AN OVERVIEW OF PERFORMANCE-BASED SEISMIC DESIGN METHODOLOGY FOR BRIDGES

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Abstract - The Performance-Based Seismic Design (PBSD) is an advanced approach to designing earthquake-resistant structures, ensuring that a building meets specific performance objectives under seismic impacts. Unlike traditional design codes, PBSD aims to predict and control the damage to structures based on defined earthquake levels, minimizing damage and repair costs after an earthquake. The PBSD process includes defining performance objectives, selecting appropriate analysis models, conducting nonlinear analyses, and evaluating damage levels. Analytical methods such as nonlinear static pushover analysis and dynamic time history analysis are commonly applied in this process. Due to the need for in-depth knowledge and complex calculations, implementing PBSD can present significant challenges. This paper aims to present the details of PBSD based on seismic design codes and applies this approach to seismic design for bridges under earthquakes.

Keywords - Performance-based design; performance objective; push-over analysis; time history analysis; bridge.

1. Introduction

Significant historical seismic events, such as the Northridge earthquake in the US in 1994, the Kobe earthquake in Japan in 1995, the Chichi earthquake in Taiwan in 1999, and the Tōhoku earthquake and tsunami in Japan in 2011 have caused serious damage to bridges on highways, disrupting traffic and causing great economic and social losses [1-4]. Common damages include cracks and complete collapse of load-bearing structures such as columns, piers, bearings, etc. due to uneven displacement between structural components or the formation of plastic joints due to large deformation during shock absorption [2, 3, 5, 6].

Field observation studies after these seismic events have shown that the main cause of damage is that the old seismic design standards have not fully and accurately assessed the level of risk and impact of earthquakes on structures [3]. The seismic design perspective in current standards in many countries around the world still has some limitations, in which the use of linear elastic analysis methods for the entire structural system is difficult to reliably reflect the responses and damage of the structure, especially non-linear dynamic responses. Therefore, in recent decades, many studies have focused on developing and perfecting the seismic design process. One of the advanced methods is performance-based seismic design (PBSD) [7]. PBSD was initially applied to high-rise buildings in high seismic areas. The method gained traction in the 1990s, particularly after the 1994 Northridge earthquake and the 1989 Loma Prieta earthquake in California when traditional seismic design methods were found to be inadequate. The method was later extended to other types of structures, including bridges and other critical infrastructures.

PBSD is an advanced approach to earthquake-resistant structural design. It focuses on designing structures to meet specific performance objectives under different earthquake levels, rather than simply following traditional design codes. PBSD allows engineers to predict and manage the extent of damage to structures by considering factors such as acceptable damage levels, downtime, and repair costs, thereby optimizing design solutions to minimize damage and costs.

Despite many advantages over traditional methods, the application of PBSD in Vietnam is still very limited. limited by the lack of specialized human resources, technical standards, high design costs, lack of technology, and analysis software, especially the low priority of investment for large, complex projects because Vietnam is located in an area of small and medium earthquakes. Some studies have initially introduced PBSD. Specifically, in the study of Nguyen Hong Ha et al. [8], this method was briefly presented with instructions for application to high-rise buildings and frames. Some other studies, although not yet comprehensively implementing the method, have focused on analyzing the static and nonlinear dynamic behavior of structures under specific earthquake intensities using deterministic [9-14]and probabilistic [15, 16].

Worldwide, PBSD has been developed and integrated into design standards of countries such as the US, Japan, New Zealand, China, and Europe for both high-rise buildings and bridges [17-23]. Based on PBSE, a more advanced method has also been developed, which is Performance-Based Earthquake Engineering (PBEE) [24]. PBEE is a comprehensive earthquake-resistant structure evaluation and design method, focusing on predicting and controlling the specific responses of structures to earthquakes based on probabilistic models. This method not only focuses on bearing capacity but also considers other factors such as economic loss, downtime, and human safety.

On that basis, the paper aims to provide an overview of PBSD with an emphasis on the sequence and content of the method based on a review of research literature and current seismic design standards in some developed countries. Next, the paper presents guidelines for applying PBSD in seismic design for earthquake-resistant bridges. Finally, conclusions and recommendations for this design method in Vietnam conditions are presented specifically.

2. General procedure

PBSD is a sophisticated seismic design approach, first proposed and developed in the early 1990s. The concept has attracted attention from the work of researchers in the United States, especially from the Vision 2000 report published by the Structural Engineers Association of California (SEAOC) in 1995 [25]. This report laid the foundation for PBSD by defining a design framework for structures to meet specific performance objectives under different seismic hazard levels.

PBSD aims to provide an accurate and reliable assessment of the performance of a structure against different seismic intensities over its lifetime, ensuring that the structure meets the proposed performance requirements. This method has been widely deployed around the world, not only for calculating and upgrading old structures but also for designing new structures. The PBSD process begins with the establishment of specific performance objectives. Next, the consultant will carry out design and analysis steps to ensure that the structure can achieve these objectives under seismic conditions at different risk levels.

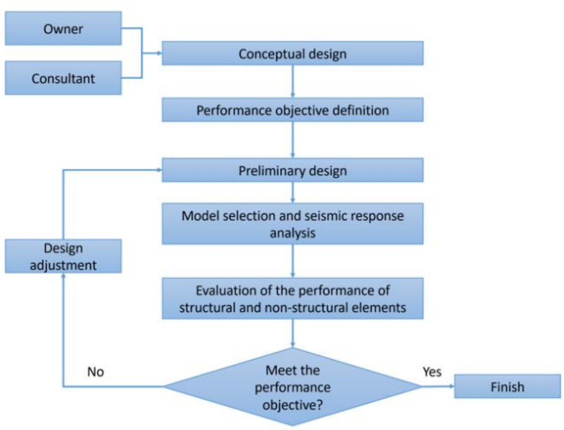

Figure 1. *General procedure of PBSD*

The general procedure of the method is shown in Figure 1 and specifically has the following main steps:

(1) Conceptual design and performance objective definition.

The PBSD process begins with conceptual design and the definition of specific performance objectives for the structure under different seismic levels. These objectives are usually agreed upon between the owner and the design consultant based on the conceptual design, including the safety and performance requirements of the structure. The performance objectives are determined based on the combination of the desired performance level of the structure and the seismic hazard level. Depending on the type of structures, scale, importance, and investment cost, appropriate objectives need to be determined to ensure that the desired safety and performance requirements are met.

(2) Preliminary design.

In PBSD, the preliminary design step is the foundation for guiding the seismic requirements of the structure. Based on the selected performance levels, seismic hazard levels, and performance objectives, the preliminary structure is established with elements such as beams, columns, partitions, and other load-bearing members, ensuring the load-bearing capacity is suitable for the determined performance objectives.

(3) Model selection and seismic response analysis.

The selection of analytical models and methods for earthquake-resistant bridges is an important part of the design and assessment of the structure's resistance to earthquakes. Based on the performance objectives and the seismic hazard levels, appropriate analytical models are developed for the structure, for example:

- 2D, 3D models;

- Linear and nonlinear models;

- Rigid model, plastic model (distributed plastic model and concentrated plastic model);

- The model considers and does not consider soil-structure interactions.

From the selection of the model, the earthquake analysis methods also need to be selected, for example:

- Equivalent horizontal static force analysis method;

- Nonlinear static analysis method of gradual push;

Time history dynamic analysis method.

Based on the selected model and analysis method, seismic analyses are performed to determine the response of the structure to different earthquake levels. Nonlinear analyses are often used to determine Engineering Demand Parameters (EDP) such as displacements, forces, and deformations of structural elements.

(4) Evaluation of the performance of structural and non-structural elements.

Results from earthquake analyses are used to evaluate the performance of structures through the evaluation of the performance of structural and non-structural elements. This process includes:

- Determine potential damage levels based on analysis results.

- Compare the seismic responses with the performance criteria.

(5) Compare and adjust designs.

At each step of design and analysis. The achievement of performance objectives should be evaluated. If the project does not achieve the stated performance objectives, design adjustments should be made.

(6) Repeat the analysis and evaluation process and finalize the design and report.

PBSD is an iterative process where the design can be adjusted and re-analyzed repeatedly until the structure achieves the desired performance goals. This ensures that the structure not only meets safety standards but is also optimal in terms of cost and efficiency. Once the design meets all performance objectives, the PBSD process concludes with a detailed report on the design process and analyses performed, including the solutions applied to ensure the project achieves the desired performance.

3. Application guidelines for bridges

3.1. Definition of performance objective

Bridge performance objectives are established to ensure that the structure can withstand different earthquake intensities while maintaining safety, operability, and structural integrity. These objectives are determined based on the importance of the bridge, its location, and its level of earthquake hazard.

Based on the synthesis of bridge design standards including American bridge design standards AASHTO LRFD [20], European standards Eurocode 8 [23], Japanese road bridge design standard JRA [21] and Canadian road bridge design standard CSA S6 [26], the performance objectives of bridges are determined according to Table 1.

Table 1*Performance objectives for bridges*

Performance Objective	Condition after the earthquake	Apply
Continued operation	In the case of a small to moderate earthquake, the bridge continued to operate with minimal or no damage. It was capable of supporting regular traffic loads right after the event without the need for extensive repairs.	This objective is vital for critical bridges that function as emergency routes, evacuation pathways, or access points to essential services like hospitals, fire stations, and disaster response centers.
Damage control	During a moderate to strong earthquake, the bridge may sustain some damage; however, this damage should remain within repairable limits. The structure should still be able to support restricted traffic or enable emergency vehicles to traverse it immediately following the event.	This characteristic is crucial for key urban and motorway bridges that support emergency operations and require rapid restoration to ensure functionality.
Life safety	In the occurrence of a design earthquake, the bridge should avoid collapse, maintaining enough structural stability for safe evacuation. While the bridge may experience moderate damage to both structural and non-structural components, repairs will be necessary to restore it to full functionality.	Most bridges, particularly those situated in regions with moderate to high seismic risk, are engineered to meet this performance objective.
Collapse prevention	During a rare and extreme earthquake, commonly known as a maximum considered earthquake (MCE), the bridge must not collapse. While substantial damage may occur, it is essential that the structure maintains its integrity to ensure that it does not fail and that safe evacuation is possible.	This performance objective is crucial for bridges in high seismic areas, particularly those that function as vital links during earthquake recovery, like major arterial routes.

Several factors influence the determination of performance objectives for bridge projects. The main factors include:

- Importance and classification of bridges: bridges are categorized based on their significance to the transportation network, including important, essential, and standard bridges. Important bridges are subject to more stringent performance objectives.

- Seismic hazard level: the level of earthquake hazard at the site affects the selection of performance objectives.

- Type of bridges: the type of bridges (e.g., girder bridge, arch bridge, truss bridge, suspension bridge, etc.) significantly impacts its seismic performance and associated objectives.

- Earthquake operability requirements: bridges that are critical for emergency rescue operations must remain functional, while others may only need to avoid collapse to ensure safety.

- Cost and risk management considerations: the balance between construction and reinforcement costs and the acceptable level of risk plays a key role in determining the selected performance objectives for the bridge.

3.2. Bridge modeling and analysis

Current design standards such as AASHTO LRFD [20], Eurocode 8 [23], JRA [21] often requires the use of dynamic analysis methods, such as response spectrum analysis or time history analysis, to evaluate the response of bridges to different earthquake scenarios. Therefore, whole bridge modeling is often performed, focusing on the main structural elements while considering nonlinearities in geometry and materials. In addition, to conduct time history analysis, the selection of suitable ground motion records is also important, so earthquake record selection algorithms need to be used to find records that are suitable for the seismic properties and characteristics of the bridge construction area.

3.2.1. Bridge modeling

Modeling of earthquake-resistant bridges typically includes the following steps:

- Structural model selection: the model must accurately capture the material properties, geometry, and dynamic characteristics of each structural component as well as the entire structure. Key structural elements, including abutments, piers, deck girder systems, and bridge bearings, should be represented in detail. During seismic events, components like piers, abutments, and bridge bearings are particularly vulnerable and are directly affected by horizontal loads generated by seismic shaking. Consequently, deck girder systems are typically assumed to operate within their elastic limits, while bridge piers, abutments, and bearings are often modeled using nonlinear approaches. Additionally, depending on the specific context, the interaction between the foundation and the structure may need to be incorporated into the model. For pile foundations, two commonly used methods for modeling the foundation-structure interaction are the equivalent soil stiffness model and the equivalent soil spring model [27, 28].

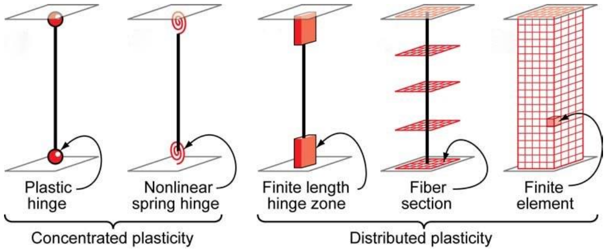

Figure 2. *Plasticity modeling methods for bridge columns*

- Nonlinear plasticity modeling: for nonlinear analysis, it is necessary to model plasticity considering both material nonlinearities and geometric nonlinearities (e.g., effects of $P - \Delta$, large deflections). There are many plasticity modeling methods as shown in Figure 2 [29]. Distributed plasticity models such as plastic hinge models, fiber section models, and FEM models give results with high accuracy; however, they are time-consuming and costly to model and analyze. Meanwhile, concentrated plasticity models are quite simple, fast to model and analyze, and capable of analyzing the deformation of structures. However, it should be noted that the parameters of concentrated plasticity models are often difficult to determine, which determines the accuracy of the model [14].

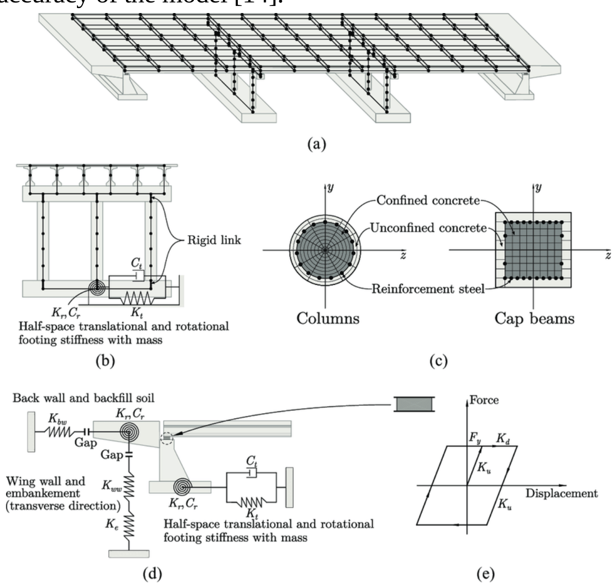

Figure 3. *An example of the numerical model of a reinforced-concrete bridge: (a) overview, (b) bent elevation, (c) fiber sections, (d) abutment, and (e) material model for elastomeric bearings*

Figure 3 presents a detailed numerical model of a reinforced concrete bridge, showcasing the various components and their respective modeling techniques [30]. In this model, the deck system is represented using linear elastic elements. For the columns and cap beams of the pier, fiber section models are utilized. This approach allows for a more nuanced analysis of the material response, considering the nonlinear behavior of reinforced concrete under various stress states.

The abutment model is comprehensive, incorporating key features such as the back wall, backfill soil, and wing wall. These elements are represented using linear spring models, which simulate the interaction between the abutment and surrounding soil, ensuring a realistic representation of lateral loads and settlement effects.

Furthermore, the foundation is modeled with translation and rotation springs, allowing for the simulation of both vertical and horizontal displacements under load. Additionally, a nonlinear hysteretic model is applied to the bearings. This choice reflects the bearings' crucial role in accommodating movements and dissipating energy during seismic events.

3.2.2. Ground motion record selection

The selection of ground motion records is an important step in the PBSD earthquake analysis. The selection of appropriate ground motion records determines the accuracy of the results of the time history dynamic analysis [31]. In addition, the selection of appropriate ground motion records must follow a strict procedure to ensure that these records accurately represent the actual earthquake conditions at the construction site, as well as ensure the requirements for the performance level of the structure. There are many selection methods presented in the reference; here, the selection method for elastic response spectrum records is presented including the following main steps:

(1) Determine earthquake characteristics at the site: earthquake magnitude, source-to-site distance, soil conditions and site class, geological properties, and soil classification greatly affect the amplification and vibration spectrum of earthquakes and elastic response spectrum.

(2) Collection and selection of ground motion records: ground motion records are collected from global and regional seismic databases, such as PEER NGA (Pacific Earthquake Engineering Research Center - Next Generation Attenuation), USGS (United States Geological Survey), and other databases.

(3) Adjustment and scaling of ground motion records: after selection, the ground motion records need to be adjusted to match the design elastic response spectrum of the structure. The adjustment process includes: (i) adjusting to the target spectrum by methods such as linear or nonlinear adjustment to ensure that the response spectrum of the ground motion record is close to the design response spectrum; (ii) scaling by a conversion factor so that the amplitude of the ground motion record matches the target vibration level; (iii) reviewing the frequency content to ensure that the selected ground motion record has appropriate frequency content, especially frequencies that are important to the response of the structure.

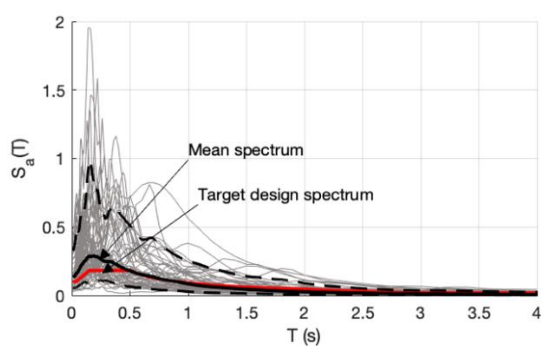

Figure 4. *Acceleration response spectra of selected ground motions from the target response spectrum*

An example of selecting a set of 30 ground motion records based on the target elastic response spectrum from the PEER earthquake record database (https://ngawest2.berkeley.edu) is shown in Figure 4. In which, the target elastic spectrum is designed for the Hoa Vang district, Da Nang City according to TCVN 9386:2012 [32].

3.2.3. Seismic response analysis

In the PBSD of bridges, two common methods are nonlinear static pushover analysis and nonlinear time history analysis. Both methods can provide detailed information about the response and capacity of a bridge structure to earthquakes.

(1) Nonlinear pushover static analysis: this method is based on the application of a series of increasing static loads until the bridge structure reaches its limit state (damage or collapse). The analysis results are presented in the form of a base shear displacement, allowing the assessment of the earthquake resistance of the bridge structure. An example of the method for a bridge pier structure and the corresponding results are shown in Figure 5.

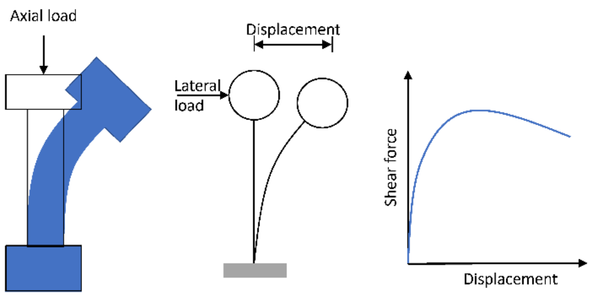

Figure 5. *Description of nonlinear static analysis of pushover on a concentrated mass model of the bridge column*

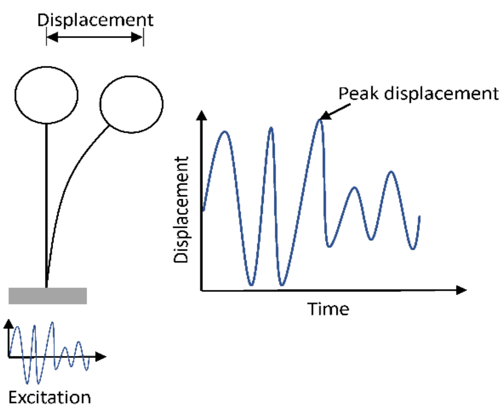

Figure 6. *Time history dynamic analysis description of a concentrated mass model of the bridge column*

(2) Time history dynamic analysis: this method simulates the response of the bridge structure under the impact of one or more earthquakes. The analysis results include information on displacements, deformations, forces, and moments over time at important locations on the structural element. An example of the method and analysis results is shown in Figure 6.

3.3. Determination of limit states of structural components and corresponding performance levels

In seismic design for bridges, structural member limit states and performance levels are two core elements to ensure safety and efficiency in the face of earthquake impacts. These limit states define the damage threshold of each bridge structural member, while the performance level describes the bridge's ability to withstand and respond to different earthquake conditions. The limit states of bridge structural members are the conditions at which a structural element can no longer perform its intended function. In seismic design, the main limit states are shown in Table 2.

Table 2*Limit states and corresponding performance levels of bridges specified by AASHTO LRFD*

Limit state	Corresponding performance level	Explanation
Serviceability Limit State (SLS)	Operational Performance Level	**Description:** The bridge is still operating normally with minimal damage. or no damage after an earthquake event. The bridge must be open to traffic immediately without significant repairs. **Criteria:** Small cracks and insignificant deformations in structural elements do not affect the function of the bridge. Ensure the continuity of components such as bearings, joints and utilities. **Application:** Critical bridges such as emergency routes require this level of performance to ensure immediate use after an earthquake.
Damage Control Limit State (DCLS)	Immediate Occupancy Performance Level	**Description:** Bridge sustained minor to moderate damage but is still safe to use. Some minor repairs may be required to restore full functionality. **Criteria:** Minor damage to abutments, piers and superstructure with reinforcing steel starting to yield. Limited and repairable damage to non-structural elements such as railings. Functionality may be slightly affected but can be recovered quickly. **Application:** Bridges serve important transportation corridors and need to remain operational immediately after an earthquake event.
Life Safety Limit State (LSLS)	Life Safety Performance Level	**Description:** The bridge may have sustained significant damage, but the structure remains stable and has not collapsed, ensuring human safety. Emergency access may be restricted until repairs are complete. **Criteria:** Cracks develop and concrete sloughs off significantly. Limited elastic deformation without loss of stability or primary load-bearing capacity. Some damage may be repairable to structural components such as abutments, piers or superstructure. **Application:** Typically applied to standard highway bridges where temporary closure for repairs is acceptable following an earthquake.
Collapse Prevention Limit State (CPLS)	Collapse Prevention Performance Level	**Description:** The bridge suffered severe damage and was in danger of collapsing, but the structure did not collapse completely, allowing people and vehicles on or around the bridge to escape safely.

Limit state	Corresponding performance level	Explanation
		Criteria: Severe damage to major structural elements with the appearance of large cracks and plastic deformation. Localized failures do not lead to sequential or total collapse. There is a possibility of non-structural elements or secondary structural components being damaged or separated. **Application:** Bridges whose main goal is to prevent complete collapse, ensuring human safety during major earthquakes.

To identify the limit states and align them with the performance levels of the structure, the following steps should be undertaken:

- Nonlinear static and dynamic analysis: employ methods such as push-over nonlinear static analysis and incremental dynamic analysis to assess the response of bridge components under various earthquake loading scenarios.

- Define specific damage criteria: establish damage thresholds for each structural element, considering factors such as curvature, displacement, stress, and safety-related criteria.

- Incorporate design standards: utilize relevant seismic design standards, including AASHTO LRFD, Eurocode 8, or local codes, to inform the design process and evaluate limit states.

After determining the limit states and corresponding performance levels for the structural elements, the next step is to conduct design verification and optimization. This ensures that the bridge design adheres to the specified limit states while maximizing cost-effectiveness and efficiency.

4. Conclusion and recommendations

In this paper, we have thoroughly examined various international standards, seismic design guidelines, and relevant research documents, ultimately providing a detailed analysis of the performance-based seismic design (PBSD) methodology for bridges. The following key conclusions can be drawn from the study:

A thorough and systematic approach to seismic design is essential to guarantee the safety, functionality, and overall integrity of bridges when subjected to seismic events. The PBSD framework offers a more adaptable alternative to conventional design methods. While PBSD has gained traction globally, its application in Vietnam remains limited and necessitates updates to the existing seismic design standards.

The assessment of earthquake risk, along with the establishment of performance levels and objectives for bridges, is crucial in the seismic design process. This study outlines four specific performance objectives for bridges: continued operation, damage control, life safety, and collapse prevention, each aligned with varying levels of earthquake risk.

The integration of nonlinear dynamic modeling and analysis is vital for accurately evaluating the response of bridges to diverse seismic conditions. These advanced methods not only facilitate the assessment of structural responses but also help identify the limit states of individual components, enabling a more effective correlation with the established performance levels. This ensures that bridges are designed not only to endure seismic forces but also to remain operational or be swiftly and safely restored post-event.

Embracing the PBSD methodology and updating current seismic design standards could significantly enhance the seismic resilience of bridges in Vietnam, particularly for critical and large-scale bridges, while also reducing costs associated with design, repairs, and rehabilitation. Further research into the adaptation of PBSD and PBEE within local contexts is essential to ensure that design strategies are both appropriate and effective.

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