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Seismic Performance Analysis and Design of High-Rise Isolated Structures under Very-Rare Earthquake

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ABSTRACT
There are many high-rise isolated structures built in China. High-rise isolated structure maintains its superstructure in elastic range or small nonlinearity under rare earthquakes. However, under a rare earthquake especially a very-rare earthquake, the isolation bearing deformation and the overturning safety is urgent to be researched. On basis of "survive a rare earthquake by sustaining significant damage but without globally collapsing" design, this paper is focus on the seismic performance of high-rise isolated structure under a very-rare earthquake. In addition, the cost and the method of high-rise isolated structure design based on "survive a very-rare earthquake" are concerned in the paper. Three structures with different heights are modeled by SAP2000 and ETABS. The dynamic responses of the isolation structures under earthquakes with different PGA are obtained from elastic-plastic time history. The failure mode of structures is obtained by comparing the responses such as the inter-story drift ratios, the isolation bearing deformations and the overturning moments. The results show that under very-rare earthquakes, the isolation bearing deformations are excessive in all three structures, while other two responses both meet the requirements. With isolation bearings increasing 20%, the new structures survive earthquake with PGA of 620gal, while the isolated effectiveness reduces slightly.

KEYWORDS: *high-rise isolated structure, very-rare earthquake, isolation bearing scale-up, seismic isolation design.*

1. INTRODUCTION

There are many high-rise isolated structures built in China. As the horizontal stiffness of the isolation layer is much less than the structure's inter-story stiffness, the isolated structure's period has been expended, the inter-story drift and the inter-story shear has been decreased by the isolation layer. Taking the energy into account, the isolation layer with damped system behaves well because the deformation is concentrated. Isolation layer can also restrain the earthquake of long period, which is good to the structure with short period. So most isolated structures are low-rise structures. Recently, the isolation technology suitable for high-rise isolated structures has been spread. After Wenchuan earthquake, many high-rise isolated structures have been built in China. Similar to soft-first story structure, high-rise isolated structure has a low redundancy. It's dangerous that the deformation of the isolation layer and the overturning moment exceed the limit under a strong earthquake. In China, over 10% cities have experienced destructive earthquake. From 2003, there are 5 earthquakes with 9 intensity and above and 12 earthquakes with 8 intensity in China[1]. However the seismic precautionary intensity of isolated structure is usually below 9. Furthermore, the structures with high earthquake fortification level need high seismic performance because of the stochastic behavior of earthquakes[2]. The performance of the isolated structure under a very-rare earthquake is urgent to be researched. On basis of "survive a rare earthquake by sustaining significant damage but without globally collapsing" design (refer to Chinese code for seismic design of buildings), this paper is focus on the seismic performance of high-rise isolated structure and the feasibility, the cost and the method of isolated structure design based on "survive a very-rare earthquake".

2. THE MODEL OF ISOLATION STRUCTURES AND EARTHQUAKES USED FOR CALCULATING

2.1. The model of isolation structures

In this paper three structures include one low-rise structure and two high-rise structures are modeled by

SAP2000 and ETABS.

The low-rise structure (LS) is a RC frame building whose height, length and breadth is 27.3m, 48.1m and 26.3m. the structure is assumed to locate at the region with seismic precautionary intensity of 8.

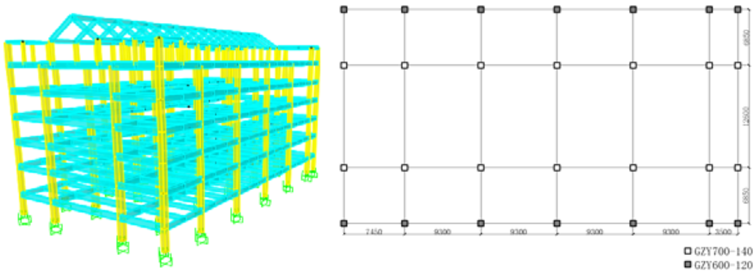


Fig. 2.1 The model and isolation bearings arrangement of LS

There are 28 isolation bearings in the isolation layer. 14 GZY600-120 bearings are arranged outside, Figure 2.1 is the model and isolation bearings arrangement of the low-rise structure. 14 GZY700-140 are arranged inside. The stiffness of the isolation layer is 57848kN/m. The first period of the structure is 2.77s, the second period is 2.63s.The horizontal seismic reduction factor is 0.45.

The first high-rise structure (HS1) is a frame shear wall structure whose height, length and breadth is 53m, 24m and 20m. The structure is also assumed to locate at the region with seismic precautionary intensity of 8.

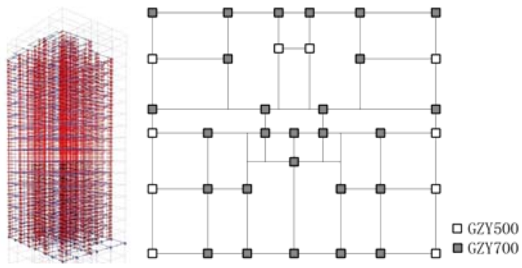


Fig. 2.2 The model and isolation bearings arrangement of HS1

There are 10 GZY500-100 bearings and 27 GZY700-140 bearings in the isolation layer. The isolation bearings are arranged symmetrical due to the fact that the vertical stress of different bearings need to be similar and the stiffness center of the isolation layer need to be on one vertical axis with the gravity center of the structure. Figure 2.2 is the model and isolation bearings arrangement of the first high-rise building. The stiffness of the isolation layer is 76171kN/m. The first period of the structure is 2.68s, the second period is 2.64s.The horizontal seismic reduction factor is 0.69.

The second high-rise structure (HS2) is a shear wall structure whose height, length and breadth is 94.7m, 38m and 20m. The seismic performance of this structure is similar to the super high-rise building. The structure is also assumed to locate at the region with seismic precautionary intensity of 8. Figure 2.3 is the model and isolation bearings arrangement of this structure.

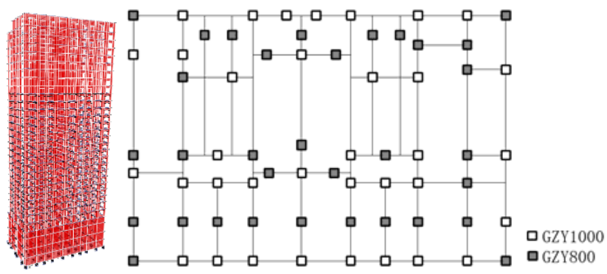


Fig.2.3 The model and isolation bearings arrangement of HS2

There are 35 GZY700-140 bearings and 33 GZY1000-200 bearings in the isolation layer. Large diameter isolation bearings with large distance are chosen to avoid bearings in tension. The stiffness of the isolation layer is 195286kN /m. The first period of the structure is 3.36s, the second period is 2.97s.The horizontal seismic reduction factor is 0.53. Table 2.1 is the parameters of the isolation bearings.

Tab.2.1 The parameters of the isolation bearings

Type	Rubber Thickness/ mm	Vertical Bearing Capacity/kN (Stress/MPa)	Vertical Stiffness /(kN·mm^{-1})	Lead Plug Diameter /mm	100%Shear Deformation		
					Elastic Stiffness /(kN·mm^{-1})	Yield Force /kN	Plastic Stiffness /(kN·mm^{-1})
GZY500-100	92	1963(15)	1802	100	4.97	62.7	0.77
GZY600-120	100	2827(15)	2614	120	5.48	94.2	0.84
GZY700-140	162	3848(15)	4022	140	6.52	115	1.00
GZY800-160	160	5026(15)	4065	160	7.97	167.5	1.23
GZY1000-200	192	7853(15)	6374	200	12.30	261.7	1.89

2.2. The model of isolation structures

5 natural earthquakes and 2 artificial earthquakes are used in elastic-plastic time history. The duration is 25s. The PGA of each earthquake are 70gal, 220gal, 310gal, 400gal, 510gal and 620gal. The seismic loads are along the minor axis. Figure 2.4 is the response spectra of selected earthquakes and code specification.

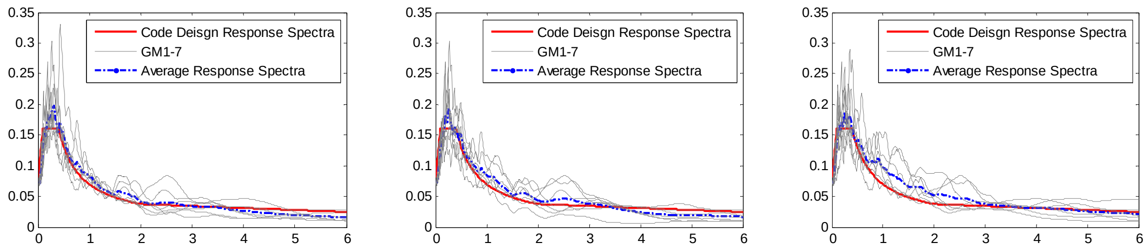


Fig. 2.4 Response spectra of selected earthquakes and code specification

3. THE SEISMIC PERFORMANCE OF ISOLATION STRUCTURES IN VERY-RARE EARTHQUAKE

3.1. Calculation of inter-story drift ratios

The weak story elastic-plastic distortion is measured by inter-story drift ratio. Different types of structure have different limits of inter-story drift ratios in Chinese code. Table 3.1 shows the maximal inter-story drift ratios. The results show that the inter-story drift ratios can meet the requirement under rare earthquake.

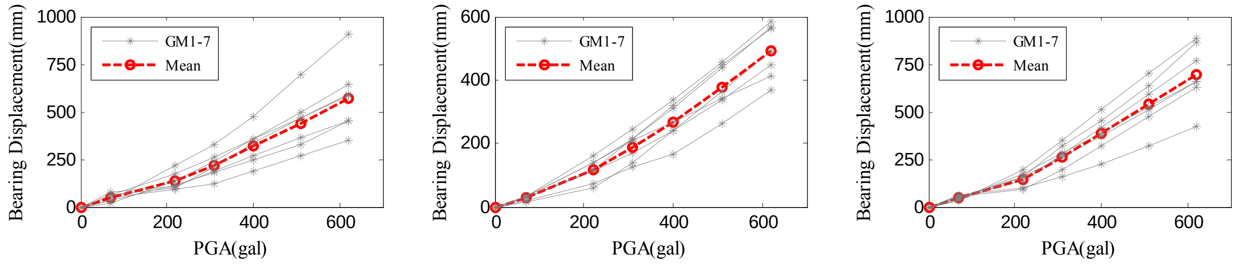
Tab.3.1 Maximal inter-story drift ratios

	LS		HS1		HS2	
PGA	ISDA	ISDA/Limit	ISDA	ISDA/Limit	ISDA	ISDA/Limit
70gal	1/576	17.4%	1/909	22.0%	1/2500	9.6%
220gal	1/200	50.0%	1/454	44.0%	1/1429	16.8%
310gal	1/145	68.8%	1/345	58.0%	1/1111	21.6%
400gal	1/111	90.0%	1/278	72.0%	1/909	26.4%
510gal	1/85	117.6%	1/222	90.0%	1/714	33.6%
620gal	1/68	147.0%	1/185	108.2%	1/588	40.8%
Limit	1/100	—	1/200	—	1/240	—

Under a very rare earthquake, the weak story elastic-plastic distortion can a meet the requirement according to the <Code for seismic design of buildings>. The weak story deformation won’t cause the collapse. The isolation technique behaves well on decreasing the story distortion for shear wall structure whose story stiffness is large. The structure enters the plastic state under the earthquake whose PGA is 400gal. It confirms with the design principle of “resist moderate earthquakes without damage and maintain function with repairable damage under rare but severe earthquakes”. The safety level of the inter-story draft ratio is high enough under very-rare earthquake.

3.2. Calculation of isolation bearing deformation

In isolation design, the isolation bearing deformation should not exceed 0.55 time of the diameter of the isolation bearing in accordance with the axial load limit, and it also should not exceed 3 times of its thickness in the light of the shear deformation limit[3]. Figure 3.1 is the maximal isolation bearing displacement (IBD) in 7 earthquakes. Table 3.2 is the average maximal isolation bearing displacement (IBD) and its limit.



(a) LS (a) HS1 (c) HS2

Fig.3.1 Max isolation bearing deformation

Tab.3.2 Average max isolation bearing displacement and its limit

	LS		HS1		HS2	
PGA	IBD /mm	Maximum /Limit	IBD /mm	Maximum /Limit	IBD /mm	Maximum /Limit
70gal	47.6	14.4%	26.6	9.7%	46.9	12.2%
220gal	133.7	40.5%	114.8	41.7%	145.2	37.7%
310gal	218.6	66.2%	187.8	68.3%	262.6	68.2%
400gal	316.2	95.8%	268.9	97.8%	383.7	99.7%
510gal	440.1	133.3%	378.5	137.7%	537.3	139.6%
620gal	569.1	172.5%	490.8	178.5%	698.2	181.3%
Limit	330	—	275	—	385	—

Different isolation bearings in the same structure has about the same maximal isolation bearing deformation. So the smallest isolation bearings lose their bearing capacity first. To each structure the limit of isolation layer deformation can be obtained through the smallest isolation bearings. Table 3.2 compares the ratio between average maximum isolation bearing displacement and its limit under different earthquakes.

The isolation bearings can ensure the safety of each structure under the earthquake whose PGA is 400gal. But the isolation bearing displacement increases and exceeds the limit under the earthquake whose PGA is 510gal. When the PGA is 620gal, it exceeds 1.7 times of the limit. This shows that the inter story deformation is transferred to the isolation layer. The safety level can be ensured but the security reserve would not increase.

In Figure 3.1, the isolation bearing displacement increases approximately linearly with the PGA in all three structure. In Table 3.2, the ratios between average maximum isolation bearing displacement and its limit are basically the same. It means that the isolation bearing deformation can be decided according to the isolation layer design. Different heights or aspect ratios just have a small influence on it.

In general, on basis of "survive a rare earthquake by sustaining significant damage but without globally collapsing", isolated structure has a poor seismic performance under a very-rare earthquake. Under an earthquake, the superstructure maintains in elastic range or small nonlinearity, and the acceleration is also small, so it's dangerous that the damage is unapparent before collapse and the redundancy is not enough.

3.3. Calculation of overturning moment

Generally speaking, the aspect ratio of isolated structure has a great influence on the stability against overturning. The capsizal capability can also be analyzed according to the vertical forces of isolation bearings. According to GB50011-2010 <code for seismic design of buildings> in China, the tensile stress of the isolation bearing should be less than 1MPa, the compressive stress should be less than its limit. In this paper, the bearing compressive stress limit of the three structures is 12MPa.

From the result, the stress of the isolation bearing can meet the requirement in rare and very-rare earthquakes. In isolation design, few inner bearings and large-spaced bearing arrangement are suitable in view of the tensile stress limit, and large-scaled bearings are suitable in view of the compressive stress limit. The overturning capability can also be reflected by the overturning moment, which is consistent with the bearing stress requirement[4].

Overturning moment can be obtained from formula (1):

$$M_C = \sum_{j=1}^{h} \sum_{i=1}^{m} F_{ij} H_i \tag{3.1}$$

where Fij is the horizontal earthquake action of the j mode of vibration of i layer, Hi is the height of i layer.

Anti-overturning moments of three structures are:

$$[M_{LS}] = G_{\mathrm{eqLS}} \times \frac{L_{LS}}{2} = 1222766 kN \cdot m \tag{3.2}$$

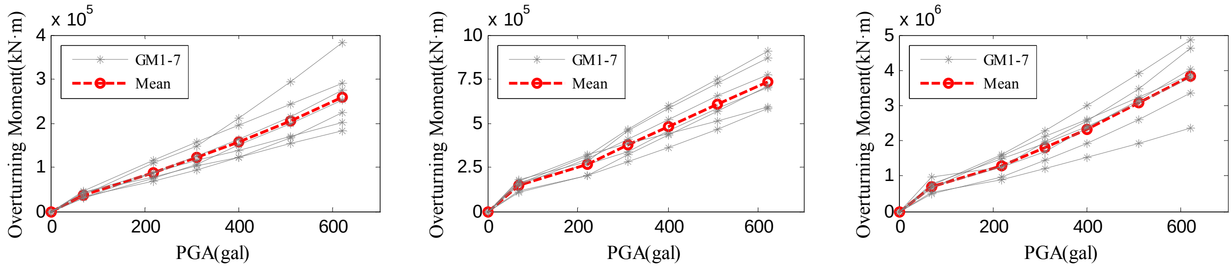
$$[M_{HS1}] = G_{\mathrm{eqHS1}} \times \frac{L_{HS1}}{2} = 1224795 kN \cdot m \tag{3.3}$$

$$[M_{HS2}] = G_{\mathrm{eqHS2}} \times \frac{L_{HS2}}{2} = 5089750 kN \cdot m \tag{3.4}$$

Where, the arm of the anti-overturning moment [M] is equal to the vertical distance between the center of gravity of each layer and the axis of isolation bearing on the edge of the isolation layer.

Anti-overturning ratio= Anti-overturning moment/ overturning moment.

In general, the structure is supposed to be safe when Anti-overturning ratio is more than 1.2 and it means the ratio between overturning moment and anti overturning moment is less than 83%[5]. Figure 3.2 is the maximal overturning moments in 7 earthquakes. And Table 3.3 is the average maximum overturning moment (OM) and its limit.



(a) LS (a) HS1 (c) HS2

Fig. 3.3 Overturning moment

Tab.3.3 Average overturning moment

PGA	LS		HS1		HS2	
	OM /kN·m	Maximum /Limit	OM /kN·m	Maximum /Limit	OM /kN·m	Maximum /Limit
70gal	3.8×10^4	3.8%	1.5×10^5	15.0%	6.9×10^5	16.4%
220gal	8.9×10^4	8.9%	2.7×10^5	27.0%	1.3×10^6	30.1%
310gal	1.2×10^5	12.0%	3.8×10^5	38.0%	1.8×10^6	42.9%
400gal	1.6×10^5	16.0%	4.8×10^5	48.0%	2.3×10^6	54.8%
510gal	2.0×10^5	20.0%	6.1×10^5	61.0%	3.1×10^6	73.8%
620gal	2.6×10^5	26.0%	7.3×10^5	73.0%	3.8×10^6	90.5%
Limit	1.0×10^6	—	1.0×10^6	—	4.2×10^6	—

The overturning moment can ensure the safety under an earthquake whose PGA is less than or equal to 620gal. The conclusion is the same as it from the stresses of the isolation bearing. The overturning moment of low-rise structure is much smaller than its limit. The moments of the other two high-rise buildings are close to the limits.

In Figure 3.2, the overturning moments of the three structures all increase approximately linearly with the seismic acceleration. But according to Table 6, the ratios between the overturning moment and the limit are different. The high-rise building with large aspect ratio is more easily to overturn because of its bending deformation.

3.4. Failure mode of isolation structure

Under an earthquake, the inter-story drift ratio is the main failure index for traditional structures, and the isolation bearing deformation and the overturning moment are the main failure index for isolated structures. Figure 3.3 and Table 3.4 shows the ratios between two maximum responses and their limits. When the responses exceed the limits, the structure is considered to be destroyed by this mode.

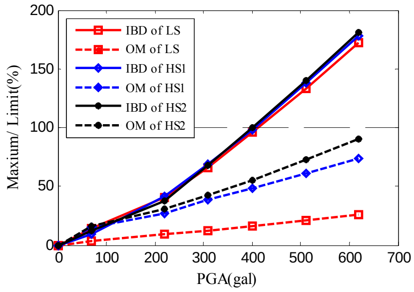


Fig.3.3 The ratios between maximum responses and their limits

Tab.3.4 The ratios of maximum responses and their limits

	LS		HS1		HS2	
PGA	IBD	OM	IBD	OM	IBD	OM
70gal	14.4%	3.8%	9.7%	15.0%	12.2%	16.4%
220gal	40.5%	8.9%	41.7%	27.0%	37.7%	30.1%
310gal	66.2%	12.0%	68.3%	38.0%	68.2%	42.9%
400gal	95.8%	16.0%	97.8%	48.0%	99.7%	54.8%
510gal	133.3%	20.0%	137.7%	61.0%	139.6%	73.8%
620gal	172.5%	26.0%	178.5%	73.0%	181.3%	90.5%

With the increase of seismic PGA, the bearing displacement and the overturning moment increase almost linearly. The displacement curves of the three structures are basically coincident. The overturning moment curves are obviously different. It shows that overturning moment has a closer relationship with the upper structure.

The failure index of isolated structures is bearing displacement under a very-rare earthquake. The isolation bearing displacement should meet the requirement first in isolation design.

The bearing displacement of the three structures in 9 intensity earthquake is about 100% more than it in 8 intensity earthquake. And the moment increases 50%. So the bearing displacement needs a larger safety level.

Isolation technique can improve the seismic capacity and enhance the safety factor of the structure. But it may cause bearing stress exceeding or structure overturning. It can't guarantee the seismic performance under a very-rare earthquake. Isolation technique is difficult to increase the security reserve.

4. AMELIORATING DESIGN THROUGH EXPANDING ISOLATION BEARINGS SIZE

To improve the safety reserve, the isolation bearings of the three structures are ameliorated through expanding isolation bearings size. As the vertical stress of each bearing meet the requirement, the layout of the bearings won't change.

The smallest isolation bearing scale needs to be expanded first. To avoid wasting bearing capacity and reducing isolation effect, the bearing sizes won't change a lot. Because the layout of the bearings is not changed, the new structure will not have partial failure in isolation layer.

4.1. Calculation of responses of new isolation structures

The results show that the inter-story drift ratios can meet the requirement under very-rare earthquakes. Figure 4.1 and Table 4.1 shows the ratios between two maximum responses and their limits of the new structure.

Tab.4.1 The ratios between new maximum responses and their limits

	LS		HS1		HS2	
PGA	IBD	OM	IBD	IBD	OM	IBD
70gal	4.8%	4.2%	4.8%	17.0%	5.8%	20.5%
220gal	20.9%	9.6%	21.8%	34.0%	19.6%	35.7%
310gal	34.3%	13.0%	34.0%	40.0%	32.5%	45.2%
400gal	50.9%	17.0%	49.4%	51.0%	49.2%	59.5%
510gal	72.5%	12.0%	71.5%	68.0%	72.2%	80.5%
620gal	96.1%	27.0%	94.8%	84.0%	95.7%	97.6%
Limit	440mm	1.0×10^6 kN·m	440mm	1.0×10^6 kN·m	550mm	4.2×10^6 kN·m

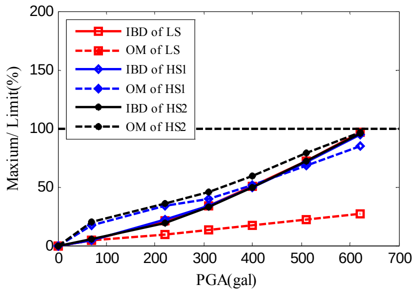


Fig. 4.1 The ratios between new maximum responses and their limits

In three new structures, the isolation bearing displacements increase approximately linearly with the seismic acceleration. The new displacements of isolation bearings decrease 20% and are able to meet the requirement. It verifies that the displacements of bearings are mainly determined by the isolation layer design. According to this design, the maximum displacements of isolation bearings only reach half of the limit under a rare earthquake. It has a high security reserve.

The overturning moments can ensure the safety under an earthquake whose PGA is equal to 620gal. The new moments increase slightly. And for the second high-rise structure, the risk exists because the new moments are close to the limit.

The response of the ameliorated structures can meet the requirements. The displacements of the isolation bearings decrease obviously, and the overturning moments increase slightly.

4.2. Contrast of two kinds of isolation designs

After amelioration, the three isolated structures can survive a very-rare earthquake. Table 6 is the isolated structures' parameters of two designs. The amount of isolation bearings is represented by the volume of all the rubber and the stiffness of isolation layer respectively.

The amount of isolation bearings increase 77%, 31%, 43% for three structures. And the stiffnesses increase 22%, 69%, 22%. The improved design of the second high-rise building has the most visible effect. Each bearing deformation capacity play a full role because of the same bearing scale. The earthquake-resistant details of seismic design would increase in the new structure as the horizontal seismic reduction factors increase.

Calculation and analysis results show that the bearing displacement under a very-rare earthquake is 100% larger than it under a rare earthquake, and the overturning moment expands one third. It is necessary to improve the seismic precautionary criterion of isolated structures in order to avoid the sudden damage under a very-rare earthquake.

Tab.4.2 Isolated structures' parameters of two designs

	Type	Rubber Volume（m^3）	Isolation Layer Stiffness(kN/m)	Period(s)	Horizontal Seismic Reduction Factor
LS	14 GZY600-120 14 GZY700-140	1.22	57848	3.17	β=0.45
New LS	28 GZY800-160	2.16	70868	2.99	β=0.62
HS1	10 GZY500-100 27 GZY700-140	1.79	76171	2.68	β=0.69
New HS1	10 GZY600-120 27 GZY800-160	2.35	129081	2.52	β=0.81
HS2	35 GZY700-140 33 GZY1000-200	6.89	195286	3.36	β=0.53
New HS2	68 GZY1000-200	9.86	238476	3.20	β=0.61

To sustaining significant damage but without globally collapsing under an earthquake whose PGA is 100gal higher than precautionary earthquake, the anti-overturning ratio needs to rise from 1.2 to 1.67, and the limit of the bearing displacement are controlled strictly to 0.4 time of the diameter of isolation bearing.

To sustaining significant damage but without globally collapsing under an earthquake whose PGA is 200gal higher than precautionary earthquake, the anti-overturning ratio needs to rise from 1.2 to 2.5, and the limit of the bearing displacement are controlled strictly to 0.26 time of the diameter of isolation bearing.

The new bearing diameter won't increase more than 20%.

5. CONCLUSION

In this paper three structures with different heights are anlysised from elastic-plastic time history under earthquakes with different PGA, The conclusion are as follows:

1. The isolated structure based on "survive a rare earthquake" design may collapse suddenly due to the isolation layer deformation exceeding under very-rare earthquakes. It's dangerous that the damage is unapparent before collapse and the redundancy is not enough. The high-rise isolation building with large aspect ratio may overturn more easily.

2. The inter story deformation of isolated structure is transferred to the isolation layer, and the structure may not survive a very-rare earthquake. The safety level can be ensured but the security reserve can not.

3. To increase the very-rare seismic performance, the anti-overturning ratio needs to rise from 1.2 to 2.5, and the limit of the bearing displacement are controlled strictly to 0.26 time of the diameter of isolation bearing. The new bearing diameter won't increase higher than 20%, and the security reserve will expand a half.

4. As the horizontal seismic reduction factors increase, the earthquake-resistant details of seismic design may increase when the safety level increases.

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