Influence of different arrangements of isolation bearings on seismic isolation effect

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Abstract. In the design of structural isolation, the displacement of the isolation structure of a single isolation support is easy to exceed the maximum deformation limit under the action of an earthquake, so the design often adopts the combination design of lead-core rubber bearing and linear natural rubber bearing. The layout of seismic isolation supports and the proportion of the two isolation supports will affect the final seismic isolation effectiveness of structures, in order to explore this influence. four groups of isolation schemes were designed. The structural isolation was achieved by varying the ratios and arrangements of these two types of rubber isolators. The SAUSAGE finite element software was employed for dynamic time-history analysis of the structures. The results indicate that the use of seismic isolation bearings significantly extends the natural vibration period of the structure, reducing its response under seismic loading. Under seismic fortification, the horizontal seismic impact coefficient is 0.39,and the seismic effect is reduced by 1 degree. Under rarely occurred earthquake, the maximum tensile stress and displacement of the seismic isolation bearings meet the relevant specifications. After isolation, the inter-story displacement angle and inter-story shear of the structure decrease substantially. When designing structures for seismic isolation, to enhance the isolation effectiveness, lead-core rubber bearings should be prioritized in the outer ring and at the four corners, while linear natural rubber bearings can be used in the inner ring.

Keywords: seismic isolation support; arrangement style; seismic isolation design; seismic isolation factor; dynamic time-history analysis

1 introduction

China is located in the Pacific seismic belt and Eurasian seismic belt, earthquakes occur frequently, and the seismic performance of some early urban and rural buildings is weak. Once an earthquake occurs, it will cause huge losses. At the same time, with the development of economy in recent years, people begin to pay more attention to the seismic performance of buildings, and the requirements are getting higher and higher,

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and the seismic fortification requirements are also increasing. The performance of traditional seismic buildings has been unable to meet the requirements. Under this background, seismic isolation technology has been widely studied and applied because it can significantly improve the seismic performance of building structures, so isolated buildings have made great progress[1]. The principle of the isolated building is to introduce some isolation devices into the building structure to isolate the vibration of the earthquake, prolong the natural vibration period of the structure and provide appropriate damping to greatly reduce the seismic response of the structure and reduce the structural damage caused by the earthquake. This technology can more effectively protect the safety of the building structure and indoor equipment, and can significantly improve the functional resilience of the building structure after the earthquake[2]. At present, laminated rubber bearing is widely used for vibration isolation in engineering.

Laminated rubber bearings are usually divided into two types, linear natural rubber (LNR) bearings and lead-core rubber (LRB) bearings, among which LNR bearings have good vertical stiffness and bearing capacity. At the same time, the LNR bearing has good horizontal deformation ability[3]; The LNR bearing is compared with the LRB bearing by adding a lead rod in the middle, due to the stable attenuation performance and trigger performance of lead-zinc rod, the lead rod inside the laminated rubber occurs full-section plastic deformation when the bearing occurs shear deformation, which absorbs energy to attenuate vibration and significantly improve the hysteretic ability[4-5].

In the usual isolation scheme, LNB bearing and LRB bearing will be used together, and the combination of them can give full play to their respective advantages and achieve the purpose and performance requirements of seismic isolation. Through conducting seismic shake table simulation experiments, Jing Liping[6] has demonstrated that employing rubber bearings for foundation isolation can significantly reduce the response of the superstructure during earthquakes. Dang Yu[7] and Chen Changjia[8] found that through reasonable allocation of isolation supports can significantly improve the seismic effect. Zhang Yafei et al.[9] found that LRB supports show excellent isolation effect in staggered isolation system, which can reduce the probability of plastic hinges. In the isolation design of practical engineering, the smaller the horizontal stiffness in the isolation layer is, the stronger the displacement performance is, the better the vibration isolation effect is, but at the same time, if the deformation is too large, it is not conducive to the safety of the whole structure. At the same time, due to the characteristics of LNR bearings, the damping ratio ζ is too small, so it consumes less energy for earthquakes. If too many LRB bearings are adopted, the overall stiffness is too large, which is not conducive to the displacement of the isolation layer, weakens the overall isolation effect, and the cost is not reasonable. Therefore, in the process of isolation design of practical engineering, the displacement of isolation layer, isolation effect, cost and other factors should be considered according to the actual situation of the building, and the proportion and location of the two kinds of supports should be determined reasonably. However, at present, the research on the combination of isolation bearings in our country is still in the stage of development, and more engineering examples are needed to analyze it. This paper takes a teaching building as an example, uses SAUSAGE finite element software to model, and analyzes different isolation bearing layout schemes in the seismic isolation module, compares the time history results, analyzes different bearing schemes, explore the influence of different factors on the isolation effect and provides some reference for the bearing layout of the isolation project in the future.

2 project overview

The teaching building is located in Zhang jia chuan County, Tian shui City, Gansu Province. the main body is a four-story reinforced concrete frame structure with an additional ceiling at the top, each layer 3.6m high. The seismic fortification intensity of this project is 8 degrees (0.2g). According to the requirements of "Standard for classification of seismic protection of building constructions" GB50233-2008 [10], The seismic fortification category of educational buildings belongs to category B key fortification. The seismic design of the project is divided into the third group, and the site category is type II, so the characteristic period is 0.45s.

3 Model construction and Seismic wave selection

3.1 Model construction

Using SAUSG for software modeling, the non-isolated structure model is shown in figure 1.

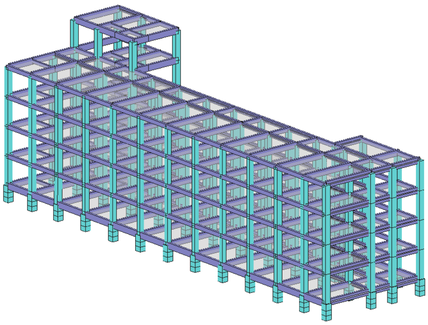


Fig. 1. SAUSG model of non-isolated structure

The mass, period and base shear force (mode decomposition response spectrum) calculated by YJK and SAUAG non-isolated integral model are compared, and the results are shown in Table 1- Table 3 Comparing the calculation results, it is known that the mass difference between the two is 2.95% < 5%, and the maximum difference between the two software cycles is 0.63 < 10%.CoMParing the calculation results, it is known that the quality difference between the two is 2.95% < 5%, and the maximum difference between the two software cycles is 0.63 < 10%.All of them meet the relevant requirements of "code for seismic design of buildings" GB5011-2010(In the following article, "Regulation" shall be shortened) [11], which shows that the result of structural analysis by using SAUSAGE software is accurate.

Table 1. mass comparison of non-isolated whole structures

YJK mass /Ton	SAUSAGE mass /Ton	Difference value (%)
5790.57	5967.42	2.95

Table 2. comparison of vibration mode periods of isolated whole structures

MODE	YJK period /s	SAUSAGE period/s	Difference value (%)
1	2.235	2.243	0.36
2	2.221	2.235	0.63
3	2.082	2.086	0.20

Table 3. comparison of seismic base shear force of non-isolated monolithic structures

YJK result /kN		SAUSAGE result /kN		Difference value (%)	
X	Y	X	Y	X	Y
13739.4	13531.24	13662.3	12698.6	0.56	6.15

3.2 Seismic wave selection

According to the Regulation, when the time-history analysis method is used to select seismic waves, the number of natural waves shall not be less than 2/3 of the total wave number, and the base shear force error between the results of single seismic wave time-history analysis and the mode decomposition method shall not be more than 30%. The average error of multiple waves should not exceed 20%, and the effective duration should be 5-10 times of the basic period of the structure. Considering the type of building site and the grouping of design earthquakes, two actual strong earthquake records are selected (SuperstitionHills-02_NO_7267 wave, ImperialValley-06_NO_163 wave) and an artificially simulated acceleration time-history curve (RH4TG055 wave).The selected seismic wave response spectrum curves are shown in figure 2, in which under the action of 8 degree 0.2g earthquake, the peak acceleration of fortification earthquake and Rare earthquake are 200m/s and 400m/s respectively.

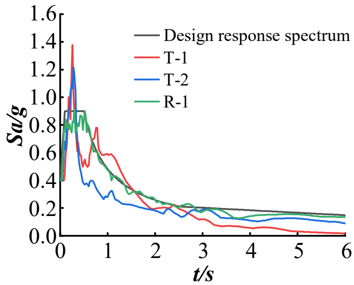


Fig. 2. Seismic wave response spectrum curve

4 Design and checking calculation of seismic isolation Scheme

4.1 Seismic isolation scheme design

Considering that after the building adopts isolation measures, there are a number of index changes that can reflect and evaluate the isolation effect, such as front and back period, Inter-story shear force, overturning moment, Inter-story displacement and so on, but the index units are different, and the magnitude and change trend are also different. in order to more intuitively evaluate and compare the effect of seismic isolation design, each index can be normalized. The concept of "isolation coefficient" is introduced.

$$Isolation\ coefficient = \text{(Seismic response value of isolated structure} - \text{seismic response value of original structure)/onse value of original structure} \times 100\% \quad (1)$$

In practical engineering, when seismic isolation measures are adopted in structures, the greater the difference between the relevant indicators before and after isolation, with longer structural vibration periods and smaller seismic response values, the better the isolation effect. Therefore, the isolation effect can be uniformly evaluated using the isolation coefficient. The larger the isolation coefficient, the better the isolation effect. Additionally, there is a positive correlation between the isolation coefficient and the structural energy dissipation capacity.

In order to explore the influence of different arrangement of isolation bearings on isolation coefficient. The type, number and layout of supports are selected according to the “GB50011-2010 Code for Seismic Design of buildings (2016 Edition)”. Four kinds of bearing layout schemes are composed of LNR500, LNR600, LRB500 and LRB600 bearings. The main parameters of each bearing are shown in Table 4.

Table 4. main parameters of isolation bearing

Parameters of isolation bearing	LRB500	LRB600	LNR500	LNR600
Rubbery shear modulus	0.392	0.392	0.392	0.392
Rubber layer thickness / mm	93	111	93	111
Vertical stiffness / (kN/mm)	1750	2200	1500	1800
Equivalent horizontal stiffness / (kN/mm)	1.236	1.538	0.806	0.970
Equivalent damping ratio /%	25	25	-	-
Pre-yield stiffness/ (kN /mm)	10.478	12.614	-	-
Post-yield stiffness / (kN /mm)	0.806	0.970	-	-
Yield force / kN	40	63	-	-
Support height / mm	187	208	187	208

The arrangement scheme of 5 groups of isolation bearings is shown in figure 3. The isolation layer is located at the top of the foundation. In scheme 1, 37 groups of LRB600 bearings and 9 groups of LNR600 bearings are used; in scheme 2, 7 groups of LRB500 bearings, 23 groups of LRB600 bearings and 16 groups of LNR600 bearings are used; 23 groups of LRB600 bearings and 23 groups of LNR600 bearings are used in scheme 3; 16 groups of LRB600 bearings and 30 groups of LNR600 bearings are used in scheme 4. Through SAUSG analysis, the first three modal periods of non-seismic structures and different isolation bearing arrangements are shown in Table 5, and the isolation coefficients of different schemes are shown in Table 6. It can be seen from tables 5 and 6 that no matter which isolation bearing arrangement scheme is adopted, the natural vibration period of the building is obviously prolonged, in which the first natural vibration period is extended by 3.3 times at most, which preliminarily shows that several groups of schemes are reasonable to a certain extent.

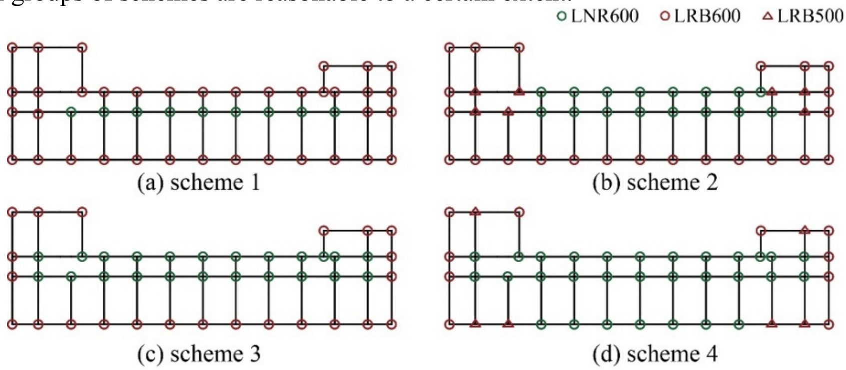


Fig. 3. layout diagram of isolation bearings

Table 5. Natural vibration period of each isolation scheme (s)

MODE	Non-isolated structure	Scheme 1	Scheme 2	Scheme 3	Scheme 4
1	0.709	2.057	2.206	2.292	2.334
2	0.647	1.996	2.166	2.244	2.292
3	0.541	1.082	1.929	2.021	2.031

Table 6. isolation coefficient of each isolation scheme (%)

MODE	Scheme 1	Scheme 2	Scheme 3	Scheme 4
1	190	211	223	229
2	209	235	247	254
3	100	257	274	275

4.2 Feasibility verification of each isolation scheme

4.2.1 checking calculation of bearing compressive stress under Rare earthquake.

Under the action of Rare earthquake (the peak acceleration of the input time-history is 400cm/s2, the three-dimensional ground motion input is adopted, and the three-dimensional input ratio of X, Y, Z is 1:0.85:0.65) the elastic-plastic analysis model is adopted. In the algorithm, the fast nonlinear modal integral algorithm is used to analyze the nonlinear seismic response of isolated structures. In the Rare earthquake analysis, the lead rubber bearing is calculated by bilinear model.

According to the Regulation, under the action of a Rare earthquake, the maximum compressive stress of the bearing shall not exceed 25 MPa. The corresponding bearing compressive stress of the three waves is calculated by software, and the envelope values are statistically compared. The compressive stress of each bearing is shown in figure 4. The maximum compressive stress in all scenarios is less than 20 MPa. Apart from a minor increase in the compressive stress of the smaller diameter bearings in Scenario 2 reaching 15 MPa, the compressive stress in the rest of the bearings is generally below 12 MPa. This indicates that all bearing arrangements in the scenarios have sufficient safety margins.

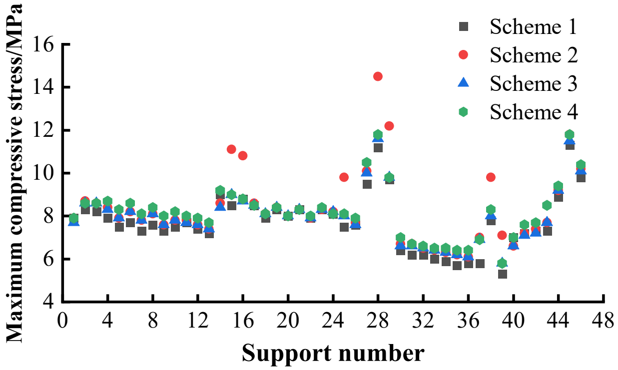


Fig. 4. maximum compressive stress of each scheme of isolation bearing

4.2.2 checking calculation of tensile stress of bearing under Rare earthquake.

According to the Regulations, when using the isolation bearing to carry out the seismic design of the structure, the tensile stress of the isolation bearing under the action of horizontal and vertical earthquake must be checked and calculated, and the maximum tensile stress is 1MPa. The maximum tensile stress results after analysis are shown in Table 7, and all schemes meet the requirements.

Table 7. maximum tensile stress of each isolation scheme under Rare earthquake

Schemes	Scheme 1	Scheme 2	Scheme 3	Scheme 4
Maximum tensile stress /MPa	0.0	0.1	0.3	0.3

4.2.3 checking calculation of maximum displacement of bearing under Rare earthquake.

Under the action of Rare earthquake, the maximum horizontal displacement of isolated rubber bearing should be less than 0.55D (D is the diameter of isolated bearing) and 3Tr (Tr is the total thickness of rubber layer). The envelope and limit values of each scheme bearing under Rare earthquake are shown in Table 8. It can be seen from the table that each scheme satisfies the limit of the maximum displacement of the bearing, and with the increase of the proportion of natural rubber bearing, the displacement of each type of bearing is also increasing. That is, the energy dissipation capacity of the bearing has also been brought into greater play, in which the increase of scheme 1 to scheme 2, scheme 3 to scheme 4 is consistent with the periodic change law.

Table 8. maximum bearing displacement of each isolation scheme under Rare earthquake

Support type	Scheme 1	Scheme 2	Scheme 3	Scheme 4	Displacement limit
LRB500		198			275
LRB600	183	205	211	232	330
LNR600	171	192	204	221	330

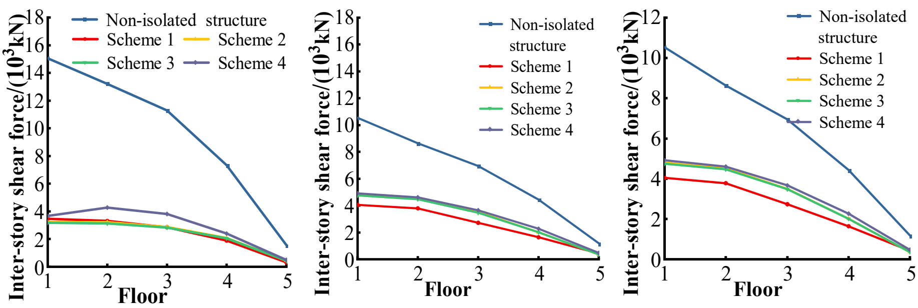
5 Analysis of Fortification earthquakes and Rare earthquakes

5.1 dynamic time-history analysis of structures under fortification earthquake

The Inter-story shear response and the corresponding isolation coefficient of the structure under fortification earthquake are analyzed, and the results in X direction are shown in figure 5.

Under the fortification earthquake, the Inter-story shear force of the isolated structure is significantly lower than that of the non-isolated structure, in which T-1 wave is taken as an example, the isolation coefficient of each layer of each scheme is more than 66%, indicating that the vibration isolation effect is good. Based on the results of three-wave time-history analysis, the results show that the overall isolation coefficient of scheme 1 is the highest, the isolation coefficient of scheme 2 is close to that of scheme 3, second to scheme 1, and the isolation coefficient of scheme 4 is the lowest, indicating that scheme 1 is the best in isolation effect.

According to the Regulation provisions, the structure belongs to a multi-story structure with low height, and the horizontal damping coefficient can be calculated by the ratio of inter-story shear force before and after isolation, and the overturning moment ratio does not need to be considered [12]. the relevant shear ratio results of time history analysis are shown in Table 9. Among them, The horizontal isolation coefficients of each scheme are 0.31, 0.39, 0.38 and 0.39 respectively, so the horizontal seismic action of superstructure and anti-seismic measures of superstructure can be reduced by 1 degree.



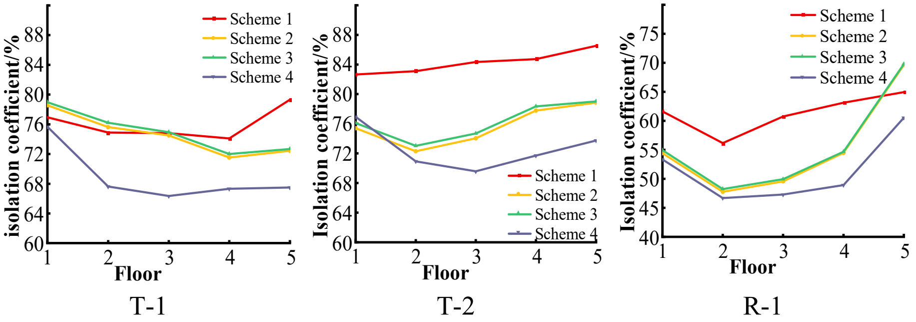


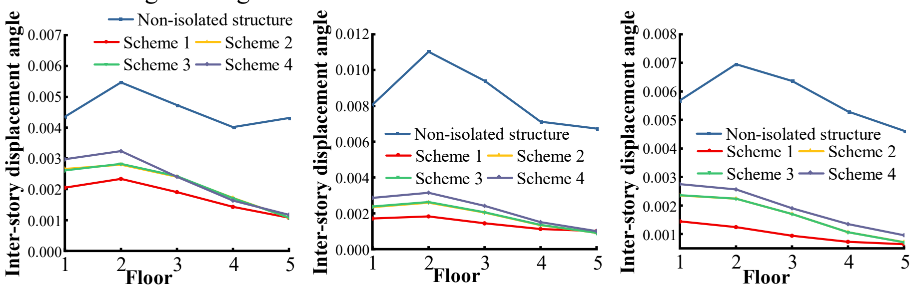
Fig. 5. Inter-story shear force and isolation coefficient of each scheme under fortification earthquake

Table 9. ratio of inter-story shear force envelope values in X and Y directions of the structure

Floor	Scheme 1	Scheme 2	Scheme 3	Scheme 4
5	0.31	0.31	0.30	0.39
4	0.29	0.27	0.27	0.38
3	0.29	0.33	0.33	0.39
2	0.29	0.39	0.38	0.39
1	0.30	0.37	0.37	0.39

5.2 dynamic time-history analysis of structures under Rare earthquakes

Under the action of Rare earthquake, the Inter-story displacement angle, Inter-story shear force and corresponding isolation coefficient of non-isolated structure and isolated structure under each scheme are shown in figure 6 and figure 7. Compared with the original structure, the inter-story displacement angle and inter-story shear force of the structure with bearing isolation decrease significantly, and the isolation coefficient increases along the height direction as a whole.



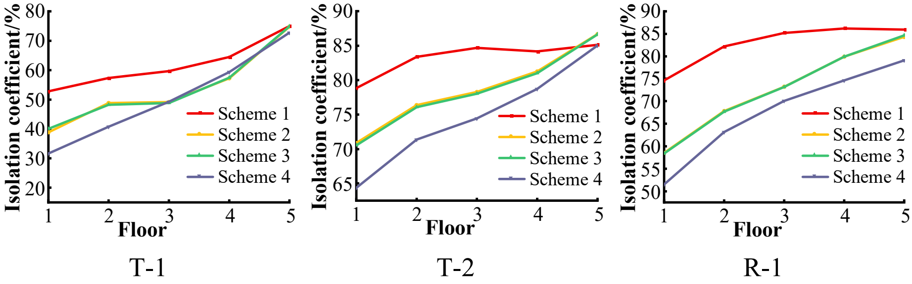


Fig. 6. Inter-story displacement angle and isolation coefficient of each scheme under rare earthquake

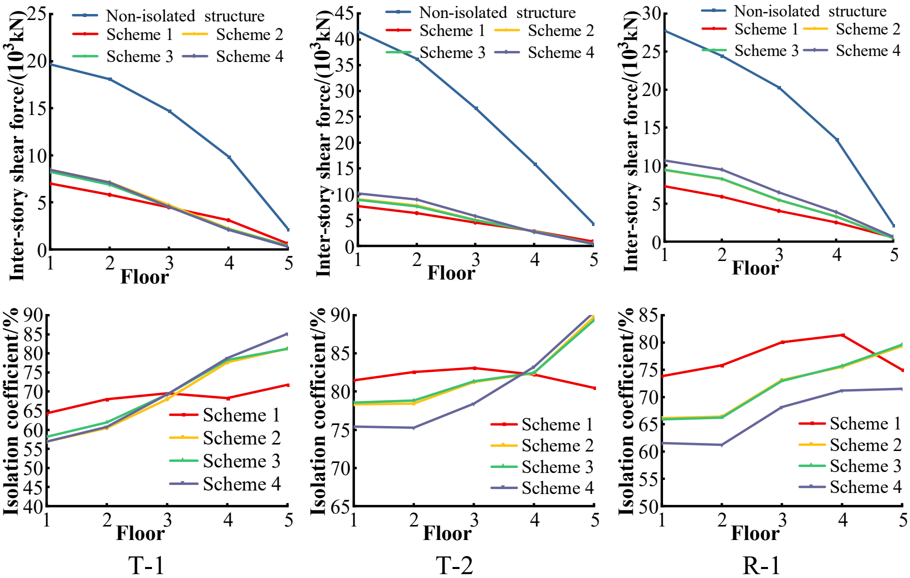


Fig. 7. interlaminar shear force and isolation coefficient of each scheme under rare earthquake

According to the results of the three waves, the isolation coefficient of scheme 1 is the highest, the isolation effect is the best, the isolation coefficient of scheme 2 and scheme 3 is the third, and the isolation coefficient of scheme 4 is the lowest and the isolation effect is the worst. From which it can be determined that scheme 1 has the best isolation performance and the most reasonable bearing arrangement.

6 conclusion

In order to explore the influence of different combination arrangement of isolation bearings on building isolation, four groups of bearing layout schemes are adopted to compare the dynamic time history results of structures before and after seismic isolation under fortification earthquake and Rare earthquake.

(1) after the structure is isolated with isolation bearings, the maximum natural vibration period of the structure is extended from 0.709 to 2.334, and the isolation coefficient of each isolation scheme is 190% ~ 209%, indicating that each isolation scheme can effectively prolong the natural vibration period of the structure, In addition, under the action of Rare earthquake, the maximum displacement of the isolation bearing of the four schemes increases in turn, but all of them do not exceed the limit, indicating that the combination of supports can play a good isolation effect. And the performance of the two kinds of supports can be better developed

(2) In the comparison of the four isolation schemes, it is found that the natural vibration period of the structure increases gradually with the increase of LNR bearings, However, under rare earthquake action, the isolation coefficient gradually decreased, The results show that when the structure is isolated, the natural vibration period of the structure after isolation is not completely equal to the isolation effect, and the overall damping of the isolation layer has a great influence on the isolation effect, and the natural vibration period after isolation can not be used to evaluate the scheme in the future practical engineering.

(3) The comparison of the results of the four groups of schemes shows that the change of rubber bearing type of the outer ring has a significantly greater impact on the isolation effect than that of the change of bearing type of the inner ring. At the same time, considering the torsion effect and the larger displacement of the outer part of the building structure, the arrangement of LRB bearings on the outer part of the structure and the appropriate arrangement of LNR bearings on the inner ring are more conducive to earthquake isolation.

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