTAIN BRIDGES

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**ABSTRACT**

Because of complex topography of bridge sit, many high piers bridges with unconventional configurations in western mountainous areas of China are used in highway. The damage of the bridges in the Wenchuan earthquake told us that the new concepts and measures should be used in mountain bridges design. The importance of the seismic concept design, the structure analysis and the details of seismic measures for bridge was discussed. Some advices in the seismic design of bridge are given.

**Keywords:** mountain bridges, high piers, earthquake resistant design, seismic measure.

## INTRODUCTION

In these years, many highways are being built in the southwest and northwest of China. Because of complex topography of bridge sit, many high piers bridges with unconventional configurations in mountainous areas are used. A investigation about highways' bridges, including those who have completed and are planning, show that about 40% bridges, the height of piers, are more than 40-meter high. Such as Lancangjiang bridge of Xiaowan nuclear power station in Yunnan province, the highest pier is 115-meter high, Luohe bridge of Huangyan highway in Shanxi province, the highest pier is 143-meter high, etc. The mountain bridges have several characteristics. First, many small-radius curved bridges are used (Figure-1). Second, the continuous beam bridges and rigid frame bridges are always used in superstructure. Third, thin-walled hollow piers are always used in substructure, the height of pier is varying a great deal and the slenderness ratio is large (Figure-2).

For the severe damage of bridges in the Wenchuan (Sichuan province, China) earthquake, most designers have pay attention to the seismic design of high piers for mountain bridges [10]. The newly revised rules of "Guidelines for Seismic Design of Highway Bridges" (JTG/T B02-01-2008, issued by Ministry of Transport, China), for not more than 40m high piers of the regular bridge, have done a detailed provisions [8]. For irregular bridges and special bridges, the new rules call for a special study. It is difficult to repair after the bridge damaged by the earthquake, because designers of domestic and foreign lack the design experience about high piers under high-intensity earthquake.

After summing up the damage of the major earthquake and Wenchuan earthquake in the world, the damage of high piers bridge in mountain mainly focuses on the following. First, the damage of abutment (Figure-3), such as position of abutment changed, abutment settlement, wing-wall damaged and cracking, dislocation of construction joints as well as collision and damage of the main beam. Second, the damage of piers and piles (Figure-4), such as piers and piles inclined, breaking and cracking, the steel yielded of lower part of concrete bridge pier, etc.

**Figure-1.** Curve bridge of highway in Guizhou province

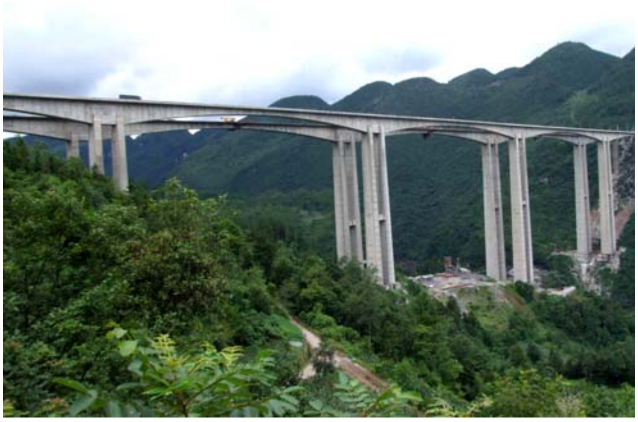

**Figure-2.** Mashuihe bridge (142m high of pier)

Third, the damage of supports (Figure-5), such as supports inclined, cut, anchor bolt pull-out, roller supports rolling off, supports its own destruction, etc. Forth, the damage of main beams(Figure-6), falling of the beam is the most common, the reasons are the collapse of piers, damage of supports, collision of beams and large relative displacement between adjacent piers resulted in lacking of adequate beam device.

In this paper, three aspects about seismic design of high piers bridge, including seismic concept design, seismic computing and details of seismic measures, are recommended.

**Figure-3.** Damage of abutment.

**Figure-4.** Concrete crusher of pier.

**Figure-5.** Damage of support.

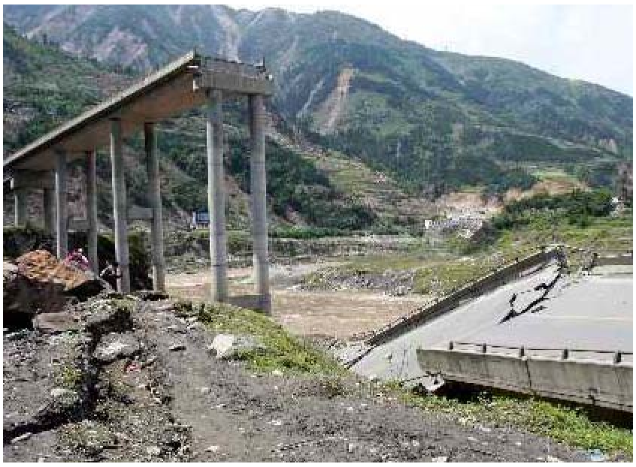

**Figure-6.** Damage of main beam.

## SEISMIC CONCEPT DESIGN OF MOUNTAIN HIGH-PIER BRIDGE

Data show that the reasonable form and successful seismic design of the structure can greatly reduce or even avoid the occurrence of damages [3, 9]. The arch bridge, rigid-frame Bridge, simply supported Beam Bridge, and continuous girder bridge has a different performance in the Wenchuan earthquake. For example, Miaoziping Bridge (Figure-7) has a better concept of design in Wenchuan earthquake. The main bridge uses rigid frame bridge, and the members of crossing the fault use the structure of simply supported beam. Only one beam is falling, and full-bridge collapse did not happen.

The reasonable concept design, including the choice of bridge site, the selection of Bridge-program, the choice of the lower part of the structure and the upper part of the structure, the choice of connecting components and the choice of reinforcement, and so on, all the members of bridge should meet the requirements of seismic design.

(A) (B)

**Figure-7.**
**A**. Main bridge of Miaoziping.
B. Falling beam of Miaoziping auxiliary bridge.

### Arrangement of high-pier about bridge in mountain

The displacement of pier-top is relatively large about high-piers bridges in the earthquake. Using simply supported beam than using continuous beam is more easily falling beam in the earthquake. The seismic force that passed to the upper part of the skew bridge pier interacts with the bridge, which can make the upper part of the structure of the bridge rotate in plane. When the seismic

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block of bridge cap can not resist the rotation of the upper part, the falling beam damage will happen. The rotation of bridge will increase the collision between the main beam, which can cause the destruction of the main beam, joints and other components. If the piers and beams are consolidated, the redundant constraints which can form plastic hinge will be a large number of energy-consuming members in strong earthquake, which can improve the seismic performance of bridges.

Another reason that resulted in a large displacement of the top in high-pier Bridge is the imbalance of quality and stiffness about piers. As a result of the valley on both sides of the mountain slope, the heights of the piers are often significant differences and using non-uniform span. The large difference in stiffness about the piers will lead to large difference distribution in the level of seismic force between the piers, and the large stiffness of the pier will subject to large level forces, which can affect the seismic capacity of the structure. If the center of stiffness and mass reverse the deviation, the upper member of the bridge will have a rotation with an increase probability of the beams falling, collisions and other damages. For the continuous girder bridge, the stiffness of the piers in the same conjunction should be as close as possible.

In the "Guidelines for Seismic Design of Highway Bridges", China's newly rules promulgated in 2008, the stiffness and mass balance is not explicitly requested. But in the "Caltrans seismic design criteria" of United States, the continuous girder bridge pier stiffness ratio and the basic cycle have done the provisions [2]. The anti-push stiffness of any two piers and the anti-push stiffness of two adjacent piers shall meet formula (1) and (2). The fundamental natural vibration period of two adjacent joins should meet the ratio of formula (3).

$$\frac{K_i / M_i}{K_j / M_j} \geq 0.5 \tag{1}$$

$$\frac{K_i / M_i}{K_j / M_j} \geq 0.75 \tag{2}$$

$$\frac{T_i}{T_j} \geq 0.7 \tag{3}$$

Where, $K_i$ and $K_j$, anti-push stiffness of the pier No. $i$ and $j$ respectively, $K_i \leq K_j$; $M_i$ and $M_j$, the equivalent concentrated mass at the top of pier No. $i$ and $j$ respectively, if the bridge is non-widened, then $M_i = M_j$; $T_i$ and $T_j$, the first basic-cycle of join No. $i$ and $j$ respectively, $T_i \leq T_j$.

The combination of anti-push stiffness is a series connection stiffness of piers and supports, which is satisfied to the following formula:

$$K = \frac{K_b \cdot K_P}{K_b + K_P} \tag{4}$$

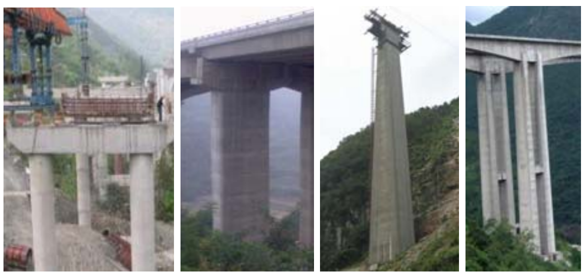
Where: $K$ is a combination of anti-push stiffness, that $K_b$ is the level stiffness of the piers, and $K_p$ is the shear stiffness of the supports.

The changes are significant about the height of the piers in mountain, from the formula (4) we can see that the bridge should to ensure the balance of quality and rigidity. First, the piers should use the same high-pier, and the span and the width of deck should be equal as far as possible. The second is to adjust the diameter of piers and the support forms and so on, which is used to improve the stiffness balance of the bridge.

**Choice of pier forms**

Mountain Bridge is generally Curve Bridge of changing height, not only the geometry of the curve bridge will affect its earthquake response; the type of pier is also one of the main factors to affect its earthquake response. Under the force of earthquake, the combination of high pier and short pier made the force of bridge even more complicated, when high-pier is not coupled with the short pier, it may lead to high pier seismic displacement too large, the selection of high-pier forms and design has an important significance for the seismic safety of full-bridge

Highway in mountain, as a result of restrictions in terrain and landforms, the irregular bridge that the pier height is 40m high or more are many. For those in the height of 30m high piers, girder bridges are often using double-cylindrical piers. When the height of pier is more than 30m high, single column T-pier, hollow thin-wall pier and gantry type bridge pier and so on, are often used (Figure-8). These piers have their own type of characteristics.



(A) (B) (C) (D)

**Figure-8.**
A. Double-cylindrical pier; B. Single column T-pier ;
C. Hollow thin-wall pier; D. Double thin-wall pier.

If the bridge is located on the curve, the seismic response of piers is coupled with bending and torsional vibration. The cross-section types of piers require a better bending rigidity and torsional rigidity. The horizontal

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bending stiffness of ordinary double-cylindrical pier is well, but the longitudinal bending stiffness and torsional rigidity is poor.

When the height of pier is more than 30m high, it is not recommend using double-cylindrical pier. If the pier is high, the double-column pier is prone to be damaged for the instability under the combined effect of the bending moment, shear force and axial force.

There are many advantages of the single column T-pier and hollow thin-wall pier, that the flexural rigidity in all directions, and torsional rigidity, is overall good. The single column T-pier General is a combination type of pre-stressed cantilever cap beam and pier. The characterized is the smaller sizes horizontal cross-section and smaller cross-section stiffness. Generally applied to the piers is not more than 60 m high bridge.

The appearances of thin-walled hollow pier and single column T-pier are relatively close. For the cross-section size and the lateral stiffness, the thin-walled hollow pier is larger than the single column T-pier. The thin-walled hollow pier, used in less than 80 m high pier, has obvious advantages.

Stiffness of gantry piers is better than the regular double cylindrical pier. With the increase in height of bridge piers, the two columns of gantry piers are linked by the horizontal tie beams. The lateral rigidity, the integrity, and the torsional rigidity of gantry piers are less than those of double cylindrical pier, therefore, the gantry piers are used for not more than 90m high bridges.

If the selection of pier form is to be considered, single T-pier and hollow thin-wall pier used in Girder Bridge have a certain advantage. Single thin-wall pier and double thin-walled pier are always applied to prestress concrete rigid frame bridge. Table-1 shows the corresponding relationship between the height of pier and the form of pier.

**Table-1.** Relationship between the height and the type of pier.

| **Superstructure** | **Pier height** | **Pier forms** |
|---|---|---|
| Beam bridge | <30m | Double cylindrical pier |
| | 30-60m | Single T-pier |
| | 60-80m | Single T-pier, hollow thin-wall pier |
| | >80-100m | Hollow thin-wall pier, gantry piers |
| | >100m | Hollow thin-wall pier, combination of piers |
| Rigid frame bridge | ---- | Single-thin-wall pier, double thin-walled pier |

## SEISMIC CALCULATION OF HIGH-PIER BRIDGE

For the high mountain valleys on both sides of the mountain slope, the height of the piers are often significant differences between non-uniform span. Seismic force distributions between the piers are generally not good enough, so the calculation of bridge seismic mountain has its difficulties and characteristics [5, 6].

Because of the complexity of the terrain, the long-span bridge (> 600m) which is cross-faults, near-fault and large changes in terrain, need to consider the impact of multi-support excitations. A large number of seismic records show that the earthquake at the same time, the reaction of the entire surface is different, even if the distance is only tens of meters, vibration amplitude, phase and spectral characteristics are not the same, and its spatial variation is very complicated [1, 4]. Therefore, irregular mountain bridge should target to consider the impact of multi-point earthquake excitations.

The impact of dynamics nonlinear should be considered in high bridge pier. Many high-pier bridges even under the static load will produce a significantly non-linear deformation. The large-span rigid frame bridge is very sensitive to deformation. Therefore, the mountain high pier seismic analysis of bridges should be taken into account the impact of non-linear.

Seismic analysis of bridge piers should be taken into account the impact of higher-order vibration mode. Natural vibration period of the high pier will be very long and the quality will be very large, and two or more plastic hinges may be formed under strong earthquake. If the seismic analysis overlooks the contribution of higher-order modes, it is difficult to ensure the seismic safety of structures. According to the characteristics of the seismic calculation about high-pier Bridge, it is necessary to study the applicability of seismic calculation methods.

Under the earthquake excitations, the changed loads of structure over time are the displacement caused by the support movement. If the constitutive relations, sporting state, and the mechanical state of structures are identified, and time-varying changes of the support has a certain velocity and acceleration, then the non- support part of the structure will produce the same displacement, velocity and acceleration. If the freedom of structure is divided into support freedom and non- support freedom, the dynamics balance equations have the following form:

$$M\ddot{u} + C\dot{u} + Ku = R \quad (5)$$

Also can be expressed as

$$\begin{bmatrix} M_{ss} & M_{sb} \\ M_{bs} & M_{bb} \end{bmatrix} \begin{Bmatrix} \ddot{u}_s \\ \ddot{u}_b \end{Bmatrix} + \begin{bmatrix} C_{ss} & C_{sb} \\ C_{bs} & C_{bb} \end{bmatrix} \begin{Bmatrix} \dot{u}_s \\ \dot{u}_b \end{Bmatrix} + \begin{bmatrix} K_{ss} & K_{sb} \\ K_{bs} & K_{bb} \end{bmatrix} \begin{Bmatrix} u_s \\ u_b \end{Bmatrix} = \begin{Bmatrix} 0 \\ R_b \end{Bmatrix} \quad (6)$$

Where, $\ddot{u}_s$, $\dot{u}_s$, $u_s$ are the motion vectors of superstructure in the absolute coordinate; $\ddot{u}_b$, $\dot{u}_b$, $u_b$ are the ground motion vectors in the absolute coordinate; *M,C,K* are the matrix of mass, damping and stiffness, the meaning of

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lower Figures $ss$, bb, $sb$ are the freedom of superstructure, base and their couple item; $R_b$ is reaction of base (If the response of structure have been got, the $R_b$ can be calculated by the second equation of formula (6) ) So the dynamic equation about $\ddot{u}_s$, $\dot{u}_s$, $u_s$ can be got from the first equation of formula(6) as

$$M_{ss}\ddot{u}_s + C_{ss}\dot{u}_s + K_{ss}u_s = -(M_{sb}\ddot{u}_b + C_{sb}\dot{u}_b + K_{sb}u_b) \quad (7)$$

If the lumped mass model of structure is used, the $M_{sb}$ is equal to zero; the damping matrix is difficult to be calculated, and the damping force $-C_{sb}\dot{u}_b$ is always neglected; so the equation (7) can be written as

$$M_{ss}\ddot{u}_s + C_{ss}\dot{u}_s + K_{ss}u_s = -K_{sb}u_b \quad (8)$$

Where, $u_b$ is the vector of ground motion; $-K_{sb}u_b$ is the force of superstructure for the ground motion in the absolute coordinate. Equation (8) is the basic formula of analysis structure under ground motion.

As can be seen from the equation, studying on dynamic response of the bridge under earthquake is actually a study of equation (8). From the above formula, four common seismic analytical methods can be got; they are response spectrum method, random vibration method, pushover analysis method and time history analysis method.

**Response spectrum method:** In seismic analysis of bridge structures, the response spectrum method is the most fundamental and most widely used analytical methods. But the response spectrum method can't consider the impact of multi-support excitations. This method assumes that all the supports are in accordance with the laws of the same movement. Research shows that when the span of the structure meet or exceed the seismic wavelength 1/4, the movement of the surface supports can't be considered as a consistent. Vibration mode superposition method based on the response spectrum method is a linear method. For non-linear analysis, it may lead to large errors.

**Random vibration method:** Earthquake ground motion is a non-stationary random process. Random vibration method takes full account of the probability characteristics of the earthquake. It is generally agreed that the random vibration method is a reasonable analysis method. The shortcomings of random vibration method are the large size of calculation and for non-linear problem may lead to large errors. Pseudo-excitation method [7] solves the problem of large size of calculation. Pseudo-excitation method in some aspects makes up the deficiencies of response spectrum method. However, the method in dealing with the strongly nonlinear problem of high pier under rare earthquake has its limitations.

**Pushover analysis method:** Push-over method has a certain value for similar nonlinear seismic analysis, and it is mainly used for the deformation analysis of structure. However, it is using static analysis methods to study the dynamic response of the structure, and the mechanical model of itself has its limitations.

**Time history analysis method:** The study showed that the high bridge pier may enter a state of serious non-linear elastic-plastic under a strong earthquake. At this point, the time history analysis method is more adaptive than the response spectrum method and random vibration method. It will be a very good contact of the characteristics of the earthquake and the inherent characteristics of the structure, especially linked with the elastic-plastic seismic response of structures. However, the large size of the calculation is still a shortcoming of the time-history analysis method. To conduct multi-support excitation time-history analysis, Space earthquake ground is also need to be generated.

As can be seen from the above, with the understanding of ground motion in depth and the development of computer technology, although the time-history analysis method has a certain defect, it is one of the best solution to calculate the non-linear response of high-pier irregular bridge in mountain under multi-support excitation. In this paper, the response spectrum method, random vibration method, static pushover analysis and time history analysis are proposed in linear analysis of high pier bridge. The time-history analysis method is one of the best choices for the nonlinear analysis and the multi-support excitation analysis.

## DETAILS OF SEISMIC MEASURES ABOUT HIGH PIER

In Wenchuan earthquake, many bridges there have the damage of falling beams and destruction of piers, abutments and supports. At this point, this paper summarizes some details of seismic measures, which can be applied to high-pier bridge seismic design of mountain. The effective details of seismic measures have the following:

The using of limit-displacement apparatus in piers and abutments. The seismic code of United States and Japan recommend that the limit device should be installed in joints to limit the relative displacement, and the design method of limit device is also specified. Japanese bridge design specification also takes into account the impact of collision, and relative displacement response spectrum is also used in the design to prevent the occurrence of beam falling. Seismic designs of China only pay attention to the strength and deformation capacity of bridges. Limit device have been adopted by some of the bridge in China, but it is also a lack of systematic study in-depth.

Rational design of block about piers and abutments is important. The current code for the details seismic design of bridges should be improved in China. A large number of bridge damages took place in the block in Wenchuan earthquake, and the damage phenomenon is cutting block or the shear crack of block. This shows that the reasonable seismic design and construction of block is very important. Block design should pay attention to the following areas: The ratio of the stiffness about block and main beam should be reasonable; the extent of shear cracks about block should be moderate; different span and type of bridge should use different size of block.

The using of seismic isolation support, this includes the using of laminated rubber support, PTFE support, LRB, etc. To increase the flexible in the beam body and increase the damping of connecting parts about pier and abutment, which can reduce the seismic response of bridges.

The using of seismic isolation supports and damper combination system, in these 20 years, the United States, New Zealand and Japan and other countries, about the bridge seismic isolation and ductility design are included in the corresponding norms. Chinese specification is also not specific enough.

The using of ductility damping pier, ductility damping members, which have sufficient ductility enable bridge form a stable plastic hinge under strong earthquake, is designed to be some parts. The elastic-plastic deformation of structure can extend the natural cycle of structure, and consume seismic energy.

Development and utilization of new materials to make a bridge isolate, absorb and dissipate seismic energy and reduce the seismic response of bridge, and the deformation of the bridge is limited in a scope to avoid the residual damage and permanent deformation caused by accumulation of plastic deformation. For example, concrete-filled steel tube structure and steel reinforced concrete, etc. are effectively improving the seismic capacity of bridges. Most of Japan's new bridge on the use of steel shows the trend of this development.

## CONCLUSIONS

Ground motion itself is a complex random process. The irregular nature of the high pier bridge in mountain areas makes the seismic design of bridge to be difficult. The following conclusions can be adopted in this paper:

To strengthen the seismic concept design of the high-pier bridge in mountains, it is preferred to select the form of pier to resist large bending moment, shear force and torque. It is important to adjust the stiffness balance of the component, and enhance the integrity of the upper structure.

For the complexity of the situation in mountainous terrain, the non-linear analysis of high pier should to be strengthened, and the multi-point seismic analysis and spatial seismic analysis should to be taken targeted.

The high pier bridge in the mountains should take full account of the details of seismic measures. The type of structure should be selected according to different seismic programs. It is indispensable to attend the details of measures and the stiffness balance of structure.

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