Performance Based Design Method of Base Isolated Structure Using Cost-Benefit Criterion

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Abstract: In order to study the performance based design method of base isolated structure using cost-benefit criterion. Firstly, the life cycle cost which includes the initial cost, the rubber bearing cost, the viscous damper cost and the use and maintenance cost is analyzed. Secondly, the concept of cost-benefit ratio of base isolated structure is proposed. And then the performance based design of base isolated structure based on cost-benefit criterion is studied. The design parameters of base isolated structure are determined by the optimal cost-benefit ratio. Finally, through two particle model and probability density evolution method, we got the mean of peak value of story displacement of the isolation story under different damping ratio, period ratio and yield force ratio. The value of three parameters can be determined by the optimal cost-benefit ratio. This design method has guiding significance to the design of base isolated structure.
Keywords: base isolated structure; cost-benefit ratio; performance based design method; life cycle cost

The base isolation technology is an effective passive control technology. It can isolate seismic waves and ensure the safety of the superstructures of buildings. Compared with the reliability of the base isolated structure, the cost of isolation devices and the isolation effect under earthquakes are more important reasons for owners to choose this technology. As a result, the base isolation technology should meet the specific purpose of the structure and the specific performance requirements of owners. It also have to achieve the expected isolation effect and have reasonable economy.

As a basic principle of performance based seismic design method, the cost-benefit criterion reflects the idea of structural seismic design, which changes from focusing on structural safety to focusing on structural safety and economy together. However, in the structural passive control field, the use of cost-benefit criterion is relatively less. Dang [1] and Zhang [2] mainly focuses on the economic analysis of base isolated structure. Ang and Lee optimized the cost of reinforced concrete structure [3]. Sarma and Adeli optimized the life cycle cost of steel structure [4]. Liu analyzed the seismic fortification and earthquake vulnerability of high-rise base isolated buildings [5]. Yuan made a comparative analysis on the life cycle cost and insurance rate of the middle and low-rise base isolated buildings under different design schemes [6].

Based on the research at home and abroad, it is found that there is little research on the performance based seismic design of base isolated structure based on cost-benefit criterion. Therefore, this method needs more research. According to the structural characteristics of base isolated structure, the life cycle cost of base isolated structure is introduced.

In the weigh of between the investment and the isolation effect, the concept of cost-benefit ratio is introduced to analyze the cost and the benefit. In order to find out the optimal cost-benefit ratio. And then obtaining the design parameters of the base isolation control system. This method can be used to compare and analyze the economy of base isolated structure. The owner can choose the appropriate control strategy according to the actual situation, which widens the situation for the application and development of the base isolation technology.

1 Life Cycle Cost of Base Isolated Structure

1.1 Cost-benefit criteria

The basic idea of aseismic design based on cost-benefit criterion is: during the design working life of structure, when encountering different levels of earthquake, the structure should reach the determined performance level and fortification target. So it makes the life cycle cost minimum. According to the international standard "General Principles of Structural Reliability" [7], it is pointed out in the model of determining the target level of reliability: according to the economic view, the target level of reliability should depend on the balance between the failure consequence and the cost of safety measures. Therefore, the total life cycle cost C_T of the building is:

$$C_T = C_b + C_m + \Sigma P_f C_f \qquad (1)$$

in this formula, C_b is the cost of building construction, C_m is the expected cost of maintenance and demolition, C_f is the failure cost, and P_f is the failure probability of life cycle.

1.2 Composition of life cycle cost of base isolated structure

In the 1960s, the United States first proposed the concept of life cycle cost. It mainly studies the life cycle cost optimization of project construction. It puts forward the whole life cycle management concept from the cost angle. It should comprehensively consider the construction cost and select the optimal scheme of the life cycle cost.

In the study of the base isolated structure cost, the life cycle cost of this system is the combination of all costs which include scheme design, engineering development, production, use, maintenance and retirement of the isolation devices. These steps are in the expected life cycle of all the isolation devices in the isolation story. The life cycle cost of base isolated structure is the sum of initial investment and risk expectation.

According to the characteristics of the base isolated structure, the total cost W of the base isolated structure in the whole life cycle is divided into two parts: the first part is the initial cost C of the isolated structure; the second part is the expected value M of the use and maintenance cost. Therefore, the total cost W of the base isolated structure in the whole life cycle is:

$$W = C + M \qquad (2)$$

(1) Initial cost

The initial costs of the isolation system includes the design cost of isolation story and the cost of the isolation devices production. The design cost of the isolation story mainly includes the feasibility demonstration of the isolation scheme, calculation, design and related tests of the isolation structure. In the current social and technological level, this cost generally accounts for 10% of the whole life cycle cost. It can be considered as a fixed value. The design cost of the isolation story can be defined as C_0, which does not increase or decrease with the change of the isolation story.

The isolation story is generally composed of isolation bearings and dampers. The base isolation technology does not need external energy. As a result, the production cost of the whole life mainly depends on the cost of each product. The most widely used isolation devices are laminated rubber bearing and viscous damper. Typical laminated rubber bearing and viscous damper are shown in Figure 1 and Figure 2.

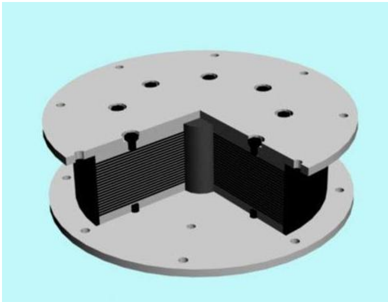

Figure 1 Laminated Rubber Bearing

Figure 2 Viscous Damper

(2) Laminated rubber bearing

Laminated rubber bearings are widely used in base isolated buildings because of their high safety, good durability and reasonable cost. According to the product information provided by Shanghai Jianke Engineering Consulting Co., Ltd., the price of laminated rubber bearing is proportional to its diameter. And the price of laminated rubber bearing does not change with its horizontal characteristics. Table 1 shows the prices of laminated rubber bearings with different diameters.

Table 1 Prices of laminated rubber bearings of different diameters

Diameter of bearings (mm)	200	300	400	500	600	700	800	900	1000	1100	1200	1300
Price (10, 000 Yuan)	0.1	0.2	0.3	0.4	0.6	0.8	1.0	1.5	2.0	3.0	4.0	5.0

In the design process, the weight of the superstructure determines the vertical load of the laminated rubber bearing. Therefore, the diameter and number of rubber bearings should be selected according to the design value of vertical load and the type of structure. The cost of available rubber bearings is C_1, and $C_1=n_1 \cdot P_d$. In this formula, where n_1 is the number of available laminated rubber bearings and P_d is the price of rubber bearings corresponding different diameters.

(3) Viscous damper

In order to prevent excessive displacement of laminated rubber bearing under rare earthquake, the isolation story will be overturned. In the design process of the isolation story, the damper is used to limit the displacement of the laminated rubber bearing and consume the seismic energy. Viscous damper is one of the most widely used dampers in the isolation story. Its cost is mainly determined by the maximum damping force and stroke, which shows a nonlinear increasing relationship. According to the product information provided by Shanghai Jianke Engineering Consulting Co., Ltd., the price of each tonnage of viscous damper is shown in Table 2. It can be seen that the cost of damper is C_2, and $C_2=n_2 \cdot P_t$. In this formula, where n_2 is the number of available dampers and P_t is the price of dampers corresponding different tonnage.

Table 2 Prices of viscous dampers of different tonnage

ton	5	10	15	20	25	30
Price (10, 000 Yuan)	2.0	4.0	6.0	10.0	15.0	20.0

1.3 Use & maintenance cost

The use and maintenance cost of base isolated structure is a complex problem. It is related to initial cost and economic conditions. When the initial cost is relatively large, with the high technology level, the expected cost value of maintenance is small.

The manufacturer is generally responsible for the maintenance and repair costs of viscous dampers. Therefore, in the using process, the cost is small. The expected value of the use and maintenance cost of the base isolated structure can be expected to be 5% of the initial cost without considering the cost of its scrapping treatment, namely:

$$M = 5\% \cdot C \quad (3)$$

Where, M is the expected value of use and maintenance cost; C is the initial cost of base isolated structure, $C=C_0+C_1+C_2$. Therefore, the life cycle cost of the base isolated structure W is:

$$W = C_0 + C_1 + C_2 + M \quad (4)$$

in this formula, C_0 is the design cost of base isolation system; C_1 is the total cost of laminated rubber bearings; C_2 is the total cost of dampers.

2 Analysis of The Cost-Benefit Ratio of Base Isolated Structure

2.1 The concept of cost-benefit ratio

In the analysis of cost-benefit ratio, effectiveness refers to the benefit in economic or social activities, which is called effect in a work or activity. It is also called efficiency in the military equipment, civil equipment or systems and organizations. Cost refers to the capital and cost invested, including the sum of a series of costs such as product or project research, feasibility demonstration, production, use, maintenance and scrapping. And this is called life cycle cost [1]. The cost-benefit ratio uses the ratio of effectiveness divided by life cycle cost for comparison. The larger of the ratio, the better of the scheme used. In addition, the model is constrained by both the lowest efficiency and the highest cost of the system.

2.2 Cost-benefit ratio analysis

The goal of cost-benefit ratio analysis is to minimize all costs including one-time input cost, use and maintenance cost on the premise of ensuring the owner's use effect requirements. The concept of cost-benefit ratio is introduced into the passive control technology of structure. The vibration control effect and the consumed cost of base isolated structure are analyzed. Under the condition of satisfying the performance level and fortification target set by the owner or the code, through the analysis of the cost-benefit ratio of base isolated structure, we can get a balance point between the effectiveness and the economy. The cost-benefit ratio V of base isolated structure is defined as:

$$V = \frac{E}{W} \quad (5)$$

Where, W is the life cost of the isolation devices. E is the effectiveness of the isolation story. The displacement of the isolation story under rare earthquake is taken as the evaluation index of the effectiveness of base isolated structure. Because of the displacement of the isolation story is too large, the isolation story will overturn. The displacement of the isolation story under rare earthquake is taken as the effectiveness index, which can evaluate the safety of the base isolated structure, so as to ensure the overall stability of the structure without failure.

3 Design Method of Base Isolated Structure Based on Cost-Benefit Criterion

According to the cost-benefit criterion, the structural design should in accordance with the structural function and the specific requirements of the owner. It also should use the available resources to seek a reasonable and safety design scheme. In order to make a balance between the safety and economy of the structure. As a result, the designer must minimize the total cost of the structure in the life cycle. Based on the characteristics of base isolated structure, the design method based on cost-benefit criterion is studied. It includes the following steps:

(1) In order to study the cost composition of the base isolated structure in the whole life cycle. We should classify and investigate the devices used in the isolation story and obtain the corresponding cost of the base isolated structure.

(2) For the actual base isolation engineering, because the vertical load of the structure has been determined, the number and the diameter of the rubber bearings can also be determined. So the investment cost of the isolation bearings is basically a fixed value. The main factor affecting the investment cost of the isolation story is the change of the isolation story dampers. The change of the damping ratio of the isolation story is taken as the influence factor. Considering the effect of the damping ratio of different isolation story on the cost-benefit ratio of base isolated structure.

(3) Based on the analysis of the cost-benefit ratio of base isolated structure, the relationship between the life cycle cost of base isolated structure and its isolation effect, damping ratio of the isolation story is found out, and the base isolated structure is designed according to the optimal cost-benefit ratio.

(4) Evaluate the isolation effect to see whether it meets the specific performance requirements. If it meets the requirements, we can design the isolation devices according to the optimal parameters. If it does not meet, we can adjust the cost-benefit ratio and select the largest cost-benefit ratio to design the base isolated structure until it meets the requirements.

By this design scheme, the base isolated structure can meeting the specific performance level, having the lowest cost and avoiding the waste of resources.

4 Engineering Practice

Taking a 12 story base isolated building as an example. The fortification intensity of the building area is 8 degrees, 0.3g in Jiangsu Province, China. The site soil category is III. We study the relationship between the change of damping ratio and the cost-benefit ratio of base isolated structure under rare earthquake. According to the vertical load and structure type of the superstructure, control the long-term surface pressure of each rubber bearing within 10MPa. It is selected 33 lead rubber bearings with the diameter of 600mm. And selected 25 natural rubber bearings of the diameter of 700mm and 2 natural rubber bearings of the diameter of 800mm on the top surface of the structural basement. Figure 3 is the isolation story arrangement.

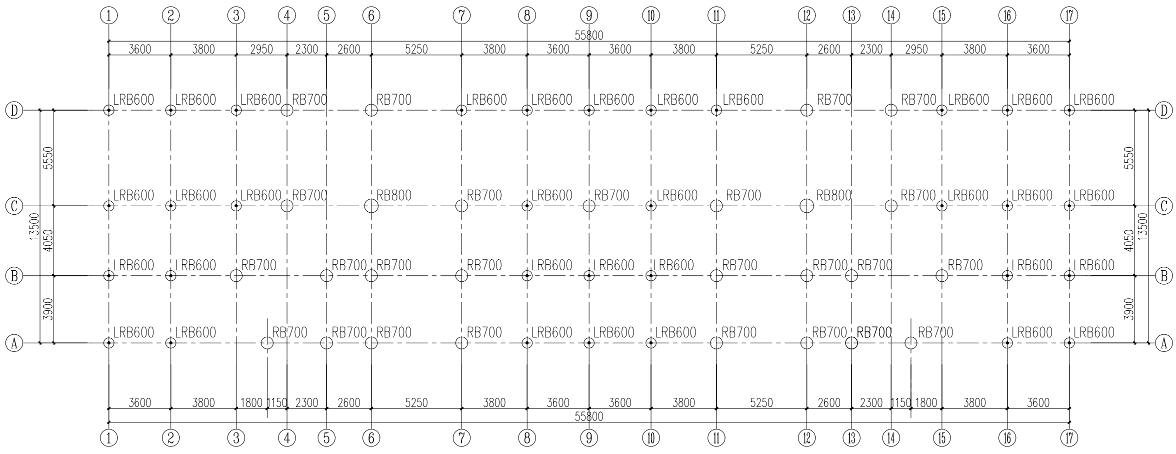

Figure 3 The rubber bearing layout of twelve-story base isolated structure

According to the data provided in Table 2, the isolation story is arranged with 10 ton viscous damper. And the specific performance parameters of rubber bearings and viscous dampers used in the project are given in Table 3 and table 4.

Table 3 The parameters of rubber bearings

Type	Area (cm^2)	Lead Diameter (mm)	Total Rubber Thickness (mm)	K_V (kN/mm)	K_L (kN/mm)	K_1 (kN/mm)	K_2 (kN/mm)	Q_d (kN)
LRB600	2714	120	110	2667	1833	13.182	1.014	90.2
RB700	3839	/	110	3632	1350	/	/	/
RB800	5014	/	160	3664	1210	/	/	/

Table 4 The parameters of viscous damper

Type	α	Maxim damping force (kN)	Damping coefficient (kN/(m/s)$^\alpha$)
Viscous Damper	0.4	1000	1000

Because of the load of superstructure is fixed, the quantity and diameter of isolation bearing have also determined by the upper load. The principle of arrangement is to put the lead rubber bearings around the story and the laminated rubber bearings in the middle. The total yield force of the lead rubber bearing is 3% of the total weight of the structure. Based on these principles, the number and location of laminated rubber bearings can be determined. Therefore, only changing the number of dampers can lead to the change of the damping ratio of the isolation story. The cost of laminated rubber bearings in the isolation story C_1 remains unchanged. But the cost of dampers in the isolation story C_2 changes. Table 5 gives the number of laminated rubber bearings and dampers corresponding to the damping ratio of different isolation story. Table 6 shows the cost of isolation story with different damping ratio.

Table 5 Damping ratio range of isolation story

The change of damping ratio of the isolation story	5%	10%	15%	20%	25%	30%
The number of laminate rubber bearings	60	60	60	60	60	60
The number of viscous damper	0	2	4	8	16	32

Table 6 Cost of isolation story with different damping ratio

Each Cost	5%	10%	15%	20%	25%	30%
Rubber bearings	41.8	41.8	41.8	41.8	41.8	41.8
Viscous Dampers	0.0	12.0	24.0	48.0	96.0	192
Research & Development	25.0	25.0	25.0	25.0	25.0	25.0
Use & main	2.39	2.69	3.29	4.49	6.89	11.69
Life Cycle Cost	75.19	81.49	94.09	119.29	169.69	270.49

The cost of laminated rubber bearings is constant. In a certain level of social technology, the cost of technical research and development is also fixed. Therefore, with the increase of the damping ratio of isolation story, the proportion of the cost of rubber bearing C_1 and the cost of technical research and development C_0 in the total life cycle cost is smaller and smaller, as shown in Figure 4 and Figure 6. The cost C_2 of viscous damper increases rapidly with the increase of damping ratio of isolation story, and the proportion of the viscous dampers cost in the whole life cycle becomes larger and larger, as shown in Figure 5. The cost M of use and maintenance increases linearly with the increase of isolation story damping ratio. As the cost M is relatively small, its proportion in the total life cycle cost increases slightly with the increase of damping ratio of the isolation story, as shown in Figure 7.

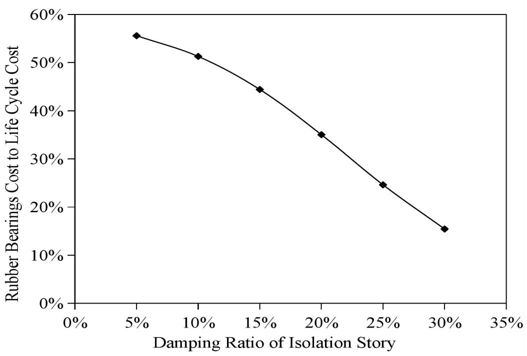

Figure 4 C_1 to Life Cycle Cost under Different Damping Ratio of Isolation Story

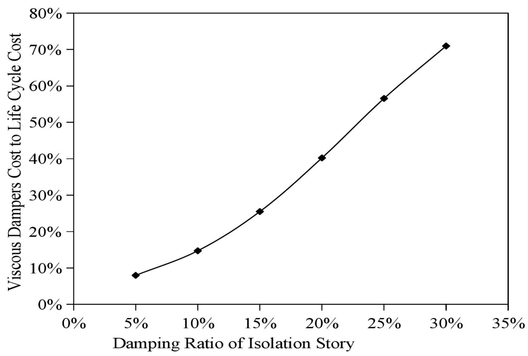

Figure 5 C_2 to Life Cycle Cost under Different Damping Ratio of Isolation Story

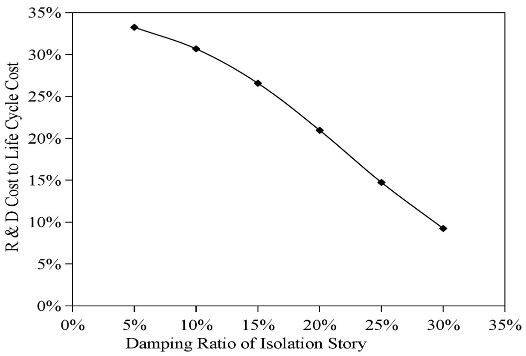

Figure 6 C_0 to Life Cycle Cost under Different Damping Ratio of Isolation Story

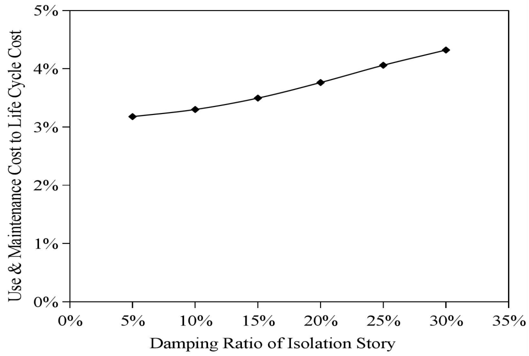

Figure 7 M to Life Cycle Cost under Different Damping Ratio of Isolation Story

Figure 8 shows the relationship between the different damping ratio of isolation story and the total life cycle cost of base isolated structure. It can be seen from the figure that with the increase of the damping ratio of the isolation story, the total life cycle cost increases non-linearly. When the damping ratio is bigger than 20%, the total life cycle cost increases rapidly with the increase of the damping ratio. Though increasing the damping ratio can control a certain amount of displacement and achieve a good isolation effect, the huge economic investment is unacceptable.

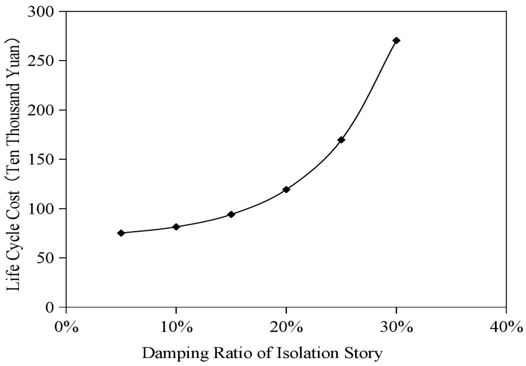

Figure 8 The W under different damping ratio of isolation story

In order to study the effect of different design parameters on the cost-benefit ratio of base isolated structure, the two particle model [8] is used to study the base isolated structure. The change rules of the cost-benefit ratio and damping ratio of isolation story under different period ratio and yield force ratio are analyzed. Based on the Probability Density Evolution Method (PDEM), the mean values of isolation story displacement are obtained. Figure 9 shows the isolation story displacement response under different damping ratio and period ratio.

Figure 10 shows the displacement control effect under different damping ratio and period ratio. The displacement of isolation story under rare earthquake is 150 mm. Under different design parameters, the efficiency $\boldsymbol{E}$ of the isolation story is: | (0.15-mean value of displacement) / 0.15|, as shown in Figure 10.

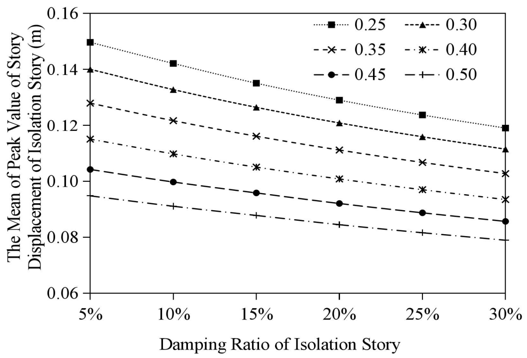

Figure 9 The mean of isolation story displacement under different damping and period ratio

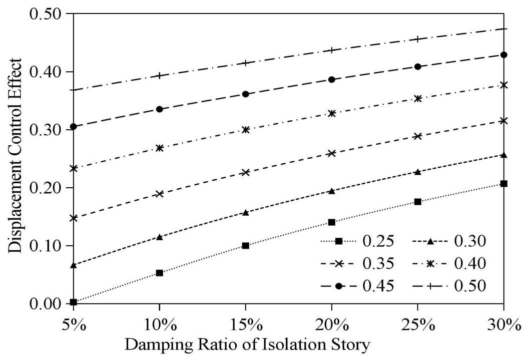

Figure 10 The displacement control effect under different damping ratio and period ratio

Figure 11 shows the displacement response of isolation story under different damping ratio and yield force ratio. Figure 12 shows the displacement control effect under different damping ratio and yield force ratio of isolation story. Obviously, with the increase of damping ratio and yield force ratio, the isolation story displacement reduce rapidly. The displacement control effect is better .

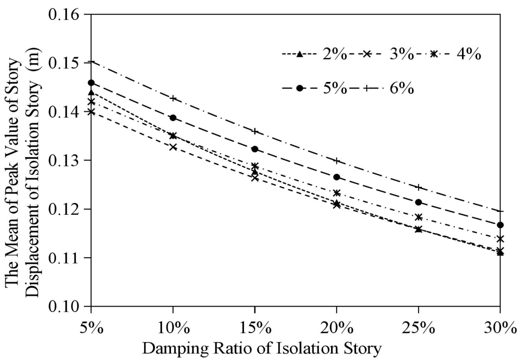

Figure 11 The Mean of isolation story displacement under different damping ratio and yield force ratio

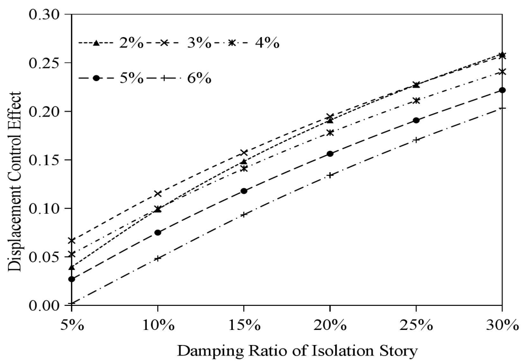

Figure 12 The displacement control effect under different damping ratio and yield force ratio

Figure 13 shows the cost-benefit ratio of isolated story under different damping ratio and period ratio. It can be seen from the figure that when the period ratio is bigger than 0.40, the cost-benefit ratio of base isolated structure decreases with the increase of the damping ratio. When the period ratio is smaller than 0.40, the optimal efficiency cost ratio is between 15% and 20%. Figure 14 cost-benefit ratio of base isolated structure under different damping ratio and yield force ratio. It can be seen from the figure that no matter what the yield weight ratio is, the base isolated structure has the optimal cost-benefit ratio when the damping ratio of the isolation story is between 15% and 20%.

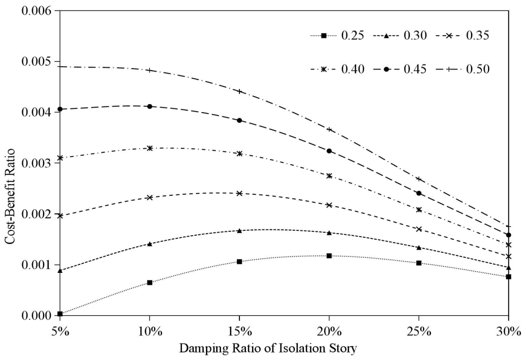

Fig.13 The cost-benefit ratio of isolation story under different damping ratio and period ratio

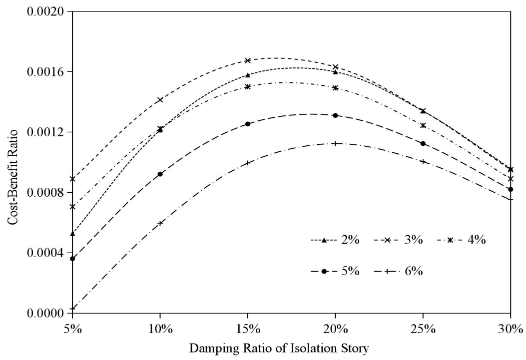

Fig.14 The cost-benefit ratio of isolation story under different damping ratio and yield force ratio

As a result, when the damping ratio of isolation story is between 15% and 20%, the displacement cost-benefit ratio of the isolation story is the highest. The number of laminated rubber bearings is 60. And the number of viscous dampers is 4-8. In this way, the structure can not only control its displacement under rare earthquake, but also make the economic investment in a reasonable range.

5 Conclusions

Based on the analysis of the interaction between the safety and the life cycle cost of base isolated structure. A new design method based on cost-benefit criterion is proposed. The effectiveness and feasibility of the method are verified by an actual base isolation project. It shows that the method has certain application value. The main conclusions are as follows:

(1) Based on the cost-benefit criterion, the composition of the life cycle cost of base isolated structure is studied. And the relationship between the cost of different devices and the life cycle cost of base isolated structure is studied. It provides a reference for the calculation of the life cycle cost of base isolated structure.

(2) The design method of base isolated structure based on cost-benefit criterion is put forward, and the specific design process is given. The displacement of isolation story under rare earthquake is taken as the isolation effect index. The relationship between different damping ratio, yield force ratio and period ratio with cost-benefit ratio of isolation story is also studied. The feasibility of the design method is verified by the actual base isolation engineering.

(3) With the increase of the damping ratio of the isolation story, the ratio of laminated rubber bearing cost to the life cycle cost decreases, but the damper cost increases. The research and development cost decrease with the increase of damping ratio. The use and maintenance cost increase with the increase of damping ratio. And the total life cycle cost increases with the increase of damping ratio. The design method of base isolation structure based on cost-benefit criterion provides an evaluation index for the effectiveness, economy and reliability of base isolated structure. It is a good significance for saving social resources and promoting base isolation technology.

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