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Seismic Damage-Oriented Lifecycle Risk Cost Calculation for Cable-Stayed Bridge Infrastructure Using Fragility Method

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Abstract. Cable-stayed bridges are critical components of modern transportation infrastructure, but their vulnerability to seismic events presents substantial risks to their long-term performance and safety. This paper focuses on the assessment of seismic damage in the lifecycle risk cost calculation for cable-stayed bridge infrastructure. The fragility method is utilized as a key approach to quantify seismic vulnerability and estimate associated risk costs throughout the bridge's lifespan. Seismic fragility curves are developed by analyzing the structural response to various earthquake scenarios, providing a probabilistic representation of the bridge's performance based on ground shaking intensity. This facilitates the evaluation of potential damage levels and their corresponding costs. The risk cost calculation encompasses direct expenses, including repair and replacement of damaged components, and employs statistical methods to estimate expected expenses. Stakeholders and decision-makers can utilize this approach to make informed choices regarding risk reduction investments, maintenance planning, and long-term sustainability considerations. A specific case study is conducted on a cable-stayed bridge, focusing on longitudinal seismic waves. The findings reveal that the main tower exhibits greater resilience compared to the tower abutment. The failure probabilities of slight, moderate, severe, and absolute damage for the main tower are determined as 9.8%, 1.1%, 0.3%, and 0.2% respectively, while the corresponding failure probabilities for the main abutment are 35.2%, 21.1%, 7.4%, and 2.9%. The maintain life cycle cost associated with seismic events for this bridge is estimated at 0.548 million USD. These results provide valuable insights for decision-making processes regarding risk reduction strategies, maintenance planning, and long-term sustainability considerations.

Keywords. Lifecycle Risk Cost, Decision Making, Fragility, Risk Assessment

1. Introduction

Cable-stayed bridges serve as critical components of transportation infrastructure, enabling efficient and reliable connectivity [1]. However, their susceptibility to seismic events poses significant risks to their long-term performance and safety. To mitigate these risks, engineers and researchers have embraced Performance Based Seismic

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Design (PBSD) approaches, which provide a robust framework for evaluating the performance of bridges under seismic loading conditions [2]. This paper focuses on the specific concern of seismic damage in the lifecycle risk cost calculation for cable-stayed bridge infrastructure, employing the fragility method as a key component of the PBSD approach [3-5].

Traditionally, seismic design has relied on deterministic approaches [6], which consider earthquakes as singular events with predetermined characteristics. However, this approach fails to capture the inherent uncertainties associated with seismic hazards and their impact on structural response [6]. In contrast, PBSD approaches integrate probabilistic seismic hazard assessment, structural analysis, and performance-based engineering principles to account for uncertainties and provide a more comprehensive understanding of the bridge's behavior.

In this paper, we present a comprehensive framework for the lifecycle risk cost calculation of cable-stayed bridge infrastructure, with a particular focus on seismic damage. The fragility method, integrated within the PBSD approach, allows for the assessment of potential damage levels and associated costs based on probabilistic seismic hazard analysis. Through the application of the fragility method and PBSD principles, stakeholders and decision-makers can gain insights into the economic implications of seismic damage scenarios for cable-stayed bridge projects [7]. This information enables informed decision-making processes regarding risk reduction investments, maintenance planning, and long-term sustainability considerations [8]. By integrating probabilistic seismic design principles, this research contributes to the development of resilient infrastructure systems that can withstand seismic hazards and ensure the safety and functionality of cable-stayed bridges throughout their lifecycle.

The structure of this paper is as follows: In Section 2, a concise overview of the theory behind seismic fragility analysis and lifecycle risk cost estimation is provided. Section 3 presents the cable-stayed bridge under consideration, along with the seismic waves used in the analysis. Subsequently, Section 4 evaluates the fragility of the cable-stayed bridge and calculates the corresponding life cycle cost (LCC). Finally, Section 5 concludes the paper, summarizing the key findings and their implications.

2. Theory of Fragility Analysis and Life Cycle Estimation

According to the classical reliability analysis theory, structure fragility is described as the conditional probability of failure under a given ground motion intensity. The following formula can be established according to the definition:

$$P_f = P\left[\frac{S_d}{S_c} \geq 1\right] \tag{1}$$

where P_f is conditional probability of failure, S_d is the structural seismic demand and S_c is the structural seismic capacity. S_d and S_c are assumed to follow a lognormal distribution. Equation (1) can be rewritten as follows:

$$P_f = P\left[\ln\frac{S_d}{S_c} \geq \ln 1\right] \tag{2}$$

$$P_f = P\left[\ln S_d - \ln S_c \geq 0\right] \tag{3}$$

because

$$\ln S_d \sim N(\lambda_d, \beta_d^2), \ln S_c \sim N(\lambda_c, \beta_c^2) \tag{4}$$

where λ is the mean and β is the standard deviation of the normal distribution.

It is known that:

$$\ln S_d - \ln S_c \sim N(\lambda_d - \lambda_c, \beta_d^2 + \beta_c^2) \tag{5}$$

$$P_f = P[\ln S_d - \ln S_c \geq 0] = \Phi(\frac{\lambda_d - \lambda_c}{\sqrt{\beta_d^2 + \beta_c^2}}) \tag{6}$$

Eq. (6) indicates that the cumulative distribution function (CDF) of P_f is a log normal distribution. Therefore

$$\begin{aligned} P_f &= P(S_d \geq S_c | IM) \\ &= \int_0^{IM} \frac{1}{\sqrt{2\pi}\beta IM} \exp\left[-\frac{(\ln IM - \ln \lambda)^2}{2\beta_{IM}{}^2}\right] d(IM) \\ &= \Phi\left(\frac{\ln IM - \ln \lambda}{\beta}\right) \end{aligned} \tag{7}$$

where λ and β represent the insensitive measure (IM) and the standard deviation in the Logarithmic space, respectively.

Once the structural failure probability of different component is confirmed, the related LCC can be evaluated using Eq. (8) [9]:

$$C_{LCC} = C_{IC} + C_{OC} + C_{MC} + C_{FC} + C_{DC} \tag{8}$$

where C_{IC} represents input costs, which include procurement costs and construction costs. C_{OC} stands for operating costs. C_{MC} refers to maintenance costs, which involve expenses for the regular replacement of spare parts and components according to maintenance requirements during the equipment's lifespan. It also includes costs for emergency repairs, maintenance, testing, inspections, and related expenses such as material costs, labor costs, and transportation costs. C_{FC} represents failure costs, which are also known as penalty costs. C_{DC} represents decommissioning costs, which include expenses associated with dismantling and disposal after the equipment reaches the end of its useful life. This research using the fragility framework to calculate the C_{MC}, which is an issue for bridge program management.

3. Bridge introduction and seismic uncertainty

3.1. Bridge introduction

The investigated bridge is a representative example of a prestressed concrete (PC) cable-stayed bridge, featuring a single tower and double cable-stays, as illustrated in Figure 1. The bridge consists of three spans with lengths of 180m, 103m, and 44m, respectively, and an additional auxiliary pier designed for the side span. The structural system employed is the tower-pier beam system. The main tower, constructed using C50 concrete, is a gate-shaped concrete tower with a height of 120m and a box cross-section. The main beams, also made of prestressed concrete, have a bridge deck width of 43m, a central beam height of 3.3m, and a single-box three-cell cross-section, constructed using C55 concrete. The side piers and auxiliary pier, constructed using C50 concrete, have gate-shaped configurations with slab bodies. The bridge comprises a total of 62 pairs of 124 cables, utilizing parallel wire strands (φ7) with a tensile strength of 1770MPa. In the cable-dense area of the side span, iron sand concrete counterweights are implemented, and the tops of the side piers and auxiliary pier are supported by lead-core rubber bearings. To evaluate the static and dynamic (seismic) behavior of the bridge, a finite element model (FEM) is developed using Midas Civil and OPENSEES software. Figure 2 provides a visual representation of the FEM.

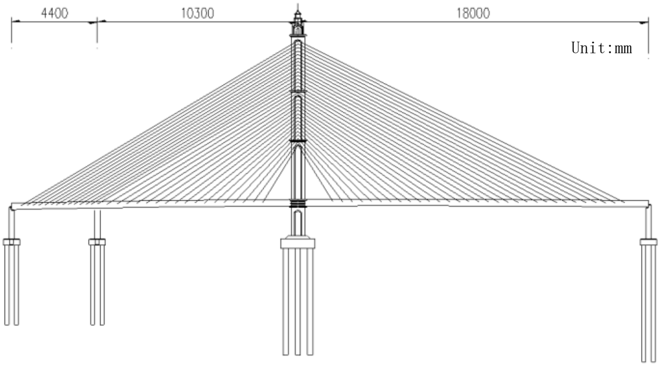

Figure 1. Layout of this cable-stayed bridge.

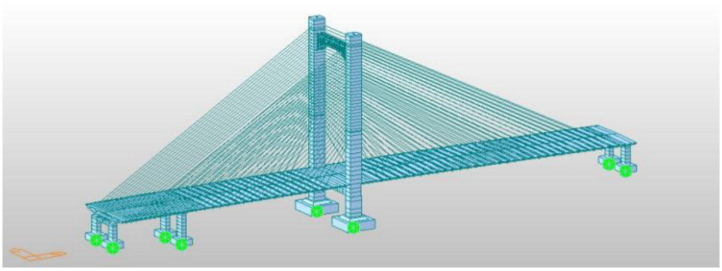

Figure 2. Visual representation of the bridge FEM.

3.2. Seismic Uncertainty

Earthquake ground motion is a non-stationary random process characterized by significant uncertainties. The response of a bridge structure to seismic forces can vary significantly under different ground motion inputs. Therefore, it is crucial to select appropriate seismic waves for the seismic vulnerability analysis of bridge structures. Currently, there are two main approaches to obtain seismic waves: using recorded earthquake ground motion data and synthesizing artificial seismic waves [10]. Considering the strong randomness of earthquake ground motion and the need for accurate vulnerability analysis results, this study chooses to utilize recorded seismic waves for the analysis of bridge seismic vulnerability. Specifically, 10 natural seismic waves are selected from the earthquake database of the Pacific Earthquake Engineering

Research Center (PEER) in the United States, as displayed in Table 1. These seismic waves are chosen based on the site conditions of the bridge in the case study, with a range of earthquake magnitudes between 6.5 and 7.5 and epicentral distances greater than 30 km.

Table 1. Selected seismic waves.

Name	Recording station	Time	Magnitude	Epicentral Distance
San Fernando	LA-Hollywod	1971	6.6	39.5
Imperial Valley	El Centro Array #11	1979	6.5	29.4
Imperial Valley	Delta	1979	6.5	33.7
Superstition Hills	El Centro Imp. Co.	1987	6.5	35.8
Loma Prieta	Gilroy Array #3	1989	6.9	31.4
Manjil-Iran	Abbar	1990	7.4	40.4
Landers	Coolwater	1992	7.3	82.1
Landers	Yermo Fire Station	1992	7.3	86
Kobe-Japan	Shin-Osaka	1995	6.9	46
Duzce-Turkey	Bolu	1999	7.1	41.3

4. Failure Calculation

4.1. Structural Capacity

The seismic fragility calculation relies on the assessment of the structural capacity (Sc) corresponding to various damage states. Choi et al. [11] suggested that the curvature ductility factor can be employed to evaluate the damage in the main tower, while the displacement ductility factor can be used to characterize the damage states of the bridge supports, as presented in Table 2. The damage states, LS1 to LS4, represent slight damage (LS1), moderate damage (LS2), severe damage (LS3), and complete damage (LS4) respectively. By utilizing the fragility curves for different damage levels, the C_{MC} can be evaluated, providing a comprehensive assessment of the bridge's vulnerability to seismic events.

Table 2. Statistic values of the damage states

Damage States	Curvature Ductility Factor	Displacement Ductility Factor
LS1	$1 < \mu_\theta \le 2$	$1 < \mu \le 1.5$
LS2	$2 < \mu_\theta \le 4$	$1.5 < \mu \le 2$
LS3	$4 < \mu_\theta \le 7$	$2 < \mu \le 2.5$
LS4	$\mu_\theta > 7$	$\mu > 2.5$

4.2. Fragility Curves and Cost Evaluation

Figure 3 shows the fragility of the main tower. Figure 4 display the fragility of the abutment of the main pier and side pier respectively.

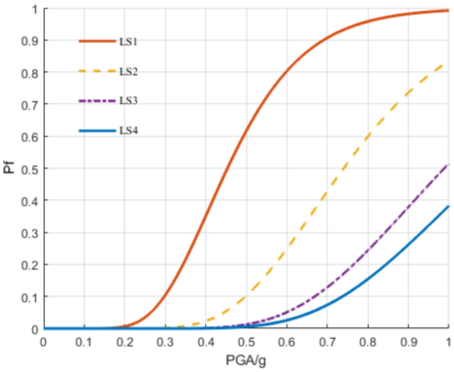

Figure 3. Fragility of the main tower.

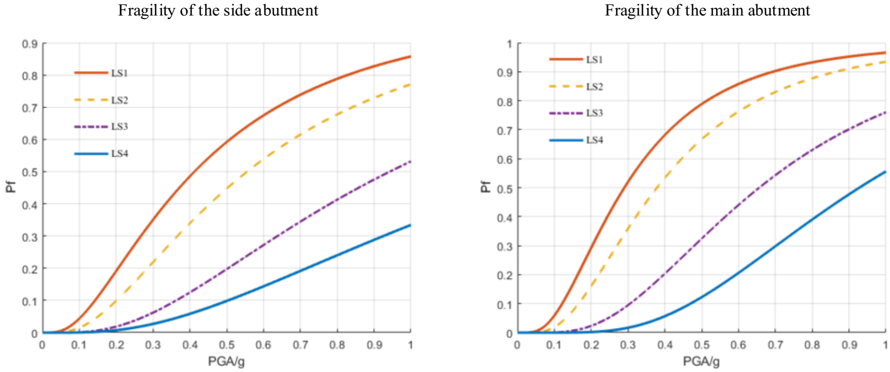

Figure 4. Fragility of the abutment.

According to the fragility curves for various components, it can be observed that as the PGA increases, the failure probabilities for the main tower and bridge supports in different damage limit states also increase. Specifically, for the case of the cable-stayed bridge in this study, the vulnerability of the supports is as follows: the side span abutments exhibit a higher vulnerability compared to the main span abutments, while the probability of severe or complete damage occurring in the main tower is relatively low.

In accordance with the Chinese design code GB55002-2021 (General code for seismic precaution of buildings and municipal engineering), the bridge is designed to withstand a peak ground acceleration (PGA) of approximately 0.2g. However, to ensure a more conservative analysis, this research adopts a higher threshold PGA of 0.3g. The corresponding failure probabilities for different bridge components under this threshold are presented in Table 3.

In the conventional retrofitting approach, the beam and pier of the bridge are strengthened using fiberglass reinforced plastic (FRP) materials. However, given the critical nature of the main tower as a key component, additional reinforcement measures are necessary following seismic events. According to the data presented in Table 3, the main tower has a low probability (less than 1%) of experiencing moderate damage or higher, leading to the decision to disregard these damage states based on the recommendation of the construction company. The construction company also provided information on the maintenance fee for similar bridges' main towers, which averages around 1-3 million USD. For simplicity, a value of 1 million USD is adopted in this analysis.

Table 3. Failure probability of different component when PGA equals 0.3g.

Component	Main Tower	Main Abutment	Side Abutment
LS1	0.098	0.352	0.515
LS2	0.011	0.211	0.344
LS3	0.003	0.074	0.097
LS4	0.002	0.029	0.031

Regarding the abutments, the estimated replacement fee for damage states LS3 and LS4, as well as the construction blocking-up fee, amounts to approximately 0.15 million USD per abutment. For damage states LS1 and LS2, the corresponding fee is around 0.08 million USD per abutment, and the actual damage fee is calculated by

$$\text{maintanence fee} = \text{replacement fee} \times \text{failure probability} \tag{9}$$

Consequently, the cumulative maintenance cost (CMC) is calculated to be 0.548 million USD, as shown in Table 4.

It is noteworthy that the maintenance costs described in this article refer to the expenses associated with reinforcing structures that have been identified as requiring strengthening after inspection, rather than the costs of traditional aesthetic maintenance. Therefore, there is no issue of periodicity; all costs are one-time expenses.

Table 4. The estimated C_{MC} (million USD) under PBSD.

Component		Main Tower	Per Main Abutment	Per Side Abutment
Estimated Fee	LS1	0.098	0.02816	0.0412
	LS2	/	0.01688	0.02752
	LS3	/	0.0111	0.01455
	LS4	/	0.00435	0.00465
Total Fee		0.548		

5. Conclusion

In conclusion, this paper focused on assessing seismic damage and calculating the lifecycle risk cost for cable-stayed bridge infrastructure. The fragility method was employed as a key approach to quantify the seismic vulnerability and estimate associated risk costs over the bridge's lifespan. Through the development of seismic fragility curves based on the structural response to various earthquake scenarios, the probabilistic representation of the bridge's performance in relation to ground shaking intensity was obtained. This facilitated the evaluation of potential damage levels and their corresponding costs.

A specific case study was conducted on a cable-stayed bridge, with a focus on longitudinal seismic waves. The findings revealed that the main tower exhibited greater resilience compared to the tower abutment. The failure probabilities for slight, moderate, severe, and absolute damage for the main tower were determined as 9.8%, 1.1%, 0.3%, and 0.2%, respectively. The corresponding failure probabilities for the main abutment were 35.2%, 21.1%, 7.4%, and 2.9%.

Based on the analysis, the estimated lifecycle cost associated with seismic events for this bridge amounted to 0.548 million USD. These results provide valuable insights for decision-making processes regarding risk reduction strategies, maintenance planning, and long-term sustainability considerations. They contribute to enhancing the resilience and safety of cable-stayed bridge infrastructure. Future research can further refine the fragility analysis and explore additional risk mitigation strategies to optimize the lifecycle risk cost calculations for these critical structures.

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