Research on the Vibration Control Effect of High-Rise isolation system combined with damping device under Strong ground motions

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Abstract. Considering large deformation of the upper structure for base isolation structure and easily overturned whole structure under strong ground motion, the characteristics of earthquake control and seismic response of a high-rise base isolation structure with viscous dampers are studied in this paper. At first, the motion equation of high-rise base isolation structure and high-rise combined control system is established based on the calculation model of multi-degree of freedom system with lumped masses of isolation structure; Then, the state space method and variable order numerical differential algorithm are used to calculate the seismic response of the structure; Finally, the ordinary ground motion records and near-source pulse-like ground motion records are selected as input, and the seismic response of high-rise base isolation structure and high-rise combined control system are calculated, furthermore, its characteristics of seismic response and control effect are compared. The results show that the high-rise base isolation structure with viscous dampers can reduce the structural displacement response significantly, and the displacement demand of isolation bearing can be reduced dramatically too. It is an effective way to develop the new type bearing with low yield stiffness, large deformation and a high tensile strength to solve these questions of base isolation technology in high-rise structure applications.

1. Introduction

In recent years, the isolation technology has been applied in large scale in engineering structure. The research on seismic performance of high-rise base isolation system is one of the research hotspots in the field of engineering seismic protection, and it is being paid more and more attention by researchers. Jain S. K et al[1] pointed out that the stiffness of the superstructure is properly adjusted, and the isolation technology can be applied to the high-rise structure; Becker T C et al[2] analyzed the seismic response of a high-rise isolated structure in Japan and found that the structural response fluctuation obtained by selecting the ground motion according to the US norm is relatively large, and the tensile stress of some supports exceeds the limit; Zhao Guifeng et al[3] analyzed the vulnerability of the high-rise frame shear wall isolation structure with the displacement angle of the interlayer and the displacement of the isolation layer as the damage index. The results show that the structure has the risk of collapse under the action of large earthquakes; Chen Peng et al[4] carried out a scale shaking table test on the frame-core tube base isolation structure. The results show that the upper structure has obvious damping effect, but the isolation bearing is pulled under the rare earthquake. The structure has the possibility of overturning.
this paper intends to use the base isolation and viscous damper combined vibration control strategy to control the high-rise structure, and compare the seismic response characteristics and the effect of the earthquake control.

2. Calculation model and equation of motion

The high-rise isolated structure can cause the vibration of the isolation layer under the action of horizontal earthquakes. At the same time, the upper structure has a large bending moment. The calculation of the seismic response needs to consider the influence of the upper structure oscillation. When the shear deformation is dominant or the bending deformation has no significant effect on the response of the structure, the model is simplified as a shear and rotation model with multiple layers of particles in series. The structural calculation diagram is shown in Figure 1.

![Figure 1](image)

Fig 1. Multi-degree of freedom system with lumped masses of flat swing calculation model with combination control system

Based on the multi-mass flat swing calculation model and its equation of motion established by Zhou Fulin and Liu Wenguang [5], the joint control system is regarded as two parts: the isolated structure and the additional damping system. The equation of motion is established as follows:

\[ M\ddot{X} + C\dot{X} + KX + L_0\dot{\theta}_b + F_D = -MH\ddot{\theta}_b - MI\ddot{x}_g \]  
(1)

\[ H^T M\ddot{X} + H^T MH\ddot{\theta}_b + k_0\theta_b = I^T MH\ddot{x}_g \]  
(2)

The calculation formula proposed in the literature [5,6] is used:

\[ k_0=0.5B^2K_{v,s} \]  
(3)

\[ K_{v,e}=A_eK_{v,s}/A \]  
(4)

Among: B is the width of the structure, \(K_{v,s}\) is the vertical stiffness of the isolation bearing without shear deformation, \(K_{v,e}\) is vertical stiffness under shear deformation; \(A_e\) and \(A\) the effective bearing area of the isolation bearing and the plane area of the inner rubber.

The restoring force of the additional viscous damper system uses a simplified Maxwell model. The relationship between force and displacement is expressed as:

\[ f_d = c_\alpha j |\ddot{x}_j - \ddot{x}_{j-1}| \cos \theta_j \times \text{sgn}((\ddot{x}_j - \ddot{x}_{j-1})\cos \theta_j) \]  
(5)

According to the literature [7], the additional damping matrix is:

\[
F_D = \begin{bmatrix}
 f_{d1} - f_{d2} \\
 f_{d2} - f_{d3} \\
 \vdots \\
 f_{d(0-1)} - f_{dn} \\
 f_{dn}
\end{bmatrix}
\]  
(6)

Among:

\[ f_{dj} = c_\alpha j |(\ddot{x}_j - \ddot{x}_{j-1})\cos \theta_j| \times \text{sgn}((\ddot{x}_j - \ddot{x}_{j-1})\cos \theta_j) \]  

\(c_\alpha j\) is damping coefficient of the \(j\) layer of the viscous damper, \(\theta\) is angle between the viscous damper and the horizontal direction.

The state equation is established by the simultaneous equations (1)–(6) and rewritten into the form of the first-order differential equation (7):

\[ \dot{Y} = -M_0 Y + L_1 Z - C_0 - D_0 \dddot{x}_g \]  
(7)
So, using the numerical differentiation algorithm to solve the equation (7), the seismic response of the joint control system can be obtained.

3. Engineering study

3.1 Project Overview

Taking a 17-story high-rise frame foundation isolation structure as an example, the first layer is 3.6m high, the other floors are 3.3m high, the seismic fortification intensity is 8 degrees 0.2g, the site category is Class II, and the characteristic period is 0.4s. design earthquake grouping into the second group. The column cross-section dimensions are mainly 700×1000mm, 700×800 and 600×600mm, and the beam cross-section dimensions are 350×700mm and 350×600mm. Design load: the floor constant load is 5.0kN/m² and the live load is 2.0kN/m².

Table 1 lists the types and related parameters of the lead rubber isolation bearing.

| Isolation bearing | Pre-flexion stiffness | Equivalent stiffness | Yield displacement |
|-------------------|-----------------------|----------------------|-------------------|
| LRB900            | 26                    | 19.76                | 2.64              | 11.03              |
| LRB1000           | 9                     | 21.32                | 2.96              | 12.80              |
| Equivalent bearing| 35                    | 20.16                | 2.72              | 11.51              |

Table 4 lists the 18 long-period seismic records used in the seismic response analysis of this paper, including 9 pulse-type seismic records (Group B), and the selected seismic records are uniformly amplitude-modulated to 400 cm/s².

| Num | Seismic wave     | β   | PGA(g) | Pulse period Tp | Num | Seismic wave     | β   | PGA(g) | Pulse period Tp |
|-----|------------------|-----|--------|-----------------|-----|------------------|-----|--------|-----------------|
| n1  | LANDERS-833      | 0.407| 0.052  | --              | n10 | Kobe-1114        | 0.549| 0.198  | 2.828           |
| n2  | LANDERS-842      | 0.423| 0.043  | --              | n11 | ChiChi-1478      | 0.608| 0.158  | 8.869           |
| n3  | LANDERS-843      | 0.521| 0.043  | --              | n12 | ChiChi-1481      | 0.652| 0.145  | 8.582           |
| n4  | LANDERS-846      | 0.847| 0.030  | --              | n13 | Darfield-6897    | 0.540| 0.237  | 7.931           |
| n5  | LANDERS-849      | 0.438| 0.068  | --              | n14 | Darfield-6960    | 0.464| 0.234  | 9.352           |
| n6  | LANDERS-851      | 0.541| 0.040  | --              | n15 | Darfield-6966    | 0.468| 0.192  | 7.238           |
| n7  | ChiChi-1476      | 0.521| 0.158  | --              | n16 | Darfield-6969    | 0.649| 0.170  | 9.660           |
| n8  | ChiChi-1479      | 0.451| 0.105  | --              | n17 | Darfield-6975-63W| 0.417| 0.208  | 8.134           |
| n9  | El Mayor-8161    | 0.454| 0.406  | --              | n18 | El Mayor-8606    | 0.456| 0.281  | 6.524           |

3.2 Analysis of seismic response characteristics

Figure 2 shows the distribution of the interlayer displacement angle of the base isolation structure along the floor under two sets of earthquakes. It can be seen from the figure that under the long-term rare earthquakes of the two groups A and B, the interlayer displacement angle of the high-rise isolated structure is much smaller than the limit of 1/550=0.02 of the specification, indicating that the base isolation is used in the high-rise structure. The technique is feasible and can significantly reduce the deformation of the superstructure.
Figure 6 shows the average interlayer displacement angle of the base isolation structure and the joint vibration control structure. It can be seen from the figure that after the viscous damper is installed, the interlayer displacement angle of the combined vibration control structure is significantly smaller, and the seismic performance of the structure is improved.

3.3 Analysis of the effect of earthquake control

Figure 5 shows the distribution of the interlayer displacement angle along the floor of the combined seismic structure under the action of two groups of earthquakes. It can be seen from the figure that under the long-term rare earthquakes of the two groups A and B, the interlayer displacement angle of the combined vibration control structure is significantly smaller, and the seismic performance of the structure is improved.

Fig 2. Inter-storey drift angle of isolated structure

Fig 3. Inter-storey drift angle of combined control structure

Fig 4. Average Inter-storey drift angle of structure

FIG 5. Maximum displacement of structural isolation bearing under long period earthquake
Figure 8 shows the maximum displacement of the isolation bearing of the base isolation structure and the joint vibration control structure. It can be seen from the figure that the base isolation structure has excessive deformation under the action of multiple long-period earthquakes, which may cause the cracking failure of the isolation bearing and cause the structure to be overturned. After a large number of large-stroke viscous dampers are set, although the displacement of the seismic isolation bearing can be effectively reduced, there are still some limits exceeding the limit, indicating the use of viscous dampers to control the dynamic behavior of high-rise isolated structures under long-period earthquakes. The seismic effect has a great relationship with the characteristics of the input ground motion.

4. Conclusions
By studying the seismic response and the effect of earthquake control of high-rise base isolation structures and joint vibration-control structures under long-period earthquakes, the following conclusions can be drawn:

(1) Under the action of long-period earthquakes, the high-rise structure with base isolation and viscous dampers combined control strategy after earthquake can significantly reduce the displacement response of the structure, and greatly reduce the displacement of isolation bearing demand, but in some under earthquake action, there is still a isolation bearing displacement overrun, causing bearing cracking failure, may capsize the structure as a whole.

(2) Attaching a viscous damper can significantly reduce the acceleration response in the middle of the high-rise isolated structure, but it may slightly increase the acceleration response of the structural isolation layer and the top layer, which will have certain adverse effects on the structure.

(3) Lead-core rubber isolation bearing may have excessive deformation and tensile stress over-exposure under long-period earthquakes. The development of low yield, large deformation and tensile isolation bearings can be used as an effective way to solve the problems of the basic isolation technology in the application of high-rise structures.

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