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Seismic Performance Assessment and Enhancement Strategies for Civil Engineering Structures

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Abstract: Against the backdrop of rapid socio-economic development in our country and the accelerated pace of urbanization, the construction industry has been provided with a vast space for vigorous development. With the increasing demands for building quality, the design of civil engineering structures faces higher challenges and standards. Designers, in the design process, must not only pursue the aesthetic effect of buildings but also pay more attention to the safety of structures. Seismic design has received widespread attention in today's society, as its effectiveness is directly related to the stability and durability of building structures, which in turn affects the personal safety of building users. Therefore, in the design process of civil engineering structures, designers must establish advanced seismic design concepts, making seismic performance one of the core elements of design. To achieve this goal, designers need to scientifically and reasonably determine the seismic grade of buildings by combining multiple factors such as the geological conditions of the project location, history of seismic activity, and building usage. Meanwhile, advanced seismic technologies and materials need to be adopted to ensure that building structures can effectively absorb and disperse seismic energy during earthquakes, thereby maximally protecting the safety of buildings and their users.

Keywords: Civil Engineering; Seismic Design; Structural Design.

1. Key Points of Seismic Design

1.1. Requirements for Seismic Design

The performance goal of seismic design in civil engineering is to ensure the safety of buildings under different earthquakes, as shown in Table 1. The standard for normal use (a) requires that both structural and non-structural components are essentially undamaged, ensuring building functionality[1-2]. The temporarily usable standard (b) allows for minor damages that can be easily repaired for use. The life safety standard (c) emphasizes structural stability, adequate vertical bearing, and non-structural damages not endangering life safety. The collapse prevention standard (d) requires that buildings, even if damaged, do not collapse. All buildings need to meet the requirements of combinations a, b, c, d to ensure basic safety and usability during earthquakes. Important buildings also need to meet the higher requirements of combinations e, f, g, ensuring uninterrupted functionality and rapid recovery. Buildings with high safety requirements need to achieve combinations h, i, j, targeting structural integrity and continuous functionality under extreme earthquakes. Seismic design is crucial for the safety of both buildings and people, with different performance goals guiding the design to ensure buildings perform as expected during earthquakes. Designers must select appropriate performance goals based on factors like geology, usage, and cost, to balance safety and economy.

Table 1. Performance Goals for Seismic Design in Civil Engineering

Levels of Earthquake Exposure	Civil Engineering Performance Levels			
	Normal Use	Temporary Use	Life Safety	Collapse Prevention
Frequently Occurring Earthquakes	a			
Occasionally Occurring Earthquakes	e	b		
Rarely Occurring Earthquakes	h	f	c	
Very Rarely Occurring Earthquakes	j	i	g	d

1.2. Calculation Methods for Seismic Design

Currently, the two main seismic calculation methods widely used in the field of civil engineering are the modal combination response spectrum method and the elastic dynamic time-history method. The modal combination response spectrum method is a calculation method based on the vibrational characteristics of structures. It analyzes the response of structures under different modes and combines these responses to obtain the overall response of the structure under seismic actions. The elastic dynamic time-history method calculates the dynamic response of structures under seismic waves through direct integration[3]. This method can consider the impact of the spectral characteristics and duration of seismic waves on structural response, making it suitable for more accurate modeling and analysis of the nonlinear behavior of structures under strong earthquakes. However, when the building and structural systems are complex, with uneven distribution of mass and stiffness vertically, the applicability of the above two methods may be limited. In such cases, choosing the elastoplastic dynamic time-history method for calculation is a wiser choice. This method fully considers the elastoplastic behavior of structures under strong seismic actions, including material nonlinearity, geometric nonlinearity, and contact nonlinearity, among others. Through this method, a more accurate and comprehensive simulation and analysis of the complete response of complex structures under seismic actions can be performed, thus providing a more reliable basis for the seismic design and reinforcement of structures.

1.3. Calculation of Seismic Structures

In the calculation of seismic structures for civil engineering, several core principles must be rigorously followed. First, for load and non-load actions, the elastic method must be used for accurate calculations, which is the basis for ensuring structural safety. Any negligence could lead to serious consequences. Second, the impact of non-load actions on the internal forces of structures cannot be underestimated. Especially, the creep of concrete plays an important role in the stress process of structures and should be included in calculations to accurately reflect the structural stress state. Third, the calculation of seismic structures should be based on actual calculation diagrams and refined calculations should be carried out using three-dimensional spatial analysis methods[4]. Special attention should be paid to the influence of torsion, which is a key factor affecting the stability of the structure. At the same time, using more than two mechanical models for verification can greatly improve the accuracy and reliability of the calculations. Fourth, the calculation of gravity load actions should not be ignored. Obtaining structural stiffness information through construction simulation and understanding the formation process of gravity loads provides strong support for subsequent design. Fifth, the overall stability and anti-overturning verification are key to ensuring the safety and stability of the structure under extreme conditions. This part of the calculation must be rigorous and meticulous to ensure the safety and stability of civil engineering structures.

The formula for stability verification is as follows:

$$\mathrm{Gte} \leq \mathrm{EJd/8H2} \tag{1}$$

Where Gte is the standard value of the equivalent gravity load at the top; EJd is the equivalent stiffness against overturning in the main axis direction; H is the building height.

The anti-overturning verification formula:

$$\mathrm{Mr} \geq 1.3\mathrm{MOV} \tag{2}$$

Where MOV is the standard value of the overturning moment calculated based on wind loads and seismic forces; Mr is the standard value of the civil engineering structure's resistance to overturning moment.

2. Seismic Performance Evaluation of Civil Engineering Structures

2.1. Evaluation Based on Historical Seismic Damage Records

Evaluation based on historical seismic damage records is a method that predicts and evaluates the seismic performance of current structures in potential earthquakes by reviewing and analyzing the seismic damage data of similar structures in historical earthquakes. When conducting an evaluation based on historical seismic damage records, the following key steps are usually considered, as shown in Figure 1.

First, collect historical seismic damage data of structures similar to the target structure.

Second, filter out the most similar cases to the target structure from the collected data, and process these data for subsequent analysis and comparison.

Third, conduct detailed seismic damage analysis of the selected historical cases, including structural damage modes, damage degrees, and performance degradation, etc.

Fourth, infer the seismic performance of the current structure in potential earthquakes based on the results of the seismic damage analysis. This can be achieved by using empirical formulas, regression analysis, probability models, etc. For example, using the following simple formula to evaluate the seismic performance index of a structure:

$$SPI = \frac{\sum_{i=1}^{n}(Di \times Wi)}{\sum_{i=1}^{n} W_i}$$

Where (Di) is the degree of damage of the structure in the (i)th historical case (which can be a qualitative or quantitative indicator), (Wi) is the weight of the case (which can be determined based on factors such as similarity to the target structure, the magnitude of the earthquake, distance from the epicenter, etc.), (n) is the total number of historical cases.

Fifth, interpret the evaluation results and propose suggestions for improving design or reinforcing structures as needed.

However, when using this method, its applicability and limitations need to be fully considered, and it should be combined with other seismic evaluation methods and means to ensure the accuracy and reliability of the evaluation results.

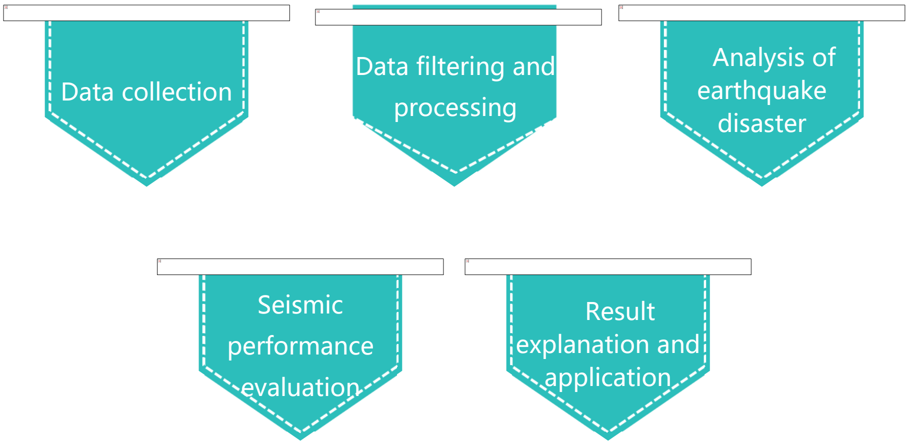

Figure 1. Steps in the Evaluation of Historical Seismic Damage Records

2.2. Evaluation Based on Seismic Motion Parameters

Evaluation based on seismic motion parameters is an important seismic design method. Seismic motion parameters, such as peak acceleration, peak velocity, and response spectra, are key physical quantities used to quantify the characteristics of seismic waves. These parameters not only reflect the intensity and characteristics of the earthquake itself but are also closely related to the dynamic response of engineering structures[5]. In seismic design, by analyzing the relationship between these seismic motion parameters and the dynamic characteristics of structures, the response and possible damage of structures under seismic actions can be predicted and evaluated. This prediction and evaluation provide important references for structural designers, helping them to take necessary seismic measures at the design stage to ensure the overall safety and stability of the building structure. However, to achieve accurate predictions and evaluations, reliable seismic motion parameters and structural dynamic characteristics data are essential. Therefore, in the evaluation based on seismic motion parameters, the collection, processing, and analysis of data are particularly important. Only by ensuring the accuracy and reliability of the data can we confidently face the challenge of earthquakes, a natural disaster, and build safer and more stable building structures.

3. Strategies for Improving the Seismic Performance of Civil Engineering Structures

3.1. Enhancing the Effectiveness of Construction Site Selection

The selection of construction sites for civil engineering is crucial to the seismic performance, directly affecting the safety of buildings in earthquakes and other natural disasters. Therefore, in the site selection process, civil engineers must have a deep understanding of seismic regulations and closely integrate cutting-edge seismic design concepts to ensure the harmony and unity of structural design with external environmental conditions. Before construction, designers need to conduct thorough site investigations to fully understand the geographical and geological characteristics of the project site, especially the seismic activity. Judging whether the project is located in or near a seismic zone is a key factor in site selection decisions. Comprehensive evaluation of the entire construction site is also crucial, and construction in areas with adverse geological conditions, such as soft soil and liquefied soil, must be avoided. Ideal construction sites should choose dense and uniform hard soil areas with strong bearing capacity, which can provide a stable foundation for buildings and effectively resist the action of seismic forces. For the construction site selection of the same building unit, the consistency of the foundation is particularly important. If adverse soil layers are found, such as liquefied or cohesive soil, timely measures must be taken for reinforcement, or solutions such as deep foundations should be used to improve the stiffness and seismic resistance of the foundation. These meticulous considerations and measures are key to ensuring the safety and stability of civil engineering in earthquakes.

3.2. Optimizing Material Selection

Material optimization is a critical aspect of construction, as the choice of materials significantly impacts the quality and overall effectiveness of civil engineering projects. Before construction begins, it is essential for contractors to commission professional technicians to conduct thorough site investigations to accurately determine the seismic coefficient for the project. This coefficient not only provides clear guidance for construction but also serves as a crucial basis for material procurement. Given the significant differences in the seismic performance of various construction materials, it is necessary for contractors to select isolation materials specifically and apply seismic isolation treatments to enhance the overall seismic effectiveness of the project. At the same time, optimizing and improving design methods is also crucial. Traditional seismic design in civil engineering often involves laying sand or clay at the base, which can achieve the desired effect to some extent. However, in the new era, as technology advances, this method has become somewhat outdated. To significantly improve the seismic performance of projects, it is necessary to innovate traditional methods, such as considering the use of new materials like asphalt at the base, which not only effectively enhances the stability of the base but also significantly improves the overall seismic effect of the project.

3.3. Optimizing Seismic Plane Design

Optimizing seismic plane design is also crucial when designing the foundation location of civil engineering projects. The primary considerations are the building's seismic design category and geological conditions, which directly determine the bearing capacity and stability of the foundation. Every detail of the design scheme must be carefully deliberated. Designers must possess profound knowledge of civil engineering and a deep understanding of earthquake dynamics to ensure buildings can withstand earthquakes. Besides foundation design, the external shape and rigidity characteristics of buildings are key factors in enhancing seismic capability. Designers must fully understand these characteristics and consider them in the design, as any negligence could lead to severe damage or collapse of buildings during earthquakes. Uniformity and symmetry are vital principles in seismic design. Any form of asymmetry could lead to local damage or even total collapse of buildings during earthquakes. Thus, optimizing seismic plane design to ensure structural balance and symmetry in buildings is an effective way to enhance their seismic performance. For common structures like unit buildings, designers can use advanced design concepts like the vertical transportation method to integrate spaces organically, improving overall rigidity and torsional resistance. It's also important to mitigate the effects of adverse factors like corner effects to maintain stability during earthquakes.

4. Conclusion

In conclusion, civil engineering construction is not only crucial for economic and social development but also closely related to people's daily lives. Every building embodies people's aspirations for safety, comfort, and a better life. Therefore, enhancing the safety of buildings is an essential task. Strengthening seismic design is an indispensable part of ensuring building safety and achieving this goal. During the seismic design process, designers bear a significant responsibility and must adhere to the principle of simplifying structures to avoid stress concentration and decreased seismic performance due to overly complex structures. Moreover, improving the overall performance of buildings to ensure they can resist external forces as a whole during extreme events like earthquakes is crucial. Additionally, enhancing the resistance of buildings by using high-strength materials and optimizing structural layouts to continuously improve their seismic capability is essential for ensuring the safety of people's lives and property.

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