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Original scientific paper

Construction Stage Seismic Resilience Evaluation of a Continuous Girder Bridge with the Cast-in-Place Cantilever Construction Method

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Abstract: To rapidly evaluate the seismic resilience of the bridges under construction, the construction stage seismic resilience evaluation method was proposed. Based on a case bridge of continuous girder with the cast-in-place cantilever construction method, the seismic resilience of bridges at different construction stages was researched and compared. The bridge model was established by utilizing the construction stage module in the Midas Civil finite element modelling software. The functional losses of the bridges at different construction stages were computed. The three dimensional functional surfaces of Function-Time-PGA (Peak Ground Acceleration) were drawn. The resilience indexes at different construction stages with different seismic PGAs were compared, the resilience indexes with and without consideration of the delay recovery period were compared and analysed. The research results show: 1) in the control period, the functional loss is directly proportional to the PGA, but the function and resilience indexes are inversely proportional to the PGA; 2) the seismic resilience indexes of bridges at different construction stages are vastly different; 3) the resilience indexes with and without consideration of the delay recovery period are different; for the case bridge with the delay recovery period to recovery period ratio of 20%, the difference of the resilience indexes with and without consideration of the delay recovery period can reach 17% when the seismic PGA is 1.0 g. This paper provides a new method to evaluate the seismic resilience of construction stages, and it can be used to provide suggestions for the seismic damage evaluation and post-seismic recovery scheme.

Keywords: bridge; cantilever construction; construction stage; seismic resilience; seismic vulnerability

1 INTRODUCTION

For a modern city, the recovery speed of the city function always plays an important role after disasters [1]. Assessing the structural integrity and sustainability during earthquakes is an effective way to reduce or even avoid large losses of life and property damage [2]. The resilience evaluation is significant for the selection of post-seismic recovery scheme [3]. Since entering the 21st century, many scholars have been researching and exploring on the seismic resilience evaluation, more and more deeply.

Bruneau et al. [4] defined the "4R" properties (robustness, redundancy, resource fulness and rapidity) for the resilience. Fu [5] found the exposal values in the seismic risk of structure at different construction stages are different. Hsu et al. [6] researched the seismic exceedance probability and seismic losses. Six hospitals being regarded as a network system, Cimellaro et al. [7, 8] researched the seismic losses and resilience level of the buildings in the hospital network system. They presented a system resilience evaluation method and pointed out the influence of the seismic losses on rapidity and robustness. In the majority of house building seismic resilience evaluations, the research objects are usually the reinforced concrete frame structure [3, 5, 6, 9-11] and the damage indexes are usually the inter-story drifts [12]. The seismic resilience evaluation method [3, 10, 11] of the house building is similar to that of the bridge engineering. The author [3] researched the structural seismic resilience index (R) and the structural collapse margin ratio (CMR). She regarded the structural residual anti-seismic capacity as the function index, and the inter-story drift as the damage index, to further evaluate the structural residual anti-seismic capacity. She mainly researched the structural vulnerability and collapse margin ratio, but the insufficiency of her research was the lack of the research on the resilience evaluation index. In addition, He et al. [9] researched the vulnerability and resilience of a reinforcement concrete office building. Wang et al. [13] evaluated the seismic fragility of a non-structural component.

For the seismic resilience evaluation of bridges, some studies were also conducted. Dukes et al. [14] proposed the bridge-specific fragility method. Fu et al. [15] explored a probabilistic resilience-based cost-benefit model that can be used to identify the best retrofit measures for bridges. Andrić and Lu [16] proposed novel seismic recovery functions and metric for seismic resilience assessment employing the concepts from fuzzy sets theory. Biondini et al. [17] investigated the seismic performance of bridge structures and the functionality and resilience of highway networks in probabilistic terms.

The seismic resilience assessment of bridges is a highly uncertain process since it requires complex analysis of various factors that have contributed to different types of uncertainty [16]. For the resilience evaluation, the main decisive factors are function index, recovery cost ratio, recovery period, recovery function, and delay recovery period. The following four paragraphs will respectively discuss the four decisive factors.

How to select the function index? In the bridge resilience researches, based on the statistic or forecast traffic volume, some researches [18-20] regard the traffic volume as function index, so their research object must be completed bridges on service. Accordingly, the researches on the bridges under construction are relatively fewer. For the bridges under construction, the traffic volume cannot be regarded as the function evaluation index because the traffic has not yet been open. In the bridge engineering, the pier bottom sections are always seismic fragile for both the completed bridges and the bridges under construction. The pier bottom moment and curvature values are usually regarded as the bridge function index.

How to calculate the recovery cost ratio and recovery period? Li et al. [21] fitted the recovery period ratio function and recovery cost ratio function by the polynomial fitting method. Yang [10] got the recovery period and recovery cost ratio by the polynomial fitting method. Li et al. [11] got the recovery period by the polynomial fitting function and got the recovery cost ratio from the relevant specifications.

How to select the recovery function? Since the recovery method and the recovery period can be very different, the bridge recovery schemes can have infinite kinds of possibilities [22], which will result in the recovery function also having infinite kinds of possibilities. Decò et al. [18] put forward a sine continuous functional function of six parameters. But in the sine function of six parameters, the period and amplitude, which would decisively influence the recovery function, still relied on the empirical assumptions so that it would lead to some errors. Therefore, the functional curve from the sine function can be applied only in the working condition that the recovery process fits the sine function. So, the sine continuous functional function is not universal. Fu et al. [15] proposed two exponential recovery functions, but the imperative parameters in the functions relied on the personal decisions. Based on the Susceptible-Infective-Removal (SIR) recovery model which derived from the epidemic typical model, He et al. [9] introduced weight coefficient into the resilience evaluation and presented exponential difference function model. But the weight coefficient formula and the parameters can be applied only in the system consisting of multi buildings and also relied on some personal decisions. Andrić and Lu [16] proposed novel seismic recovery functions by employing the concepts from fuzzy sets theory. But the fuzzy triangular numbers were hard to determine. Based on the linear recovery function, Venkittaraman et al. [23] researched the resilience promotion in the reinforcement process. Their research shows the linear recovery function is simple and practical, which can show the universal characteristics in the function recovery process.

Should the delay recovery period be considered? In some references [7, 10, 11, 24], the resilience index without considering the delay recovery period had been applied. However, for the practical bridges after earthquakes, it often delays some time before the emergency reinforcement or repair recovery.

For the rapid evaluation on seismic fragility and resilience, some researches have been carried out. Harirchian et al. [25] conducted a comprehensive literature review of the most commonly used and newly developed innovative methodologies in rapid visual screening and damage classification using powerful soft computing techniques. Based on the base interface software with php and MySQL data base from a website, Işık et al. [26] proposed a rapid seismic damage assessment method for reinforcement of concrete buildings. Based on seismic hazard maps and statistical Census data for buildings, Kalman Šipoš and Hadzima-Nyarko [27, 28] proposed a rapid assessment method for seismic risk of the Croatian Cities.

In addition, Karamlou et al. [19, 29, 30] researched the exceedance probability function of functional losses in some scope, and regarded the exceedance probability as the dependent variable to draw a three dimensional surface with the time and seismic intensity as the independent variables [19, 30]. Ren and Qi [31] compared and concluded some expressions about structural robustness, redundancy and vulnerability. They proposed the evaluation indexes based on the strain energy, to further analyse the relationship among robustness, redundancy and vulnerability. Lv et al. [32] defined the resilience as the system capacity of absorbing disturbance and rapid recovery. Cimellaro [33] summarized the research and application achievements on the resilience in different fields of civil engineering.

In the statistic of bridge collapse cases [34], the bridges under construction collapse cases comprised nearly half, while natural disasters accounted for about one third. It shows that cases under construction and natural disasters are both important risk factors leading to bridges collapse accidents. Therefore, if a bridge under construction experiences an earthquake, the safety will be seriously threatened. Great attention should be paid to the seismic resilience evaluation, especially for the bridges under construction.

The cantilever cast-in-place construction method, as a common bridge construction technique, is applied widely in the world. For the continuous girder bridges at different construction stages with the cantilever cast-in-place construction method, the mechanical system converts between hyper static state and static state, which will lead to complex mechanical characteristics and great uncertainty of the post-seismic recovery capacity. So far, although the research on the seismic resilience evaluation of bridges has started widely, the research on the construction stage seismic resilience evaluation of bridges is relatively less. In particular, it is very scarce for the seismic resilience evaluation aiming at the cantilever cast-in-place construction method.

The construction stage seismic vulnerability has been researched by Li et al. [35-37] and it has been suggested to apply in the seismic insurance by Li et al. [36]. On the basis of Li et al. [35, 36], the construction stage seismic resilience will be further studied in this study. The construction stage seismic resilience evaluation process will be proposed. Based on a case study of a continuous girder bridge with the cast-in-place cantilever construction method, the bridge seismic resilience of different construction stages will be evaluated and compared in detail. The effect of delay recovery period on the seismic resilience will be researched.

2 SEISMIC RESILIENCE EVALUATION METHOD FOR THE CONSTRUCTION STAGES

2.1 Resilience Basic Definition

The system resilience is the capacity to keep some function or performance state in the control period for the houses, bridges, lifeline network or community. In the reference [33], the system resilience index analytic expression is:

$$R(t)=\int_{t_0}^{t_0+T_{\mathrm{LC}}}\frac{Q_{\mathrm{TOT}}(t)}{T_{\mathrm{LC}}}\mathrm{d}t=\int_{0}^{T_{\mathrm{LC}}}\frac{Q_{\mathrm{TOT}}(t)}{T_{\mathrm{LC}}}\mathrm{d}t \tag{1}$$

where: t - the time; t_0 - the time when the disaster accident occurs; T_{LC} - the control period; $Q_{\mathrm{TOT}}(t)$ - the total performance function of researched system.

According to the seismic resilience conceptual definition [4], a common function-time curve is shown in Fig. 1. The function-time function $Q(t)$ is a piecewise continuous function. The function-time curve can be drawn with the time t as the independent variable and the function index Q as the dependent variable. The unit of time t is usually day, month or year. The function index Q has no unit, the value of 1 means no damage and 0 means complete damage.

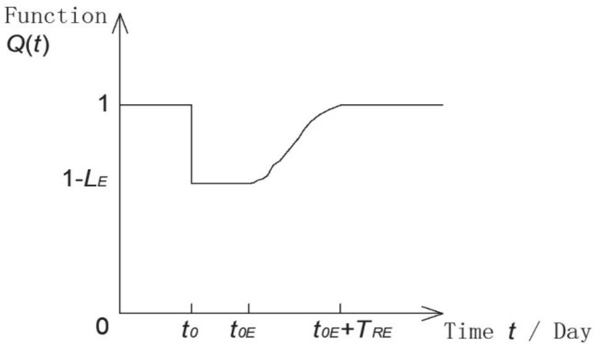


Figure 1 Schematic diagram of function-time curve

In Fig. 1, t_0 is the earthquake stop time, the earthquake causes the system function to drop rapidly from 1 to $1 - L_E$. In the period from the earthquake stop time to the recovery start time, all the project parties should check and evaluate the engineering damage situation, discuss and design recovery scheme, mobilize and organize the engineers, machines and materials for the retrofit and repair, demolish the damage components and other works before the function recovery starts. And this period is called delay recovery period ($t_{0E} - t_0$), in which the system function remains at $1 - L_E$. The t_{0E} is the recovery start time, the T_{RE} is the recovery period, so, the recovery finish time is $t_{0E} + T_{RE}$. In the recovery period, the system function recovers from $1 - L_E$ to $Q(t_{0E} + T_{RE})$.

The delay recovery period is:

$$T_d = t_{0E} - t_0 \tag{2}$$

The ratio of delay recovery period to recovery period is defined as:

$$DRTR = \frac{T_d}{T_{RE}} \tag{3}$$

So, the delay recovery time can be derived as:

$$T_d = T_{RE} \cdot DRTR \tag{4}$$

The period from the earthquake stop time t_{0E} to the recovery finish time $t_{0E} + T_{RE}$ is called control period (T_{LC}). So, the control period is:

$$T_{LC} = t_{0E} + T_{RE} - t_0 \tag{5}$$

In the function-time curve, the functional function [9] is shown in Eq. (6).

$$Q(t) = 1 - L_E \cdot \left\{ H(t - t_{0E}) - H\left[t - (t_{0E} + T_{RE})\right] \right\} \cdot f_{Rec}(t, t_{0E}, T_{RE}) \tag{6}$$

where: L_E - the functional loss; $f_{Rec}(t, t_{0E}, T_{RE})$ the recovery function; $H(x)$ - the Heaviside step function.

The functional loss is the ratio of lost function to original function, and the scope of the functional loss is 0 to 1. The structural seismic functional loss is:

$$L_E = \sum_{j=1}^{k} \left(\frac{C_{S,j}}{I_S} \cdot p_j \right) \tag{7}$$

where: j - the damage state; k - the total kinds of the damage states; $C_{S,j}$: the recovery cost for the damage state j; I_S : the replacement cost; $C_{S,j}/I_S$: the loss ratio; p_j : the probability of occurrence for the damage state j.

In the resilience evaluation index, the functional loss is decisive, and it is also the bond between structural vulnerability and resilience evaluation index.

The linear recovery function for the uniform recovery process is:

$$f_{Rec}(t, t_{0E}, T_{RE}) = 1 - \frac{t - t_{0E}}{T_{RE}} \tag{8}$$

2.2 Functional Function

The functional function is a piecewise function. With consideration of delay recovery period, the time axle is divided into four periods: period before earthquake, delay recovery period, recovery period, and period after recovery. For the linear recovery function, the functional function is shown in Eq. (9).

$$Q(t) = \begin{cases} 1, & t < t_0 \\ 1 - L_E, & t_0 \le t \le t_0 + DRTR \cdot T_{RE} \\ 1 - \left(-\frac{1}{T_{RE}} \cdot t + \frac{t_0}{T_{RE}} + 1 + DRTR \right) \cdot L_E, & t_0 + DRTR \cdot T_{RE} < t \le t_0 + (1 + DRTR) \cdot T_{RE} \\ 1, & t > t_0 + (1 + DRTR) \cdot T_{RE} \end{cases} \tag{9}$$

2.3 Resilience Index

For a single accident, in some references [7, 10, 11, 24], different projects have different delay recovery periods, the delay period is random and influenced by the resource fulness.

For the condition without considering the delay recovery period, the resilience index is:

$$R0=\int_{t_{0\mathrm{E}}}^{t_{0\mathrm{E}}+T_{\mathrm{RE}}}\frac{Q(t)}{T_{\mathrm{RE}}}\mathrm{d}t=\int_{0}^{T_{\mathrm{RE}}}\frac{Q(t)}{T_{\mathrm{RE}}}\mathrm{d}t=1-\frac{1}{2}\cdot L_{\mathrm{E}}+\frac{t_0}{T_{\mathrm{RE}}} \quad (10)$$

For the condition with considering the delay recovery period, the resilience index is:

$$R=\int_{t_0}^{t_{0\mathrm{E}}+T_{\mathrm{RE}}}\frac{Q(t)}{T_{\mathrm{LC}}}\mathrm{d}t=\int_{0}^{T_{\mathrm{LC}}}\frac{Q(t)}{T_{\mathrm{LC}}}\mathrm{d}t= =1-\frac{2\cdot DRTR+1}{2\cdot DRTR+2}\cdot L_{\mathrm{E}}+\frac{t_0}{(DRTR+1)\cdot T_{\mathrm{RE}}} \quad (11)$$

So, the relative difference of the resilience indexes with and without consideration of the delay recovery period is:

$$\Delta R=\frac{R0-R}{R}\times 100\%= =\frac{DRTR+\dfrac{2\cdot DRTR\cdot t_0}{L_{\mathrm{E}}\cdot T_{\mathrm{RE}}}}{\dfrac{2\cdot(DRTR+1)}{L_{\mathrm{E}}}-(2DRTR+1)+\dfrac{2\cdot t_0}{L_{\mathrm{E}}\cdot T_{\mathrm{RE}}}}\times 100\% \quad (12)$$

2.4 Seismic Resilience Evaluation Process

For the different construction stages, the seismic resilience should be separately evaluated. In this study, the seismic resilience evaluation processes for construction stages are as follows:

1) The bridge model should be established with consideration of different construction stages in the finite element modelling (FEM) software. The fragilities of different construction stages are achieved by the Incremental Dynamic Analysis (IDA) method. Then the occurrence probabilities of different damage states at different construction stages with different seismic intensities can be calculated.

2) The recovery cost ratio can be found from the relevant specification. The mean loss ratios at different construction stages with different seismic intensities are calculated. The mean loss ratio can be regarded as the parameter to measure the functional loss.

3) The recovery period should be determined referring to the construction speed arrangement before earthquake. Based on the recovery scheme, the delay recovery period and recovery function can be determined. The Function-Time-PGA three dimensional functional surfaces of different construction stages are drawn and compared.

4) The resilience indexes at different construction stages with different seismic intensities are achieved and compared.

The flow chart of the vulnerability evaluation process is introduced in Li et al. [35, 36]. The flow chart of the resilience evaluation process starting from the vulnerability is shown in Fig. 2.

In Fig. 2, the contents in the double line boxes are the basic data that should exist before the resilience evaluation, while the contents in the single line boxes are the intermediates in the evaluation process. Fig. 2 shows that the functional loss, recovery period, recovery function and delay recovery period are at the central position in the seismic resilience evaluation process, and they are the critical factors to determine the resilience index.

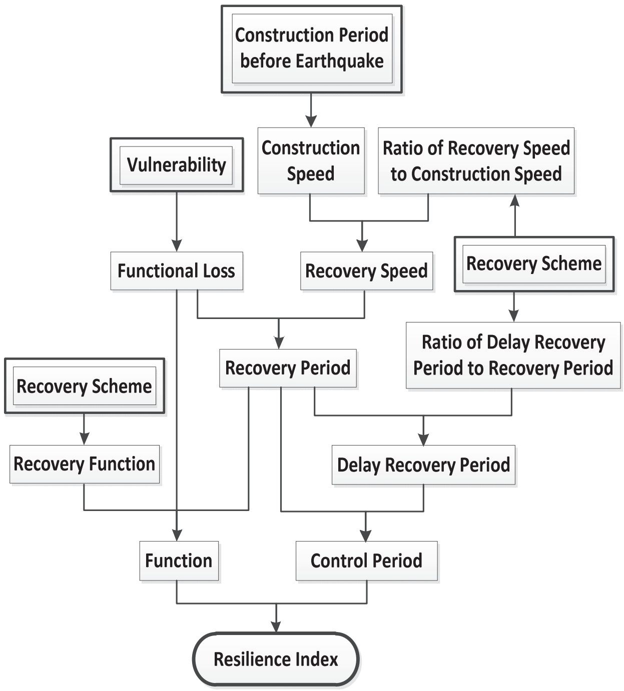


Figure 2 Flow chart of the resilience evaluation process

3 FINITE ELEMENT MODELLING OF CASE BRIDGE

3.1 Case Bridge Introduction

The case bridge is a concrete continuous girder bridge. The height of piers is 9 m. The cross section of piers is a rectangle with the size of 3.5 × 7 m. The bridge has three spans with the length of 51 m, 85 m and 51 m. The girder cross section is a single box single chamber variable section. The more detailed information about the case bridge was introduced in Li et al. [35, 36].

The case bridge applies the cast-in-place cantilever construction method. The main construction stages are as follows: substructure construction stage, girder cantilever construction stages by blocks, the side spans cast-in-place construction stage, the side spans closure construction stage, the middle span closure construction stage and the bridge completion stage.

Table 1 Researched construction stages construction period

No.	Construction Stage	Cumulative Construction Period / Day
1	Substructure	28
2	Middle Cantilever	118
3	Long Cantilever	166
4	Middle Span Closure	204
5	Bridge Completion	240

Referring to the practical seismic damage characters of the cast-in-place cantilever construction method, based on the case bridge practical construction organization scheme, five typical construction stages are selected as the main research construction stages. The five researched construction stages and their cumulative construction periods are shown in Tab. 1.

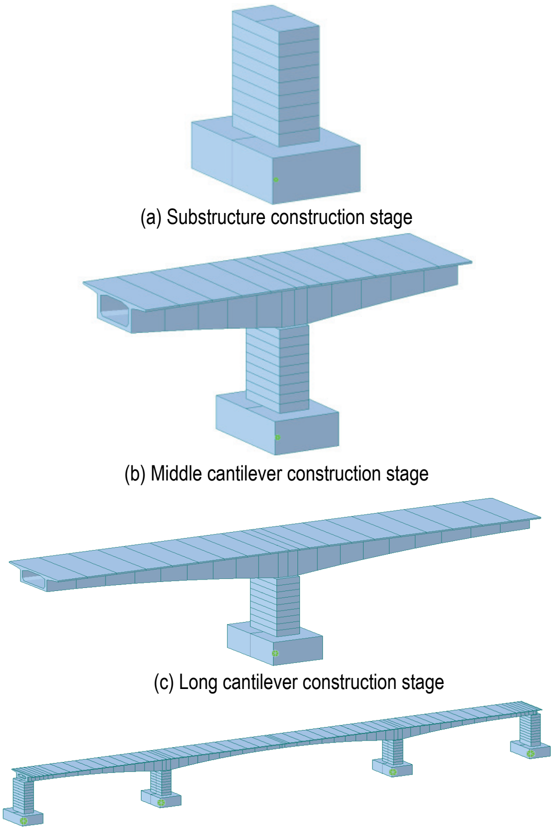
3.2 Case Bridge Modelling

The case bridge in this paper is the same as that in Li et al. [35, 36], and it is a continuous girder bridge with the cast-in-place cantilever construction method. The case bridge was designed conforming to the relevant design specifications of China. The model is established in the Midas Civil FEM software. The cushion caps, piers and girders are simulated by the beam element, and the materials of them are concretes with the strength of C35, C40 and C60, respectively. The supports are simulated by the elastic couplings. The nonlinear plastic hinges are set at the bottom elements of piers. The stress-strain relationship of the plastic hinges is the same as that in Li et al. [35, 36]. The Construction Stages module in the Midas Civil software is applied to simulate the bridges at different construction stages. The more detailed information about the design parameters and modelling method of the case bridge was introduced in Li et al. [35, 36]. The researched construction stages in this study are shown in Fig. 3. The cushion caps are fixed at the bottom, which are shown in Fig. 3 by the green points, and the effect of soil is ignored.

Twenty sets of seismic records from five practical earthquakes that occurred in eastern China are selected as the seismic excitation in the FEM software. Each of the records contains three record components. The identifications of the applied seismic records are listed in Tab. 2. The seismic records data for this study are provided by the Institute of Engineering Mechanics, China Earthquake Administration.

For the damping ratio of 5%, the seismic response spectra of the twenty seismic records are shown in Fig. 4.

According to the practical direction of the case bridge, the modified seismic excitations of the north-south, east-west and up-down directions are input to the bridge model of the transversal, longitudinal, and vertical directions, respectively.



(a) Substructure construction stage

(b) Middle cantilever construction stage

(c) Long cantilever construction stage

(d) Middle span closure construction stage and bridge completion construction stage

Figure 3 Researched construction stages of the case bridge

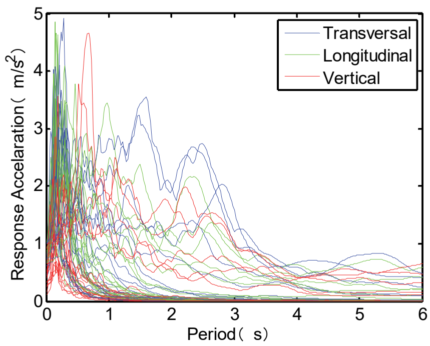


Figure 4 Response spectra of twenty sets of seismic records

Table 2 The identifications of the seismic records

Time (UTC+8)	Epicenter Position	Magnitude / Ms	Depth / km	Station Position	Site Condition
2011-01-19 12:07:43	N30.659, E117.099	4.4	6	N32.000, E119.199	Soil
				N31.700, E119.000	Soil
				N31.500, E119.300	Soil
				N31.600, E118.300	Soil
				N31.500, E118.300	Soil
2012-07-20 20:11:51	N33.04, E119.569	4.9	15	N34.400, E118.400	Soil
				N33.299, E119.300	Soil
				N32.799, E120.300	Soil
				N32.099, E119.699	Soil
				N33.799, E119.800	Soil
2013-11-23 13:44:11	N37.099, E120.019	4.5	10	N36.799, E118.900	Soil
				N36.400, E119.800	Soil
				N36.500, E119.400	Soil
				N36.799, E119.800	Rock
				N37.599, E121.000	Rock
2014-03-19 20:19:22	N24.049, E122.419	5.9	10	N26.600, E118.199	Rock
				N25.500, E119.800	Rock
				N25.700, E117.099	Rock
2014-05-21 08:21:13	N23.76, E121.489	5.9	20	N25.799, E116.400	Rock
				N25.500, E119.800	Rock

4 SEISMIC RESILIENCE EVALUATION OF THE CASE BRIDGE

4.1 Bridge Functional Loss Ratio after Earthquake

The construction stage seismic vulnerability evaluation was carried out by the IDA method in Li et al. [35, 36]. With regard to the relationship between the ground motion acceleration and the seismic fortification intensity [38-40], as well as for the structural probable damage situation, the PGAs of the twenty sets of seismic acceleration time-history records are modified to 0.1 g, 0.2 g, 0.4 g, 0.8 g, and 1.0 g. The pier bottom moment and curvature values of different construction stages under different seismic intensity can be achieved after seismic response analysis in the FEM software. The exceedance probability of different construction stages can be further computed. According to the functional loss formula in Eq. (7), the seismic mean loss ratio at different construction stages with different PGAs can be calculated. The seismic mean loss ratios were fitted to curves and shown in Fig. 5. More detailed computation process of the construction stage seismic vulnerability has been studied in Li et al. [35, 36].

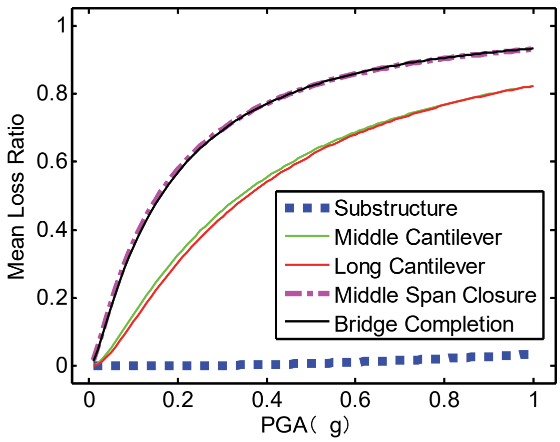


Figure 5 Seismic mean loss ratio curves of different construction stages [35]

4.2 Functional Function

Based on the case bridge practical condition and to make the study easy, the earthquake stop time is set as 0, the linear recovery function is applied, and the recovery speed in the recovery period is considered the same as the construction speed in the construction period before earthquake. The recovery period can be expressed as:

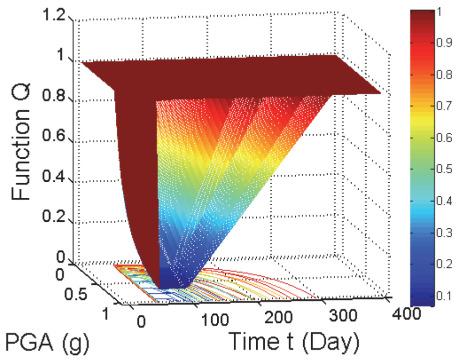
$$T_{\mathrm{RE}} = T_{\mathrm{c}} \tag{13}$$

where: T_{c} - the cumulative construction period, which has been listed in Tab. 1.

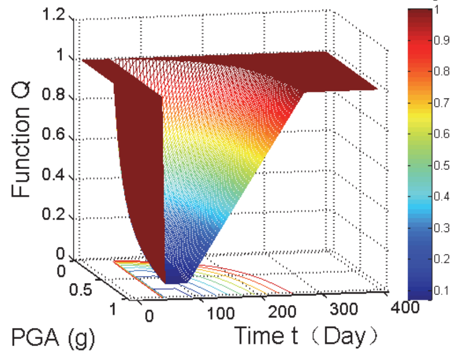
The delay recovery period can be influenced by many factors such as the local policy, the working efficiency, the personnel ability. So, the delay recovery period to recovery period ratio can be any positive number. Based on the case bridge practical condition, for all the construction stages, the delay recovery period to recovery period ratio of 20% will be taken as the example to carry out the research.

Based on Eq. (9), for the case bridge, the functional function is:

$$Q(t) = \begin{cases} 1, & t < 0 \\ 1 - L_{\mathrm{E}}, & 0 \le t \le 0.2 \cdot T_{\mathrm{RE}} \\ 1 - \left(-\dfrac{1}{T_{\mathrm{RE}}} \cdot t + 1.2 \right) \cdot L_{\mathrm{E}}, & 0.2 \cdot T_{\mathrm{RE}} < t \le 1.2 \cdot T_{\mathrm{RE}} \\ 1, & t > 1.2 \cdot T_{\mathrm{RE}} \end{cases} \tag{14}$$



(a) Function-Time-PGA surfaces of different construction stages



(b) Function-Time-PGA surface of middle span closure construction stage

Figure 6 Function-Time-PGA three dimensional surfaces

To compare the resilience of bridges at different construction stages, the finish time and the earthquake stop time of different construction stages should be transferred to the same time. The project monitoring and management time (which is not the cumulative construction period) is regarded as the time axle. For the case bridge, the Function-Time-PGA three dimensional surfaces of bridges at different construction stages are shown in Fig. 6a. The Function-Time-PGA surface of middle span closure construction stage is taken as the example and shown in Fig. 6b.

Fig. 6a shows the Function-Time-PGA surfaces of different construction stages are quite different. Fig. 6b shows for some construction stage, with the PGA increase, the function when the earthquake stops will decrease while the function after earthquake will recover slower.

The Function-Time curve of different construction stages at the working condition with the seismic PGA of 0.4 g is taken as the example and shown in Fig. 7.

Fig. 7 shows under the same seismic excitation, with the construction process runs, the functional loss and the recovery period will generally increase. The reason is: with the construction process runs, more and more finished construction works will be exposed to the seismic risk, and the recovery process will be more complex and harder; in addition, the supports conversion also plays some role in the bridge seismic resilience.

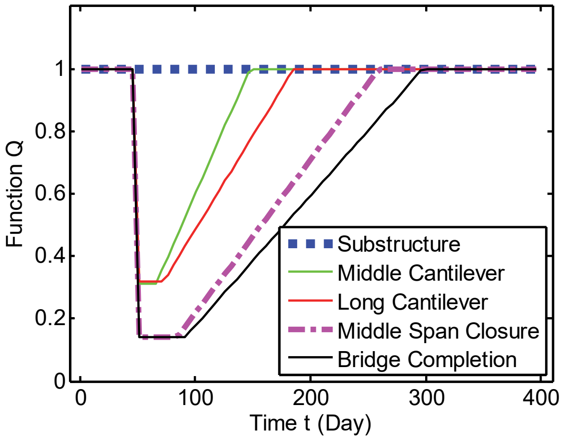


Figure 7 Function-Time curves of different construction stages (PGA = 0.4 g)

4.3 Resilience Index

Based on Eq. (10), for the case bridge, the resilience index function without consideration of the delay recovery period is

$$R0=\int_{t_{0E}}^{t_{0E}+T_{RE}}\frac{Q(t)}{T_{RE}}\mathrm{d}t=1-\frac{1}{2}\cdot L_{E} \quad (15)$$

For the case bridge, the resilience indexes without consideration of the delay recovery period are shown in Tab. 3.

The resilience indexes curves with consideration of the delay recovery period of different construction stages are shown in Fig. 8.

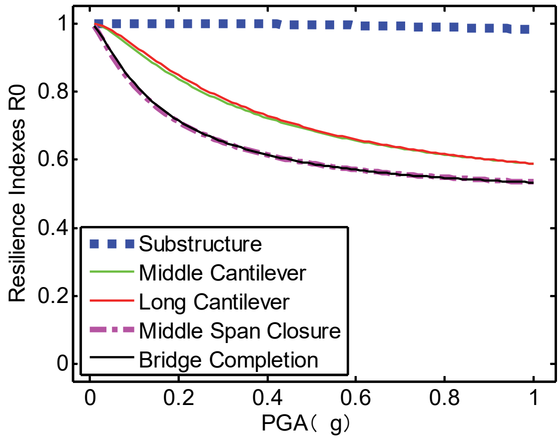


Figure 8 Resilience indexes without consideration of delay recovery period

Based on Eq. (11), for the case bridge with the delay recovery period to recovery period ratio of 20%, the resilience index function with consideration of the delay recovery period is

$$R=\int_{0}^{T_{LC}}\frac{Q(t)}{T_{LC}}\mathrm{d}t=1-\frac{7}{12}\cdot L_{E} \quad (16)$$

Table 3 The resilience indexes without consideration of the delay recovery period

PGA / g	Construction Stages				
	Substructure	Middle Cantilever	Long Cantilever	Middle Span Closure	Bridge Completion
0.1	1.0000	0.9247	0.9348	0.8179	0.8249
0.2	0.9998	0.8367	0.8479	0.7111	0.7150
0.4	0.9981	0.7222	0.7292	0.6139	0.6144
0.8	0.9892	0.6155	0.6168	0.5482	0.5471
1.0	0.9831	0.5882	0.5882	0.5345	0.5334

Table 4 The resilience indexes with consideration of the delay recovery period

PGA / g	Construction Stages				
	Substructure	Middle Cantilever	Long Cantilever	Middle Span Closure	Bridge Completion
0.1	1.0000	0.9122	0.9240	0.7876	0.7957
0.2	0.9998	0.8095	0.8225	0.6630	0.6675
0.4	0.9978	0.6759	0.6841	0.5496	0.5501
0.8	0.9874	0.5514	0.5529	0.4729	0.4716
1.0	0.9802	0.5196	0.5196	0.4570	0.4556

For the case bridge, the resilience indexes with consideration of the delay recovery period are shown in Tab. 4.

The resilience indexes curves with consideration of the delay recovery period of different construction stages are shown in Fig. 9.

Table 5 The relative differences of resilience indexes with and without consideration of delay recovery period

PGA / g	Construction Stages				
	Substructure	Middle Cantilever	Long Cantilever	Middle Span Closure	Bridge Completion
0.1	0.00%	1.38%	1.18%	3.85%	3.67%
0.2	0.00%	3.36%	3.08%	7.26%	7.12%
0.4	0.03%	6.85%	6.60%	11.71%	11.68%
0.8	0.18%	11.62%	11.55%	15.92%	16.00%
1.0	0.29%	13.21%	13.21%	16.98%	17.07%

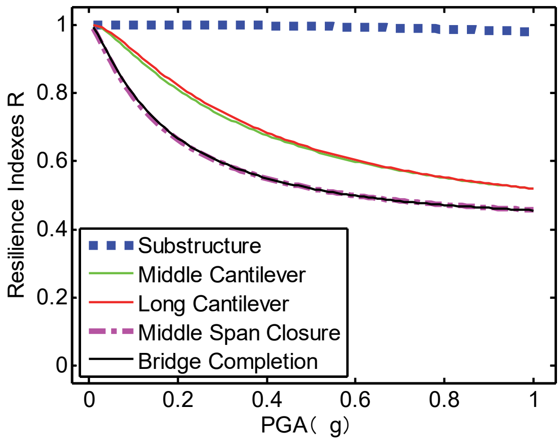


Figure 9 Resilience indexes with consideration of delay recovery period

As shown in Fig. 8 and Fig. 9, the resilience index always decreases with the increase of the seismic PGA, and the resilience indexes of different construction stages with consideration of delay recover period are vastly different. The resilience index of substructure construction stage is large and the resilience indexes of middle span closure stage and bridge completion stage are relatively low. The resilience indexes curves trends with and without consideration of the delay recover period are similar, but the values are different.

Based on Eq. (12), for the case bridge with the delay recovery period to recovery period ratio of 20%, the relative difference of the resilience indexes with and without consideration of the delay recovery period is

$$\Delta R = \frac{R0 - R}{R} \times 100\% = \frac{1}{\frac{12}{L_{\mathrm{E}}} - 7} \times 100\% \tag{17}$$

For the case bridge, the relative differences of the resilience indexes with and without consideration of the delay recovery period are shown in Tab. 5.

The relative differences of resilience indexes with and without consideration of the delay recovery period are shown in Fig. 10.

Based on Fig. 10 and Eq. (17), it can be found that, if the ratio of delay recovery period to recovery period remains unchanged, with the increase of the seismic PGA, the seismic functional loss will grow, the relative difference of resilience indexes with and without consideration of delay recovery period will rise, the effect of delay recovery period on resilience index will increase. The resilience index of the bridges at middle span closure or completion construction stage is more sensitive to the delay recovery period than that at the other construction stages. If the ratio of delay recovery period to recovery period is 20%, for the working condition that the seismic PGA is of 1.0 g, the effect of delay recovery period on the resilience index of bridges at middle span closure or completion construction stage can reach more than 18%.

It can be concluded that the length of delay recovery period can show the resource fullness and rapidity in the resilience evaluation and it will directly affect the resilience index. Therefore, the effect of the delay recovery period on the resilience index should not be ignored.

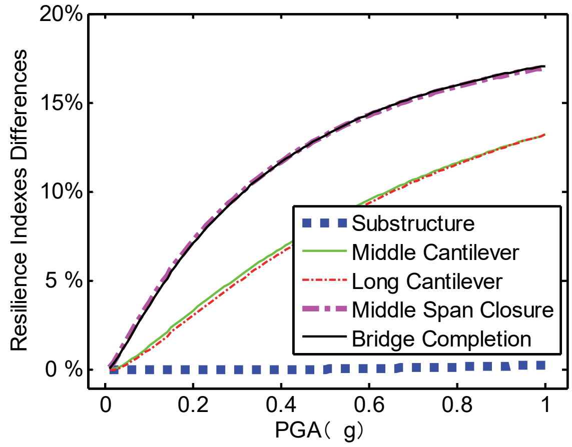


Figure 10 Relative differences of resilience indexes with and without consideration of delay recovery period

5 CONCLUSION

In this paper, the seismic resilience evaluation method of the bridges under construction was proposed. Based on a case bridge of continuous girder with the cast-in-place cantilever construction method, the seismic resilience of the bridges at different construction stages was evaluated and compared. The effect of delay recovery period on the seismic resilience was researched. The conclusions are as follows:

1) In the control period, with the increase of the seismic PGA, the system functional loss will increase, while the system function and resilience index will decrease.

2) The difference of the seismic resilience indexes with and without consideration of the delay recovery period can be large so that the delay recovery period should be considered in the resilience evaluation process.

3) For the bridges at different construction stages, the mean loss ratios and the resilience indexes are both vastly different. For the case bridge at the substructure construction stage, the seismic safety redundancy is large. For the case bridge at the middle span closure or completion construction stage, the seismic resilience is relatively weak.

4) For the bridge under construction, the seismic resilience is strongly affected by the seismic vulnerability. Compared with Li et al. [35-37], the research in this paper has pushed forward the study on the bridge under construction from the seismic vulnerability to the seismic resilience.

In addition, only the linear recovery function is researched, the other recovery function such as sinusoidal function could also be researched by the study method proposed in this paper. The construction stage seismic resilience evaluation method proposed in this study can be applied to the other bridge construction methods, the other bridge types, and even the other disasters such as some extreme weather conditions.

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