Research on Three-Dimension Isolated System

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ABSTRACT :

In this paper, with a view to the limitation that the preset base isolation system can not decrease the vertical seismic reaction, a kind of vertical semi-active isolated device with disk spring was developed. The vertical semi-active isolated device is made up of oil cylinder within disk spring and electromagnetic valve that control the oil route between the oil cylinder and oil box, then achieve the vertical semi-active isolation, and put forward a semi-active control strategy suited to vertical semi-active isolated control. Combining vertical semi-active isolated device with horizontal isolated bearing can achieve three-dimension isolation. The control efficiency of three-dimension isolation system was validated through the shaking table tests and numerical simulation, this research help to reform the isolation technique in high intensity zone.

KEYWORDS: base-isolation， semi-active vertical isolation，three-dimension isolation，Shaking table test

1. Introduction

In recent 20 years, modern seismic isolation technology with good effects of decreasing vibration, safety, durability, economy, and applicability, has been widely used in civil engineering, which is rather mature, and has become an important structure control technology. Base-isolation building with Laminated Rubber Bearing has been widely used in our country, and mostly distributed in high intensity zone in China. Japan, America, New Zealand, France, Italy, and Chile have constructed a lot of isolated buildings and bridges. But for the limitation of common Rubber isolator’s behavior, common seismic isolation technology has insurmountable disadvantages.

Firstly, common seismic isolation technology can decrease buildings’ seismic responses, meanwhile, magnify displacement of isolation layer, especially in near-field earthquake with high velocity pulse. Some researches have made on the problem of too large displacement of isolation layer in some counties. considering that to reduce the displacement of the isolation layer only by increasing the passive damping is at the cost of increasing the deformation and acceleration of the uppersturcure, many scholars advocate employing semi-active device in isolation layer, to decrease displacement of isolation layer and make sure superstructure isolation effect.

Secondly, now applied base-isolation components can't effectively decrease vertical earthquake action, sometimes even result in disadvantage. Plenty of earthquake damages show that vertical earthquake effect is not slighting, vertical ground motions in near-field earthquake or close to earthquake fault, sometimes exceeds horizontal earthquake motion, also because of large vertical structural stiffness, its vertical natural period is close to predominant period of vertical seismic wave, so structural vertical vibration be obtained more attention, scholars in many countries more and more pay attention to the research of vertical seismic action. Now base-isolated technology mainly reduces horizontal vibration. But strong earthquake record of isolation buildings shows that vertical earthquake response almost has not decreased. After isolation system decrease horizontal earthquake motion, then vertical earthquake action is likely to main earthquake action and bring vertical damages, therefore the research on vertical earthquake action is necessary.

For vertical isolation problem of isolation buildings, some researches have been done. Researchers

suggest making use of vertical stiffness and damping of Rubber Isolator to decrease vertical earthquake response. Asano etc. studied isolation effect of structural vertical and rocking vibration of rubber isolator in Kobe earthquake. By analyzing actual earthquake response records of buildings, Lew and Hudson pointed out that vertical earthquake in high intensity cannot endanger isolated buildings. All above, their researches are valuable, but not complete. First, rubber isolator is designed for horizontal isolation, its vertical stiffness and damping dissatisfy vertical isolation request. Second, vertical earthquake response of isolated buildings increases vertical force of isolation bearing, increases instability of isolation layer, and cause large axial force of isolated buildings' columns, consequently axial compression ratio exceeds allowable value,which is potential factors resulting into damage. Muraji (Japanese Kobe University) put forward an isolated device, called vertical vibration absorb energy device, and made some experimental analysis and gained some progress,The University of Western Australia put forward an euler vertical isolation device.
In a word, to develop new isolation technology is very necessary. Combining active control with intelligent material to developing new type isolation device, the isolation technology will be expected to apply to High-rise Buildings, irregular and complex buildings, bridge and so on, to expand the isolation technology' efficiency and applicable scope. In order to realize multi-dimension isolation, vertical isolated device is still a problem to be solved. Moreover, to develop isolation device combining vertical isolation with horizontal isolation is an important problem.

2. Three-Dimension Isolation System

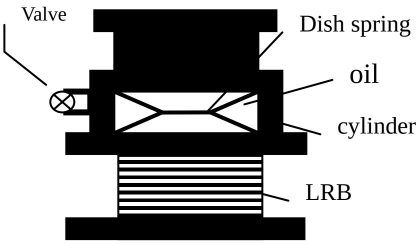

Figure 1 three dimension isolated device

Dish spring, with the merit of large stiffness, simple structure, easy collocation, and avoiding over loading, is widely used in industrial products. Because of deformation and loading capacity of single spring cannot fulfill application request, therefore disk spring can be collocated with congruence, involution form or both form. In addition, Friction among dish spring could bring damping, in order to improve vibration control efficiency; added damping devices may be attached. Thereby dish spring becomes a practical effective vertical isolation element suit to buildings. In normal service conditions, buildings should have enough large vertical stiffness, so place dish spring in airtight oil cylinder, which is full of oil. There is an open –close valve, when vertical isolation works, open valve, dish spring provide lesser and proper vertical stiffness, then an effective vertical semi-active isolation device is developed. In order to enhance damping value of vertical semi-active isolation device, large damping material may be set in oil cylinder. Properly combining vertical semi-active isolation device with Laminated Rubber Bearing, will develop a complex three-dimension isolation device: Both Laminated isolation Bearing (LRB) and vertical semi-active isolation device are in series, as shown in fig 1,three-dimention isolation device.
The vertical semi-active isolation device is made up of oil cylinder within dish spring and electromagnetic valve that control the oil route between the oil cylinder and oil box. Semi-active control strategy of vertical isolation device is, when without encountering earthquake or vertical acceleration response of isolation buildings doesn't exceed allowed value, electromagnetic valve is close, at this time vertical stiffness of vertical isolation device is strong; when encountering earthquake or vertical acceleration response of isolation buildings exceeds allowed value, electromagnetic valve will be open, at this time complex isolation device provides lesser vertical stiffness and definite vertical damping, then realizes vertical isolation, works with horizontal rubber bearing, consequently realizes three-dimension isolation.

3. Shaking Table Tests and Simulation Analysis of Three-Dimension Isolation System

3.1 Testing Steel Frame Model

Testing model is one-story, one-bay steel frame. Steel frame has different stiffness in two directions. Only input earthquake motion in lesser stiffness direction in testing. Horizontal first natural frequency of the model is 3.52Hz in lesser stiffness direction, vertical first natural frequency of model could be calculated, about 50.72Hz.

3.2 Design and development of Three-Dimension Isolated Device

A photo of three-dimension isolated is shown in Fig 2. Thereinto horizontal isolation device is Laminated Rubber Bearing without lead core, its equivalent horizontal stiffness is 0.121×106N/m, equivalent damping ratio is 0.05(the most displacement is 100％), thus horizontal fundamental frequency of the model is decreased to 1.51Hz， its vertical stiffness is about 2.27×107N/m by testing, vertical fundamental frequency of horizontal isolation model is about 20.5Hz; Thereinto vertical isolation device mainly make up of oil cylinder and inner dish spring.

Figure 2 three dimension isolated device

Considering testing model, the request of bearing capacity, size and stiffness, select series B, type 2 dish spring (according to dish spring GB/T1972-92), its specific sizes, parameters are shown in table 1

Table 1 dish spring parameters of vertical isolation device

Type	*D*	*d*	*δ*	*h*	*H*	*P*	*f*	*H-f*
						f=0.75 h		
						N		
2	112	57	4	3.2	7.2	17800	2.4	4.8

In order to decrease vertical stiffness of three-dimension isolation bearing, adopting the involution form. its elastic stiffness of single piece of this kind is about 8.338×106N/m，after involuting 50 pieces, stiffness is about 0.167×106N/m，therefore make vertical frequency of testing model decrease to about 1.77Hz. For the sake of gaining actual vertical stiffness of vertical isolation device, by pseudo-dynamic test of vertical isolation device, its initial vertical elastic stiffness is about 0.172×106N/m, when its displacement exceeds 4cm,its stiffness decrease to about 0.145×106N/m, but its decrease is very small.

3.3 Research of Three-Dimension Isolation Device in Shaking Table Testing

In order to study the control efficiency of three-dimension isolation system, 4 types of working conditions in tests as follows:
Complex isolation test: (a) vertical input merely, (b) horizontal input merely, (c) vertical and horizontal input (double directions input).
Mere horizontal isolation test: (a) vertical input merely, (b) horizontal input merely, (c) vertical and horizontal input.
No-control test: (a) vertical input merely, (b) horizontal input merely; (c) vertical and horizontal input.
Mere vertical isolation test: (a) vertical input merely.
Qian'an Wave is selected as input, which horizontal peak acceleration is 0.2g; which vertical peak acceleration is 0.15g. Testing model is shown in fig 3.

Figure 3 some photos of testing model system

3.4 Analysis of Testing Data

Table2 the natural frequency results of testing models

Type	No-control model	Mere vertical isolation model	Mere horizontal isolation model	Complex isolation model
Horizontal frequency(Hz)	3.52Hz		1.42Hz	0.68Hz
Vertical frequency(Hz)		1.51Hz	20.65Hz	1.56Hz

Table3 Acceleration Amplification Coefficients in several working conditions

working conditions	input conditions	peak acceleration Amplification Coefficient of isolation layer		peak acceleration Amplification Coefficient of isolation model	
		horizontal	vertical	horizontal	vertical
No-control	horizontal input			2.730	
	vertical input				7.844
	Vertical and horizontal input			2.698	8.155
Mere vertical isolation	vertical input		0.982		0.836
Mere horizontal isolation	horizontal input	0.576		0.442	
	vertical input		4.207		6.735
	Vertical and horizontal input	0.838	3.624	0.414	6.822
Complex isolation	horizontal input	0.402		0.383	
	vertical input		0.916		0.701
	Vertical and horizontal input	0.469	0.843	0.348	0.649

Testing data is analyzed in the following:
Under Qian'an Wave, horizontal acceleration of testing steel model is magnified by 2.7 times; vertical acceleration is magnified by 8 times.
Under Qian'an Wave, merely vertical isolation device in testing steel model, its vertical acceleration decreased to 0.836 times.
Under Qian'an Wave, merely horizontal isolation in testing steel model, its horizontal acceleration decreased a great extent (decreasing to 0.4 times peak acceleration of input horizontal earthquake wave), but its vertical acceleration is magnified a lot (magnifying to 7 times peak acceleration of input horizontal earthquake wave), so it is obvious that LRB could effectively isolate in horizontal direction, but vertical isolation is not effective.
Under Qian'an Wave, three-dimension isolation device in testing steel model, its horizontal acceleration and vertical acceleration decreased a great extent (horizontal acceleration decreases to 0.1~0.2 times, vertical acceleration decreased to 0.6~0.7 times), so it is obvious that three dimension isolation device could effectively isolate horizontal and vertical earthquake, and achieve three-dimension isolation efficiency.
The control efficiency of three-dimension isolation system is validated through analysis and comparison of shaking table testing results in different working conditions.

3.5 Numerical Simulation of Three-Dimension Isolation System

Aiming at shaking table test of three-dimension isolation device, adopting SAP2000 to numerical simulation and research, validity and efficiency of established finite element model was validated, moreover by numerical simulation, then to analyze the control efficiency of three-dimension isolation system under Elcentro wave and Parkfield wave inputted.

3.5.1 Simulation Model

According as specific parameters of steel model in shaking table test, its finite element model is established in SAP2000. Beams, columns, supports of steel model are simulated by beam cell; three-dimension isolation bearing is simulated by Link cell.

3.5.2 Validation of finite element model

In order to validate efficiency of finite element model established, inputting earthquake wave inputted in shaking table tests, then carry out time-history response analysis, and comparing with time-history that was gained from test, as shown in tables 4 & 5. Finite element model could preferably simulate actual testing conditions: natural frequency error is very small, the error of acceleration response and vertical displacement of isolation layer are within 20%, horizontal displacement error is a little large, about 30%, hysteretic curve of restoring force of isolation bearing denoted in equivalent stiffness and equivalent damping ratio is the main reasons, which cause error; In addition calculation results error of acceleration simulation under vertical isolation working conditions is large, because vertical inputs of shaking table inevitably appends a little horizontal inputs. Generally finite element model could preferably simulate actual testing structures; validity & efficiency of finite element model are validated.

Table 4 Natural frequency error of finite element model

Type	No-control model	Mere vertical isolation model	Mere horizontal isolation model	Complex isolation model
Horizon	5.1%		7%	11.8%
Vertical		13.9%	4.7%	10.3%

Table 5 Response error of finite element model (Qin an earthquake wave)

working conditions	input conditions	Peak displacement of isolation layer		Peak acceleration of isolation layer		Peak acceleration of isolation structure	
		horizontal	vertical	horizontal	vertical	horizontal	vertical
No-control	Horizon					2.5%	
	Vertical						19.4%
	Vertical and horizon					0.8%	21.1%
Mere vertical isolation	Vertical		18.2%		16.2%		25.2%
Mere horizontal isolation	Horizon	33.5%		12.5%		11.5%	
	Vertical		8.7%		7.4%		10.7%
	Vertical and horizon	20.4%	18.2%	29.3%	7.5%	26.1%	3.3%
Complex isolation	Horizon	33.9%		38.7%		13.6%	
	Vertical		21.3%		21.7%		5.2%
	Vertical and horizont	35.4%	13.9%	3.4%	21.6%	8.2%	1.0%

3.6 Analysis of earthquake Response

The control efficiency of complex three-dimension isolation system is validated through the shaking table tests. In order to further study the control efficiency of complex three-dimension isolation system, choosing two typical earthquake wave as input:1 Elcentro earthquake wave (IMPERIAL VALLEY EARTHQUAKE，MAY 18, 1940), its frequency components are rich; 2. Parkfield earthquake wave (PARKFIELD EARTHQUAKE，DECEMBER 20, 1994), it is dislocation earthquake wave. For the 3-dimension isolation working condition, the semi-active control working condition that is started by the vertical isolation device is simulated when the vertical acceleration at the top of the isolated structure exceeds 0.1g - in order to distinguish from the complex isolation working condition 1 (the semi-active control working condition started by the vertical isolation device, i.e. the electromagnetic valve would be open when the earthquake occurs), this working condition is called complex isolation working condition 2. When top floor vertical acceleration of isolated structure is less than 0.1g, electromagnetic valve of vertical isolated device is close, when exceed 0.1g, it is open. Simulation results are shown in tables 6&7.

Tabel6 comparison of Peak acceleration amplification coefficient of several working conditions （Elcentro earthquake wave）

Working condition	Peak acceleration amplification coefficient of isolation layer		Peak acceleration amplification coefficient of isolation structure	
	horizontal	vertical	horizontal	vertical
No-control			3.14	3.35
Horizontal isolation	1.83	5.60	2.13	4.1
Complex isolation 1	1.90	1.42	1.769	1.07
Complex isolation 2	1.91	1.43	1.74	1.13

Tabel7 comparison of Peak acceleration amplification coefficient of several working conditons （Parkfield earthquake wave）

Working condition	Peak acceleration amplification coefficient of isolation layer		Peak acceleration amplification coefficient of isolation structure	
	horizontal	vertical	horizontal	vertical
No-control			1.2	3.69
Horizontal isolation	0.481	4.81	0.486	3.09
Complex isolation 1	0.55	1.14	0.284	0.799
Complex isolation 2	0.548	1.164	0.276	1.06

Comparison and analysis of tables 6&7:
1.No-control: when inputting Elcentro earthquake wave, horizontal acceleration of testing steel model is magnified by 3.14 times; vertical acceleration is magnified by 3.55 times; when inputting Parkfield earthquake wave, horizontal acceleration of testing steel model was magnified by 1.2 times; vertical acceleration was magnified by 3.69 times;

2.Mere horizontal isolation: when inputting Elcentro earthquake wave, horizontal acceleration of testing steel model is magnified by 2.13 times; vertical acceleration was magnified by 4.1 times; Comparing with no-control test, its horizontal isolation behaved only in horizontal direction, but isolated efficiency was not obvious, Rich frequency components of horizontal earthquake wave was main reason. when inputting; when inputting Parkfield earthquake wave, horizontal acceleration of testing steel model decreased to 0.486 times; vertical acceleration was magnified by 3.09 times; Comparing with no-control, its horizontal isolation behaved only in horizontal direction, and isolated efficiency was obvious, Rich high frequency components of horizontal earthquake wave is main reason, which can't achieve isolation in vertical direction. Horizontal isolated bearing couldn't achieve vertical isolation.

3.Complex isolation 1: when inputting Elcentro earthquake wave, horizontal acceleration of testing steel model is magnified by 1.769 times; vertical acceleration was magnified by 1.07 times; when inputting Parkfield earthquake wave, horizontal acceleration of testing steel model decreased to 0.284 times; vertical acceleration decreased to 0.799 times than input;

4.Complex isolation 2: when inputting Elcentro earthquake wave, horizontal acceleration of testing steel model is magnified by 1.74 times; vertical acceleration was magnified by 1.13 times, when inputting Parkfield earthquake wave, horizontal acceleration of testing steel model decreased to 0.276 times; vertical acceleration was magnified by 1.06 times than input. Comparing with no-control, complex isolation behaved in two directions, but the efficiency of Elcentro earthquake wave input is not very obvious than Parkfield earthquake wave input, that related to different frequency components involved in each waves.

Comparison and analysis of different working conditions above, three-dimension isolation device is validated to isolate in two directions, achieving three-dimension isolated efficiency.

4 Conclusions

Three-dimension isolation device is put forward and studied in this paper, and testing model, three-dimension isolation device, its process of shaking table tests and testing results, are introduced. The control efficiency of three-dimension isolation system is validated through analyzing the shaking table tests results of several working conditions (No-control, Mere vertical isolation, Mere isolation, Complex isolation), it could decrease horizontal and vertical acceleration response of isolation structure effectively and achieve isolation.

In addition, finite element model of shaking table tests model system is established, validity of finite element model is validated, meanwhile, and the simulation analysis of control efficiency inputted two typical earthquake waves (Elcentro earthquake wave and Parkfield earthquake wave selected) is carried out, further validated three-dimension isolated efficiency of three-dimension isolation device.

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