THEORETICAL AND EXPERIMENTAL INVESTIGATION ON MID-STORY SEISMIC ISOLATION STRUCTURES

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ABSTRACT
Isolation technique has been acceded to the "Code for Seismic Design of Buildings" in China. There are also many isolation codes in other countries, such as the United States, Japan, European Economic Community etc. But in these codes, the limits are very strict for isolated buildings, such as superstructure must be regular, the isolation layer must be located on the top of base (base isolated structure). Because of the needs of architecture and use function or the feasibility of technique, some limits have to be broken in practical projects. Sometimes isolated layer is set on the intermediate story, said the mid-story isolated structure.

For mid-story isolated structure, according to the characteristic of structure, in general, isolation layer is set in the part where the structure's vertical stiffness is suddenly changed. It can be set on the top of the first story, middle story conversion storyof the structure, and so on. L aminated rubber bearings(LRB) are adopted. Because the isolation layer is set in intermediate story, the whole structure is divided into superstructure and substructure, the structure's dynamic characteristics are changed. The mechanism of mid-story isolated structure appearsnew characteristic contrast with base isolation. The aim of mid-story isolation not only requires to reduce seismic responses of superstructure, but also to reduce seismic responses of the whole structure, as reducing or not increasing the seismic responses of substructure.

Based on the theory analysis and the shaking table test of the mid-story isolated structure, comparing with base-isolated structure and base fixed structure, theory and mechanism of mid-story isolated structure is discussed in detail. The key problems of mid-story isolated structure are the force status and the interaction of the structure up and below the isolation layer. Many factors, such as the number of story, mass, stiffness of superstructure and substructure, parameter of the isolation layer, are influence on the seismic behavior of the mid-story isolated structure. The optimum combination relationship of these factors is presented and dynamic characteristics and dynamic responses are investigated.

The viewpoints offered in this paper can be referred in design of isolated building and in corresponding code compilation.

KEYWORDS: mid-story isolated structure, shaking table test, optimum factors, finite element analysis

1. 1INTRODUCTION

Base-isolated building is an effective, economic and readily available new technology system for earthquake resistance. Many earthquake experiences at home and abroad have indicated that isolation technique, can avoid the earthquake damage to building structure and its contains. Since the first isolation building with laminated rubber bearings was built in 1993 in China, several hundreds isolation buildings have been built all over the country. But the limits are very strict for isolated buildings, such as superstructure must be regular, the isolation layer must be located on the top of base (base-isolated structure). Because of the needs of architecture and use function or the feasibility of technique, some limits have to be broken in practical projects. Sometimes isolation layer is set on the intermediate story, to form the "mid-story seismic isolation structure system".

In this paper, the simplifying calculation model of mid-story seismic isolation structure is developed. Many factors, such as the number of stories, the stiffness ratio, frequency ratio, mass ratio of superstructure and substructure, parameters of the isolation layer, influencing on the effectiveness of isolation, are investigated. A series of shaking table tests of mid-story seismic isolation structures are carried out, the results of shaking table tests are considered to be certainly accurate by comparison with calculated results.

2. THE KINEMATICAL EQUATION OF MID-STORY SEISMIC ISOLATION AND REDUCTION STRUCTURES

Because the isolation layer of mid-story seismic isolation structure was located at any middle story, there are grate difference between the stiffness and damping of isolation layer and those of superstructure and substructure, and leads obvious difference between the responses above and below the isolation layer. The part above isolation layer is like the superstructure of base-isolated structure. While the part below isolation layer is under the action of inertia force of superstructure and isolation layer besides earthquake action. So the kinematical equations are introduced separately.

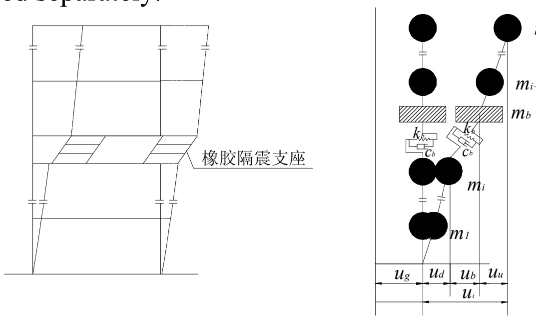


Fig. 1 Calculation scheme of mid-story seismic isolation and reduction structure

The kinematical equation of superstructure:

$$\left[M^u\right]\{\ddot{u}_u\}+\left[C^u\right]\{\dot{u}_u\}+\left[K^u\right]\{u_u\}=-\left[M^u\right]\{I\}\left\{\ddot{u}_b+\{R\}^T\left[\{\ddot{u}_d\}+\{I_1\}\ddot{u}_g\right]\right\} \quad (2.1)$$

The kinematical equation of isolation layer:

$$m_b\ddot{u}_b+c_l\dot{u}_b+k_lu_b=-\{I\}^T\left[M^u\right]\left\{\{I\}\left[\ddot{u}_b+\{R\}^T\left(\{\ddot{u}_d\}+\{I_1\}\ddot{u}_g\right)\right]+\{\ddot{u}_u\}\right\}-m_b\{R\}\left(\{\ddot{u}_s\}+\{I_1\}\ddot{u}_g\right)-F_b \quad (2.2)$$

The kinematical equation of substructure:

$$\left[M^d\right]\{\ddot{u}_d\}+\left[C^d\right]\{\dot{u}_d\}+\left[K^d\right]\{u_d\}=-\left[M^d\right]\{I_1\}\ddot{u}_g-\{R\}^T\left\{\left(\{I\}^T\left[M^u\right]\{I\}+m_b\right)\left[\ddot{u}_b+\{R\}\left(\{\ddot{u}_d\}+\{I_1\}\ddot{u}_g\right)\right]+\{I\}^T\left[M^u\right]\{\ddot{u}_u\}\right\} \quad (2.3)$$

Where $\left[M^u\right]$、$\left[M^d\right]$ is the mass matrix of superstructure and substructure respectively; $\left[K^u\right]$、$\left[K^d\right]$ is the stiffness matrix of superstructure and substructure respectively; k_l、c_l is the additional stiffness and damping coefficient respectively; m_b is the mass of isolation layer. If the isolation layer only has LRB, and has not any additional damper and spring, k_l and c_l are 0; $\left[C^u\right]$、$\left[C^d\right]$ is the damping matrix of superstructure and substructure respectively. $\ddot{u}_g$ is the acceleration of ground motion, F_b is the horizontal restoration force vector formed by isolation device of isolation layer （such as LRB, friction slipping bearing, etc.）,including elastic-plastic restoration force and viscosity damping force of each isolation device, $\{R\}$ is the influence matrix of earthquake action, $\{R\}=\{0 \quad 0 \quad \cdots \quad 1\}$.

3. MAIN FACTORS INFLUENCING MID-STORY ISOLATED STRUCTURES

3.1 control target of mid-story isolated structures

The superstructure and substructure of mid-story isolated structure are a part of building, in design of structure, the earthquake response of superstructure and substructure is the key matter to be concerned. In order to get better economical effect, mid-story isolated structure can not only use for new buildings, but also use for reha bilitation of existing buildings. The design target of mid-story isolated structure is determined primarily: by setting isolation layer, the earthquake response of superstructure can reduce obviously, so design can be reduced one degree of earthquake intensity and get better economical effect; at the same time, earthquake response of the whole structure is reduced while the earthquake response of substructure is not increased.

To simplify the superstructure (including isolation layer) as one mass model, and to equalize the substructure to one mass model upon the first period equal, so a two-mass model is to be formed. Let M_d、C_d、K_d as the mass, damping and stiffness of substructure; M_u、C_u、K_u as the mass, damping and stiffness of superstructure; $\ddot{x}_g$ as the acceleration of ground motion; x_d as the displacement response of substructure to ground.; x_u as the displacement response of superstructure to ground.

Considering the story shear force is the main basis for isolation design of structure, we take the story shear force as the main control target, and a non dimensional value, the shear–gravity ratio, as the main control target.
The shear–gravity ratio of superstructure is

$$\frac{F_u}{M_u g} = \frac{M_u \ddot{x}_u(t)\left|\ddot{x}_g(t)\right|_{\max}}{M_u g\left|\ddot{x}_g(t)\right|_{\max}} = \frac{\left|\ddot{x}_g(t)\right|_{\max}}{g} \cdot \frac{\ddot{x}_u(t)}{\left|\ddot{x}_g(t)\right|_{\max}} = k_a \cdot A_u \tag{3.1}$$

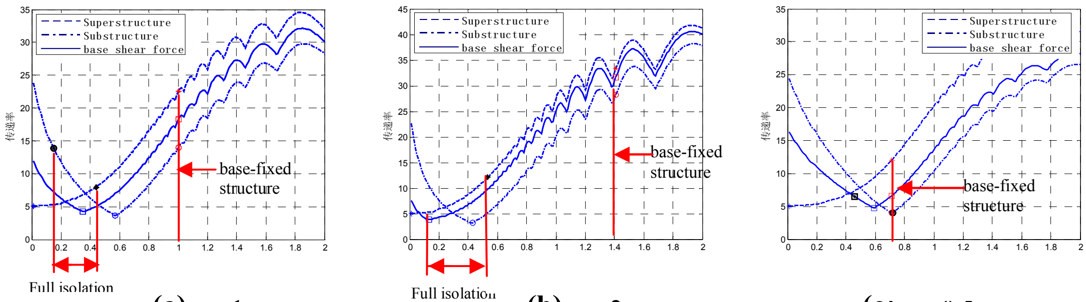
Where: F_u is the shear force of superstructure; k_a is earthquake coefficient, a constant related to earthquake intensity; A_u is acceleration amplification coefficient. For controlling the story shear force of superstructure, it is only need to control the acceleration amplification coefficient of superstructure, i.e. to control the acceleration transfer ratio of superstructure. As the same, towards substructure, for controlling the earthquake action force, it is only need to control the acceleration amplification coefficient of substructure, i.e. to control the acceleration transfer ratio of substructure.

According to the analysis above, for mid-story isolated structure, two targets must be controlled simultaneously. (1) to control the acceleration response of superstructure. In general, it is need to confirm that the story shear force of superstructure is small enough, so the design can be deduced one degree of earthquake intensity. i.e. smaller than or equal to 35%($A_u \le 0.35\mathrm{A}_{uG}$)。A_{uG} is the acceleration amplification coefficient of superstructure of relative non-isolated structure. (2) to control the acceleration response of substructure. comparing with non-isolated structure, it is need to confirm that earthquake action force of substructure does not appear increment. i.e. $A_d \le \mathrm{A}_{dG}$, A_{dG} is the acceleration amplification coefficient of substructure of relative non-isolated structure; to reduce the base shear force of the whole structure, i.e. $A_F \le \mathrm{A}_{FG}$. A_{FG} is the base shear-gravity of relative ratio non-isolation structure.

3.2 Influence of frequency ratio α on mid-story isolated structure

Frequency ratio of superstructure and substructure of mid-story isolated structure $\alpha = \omega_u / \omega_d = \frac{\sqrt{k_u/m_u}}{\sqrt{k_d/m_d}}$ is the main factor influencing mid-story isolated structure. Fig.2 gives the change curve of transfer ratio of superstructure acceleration, substructure acceleration and base shear force with frequency ratio α ,when damping of isolation layer ζ_u=0.10，damping of structure ζ_d=0.02，corresponding mass ratio μ is 1,2,0.5 respectively.

From these curves we can see that for superstructure, the smaller the frequency ratio α , the smaller the transfer ratio of acceleration, superstructure is corresponding to a single mass isolation system; for substructure, there is minimum frequency point, its location changes with the change of mass ratio μ .



(a) $\mu = 1$ (b) $\mu = 2$ (c) $\mu = 0.5$

Fig. 2 Change curve of transfer ratio of structure with frequency ratio α

When mass ratio μ=1, frequency ratio α ranges from 0.15~0.44,it can be control that the acceleration of superstructure $A_u \le 0.35\mathrm{A}_{uG}$, $A_d \le \mathrm{A}_{dG}$ and $A_F \le \mathrm{A}_{FG}$, so two design targets can be realized, we named it as full isolation. its corresponding frequency ratio is optimal frequency ratio α_{opt} .The larger the mass, the lower the location of isolation layer, the wider the range of α_{opt} , conversely more narrow. When $\mu = 2$, α_{opt} ranges between 0~0.53.When $\mu = 0.5$,it is difficult to realize full isolation. In general, full isolation needs mass ratio $\mu > 0.8$.

Out of α_{opt} range , the design targets can be realized partly only, or realized superstructure control but the earthquake response of substructure is increment, or reduced the earthquake response of superstructure and substructure simultaneously but can not reduced one degree of earthquake intensity for superstructure design. We named it as partial isolation. When mass ratio μ ranges 0.5~0.8, partial isolation can be realized.

When the location of isolation layer becomes higher, it is difficult to realize isolation design for superstructure. We can reduce the acceleration of substructure or base shear force by turn frequency, but it needs increment of acceleration of superstructure. We named it as turn frequency reduction, the corresponding mass ratio range $\mu \le 0.5$.

3.3 Influence of damping ratio of isolation layer ζ_u on mid-story isolated structure

In general, transfer ratio of structure can be reduced when damping is increasing. Especially the damping ratio ranges from 0 to 0.2, the influence on transfer ratio becomes maximum, but not while damping ratio greater than 0.2. Especially the greater the mass ratio μ , the less the influence of damping ratio, the influence on transfer ratio becomes larger even more damping raising. It should be noted that for mid-story seismic isolation structure, when mass ratio μ >0.5, corresponding optimal damping ratio is in general greater than 0.3, it is difficult to realized in practical engineering.

4. SHAKING TABLE TEST RESEARCH AND COMPARISON WITH CALCULATION ANALYSIS

4.1 Scheme of test research

A series of steel frame models, including an 1-story frame, 2-story frame, and 3-story frame. The section of beam and column of each steel frame is the same. Series of steel frame models can be set up according to different location of isolation layer.

Four diameter 100mm LRBs with low hardness (GZY100G4) are used for isolation layer. Its basic parameters are as Table 1.During test, isolation layer is set on the bottom of 1st story (base isolation), the bottom of 2nd story, the bottom of 3rd story, the bottom of 4th story, the bottom of 5th story or on the bottom of 6th story, thus a series of mid-story isolated system is formed (Fig.3). In addition, base-fixed model (no isolation layer) is tested and analyzed comparing with isolation structure system.

Two real earthquake accelerograms (El Centro, Tianjin wave) are used in test, peak value of horizontal acceleration is taken as 0.20g.

Earthquake response analysis of model structure is carried out by finite element model and compared with result of shaking table test.

Table 1 Testing value of property parameters of isolation bearing models（GZY100G4）

No. of bearing		Vertical stiffness K_v（kN/mm）	Horizontal properties（γ=100%）			
			Equal horizontal stiffness K_h（kN/mm)	Equal damping ratio h_{eq} (%)	Post-yield stiffness K_d（kN/mm）	Yield load Q_d (kN)
Test value	No.1	188.060	0.173	11.937	0.136	0.671
	No.2	188.470	0.167	10.528	0.139	0.552
	No.3	187.880	0.178	12.382	0.139	0.717
	No.4	188.600	0.167	12.679	0.130	0.737

(a)base isolation (b)bottom of 2nd st. (c) bottom of 3rd st. (d) bottom of 5th st.

Fig.3 Base isolation and mid-isolation models for shaking table tests

4.2 Dynamic property analysis

The structure's natural vibration characteristics are changed with different location of isolation layer. Table 2 shows the test values of frequencies and damping ratios of the model before shaking, and the calculated values of frequencies and modal participating factors. Test values and calculated values are conformed well (Fig.4).

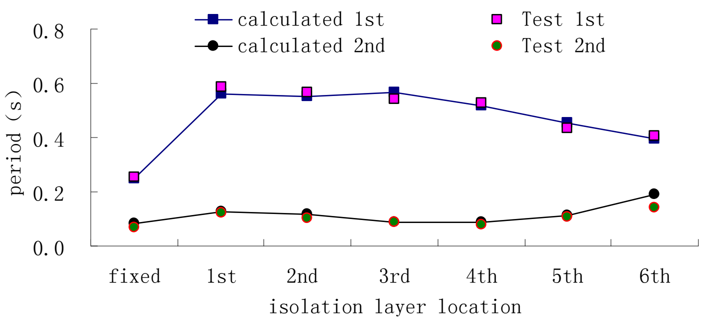


Fig.4 Relationship of structure's period with location of isolation layer

It is shown from Table 2 and Fig 4 that: (1) When the location of isolation layer is lower (bottom of 2nd,3rd, 4th),structural period is about 2 times of base-fixed structure and corresponds to that of base-isolated structure, mid-story isolation structure has the property as base-isolated, earthquake response can be reduced by lengthening the period of the whole structure system, and to attain the object of full isolation. When the location of isolation layer is higher(bottom of 5th ,6th), the structural period is close gradually to that of base-fixed structure, period lengthening is not obviously, so earthquake reduction may be performed by turning frequency. (2) The damping ratio of 1st modal of base-fixed structure is 1.20%, while that of mid-story isolation is 7.45%~15.18%, damping ratio is very larger after isolated. (3) Modal participating factors are different with the location of isolation layer. The participating factor of the 1st modal of base-isolated structure extends to 99%.In general, the sum of participating factors of the first two modals of mid-story isolated structure is greater than 80% and takes main control function. Along with raising the location of isolation layer, higher modal may be one of the important ingredients of structural vibration.

Table 2 Natural frequencies , damping ratios and participating factors of model structures with different isolation layer locations

Location of isolation layer	Order	Test value		Calculated value		Frequency error（%）
		Frequency (Hz)	Damping（%）	Frequency (Hz)	participating factor（%）	
Base -fixed	1st	3.974	1.20	4.058	72.00	2.11
	2nd	12.990	0.57	11.775	10.00	-9.35
	3rd	20.160	0.39	18.716	3.72	-7.16
Base isolated	1st	1.713	13.73	1.776	99.00	3.67
	2nd	8.320	3.44	7.794	1.03	-6.32
	3rd	19.560	1.24	20.690	0.04	5.78
Bottom of 2ndstory	1st	1.773	13.88	1.813	87.00	2.27
	2nd	9.890	0.85	8.580	0.38	-13.25
	3rd	23.800	10.36	22.998	0.00	-3.37
Bottom of 3rdstory	1st	1.852	14.16	1.772	64.00	-4.32
	2nd	11.420	1.87	11.580	23.00	1.40
	3rd	14.840	2.87	12.410	0.22	-16.37
Bottom of 4thstory	1st	1.906	15.18	1.943	63.00	1.94
	2nd	13.010	4.81	11.475	24.00	-11.80
	3rd	17.320	1.16	16.235	0.05	-6.26
Bottom of 5thstory	1st	2.305	12.83	2.214	52.00	-3.95
	2nd	9.328	4.97	8.892	31.00	-4.67
	3rd	22.580	6.16	22.330	3.13	-1.11
Bottom of 6thstory	1st	2.482	7.45	2.534	56.00	2.10
	2nd	6.992	7.65	5.264	23.00	-24.71
	3rd	15.770	0.15	14.145	6.92	-10.30

4.3 Earthquake response and analysis of model

4.3.1 Analysis of acceleration response and story shear force

Fig 5 is the comparison of peak acceleration response encirclement. It is shown that at isolation layer, acceleration has sudden change. For El Centro wave, the maximum acceleration happens below isolation layer, and larger than that at corresponding story of base-fixed structure. Acceleration at the stories above isolation layer reduced very obviously, far less than that at corresponding story of base-fixed structure, so it belongs to partial isolation. For Tianjin wave, acceleration above isolation layer suddenly changes greatly, when the location of isolation layer is higher,(bottom of 5thor 6th story), even greater than that of base–fixed structure, so it belongs to turn frequency reduction.

Fig.6 is comparison of story shear force response encirclement. For El Centro wave, although the acceleration at stories below isolation layer most greater than that of base-fixed structure, story shear force of each story is smaller than that of corresponding story of base-fixed structure. For Tianjin wave, when the location of isolation layer is higher, because it belongs to turn frequency reduction, acceleration of superstructure is greater, corresponding story shear force is also greater. But the base shear force is decreased.

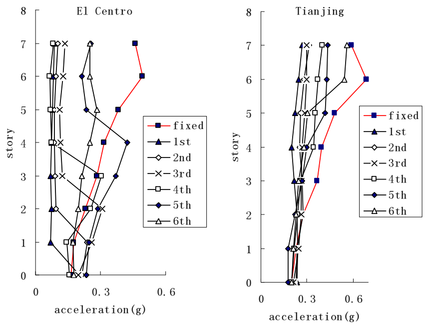


Fig.5 Comparison of peak acceleration response encirclement

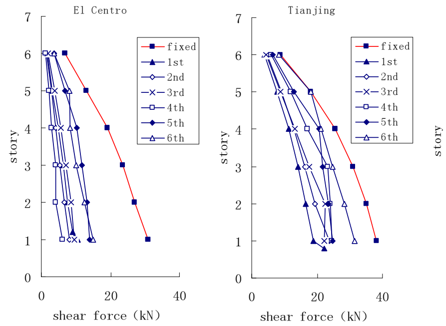


Fig.6 comparison of story shear force response encirclement

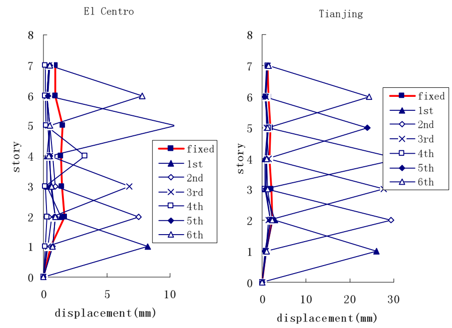


Fig.7 story displacement response encirclement

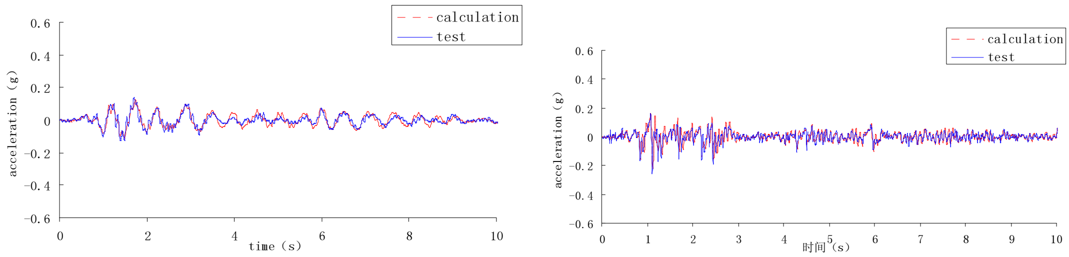
4.3.2 Story displacement response

Towards isolation structure, the deformation of structure concentrates at isolation layer, story displacement of isolation layer increases obviously (Fig.7). Comparing the story displacement of various isolation structure system with the base-fixed structure, the story displacement of all, except isolation layer, is smaller than that of base-fixed structure, the effect of isolation is obvious.

Raising the location of isolation layer, the story displacement of substructure increases gradually, the story displacement of superstructure is basically not change with the location of isolation layer.

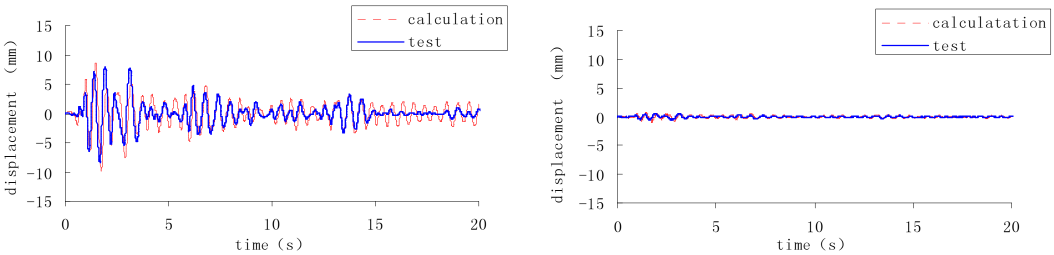
4.3.3 Comparison of time history

Fig.8 and Fig.9 are comparison of calculated acceleration time history and relative displacement time history with test result, for El Centro wave, the consistence is well.



6th story of superstructure 2nd story of substructure

Fig.8 Comparison of acceleration time history (isolated at the bottom of 3rd story)



6th story of superstructure 2nd story of substructure

Fig.9 Comparison of displacement time history (isolated at the bottom of 3rd story)

5. BASIC CONCLUSIONS

It is pointed out that mid-story isolated structure needs to realize two design targets simultaneously: to control the story shear force of superstructure and realize to reduce one degree of earthquake intensity for design; to control the story shear force of substructure and reduce the earthquake response of the whole structure.

According to the level of realizing design targets for mid-story isolated structure, isolation effect can be divided into three classes: full isolation, partial isolation, and turn frequency reduction. When the location of isolation layer is lower, two design targets can be realized simultaneously and full isolation can be reached; When the location of isolation layer becomes higher or too large reduction for superstructure, design target can only be reached partially, thus partial isolation or turn frequency reduction can be realized.

Comparing with base-fixed structure, the first period of mid-story isolated structure is lengthening obviously, damping ratio is also increasing obviously. Modal participating factors are different with the different location of isolation layer. In general, the first two modals are main control function. Along with raising the location of isolation layer, higher modal may be one of the important ingredients of structural vibration.

Since the stiffness of isolation layer is smaller, for mid-story isolation structure, acceleration at isolated layer has sudden change (larger or smaller), For full isolation and partial isolation, the maximum acceleration happens below isolation layer, for turn frequency reduction, acceleration of superstructure is the largest. The deformation of mid-story isolated structure concentrates at isolation layer. Regardless of the change of acceleration, the base shear force of isolation is less than that of base-fixed structure. The story displacement of all, except isolation layer, is smaller than that of corresponding story of base-fixed structure.

Along with the change of location of isolation layer, isolation effect can be divided into two kinds: when isolation layer is set near 1/2 height of structure or lower (in this test, 4th story and below, $\mu < 0.8$), base shear force reduces obviously, isolation effect is obvious; while isolation layer is set above 1/2 height of structure (in this test, 5th story and 6th story, $\mu > 0.8$), base shear force reduces a little, isolation effect is smaller.

Test and calculation results show that in case the property parameters of isolation layer is the same, the main factors influencing the isolation effect of mid-story isolated structure, addition to the location of isolation layer, have important relation with the frequency spectrum. When the frequency of earthquake wave is relative higher, isolated structure is relative flexible, the first period is far from exciting period, then the acceleration of superstructure reduces obviously, isolation effect is obvious. But the reduction of superstructure is substituted by the enlargement of acceleration of substructure. For review of isolation effect, we should consider comprehensively the isolation effect of superstructure and substructure and select the optimum scheme.

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