State-of-the-Art and Development of Seismic Analysis for Complex Bridges

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Abstract. Due to the complexity of dynamic response characteristics of complex bridges, it is difficult to give uniform regulations to give comprehensive and complete guidance for its seismic analysis. In order to promote the development of seismic analysis of complex bridges, the research status and progress of complex bridge seismic analysis were discussed in detail. Firstly, the characteristics of the commonly used seismic analysis methods for bridges and their applicability to complex bridges were summarized. Secondly, the selection and synthesis methods of far-field and near-field seismic used for bridge seismic analysis were concluded. Meanwhile, the seismic input methods and the most unfavorable input direction of curved bridges were discussed. Then, the anti-seismic analysis model of the main components of bridges were summed up, and the medium-structure interaction (including pile-soil-structure interaction, abutment-soil-structure interaction and water-structure interaction, etc.) were investigated. Finally, on this basis, the unsolved problems and the future development directions in this research field were pointed out. It is concluded that the seismic analysis of complex bridges still has some shortcomings, which needs to be improved and developed.

Keywords. Bridge engineering, complex bridges, seismic analysis.

1. Introduction
As the throat engineering of traffic network, bridge structures is the foundation to ensure the normal operation of traffic infrastructure. However, many large earthquakes, such as the 1995 kobe earthquake in Japan, the 1999 chi-chi earthquake in Taiwan, China, the 2008 Wenchuan earthquake in Sichuan, China, the 2010 Yushu earthquake in Qinghai, China, caused serious or collapse damage to bridge structures. The damage of bridge structures not only directly endangers the safety of life and property, but also cuts off the traffic in the earthquake area, which hinders the emergency rescue work after the earthquake. Therefore, it is very important to carry out the seismic analysis of the bridge structure [1].

With the development of bridge seismic research, the dynamic response characteristics of regular bridge under earthquake action can be well grasped by using the simplified calculation method that recommended by the code base on a large number of accumulated earthquake damage experience and theoretical research results [2]. However, for complex bridges, such as irregular bridges, skew bridges, etc., due to the complexity of structural dynamic response analysis, it is difficult to provide unified provisions to guide the seismic analysis. And with the development of China transportation infrastructure, complex bridges such as curved bridges, skew bridges, are widely used. Nevertheless, in the Wenchuan earthquake, the seismic damage to complex bridges is serious, for example, the
serious damage and failure of many high pier bridges such as Miaoziping super large bridge, the partial collapse of the curved section of Baihua bridge, the destruction of Abutment shear connector of Shoujiang bridge and Minjiang Bridge. It reflects that there are still many deficiencies in seismic analysis of complex bridges.

Based on this, aiming at the problem of seismic analysis of complex bridges, this paper systematically summarizes the existing research results of bridge seismic analysis at home and abroad, and discusses the existing problems and future development of bridge seismic analysis, including: (1) seismic analysis methods of bridges; (2) earthquake action and seismic input; (3) seismic analysis model of main components of bridges; (4) medium-structure interaction; (5) existing problems and prospects of bridge seismic analysis.

2. Seismic Analysis Methods of Bridges

The development of seismic analysis methods of bridge structures is gradually developed with the understanding of earthquake and seismic damage of bridges caused by earthquake constantly. At present, the seismic analysis methods of bridge structures mainly include response spectrum method, pushover analysis method, time history analysis method and power spectrum method. The characteristics of common methods for bridge seismic analysis and their applicability to complex bridges are discussed as shown in Table 1.

| Method                  | Characteristics and applicability                                                                                                                                 |
|-------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Response spectrum method| The principle is simple and the computational complexity is small, but it can only be used for seismic elastic analysis of complex bridges, and the influence of nonlinear factors such as geometry, material and boundary connection conditions of complex bridges cannot be considered. |
| Pushover analysis method| It can check and predict the elastic-plastic response of complex bridges under earthquake action, and determine the potential failure mechanism of complex bridge structures under E2 earthquake, and find the weak link in the structures. However, the accuracy of the result analysis depends on the target displacement and horizontal loading mode, and the analysis result is relatively rough, so the structural performance of complex bridges can only be inspected from the whole. |
| Time history analysis method| The influence of spatial variation of ground motion, medium-structure interaction, various nonlinear factors and block damping on seismic analysis of complex bridges can be considered, but the result analysis depends on the input of ground motion and the selection of damping parameters in seismic analysis. |
| Power spectrum method    | It is simple to calculate the maximum response of complex bridge structures, and the statistical characteristics such as power spectral density function and variance of complex bridge structures response can be obtained. However, it is not suitable to be directly used in seismic nonlinear analysis of complex bridge structures, and appropriate mechanical treatment should be carried out under specific conditions. |

3. Earthquake Action and Seismic Input

The time, space and intensity characteristics of earthquake occurrence have strong randomness, so it is the basic problem to determine the earthquake action and ground motion input reasonably [3].

3.1. Earthquake Action

It can be seen from Table 1 that the time history analysis method is more suitable for the seismic elastic-plastic analysis of complex bridges, and its seismic action is characterized by seismic time history. In practical engineering, we can select and adjust the actual ground motion time history.
according to the relevant indexes or artificially synthesize the time history of ground motion that matches the standard response spectrum as the input. In addition, due to the influence of focal mechanism, fault rupture process, site conditions and other factors, near-fault ground motion has significant directivity effect [4], fling-step effect [5] and hanging wall effect [6] compared with far-field ground motion. Therefore, selecting and adjusting the actual ground motion time history according to the relevant indicators may not reflect the characteristics of near-fault ground motion. The time history synthesis of near-fault ground motion can also be done by seismological methods [7]. But it needs to be pointed out that although the seismological methods have made great progress with the development of computer technology, it is very complex and seldom used in practical engineering.

3.2. Seismic Input
For complex bridges, such as long-span bridges and irregular bridges with high piers in mountainous areas, the distribution range of piers is large, and the topography, landform and soil layer distribution of each pier fulcrum may be different, which will lead to different ground motions at each pier fulcrum in the same earthquake, but it also have certain correlation. Therefore, the spatial variation of ground motion should be considered, mainly including the Traveling Wave Effect, Attenuation Effect, Incoherence Effect and local Site Effect. Therefore, the non-uniform excitation method should be used for seismic analysis of complex bridges. The spatial variation of ground motion is considered by inputting different self-power spectra at the bottom of each bridge pier foundation, and the correlation is considered by using the coherency function model [8]. At present, the commonly used self-power spectrum models include Housner model, Jinjing Jin model, Xiuli Du model, etc. At the same time, the coherency function models are also different, including Abrahnamson model and LOH model, etc.

Besides, because the ground motion may come from any direction, the curved bridges is in the complex stress state of compression, bending, shear and torsion coupling due to the existence of curvature. Moreover, due to the different directions of the mainshaft of its components, the seismic response of curved bridges is significantly affected by the input direction of ground motion compared with that of straight bridges. However, the most unfavorable input direction of the curved bridges is not obvious compared with that of the straight bridges, and there are differences in the most unfavorable input direction of the structure and components as well as different components. At the same time, because its maximum seismic response does not represent the most unfavorable input direction, the commonly used criteria, such as energy criterion, yield surface function criterion and peak response criterion, may have limitations and need further study.

4. Seismic Analysis Model of Main Components of Bridges

4.1. Seismic Analysis Model of RC Pier
In the seismic response analysis of bridges, the analysis models of reinforced concrete (RC) pier mainly include the component element analysis model at the component level and the precise finite element model at the material level.

(1) The component element analysis model: the component element analysis model includes equivalent plastic hinge model, fiber beam-column element model and shear-bending coupling analysis model. The equivalent plastic hinge model needs to assume the curvature distribution and inflection point of the member; the fiber beam-column element model is based on the fiber model to obtain the relationship between force and deformation on the section, and it can effectively consider the coupling of biaxial bending moment and axial force, but it cannot simulate the structure controlled by shear failure and shear-bending failure; the shear-bending coupling analysis model uses shear spring element to simulate nonlinear shear deformation, and connects with the bending deformation based on fiber beam-column element to consider the shear-bending coupling response of the structure, and there are mainly Lee-Elnashai model [9], Leborgne-Ghannoum model [10] and Elwood model [11], which can consider bending failure and shear failure at the same time.
(2) Precise finite element model: the basic idea of the precise finite element model is to model the reinforcement and concrete separately. The two-dimensional plane element model or three-dimensional solid finite element model can be used for concrete, the bar element is generally used to simulate the reinforcement, and the spring element can be established between the reinforcement and the concrete to consider the bond slip between the two. The precise finite element model can not only obtain the overall force-displacement hysteretic relationship of the component, but also clearly obtain the local stress, strain, cracking, crushing and other damage states of the component. However, the modeling process of precise finite element model is complex and the calculation efficiency is low, so it is not suitable for the overall seismic analysis of complex bridge structures.

4.2. Seismic Response Analysis of Bridge Shear Bond

The bridge shear bond provides lateral support for the upper structure of the bridge. In the performance-based seismic design concept of the bridge, the shear bond should be designed as a sacrificial unit in the transverse direction, so as to reduce the excessive lateral force of the abutment wall and pile foundation, and avoid its damage and fracture [12]. There are some researches on bridge shear bonds in foreign countries, and they are stipulated in specifications, such as ASSHTO [13], which clear provisions on abutment shear keys. Specifically, there are three types of seismic response analysis models of bridge shear keys abroad: (1) sliding shear friction model; (2) diagonal brace- tie beam model; (3) moment resisting model. In contrast, there are few researches on the shear bond of bridges in China [14].

5. Medium-Structure Interaction

5.1. Pile-Soil-Structure Interaction

The simulation methods of pile-soil-structure interaction under earthquake action can be divided into two types: one is the accurate simulation analysis method with the solid finite element model, and the other is the simplified analysis method with Winkler foundation beam (dynamic p-y curve).

(1) The precise analysis method with solid finite element can simulate the properties of structure and soil, and it has great advantages in dealing with complex shapes, applying external excitations and analyzing nonlinear problems. However, in order to consider the radiation damping in semi-infinite space, the finite element model of soil is usually very large, which will cost a lot of calculation time [15]. In order to solve this problem, many scholars put forward artificial boundary to reduce the scale of finite element model. The commonly used artificial boundaries include viscous boundary, viscoelastic boundary, multiple transmission formula, infinite element method, boundary element method, etc [16]. However, the current research on the local treatment of the artificial boundary of the model is not in-depth, and most of them adopt the method of consolidation-truncation, ignoring the influence of seismic scattering. Therefore, the pile-soil-structure accurate numerical analysis model is still in the development stage.

![Figure 1. The Winkler model.](image1.png)

![Figure 2. dynamic p-y curve analysis model](image2.png)
(2) Winkler elastic foundation beam model is a main dynamic calculation and analysis model of pile-soil-structure, which regards pile foundation as beam element, as shown in figure 1 [15]. The influence of soil around pile on pile is described by a series of continuous distributed and independent springs and dampers, and the load-displacement (p-y) curve of spring is determined by test or numerical analysis, as shown in figure 2 [17]. Winkler elastic foundation beam model can analyze inertial interaction and motion interaction at the same time, and the results are consistent with accurate numerical analysis, so it is widely used in current research.

5.2. Abutment-Soil-Structure Interaction
For the problem of abutment-soil-structure interaction, the research of Shamsabadi and Avriam laid a good foundation for the establishment of reasonable numerical simulation methods of bridge structures. In 2006, Shamsabadi et al. carried out numerical and experimental research on lateral earth pressure-deformation relationship of typical abutment under lateral earthquake action [18]. In 2008, Avriam et al. studied the establishment method of superstructure-abutment-soil interaction model under earthquake action, and provided a more reasonable and effective model establishment method through comparison [19].

At present, the typical abutment-soil-structure numerical analysis models mainly include sliding support abutment model, simplified abutment model, spring abutment model, elastic beam element model and elastic body element model, and its simulation are shown in table 2.

| Abutment type               | Element         | Physical phenomenon                                      |
|-----------------------------|-----------------|----------------------------------------------------------|
| Sliding supported Abutment  | Rigid Element   | Soil–abutment–structure interaction is not considered    |
| model                       |                 |                                                          |
| Simplified Abutment model   | Rigid Element   | Soil–abutment interaction is considered, abutment–structure interaction is not considered |
| Spring abutment Model       | Rigid Element   | Soil–abutment–structure interaction is considered        |
| Elastic beam Element mode   | Elastic beam Element | Soil–abutment–structure interaction is considered, the dynamic characteristics of the abutment is considered |
| Elastic body Element mode   | Elastic body Element | Overall modelling, soil–abutment–structure interaction is considered, the dynamic characteristics of the abutment is considered |

5.3. Water-Structure Interaction
For sea-spanning bridges in coastal areas and deep-water high pier bridges in western mountainous areas, all or part of the piers are located in water. Different from the onshore pier, the dynamic interaction between the deep-water pier and the surrounding water will interact under the seismic excitation, and the underwater part of the pier will be affected by the hydrodynamic pressure, which will affect the dynamic characteristics of the pier and further affect the dynamic response of the pier under seismic excitation [20].

At present, the seismic response of deep-water piers under seismic excitation is mainly studied by considering the influence of seismic action on piers, and the same time, the influence of hydrodynamic pressure generated by water-pier dynamic interaction on piers was considering, without considering the disturbance of structure on incident waves [21]. At present, the concrete analysis methods of water-structure dynamic interaction mainly include analytical method, numerical method and hybrid method [22]. Due to the limitation of calculation conditions, the analytical method is usually used to analyse the dynamic response of elastic cylinder. With the development of finite element technology, numerical analysis method has been widely used in seismic analysis of pier-water coupling. However, the numerical method has a large amount of calculation, so the hybrid method which applies hydrodynamic pressure to the pier by adding mass or load has been widely used.
6. Problems and Prospects

(1) Time history analysis method is suitable for the seismic elastic-plastic analysis of complex bridges, but its results depend on the input of ground motion and the selection of damping parameters in seismic analysis. It is necessary to use various methods for comparative analysis to ensure its accuracy. At the same time, probabilistic analysis methods, such as random vibration method, which are used for accurate seismic analysis of bridges, have also been developed in recent years. However, due to the large amount of calculation in the seismic analysis of complex bridges, the application of probabilistic analysis methods in practical engineering is still less, so it should be further studied.

(2) Although there are some researches that comprehensively consider the spatial effects of ground motion such as traveling wave effect, attachment effect, coherence effect and site effect on the spatial dynamic effect of bridges, generally speaking, it is not mature enough to give a unified quantitative analysis conclusion.

(3) The method of synthetic seismic wave based on probability can consider the random characteristics of response spectrum, but its research is not mature. At the same time, due to the particularity of near fault ground motion, there are still some shortcomings in the existing near fault ground motion synthesis model, such as the pulse parameters are not easy to determine.

(4) The existing seismic response analysis model of RC bridge pier cannot consider the seismic damage simulation of bridge structures. It is necessary to consider the establishment of a multi-dimensional dynamic damage constitutive model of the bond and slip effects between concrete and steel bars. However, it is difficult to realize the whole process of concrete material damage cracking and progressive failure.

(5) At present, the bridge shear bond analysis models were mainly developed based on the construction of specific joint and different assumptions of foreign bridges, but due to the configuration and material characteristics of shear bond in Chinese bridge code are not completely consistent with foreign situation, and the domestic bridge shear bond analysis model needs further research. Therefore, it is necessary to study the seismic performance and seismic analysis model of Chinese abutment shear bond.

(6) The accurate numerical simulation method of pile-soil-structure dynamic interaction has the disadvantages of modeling process complex, long calculation time and high requirements for equipment, which is not conducive to the application of practical engineering. Moreover, there are some differences between the simplified numerical simulation method and the experimental p-y curve. The research on how to accurately describe the p-y curve of the site from the angle of shape and amplitude etc. are not deep enough.

(7) For abutment-soil-structural interaction model, the typical simplified model such as sliding supported abutment model, simplified abutment model and spring abutment model are established based on many assumptions, which may not be consistent with the actual situation. And the elastic beam element model and elastic body model also have some problems on considering soil-abutment interaction reasonably, such as have many model elements, unstable numerical calculation, which need further study.

(8) For the study of the seismic response of deep-water piers under seismic excitation, the disturbance of the structure by incident waves is currently not considered at present. However, the motion form of incident wave will be changed due to seismic action, seabed motion and water scouring, which makes the dynamic interaction between pier and water extremely complex. Therefore, it is necessary to consider the influence of the complex geographical environment and the random effect of waves for water-pier dynamic interaction.

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