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# Dynamic Reliability Assessment Under Seismic Load of a Continuous Rigid Frame Bridge Based on Simulation Analysis and Monitored Strain Data

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## Abstract

***People have noticed that earthquake is the most destructive natural phenomenon to bridges. So, doing dynamic reliability assessment under seismic load of the bridge during in service has great significance. The most difficult thing is how to assess the safety influence of seismic load to bridges. Therefore, we take a large-span continuous rigid frame bridge as the background bridge, based on the monitored strain data collected from the structural health monitoring system (SHMS) of the bridge during in service and 3-D FEM technology, we suggest a dynamic reliability evaluation methodology in this article to evaluate the safety influence of seismic load to the background bridge during in service stage. Firstly, with using the large amount of the monitored strain data, the quasi dynamic reliability near the sensor is acquired; furthermore, by using 3-D FEM method, the simulation model of the background bridge is built and the dynamic reliability under 6 seismic intensity with different middle-span web plates were analyzed and calculated. Through comparative analysis and discussing, we get the influence degree of seismic load on the reliability of the bridge. This method can provide reference for seismic design of the bridge.***

*Keywords:* ***Continuous rigid frame bridge; Dynamic reliability assessment; Seismic Response; Structural health monitoring; and 3-D FEM model.***

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## 1. Introduction

As for bridges, the earthquake has been noticed as the most destructive phenomenon of nature. When, where, and how large the earthquake will occur are highly uncertain. When bridges encounter earthquakes and collapse, people's lives and property will suffer great losses, and the traffic will be interrupted. Also, bridge reconstruction will consume huge human, material, and financial resources. In history, large earthquakes have occurred, such as the 1995 Japan Kobe earthquake, and the 1999 Taiwan Chi-Chi earthquake, lots of bridges suffered damage or collapsed. Therefore, in order to minimize the loss caused by the earthquake, many scholars are committed to the study of seismic influence to the bridge and seismic design.

Y Tsompanakis etc., [1] perform reliability analysis of space frames under seismic loading and structural reliability analysis is performed using the Monte Carlo Simulation (MCS) method. NH Park etc. [2] investigate the rational analysis methods for seismic design of the curved bridges. K Koji etc. Zhang Hailong etc. [3] build a finite element model of a bridge by the finite element program ANSYS, to simulate the dynamic characteristics and seismic response of the bridge with considering the influence of water on the dynamic characteristics and seismic response of the structure. Koji K [4] have investigated seismic performance for the large earthquakes and the effects of the concrete fill method as the retrofitting works of existing steel bridge frame piers with circular column. D Setyowulan [5] aims to clarify the effectiveness of multiple unseating prevention devices for bridge by numerical simulations. Fragiadakis and S Christodoulou [6] propose a methodology for assessing the reliability of pipe networks, which can combine data from past nonseismic damage with the seismic vulnerability of network components. Song Baojun [7] studied the influence of pile-soil interaction on the response value of continuous rigid frame bridge under earthquake action. Zhou Hongcheng [8] use the finite element software Midas/Civil to establish the model of a bridge, and calculate the seismic response of the bridge adopting the response spectrum method, which provides theoretical basis for structural design. W Lei etc. [9] suggested a dynamic reliability analysis method for the existing RC bridge under fuzzy detective data with considering the decrease of bearing capacity induced due to reinforcement corrosion under chloride environment.

To sum up, there is short of data to help doing safety influence research of seismic load on bridge structures. The current research methods mainly use simulation technology, theoretical analysis and do experiments, and the main cause is the complexity of the earthquake itself. Then, combined with the strain monitoring data adopted from SHMS of the bridge, we presented a methodology of evaluating the safety influence of seismic load to the background bridge. This is helpfull for understanding influence mechanism of seismic load and bridge seismic design for reducing the damage of bridges under earthquakes.

## 2. Illustration of the Background Bridge

### 2.1 Presentation of the SHMS and the Sample Bridge

The location of the sample bridge is in Zhaoqing city in Guangdong province. The superstructure of the main beam is a continuous box-beam system with 8 main piers and 7 main spans. The first span is 145.4 m long. The sixth span is 87 m long. The 4 center spans are all 144 m long each. The box girder cross section is single-box and single-chamber. The box girder top plate width is 12.5. The base plate width is 6.8 m. The bridge deck transverse slope is 2.0%. The bridge deck longitudinal slope is 0.15%. The box girder cross section heights vary from 8 m in the root to 2.8 m in the mid-span with changing according to 1.6 order power parabola. The thicknesses of base plate vary from 1 m in the root to 0.32 m in the mid-span. The thickness of web plate varies from 0.9 m in the root to 0.45 m in the mid-span. The prestressed concrete structure of the main beam is provided with vertical, horizontal and longitudinal prestress. The types of prestressing tendons are $15\Phi^{j}15.24\,\mathrm{mm}$ steel strand (strength: $R_y^b = 1860\,\mathrm{MPa}$), $2\Phi^{j}12.7\,\mathrm{mm}$ steel strand (strength: $R_y^b = 1395\,\mathrm{MPa}$) and high strength rebar.

The sensor picture is show in Fig. 1. The embedded locations of strain variety sensor of the cross sections of the SHMS are illustrated in Figs 2 and 3 with given numbers. Then, each sensor can be located in the girder the one and only. Taking the sensor named 3-4MID-1 as example, we can acquire that the sensor locates in the mid-span cross-section top plate center between pier 3# and pier 4#. The parameters of JMZX-215 type strain gauge are shown in Table 1 [10]. At present, the SHMS of the bridge is still in good operation.

**Table 1:** Basic Performance Parameters of JMZX-215 Type Strain Gauge.

| Name | Range | Sensitivity | Gauge length | Remarks | Measuring time interval |
|---|---|---|---|---|---|
| Intelligent digital vibrating strain gauge | ±1500 $\mu\varepsilon$ | 1 $\mu\varepsilon$ | 157 mm | Strain gauge embedded in concrete | 1 hour |

**Fig. 1.** JMZX-215 intelligent string-type digital strain gauge installed inside the bridge before casting.

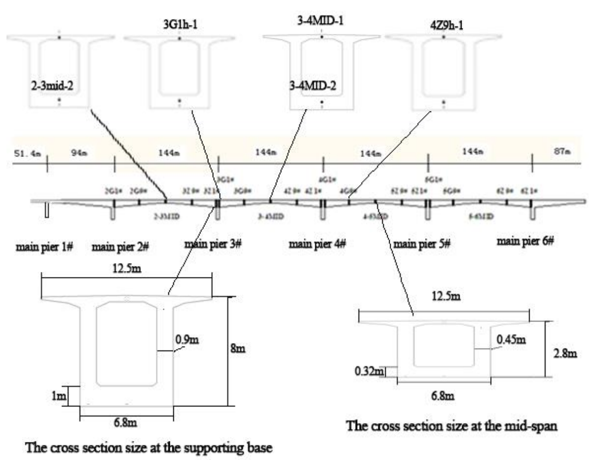



**Fig. 2.** Cross section size and locations of the embedded sensors in the bridge of SHMS.

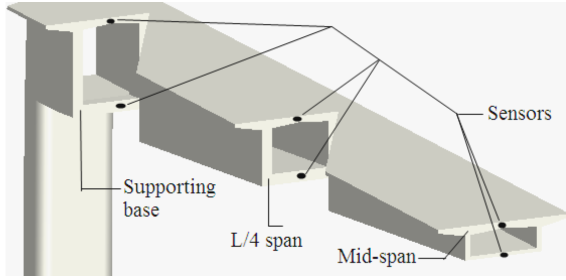



**Fig. 3**. Typical position of the embedded sensors in half-span of the bridge.

## 2.2 The Monitored Data

Here, the data (acquired by sensors 3G1H-1, 3-4MID-1, 4Z9H-1, and 3-4MID-2) are used as examples, and the selected time range is from March 2006 to April 2010. Due to the large amount of data collected from the SHMS and many influencing factors, the monitored data should be pre-processed firstly to delete some singular values and the pre-processed method can be seen in the papers [11]-[12]. The original data outline after being pre-processed can be seen in Fig. 4. Because of the system breakdown, partial data loss and some gaps appear in Fig. 4.

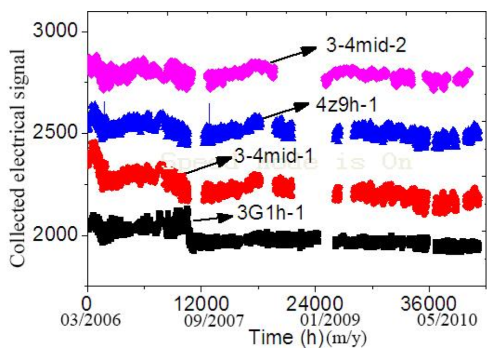



**Fig. 4.** The data profile collected from the SHMS.

## 3.The Calculation of Initial Quasi Dynamic Reliability Around the Embedded Sensor

In this paper, we use first order second moment method to calculate the safety index $\beta$ of the structural components. The reliability index $\beta$ calculation formula is as following:

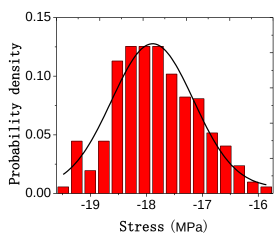
$$\beta = -\Phi^{-1}(P_f) = (\mu_R - \mu_S)/(\sigma_R^2 + \sigma_S^2)^{1/2} \quad (1)$$

In the formula: $\Phi^{-1}$ is the inverse function of the standard normal distribution; $\mu_R$ is the mean of the resistance; $\mu_S$ is the mean of the load effects; $\sigma_R$ is the standard deviation of the resistance; $\sigma_S$ is the standard deviation of load effects. The concrete strength probability distribution basically obeys Gaussian distribution, and so we can be taking it as the probability density function of the resistance $R$ . The strength characteristics of concrete of the bridge can be seen in Table 2. Because the strength parameters of concrete material are measured by testing machine at a certain strain rate, so, we call them quasi dynamic compressive strength and quasi dynamic tensile strength.

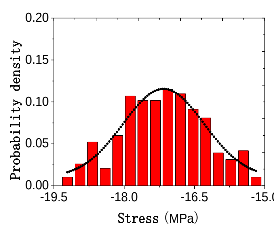
**Table 2**: The Mean and Standard Deviation Values of the Concrete Quasi Dynamic Compressive and Tensile Strength Respectively (28 days Curing).

| **Strength** | **Mean (units: MPa)** | **Standard deviation (units: MPa)** |
|---|---|---|
| compressive | 55.12 | 6.063 |
| tensile | 3.2783 | 0.361 |

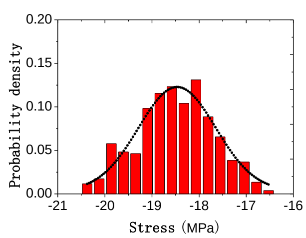
Here, the data collected from the sensors embedded in each mid-span web plate named 2-3MID-2, 3-4MID-2, 4-5MID-2, and 5-6MID-2 are selected as examples, of which the selected monitoring time range is from March 2006 to October 2006, and the amount of the data can ensure the accuracy of statistics. During March 2006 to October 2006, the bridge has just begun to enter into service. Also, due to the load effects $\sigma_S$ including the quasi dynamic load effects, such as temperature load effect, vehicle load effect etc., so, we call it the initial quasi dynamic reliability $\beta$, which reflects the quasi dynamic reliability state of the bridge at the beginning of operation. Because of prestress loss, concrete shrinkage and creep and other factors, the load effects distribution $\sigma_S$ gradually close to concrete tensile strength distribution, so, the initial quasi dynamic reliability $\beta$ is calculated by using quasi dynamic tensile strength distribution as the the resistance $\sigma_R$. The method of quasi dynamic load effects $\sigma_S$ transferred from the monitored data and initial quasi dynamic reliability $\beta$ calculation can be seen in the papers [11]-[14], and quasi dynamic load effects $\sigma_S$ distribution is shown in Fig. 5. By using equation (1), we get the initial quasi dynamic reliability $\beta$ values, seen in Table 3.



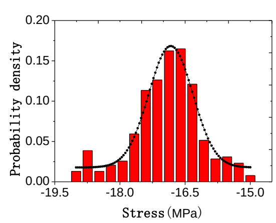

(2-3MID-2) 2006.05～2006.10




(3-4MID-2) 2006.05～2006.10




(4-5MID-2) 2006.05～2006.10




(5-6MID-2) 2006.05～2006.10

**Fig. 5.** The quasi dynamic load effects $\sigma_S$ distribution profile transferred from the monitored data and Gaussian distribution fitting.

**Table 3**: The Initial Quasi Dynamic Reliability $\beta$ Calculated by Tensile Strength Distribution Around Each Sensor Embedded in Mid-Span Web Plate.

| Sensor number | 2-3MID-2 | 3-4MID-2 | 4-5MID-2 | 5-6MID-2 |
|---|---|---|---|---|
| The initial quasi dynamic reliability $\beta$ value | 22.834 | 11.11 | 12.637 | 9.1828 |

## 4. The Building of FEM Model for Simulating the Bridge Under Seismic Load

### 4.1 FEM Model of the Background Bridge

In order to simulating the bridge under seismic load, this article uses 3-D finite software to establish 3-D model (Midas/Civil) based on the specific construction process of the bridge, shown in Fig. 6. We use CEB-FIP 90 model as the shrinkage and creep model [15]. The material parameters adopted in the simulation model are determined by field measurement. The stiffness coefficient EI is revised according to the deflection monitored data. The model defines 28 construction stages based on the construction process from stage 1# to stage 28#, which is seen in Table 3.

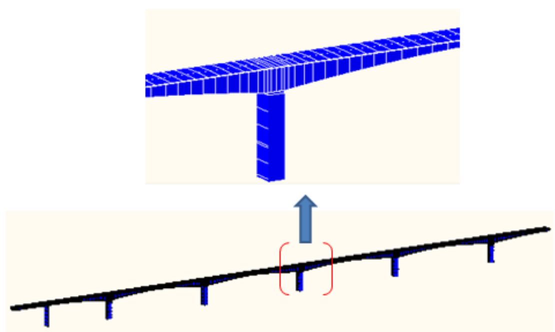
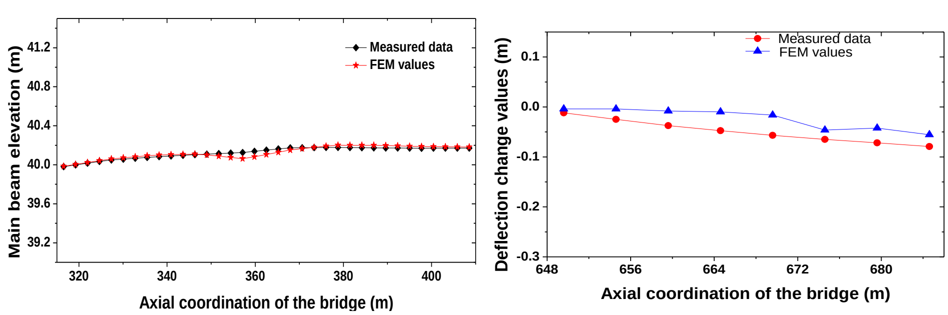


**Fig. 6.** 3-D FE model of the bridge

### 4.2 The Verification of the Simulation Model

For the sake of checking the reliability of the finite element model, a calibration work has been done by using the measured elevation data. The comparison of part of the main beam elevation and deflection changes between the FEM modal and the measured data can be seen in Fig. 7. By comparative analysis, the FEM model is basically consistent with the actual situation. So, the simulation model built in the article can be adopted to calculate the dynamic effects of bridge under earthquake load.




(a) The main beam elevation (b) Deflection changes of the main beam

**Fig. 7.** Comparison of part of the main beam elevation and deflection during construction process.

### 4.3 The Simulation Process

The bridge is located in Zhaoqing city, which is belong to The Pearl River Delta, and then the dynamic characteristics of the background bridge is simulated under most likely 6 seismic intensity [16]-[19]. In order to get the change state of stress caused by seismic, the measured seismic wave is used for numerical analysis. The input seismic wave data is shown in the Fig. 8 below, and its seismic intensity is about 6.

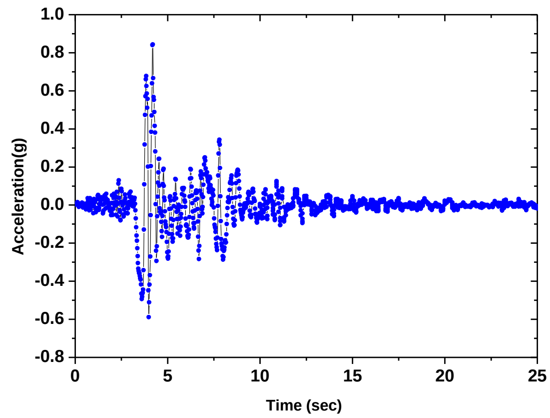
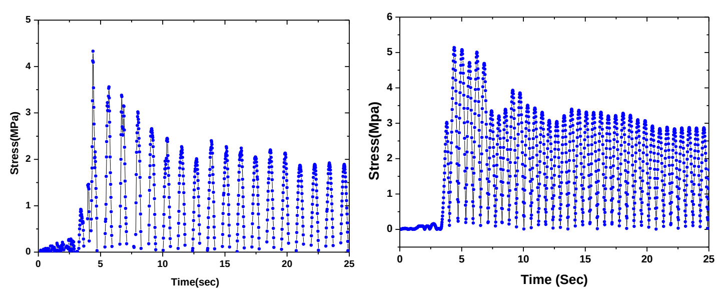
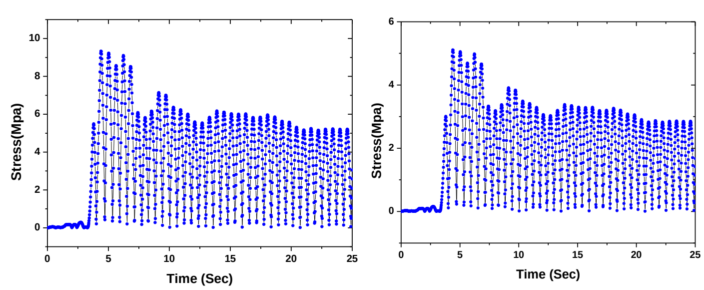



**Fig. 8.** The measured seismic wave data.

Then, the stress time history data are obtained corresponding to the positions of the sensors 2-3MID-2, 3-4MID-2, 4-5MID-2, and 5-6MID-2, seen in Fig. 9.



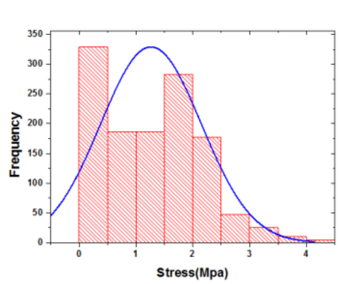

(2-3MID-2) (3-4MID-2)



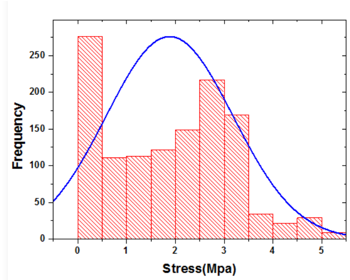

(4-5MID-2) (5-6MID-2)

**Fig. 9.** The stress time history diagrams corresponding to the sensor position embedded in each mid-span web plate.

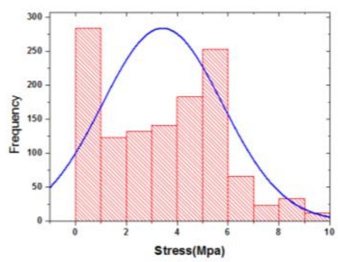
As for the stress data shown in Fig. 9, we then do statistical analysis. Seen from Fig. 10, the stress data distribution is basically normally distributed, and then we deal with the statistical data by Gaussian distribution fitting.



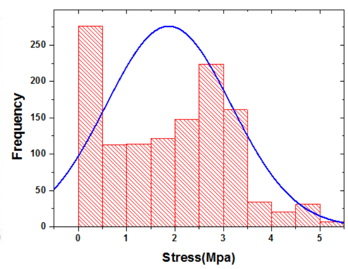

(2-3MID-2)




(3-4MID-2)




(4-5MID-2)




(5-6MID-2)

**Fig. 10.** Stress distribution statistics and Gaussian distribution fitting.

## 5. Results and Discussion

According to some properties of normal distribution, if $X \sim N(\mu_X, \sigma_X^2)$ and $Y \sim N(\mu_Y, \sigma_Y^2)$ are statistically independent normal random variables, and then the sum of them also satisfies the normal distribution:

$$X + Y \sim N(\mu_X + \mu_Y, \sigma_X^2 + \sigma_Y^2) \qquad (2)$$

In the article, we consider that the bridge stress change is in the stage of linear elasticity under 6 seismic intensity. Therefore, the seismic load effects and the quasi load effects transformed from the SHM are statistically independent random variables, combining with formulas (1) and (2), and then we can get the reliability calculation formula considering the influence of seismic loads as follows:

$$\beta_E = \frac{\mu_R - (\mu_M + \mu_E)}{\sqrt{\sigma_R^2 + \sigma_M^2 + \sigma_E^2}} \qquad (3)$$

In the formula: $\beta_E$ is the dynamic reliability index considering seismic load effects; $\mu_R$ is the mean of the resistance, and $\mu_M$ is the mean of quasi load effects converted from the SHM; $\sigma_R$ is the standard deviation of the resistance, and $\sigma_M$ is the standard deviation of the quasi load effects transformed from the SHM; $\mu_E$ is the mean of seismic load effects, and $\sigma_E$ is the standard deviation of the seismic load effects.

Through stress distribution statistics and Gaussian distribution fitting in Fig. 10, we can get the values of $\mu_E$ and $\sigma_E$, seen in Table 4.

**Table 4:** The Values of $\mu_E$ and $\sigma_E$ Around Each Sensor Embedded in Mid-Span Web Plate.

| Sensor number | 2-3MID-2 | 3-4MID-2 | 4-5MID-2 | 5-6MID-2 |
|---|---|---|---|---|
| $\mu_E$ (MPa) | 1.233 | 1.885 | 3.453 | 1.856 |
| $\sigma_E^2$ (MPa) | 2.39 | 5.2401 | 5.5947 | 5.1818 |

Based on the data in Table 1 and Table 3, through calculating by using the equation (3), we obtain the dynamic reliability index values $\beta_E$ around the embedded sensor location in the web plate at mid-span cross-section , which is illustrated in Table 5.

**Table 5:** The values $\beta_E$ Calculated by Tensile Strength Distribution Around Each Sensor Embedded in Mid-Span Web Plate.

| Sensor number | 2-3MID-2 | 3-4MID-2 | 4-5MID-2 | 5-6MID-2 |
|---|---|---|---|---|
| $\beta_E$ | 10.006 | 8.1274 | 7.9142 | 8.1164 |

Through comparative analysis of the data in Table 2 and Table 4, we can get the influence degree of seismic loads on dynamic reliability, and we name it $\Delta\beta_E$, shown in Table 6.

**Table 6:** The Values $\Delta\beta_E$ Influenced by Seismic Loads.

| Sensor number | 2-3MID-2 | 3-4MID-2 | 4-5MID-2 | 5-6MID-2 |
|---|---|---|---|---|
| $\Delta\beta_E$ | 12.828 | 2.983 | 4.723 | 1.066 |
| $\Delta\beta_E / \beta$ | 0.562 | 0.268 | 0.374 | 0.116 |

Seen from Fig. 9, the variation range of extreme stress caused by earthquake is about 4.3-9.2 MPa in the mid-span web plate, which is in the bearing capacity limit and the pressure safety reserve of bridge concrete materials when the background bridge is in the early stage of operation. Seen from Table 5-6, under 6 seismic intensity, the variation range of quasi dynamic reliability $\Delta\beta_E$ caused by earthquake is about 1.066-12.828 in the mid-span web plate. The maximum variation ratio of the initial quasi dynamic reliability induced by seismic loads is up to 56.2%, and then we can find that the seismic load effects have the greatest impact on the safety influence on the mid-span web plate between the main Pier 2# and the main Pier 3#.

## 6. Conclusions

Due to the difficulties of the seismic safety evaluation of structures, by using the monitored data and 3-D FEM technology, we put forward an evaluation methodology of dynamic reliability of this type bridge under seismic load effects, and the conclusions are as follows.

- The evaluation methodology of dynamic reliability of bridge under seismic load effects is suggested.
- The statistical results of the simulated seismic stress data by using 3-D FEM technology shows that the seismic load effects generally obey Gaussian distribution, and then we use the first order second moment method to evaluate the seismic safety influence on bridges.
- Based on the safety influence evaluation of the seismic load effects, we found that the seismic load effects have the greatest safety influence impact on the mid-span web plate between the main Pier 2# and the main Pier 3#, which means that this component is the weakest part of the background bridge.
- The future study plan should focus on the structures aging under seismic load effects with considering the bridge material strength degradation etc. After long-term operation of the background bridge, it is necessary to do analysis whether the safety reserve meet the seismic safety requirements or not.
- The methodology proposed in this article can provide reference for seismic safety evaluation of structures. Also, the method can be used for safety assessment of bridge encountering other abnormal events.

## 7. Acknowledgements

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