A review of research status of failure modes of base-isolated structures under long-period ground motions

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Abstract. As a relatively mature and effective passive damping technology, isolation technology is mostly used in engineering structures in high-intensity areas and post-earthquake reconstruction projects. In recent years, with the deepening of performance-based seismic engineering research, the study of damage failure of isolated structures under strong earthquakes has become one of the hot-spots in the field of seismic engineering research. This paper summarizes the research results of domestic and foreign scholars on the failure of the base-isolated structure under the action of long-period ground motions, and summarizes its main failure modes. Based on the main failure modes, it systematically analyzes the failure mechanism and finally points out there are still some issues to be studied.

1. Introduction
As a relatively mature and effective passive damping technology, the isolation technology has changed the traditional anti-seismic method of the structure and has an important impact on seismic engineering. There are many loads acting on the base-isolated structure, such as wind load, snow load and earthquake action. However, these loads may cause the base-isolated structure to fail, so the base-isolated structure still has many hidden safety hazards. Studying its failure mode is helpful to judge the overall performance of the structure. It is very important for structural design and evaluation of in-service structures. In recent years, with the in-depth research of scholars at home and abroad, many factors affecting the failure of isolated structures have been found, such as excessive inter-layer displacement and excessive isolation bearing, but there are certain differences in the influencing factors obtained by different scholars, so it is necessary to systematically summarize them. This article focuses on the review of the research status of the failure mechanism of isolated structures under long-period ground motions, and discusses the issues to be studied.

2. Failure mode of seismic isolation structure under long period of ground motion
There are many kinds of failure modes of the seismic isolation structure under the action of long-period ground motion, which makes it very difficult to study the destruction mechanism of the seismic isolation structure, but most of the failure modes have low probability of occurrence and little influence on the failure probability of isolated structures, so only a few major failure modes with a high probability of occurrence need to be listed. M. Bhandari et al.[1] compare the influence of maximum interstorey displacement ratio (MIDR), maximum base shear (MBS), maximum roof displacement ratio (MRDR), maximum top floor acceleration (MTFA), and maximum isolator displacement (MID) on the base isolation frame, the vulnerability analysis of the base isolation frame, under the action of near-field and far-field earthquakes, it is found that MIDR and MID are more
likely to cause adverse effects in various damage states.

Table 1. Earthquake damage grade standard.

| Evaluation factor | Earthquake damage level |
|-------------------|-------------------------|
|                   | Basically intact        |
|                   | Minor damage            |
|                   | Moderate damage         |
|                   | Serious destruction     |
| Isolation layer   | V1                      |
| Horizontal displacement | V2 0.01d~0.1d |
|                   | V3 0.1~0.3d             |
|                   | V4 0.3d~0.55d           |
|                   | V5 ≥min(0.55d, 3Tr)     |
| The upper structure |
| Peak acceleration | U1 ≤10                  |
|                   | U2 10~200               |
|                   | U3 200~1000             |
|                   | U4 1000~5000            |
|                   | U5 >5000                |
| Interlayer displacement angle | U6 1/550~1/300 |
|                   | U7 1/300~1/150          |
|                   | U8 1/150                 |
|                   | U9 ≥1/50                |
| Ductility factor  | U10 1.0~3.0             |
|                   | U11 3.0~6.0             |
|                   | U12 6.0~10.0            |
|                   | U13 >10.0               |

Note: d is the minimum diameter of the isolation bearing, Tr is the total thickness of the rubber layer.

To this end, this paper summarizes three main failure modes by summarizing: (1) Collision effects under long-period ground motions result in higher structural damage values, improper spacing settings can easily cause structural damage and failure. (2) The deformation of the isolation support under the action of long-period ground motions is more likely to exceed the limit than ordinary ground motions, which can easily lead to the failure of the isolation system. (3) The elastoplastic inter-layer displacement angle of the seismic isolation structure increases under the action of long-period ground motions, after considering the SSI effect, as the soil becomes softer, the inter-layer displacement angle increases more obviously, which may easily lead to the failure of the isolation system. In addition, combined with the "Code for Seismic Design of Construction Engineering" GB 50223-2008 and the existing research results, we can obtain the seismic damage grade standard that can be used to quantitatively determine the failure mode of the isolated structure, as shown in Table 1.

3. Mechanism of failure of seismic isolation structure under long period of ground motion

(1) In order to study the damage caused by the collision effect to the isolation structure, Ye Kun et al.[2] used SAP2000 to analyze the elastoplastic time history of a reinforced concrete plane frame with LRB base isolation structure considering collision, and discussed various factors by numerical analysis. The impact on the collision results indicates that the collision excites the high-order vibration mode of the structure and changes the basic deformation mode of the structure. The collision significantly increases the absolute acceleration and inter-layer displacement of the superstructure and causes significant permanent participation in inter-layer deformation. Liu Yang et al.[3] defined the damage of the superstructure based on the Park-Ang damage index, and used the elastoplastic time history analysis method to evaluate the damage performance of the elastoplastic side torsion coupling model of the single-layer eccentrically isolated structure, pointing out that the sudden acceleration of the superstructure is caused by the sudden increase of the collision force and sudden change of the stiffness at the moment of collision, and the frequency components of the collision excitation are mostly high-frequency components. The transmission of high-frequency components to the superstructure will cause structural resonance. In addition, Ahmed Abdelraheem Farghaly [4] considered the impact of the underlying soil on the collision of buildings, and the study found that the collision force increased with the softening of the soil, especially on the foundation.

As mentioned above, the isolation structure fails due to collision. The objective reason is that the
basic deformation mode of the structure changes after the collision, resulting in a significant increase in the structure's absolute acceleration and inter-layer displacement, and the high frequency component of the collision excitation causes the superstructure to resonate it has an adverse effect on the structure. Improper separation of isolation trenches and isolation bearings under soft soil conditions is more likely to cause failure of the isolation structure due to collision. The subjective reason is the characteristics of the structure itself, such as whether the structure is eccentric and the size of the stiffness other factors will affect its collision effect.

(2) Through the study of the spectral characteristics of the ground motion, it is found that the isolation layer has the effect of isolating the high-frequency ground motion better, the effect of isolating the long-period seismic motion is significantly reduced, and the damage index of the isolation layer is relatively discrete and irregular under the action of the long-period seismic motion. Therefore, the impact of the long-period seismic motion on the seismic isolation support needs further study[5].

To this end, Zhao Yibin et al.[6]for the base-isolated high-rise building model with practical background, input the long-period seismic wave and the seismic wave that matches the standard response spectrum for time-history analysis. It is pointed out that compared with the ground motions that meet the requirements of the standard response spectrum, the long-period ground motion will amplify the average floor shear force, inter-story displacement angle and seismic isolation layer displacement, and the average isolation coefficient is also much larger than the average isolation coefficient under the standard response spectrum; Sun Ying et al.[7]used SAP2000 to establish a numerical analysis model of a five-span, one-isolation continuous beam bridge. Through elastic time history analysis and collision effect analysis, the impact of near- and far-field long-period ground motions with obvious impulse effects on the model's seismic response was discussed. It is pointed out that whether it is a multi-span continuous bridge using lead rubber bearings or friction pendulum isolation bearings, the isolation rate of the internal force at the bottom of each pier is lower than that of ordinary earthquakes, and the long-period seismic motion the following magnifies the displacement amplitude of the two isolation structures, increasing the possibility of collision between adjacent structures.

The research results show that the existing vibration isolation system, that is, lead rubber bearings and sliding bearings have good damping effects on ordinary ground motions, but long-period ground motions will produce resonance-like effects on traditional base-isolated structures. In the bridge, the internal force response at the bottom of the pier is amplified, and the bending moment and shear isolation rate are reduced. In terms of civil construction, the structural response is amplified, resulting in huge over-deformation of the seismic isolation support, which causes overturning and instability of the superstructure. This increases the possibility of failure and destruction of the isolation structure. In addition, most seismic isolation bearings, such as LRB and HDRB, also have unrecovered residual deformation and other problems. These problems will also adversely affect the seismic isolation structure [8].

(3) The inter-story displacement angle can limit the horizontal displacement of the structure and ensure that the structure has the required stiffness. Therefore, the inter-story displacement angle is an important parameter for domestic and foreign scholars to study the impact of long-period ground motions on seismic isolation structures. Tian Yingxia et al. [9]defined the performance criteria of components based on the constitutive relationship between concrete and reinforced materials, established an elastoplastic analysis model of 5-layer reinforced concrete frame and conducted a nonlinear dynamic time history analysis on it. The research results show that the isolated structure is basically deformed linearly under the action of ordinary ground motion, and the relative displacement between the layers is small, while under the action of long-period near-field and far-field ground motion, the superstructure is shear deformed, and the relative displacement between the layers is large. Wang Yanan et al.[10] used a five-layer reinforced concrete frame base isolation structure as an example for dynamic time history analysis. Based on code design, the analog code stipulates the response of the ground motion and far-field long-period ground motion to the structure, and the
damage status of the reinforcement and concrete define and label, analyze the damage distribution law. Figure 1(a) shows the comparison of the acceleration response spectrum and the standard response spectrum of 9 long-field seismic records selected from the Pacific Earthquake Engineering Research Center (PEER) ground motion database. It can be seen from the figure that the spectral peak of the long-period seismic response spectrum has a significant "backward" phenomenon, which is the main reason for the unexpected damage to the seismic isolation structure designed based on the normative spectrum.

After considering the effect of soil-structure interaction (SSI) on the structural seismic response. Amer Hassan et al. [11] used response spectrum analysis (RSA) and time history analysis (THA) to model and analyze 3D reinforced concrete structures, and considered fast nonlinear analysis (FNA), using ETABS software to calculate the maximum possible seismic response of reinforced concrete structures. The results show that the shear value of the foundation increases with the increase of the foundation flexibility and the rigidity of the superstructure. Under soft soil conditions, the spectral acceleration (SA) and spectral displacement (SD) of the structure are high, indicating the response spectrum of the structure depending on the conditions of the soil, the inter-layer displacement increases as the soil layer flexibility increases. Zeng Jianxian et al.[12] built a large-frame base-isolated frame structure based on the lumped parameter S-R (Sway-Rocking) model. Through dynamic elastoplastic analysis, the long-period ground motions were studied under different site categories. It is pointed out that the response spectrum values of structural acceleration, velocity and displacement are significantly larger than ordinary ground motion in the long period interval, Figure 1(b) shows the acceleration response spectrum curves of 13 long-period earthquake records and 3 ordinary earthquake records selected from the Pacific Earthquake Engineering Research Center (PEER) earthquake database, it can be seen that the far-field long-period harmonic-like ground motion has obvious double-peak phenomenon. After considering the SSI effect, the seismic isolation the peak inter-layer shear force of the structure is basically not affected, but the elastoplastic displacement angle increases with the softening of the ground. The peak acceleration of the floor and the deformation value of the isolation bearing are also amplified.

In summary: Compared with ordinary ground motion, long-period ground motion will amplify the displacement angle between the layers of the isolated structure and make it unevenly distributed. From the perspective of the characteristics of ground motion itself, long-period ground motion causes the shear deformation of the superstructure. The spectral peak of the response spectrum has a significant "backward" phenomenon, and the acceleration spectrum of the long-field harmonic-like ground motion in the far field also shows a significant double-peak phenomenon, which adversely affects the
isolation structure. Considering the SSI effect, the structural period will be further extended, and the inter-layer seismic structure under long-period seismic motion will produce a greater velocity response. Although the peak inter-laminar shear force is basically unchanged, the softer the ground, the greater the inter-laminar displacement angle, which is more likely to cause severe damage to the seismic isolation structure.

4. Ways of failure of isolated structure under the action of long period ground motion
In order to study the ways of isolation structure failure, Sang-Hoon Oh et al.[13] conducted a comparative analysis of the existing inter-laminar shear force formulas to study the structural damage distribution of long-term ground motions at far faults. The inter-laminar shear force distributions obtained from different inter-laminar shear force formulas are short. The damage of periodic ground motion is mainly concentrated on the top floor, and the damage of long-period ground motion is mainly concentrated on the lower floors. The research results show that with the increase of the excellent period of seismic waves, the damage distribution trend is concentrated on the ground floor, and as the basic natural cycle of the building increases, the damage distribution trend is concentrated on the top layer. Judging by the characteristics of the material, according to the constitutive relationship between concrete and reinforced materials, the damage states of reinforced and concrete materials are defined and marked. It is found that the damage distribution of the seismic isolation structure under long-term ground motion is not uniform. The damage caused is mainly at the bottom of the structure, and the top layer of the structure is generally in the elastic state. The damage of the bottom column is the main reason for the failure of the structure. Through the structural damage calculation results, it is found that the damage failure of the seismic isolation structural members first appears in the bottom middle column, followed by the adjacent side span of the center column spans the beam and then develops upward [9,10].

5. Conclusions and issues to be studied
At present, domestic and international researches on seismic isolation structures under the action of long-period ground motions are mostly aimed at isolation structures based on LRB lead rubber bearings. Using long-period earthquakes and ordinary earthquakes as external excitations, study the inter-layer shear force, inter-layer displacement angle, and bearing deformation. Although the models and research methods used are different, the research results show that: compared with ordinary ground motions, long-period ground motions are more prone to failure and damage of the isolated structure.

(1) Although a large number of long-period seismic records have been obtained from recent earthquakes, different scholars have also studied the response of long-period seismic characteristics to isolated structures, but the general law of long-period seismic motions obtained is limited. Therefore, perfecting its regular characteristics through a large number of existing long-period seismic records and analogizing the changes in its response relationship with seismic isolation structures is currently a problem to be solved for seismic isolation structures under long-period seismic motion.

(2) At present, China's seismic design codes do not clearly specify long-term earthquake actions. Based on the existing structural seismic design method, the design model is studied and it is found that the displacement of the isolation support and the inter-layer under the long period of ground motion significantly exceeds the allowable deformation limit. Therefore, it is of great significance to study the seismic design applicable to long-period ground motions.

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