Study of Base-Isolation Building System

G. W. Ni, Y. M. Zhang, D. L. Jiang, J. N. Chen, and B. Liu

***Abstract*—**In order to improve the effect of isolation structure, the principles and behaviours of the base-isolation system are studied, and the types and characteristics of the base-isolation are also discussed. Compared to the traditional aseismatic structures, the base isolation structures decrease the seismic response obviously: the total structural aseismatic value decreases to 1/4-1/32 and the seismic shear stress in the upper structure decreases to 1/14-1/23. In the huge seism, the structure can have an obvious aseismatic effect.

***Keywords*—**Base-isolation, earthquake wave, dynamic response.

I. Introduction

A new method of protecting buildings from earthquakes has recently emerged which is called base-isolation building systems that is fast gaining popularity. This method provides an alternative choice for earthquake protection of the building. The base principle behind the base-isolation system is to set a sufficiently reliable isolation layer between the building and base to control the motion movement transfer from the ground to the superstructure. This system can separate the superstructure and component from the earthquake ground motion or bearing motion, thus reducing the structural earthquake response.

II. Principle of Base-Isolation

The principle of base-isolation can be illustrated by the structural earthquake response spectrum [1]. The ordinary low-rising reinforced concrete building has stiffness and a short period, so it has a high acceleration and a low displacement response (point A in figure 1). However, if the structure has an extended period and same damping, the acceleration response will reduce greatly, the displacement response will increase accordingly (point B in figure 1). If the structural damping increases, the acceleration will reduce continually, and the displacement response will be controlled (point C in figure 1).

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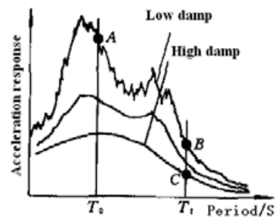
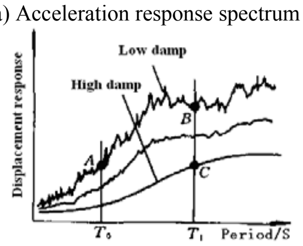
As stated previously, if the structural period is extended and the structure is confined to a certain range, the structural acceleration response will reduce greatly. In the meanwhile, the large structural displacement will be carried out by the isolation system between the structural bottom and the base. So during the earthquake, the structural deformation is extremely small, even like the slightly rigid translation. Therefore it provides a good protection from the earthquake. This is the main principle of the base-isolation of building system.



(a) Acceleration response spectrum



(b) Displacement response spectrum

Fig. 1 Methods of reducing seismic response of buildings

III. Analytical Method of Dynamic Response of Base-Isolation System

A. Assumptions of structural system

The analysis of the system (superstructure, isolation layer and so on) is based on the following assumptions:

1. Each layer has three freedoms relative to the center of mass: two horizontal freedoms and on rotational freedom.
2. All the isolation floors which are on the tops of the isolation bearings have infinite planar stiffness. And the isolation floor also has the same three freedoms which are relative to the masse center of isolation layer: two horizontal freedoms and on rotational freedom.
3. When the vibration mode of superstructure will be reduced, the number of vibration mode is the multiple of three and no less than three.
4. All the sub-structures are linked by the isolation layers.

The schematic of base-isolation building system model is shown in Figure 2. The global coordinate system is in the mass centre of isolation layer. The mass centre of all floors of superstructure is in the sub-coordinate system which is relative to the mass centre of the isolation layer.

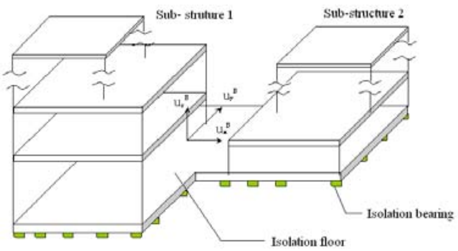


Fig. 2 Schematic of analysis model of isolation structure

B. Structural model and dynamic analysis

It is shown in Figure 2 that, in the isolation system, N_b sub-structures are linked by the isolation layer. With the structural mechanics method, the mass matrix and stiffness matrix and damping matrix of all sub-structures will be established. Then the mass matrix, stiffness matrix and damping matrix of the whole system will be formed. The dynamic equation of superstructure will be established as

$$M_s\ddot{u}_s + C_s\dot{u}_s + K_s u_s = -M_s R_s\left(\ddot{u}_b + \ddot{u}_g\right) \quad (1)$$

where, us is the displacement vector of all the structural layers relative to mass center of the isolation layer, u_b is the displacement vector of the isolation layer mass center, u_g is the earthquake displacement. The "·" of displacement vector express the time derivative. M_s, C_s, K_s, R_s are the mass matrix, damping matrix, stiffness matrix and earthquake influence matrix.

The shearing structure is taken as an example to illustrate how to establish the matrixes. The origin of global coordinate system is at the center of the mass center of isolation layer (Figure 3). In the ith structural layer, the mass and rotary inertia are mi and J_i, the coordinates of mass center are X_i, and Y_i, the layer stiffness are K_{ix}, K_{iy}, K_{ir}, the stiffness eccentricities (relative to layer mass center) are e_{ix} and e_{iy}, so the mass sub-matrix (M_i), and stiffness matrix ($K_{i,i}$) and earthquake influence sub-matrix (R_i) are as

$$M_i = \begin{bmatrix} m_i & & \\ & m_i & \\ & & J_i \end{bmatrix}, K_{i,i} = \begin{bmatrix} K_{ix} & 0 & -K_{ix}e_{iy} \\ 0 & K_{iy} & K_{iy}e_{ix} \\ -K_{ix}e_{iy} & K_{iy}e_{ix} & K_{ir} \end{bmatrix},$$

$$R_i = \begin{bmatrix} 1 & 0 & -Y_i \\ 0 & 1 & X_i \\ 0 & 0 & 1 \end{bmatrix} \quad (2)$$

The mass matrix, stiffness matrix and earthquake influence matrix are formed by the integration of all the mass matrix and stiffness matrix according to the layers and sub-structures. The structural dynamic equation of isolation layer is as follows:

$$M_b\ddot{u}_b + C_b\dot{u}_b + K_b u_b + f_N = -M_b\ddot{u}_g - R_s^T M_s\left\{\ddot{u}_s + R_s\left\{\ddot{u}_b + \ddot{u}_g\right\}\right\} \quad (3)$$

Where, M_b、C_b、K_b、R_b are the mass matrix, damping matrix, stiffness matrix and earthquake influence of the isolation layer separately, f_N is the nonlinear restoring force of all the isolation bearings, $f_N = \{f_{Nx} \quad f_{Ny} \quad f_{N_T}\}^T$.

$$f_{Nx} = \sum f_{xi}, \quad f_{Ny} = \sum f_{yi}, \quad f_{N_T} = -\sum f_{xi}y_i + \sum f_{yi}x_i \quad (4)$$

The freedom of the equation (3.4) will be reduced by the vibration mode. Superstructure displacement can be expressed by its vibration modes (in order to simplify the calculation, only the former N_e vibration modes are selected and used. The responding angular frequency is ω_i, i = 1, N_e) and generalized displacement Y_s:

$$u_s = \Phi_s Y_s, \quad \Phi_s = \left[\Phi_1 \quad \ldots \quad \Phi_i \quad \ldots \quad \Phi_{Ne}\right] \quad (5)$$

The dynamic equations of superstructure are combined with dynamic equation of isolation layer. So the whole dynamic equation of structure can be expressed as:

$$\begin{bmatrix} I & \Phi_s^T M_s R_s \\ R_s^T M_s \Phi_s & R_s^T M_s R_s + M_b \end{bmatrix}\begin{Bmatrix} \ddot{Y}_s \\ \ddot{u}_b \end{Bmatrix} + \begin{bmatrix} [2\xi_i\omega_i] & \\ & C_b \end{bmatrix}\begin{Bmatrix} \dot{Y}_s \\ \dot{u}_b \end{Bmatrix} + \begin{bmatrix} [\omega_i^2] & \\ & K_b \end{bmatrix}\begin{Bmatrix} Y_s \\ u_b \end{Bmatrix} + \begin{Bmatrix} 0 \\ f_N \end{Bmatrix} = -\begin{bmatrix} \Phi_s^T M_s R_s \\ R_s^T M_s R_s + M_b \end{bmatrix}\{\ddot{u}_g\} \quad (6)$$

Then, the dynamic equation of the whole structure will be established as

$$M\ddot{u}_t + C\dot{u}_t + Ku_t + f_t = P_t \quad (7)$$

The dynamic response under all kinds of dynamic loads can be obtained by employing the numerical method of integration to the equation (7).

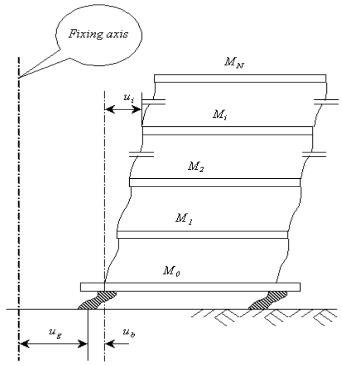


Fig. 3 Schematic of relative displacement of isolation structure

C. Numerical method of structural dynamic equation

In order to obtain the entire whole dynamic analysis of the nonlinear structural system, it is suitable to use the step by step integration method. The increment equation of the entire structural dynamic equation can be obtained as

$$M\Delta\ddot{u}_t + C\Delta\dot{u}_t + K\Delta u_t = \Delta P_t - \Delta f_t \tag{8}$$

In each step, if the right part of dynamic equation is taken as the disturbing load, the entire dynamic equation of the isolation structure is a practical linear equation group. So the Wilson-θ method and Newmark-β method can be used. The integration step of step by step integration method should be refined according to the variation of the isolation layer nonlinearity. And the Newmark-β integration method with a variable step can be applied.

During each suitable integration step, the nonlinear restoring force increment Δf_t will be calculated. In general, the increment is the function of the current displacement, velocity decrement and hysteretic displacement. Because of the nonlinearity, the Pseudo-force iteration method is employed for solution.

When the increment of velocity and displacement are calculated, the nonlinear hysteretic curve needs to be solved. So the nonlinear differential equation can be solved by the quadratic Runge-Kutta method.

The solving process is as:

1) Establishment of stiffness matrix K, mass matrix M and damping matrix C.

2) Selection of the suitable integration step.

In the sliding process of the sliding isolation bearing, when the velocity decreases, the phenomenon of minus stiffness will occur. And when the velocity increases, a huge stiffness will be led to. Under this circumstance, the selection of suitable integration step is important. And it has a significant influence on the accuracy of the calculation.

3) Calculation of stiffness matrix by the Newmark method.

4) Solution of the nonlinear restoring force increment by the Pseudo-force iteration method

① At the beginning of the iteration, the initial value of nonlinear restoring force increment will be set according to the experience.

② Calculation of the displacements, velocity and acceleration increment according to the entire system dynamic equation.

③According to the motion state and constitutive relationship of the isolation bearing, the nonlinear restoring force increment of isolation bearing will be calculated.

④ Calculation of the error of the nonlinear restoring force increment.

⑤ If the calculated error can not meet the requirement of calculating accuracy, return the (2) step.

⑥ If the error can meet the requirement of the calculating accuracy, the iteration process will finish.

5）Apply the Newmark method to solve the system motion, return to the (2) step and calculate with another time step.

According to the former analyzing principle, the Flow chart of dynamic response of horizontal base-isolated structure will be worked out on the basis of the related research achievements. The flow chart is shown in Figure 4.

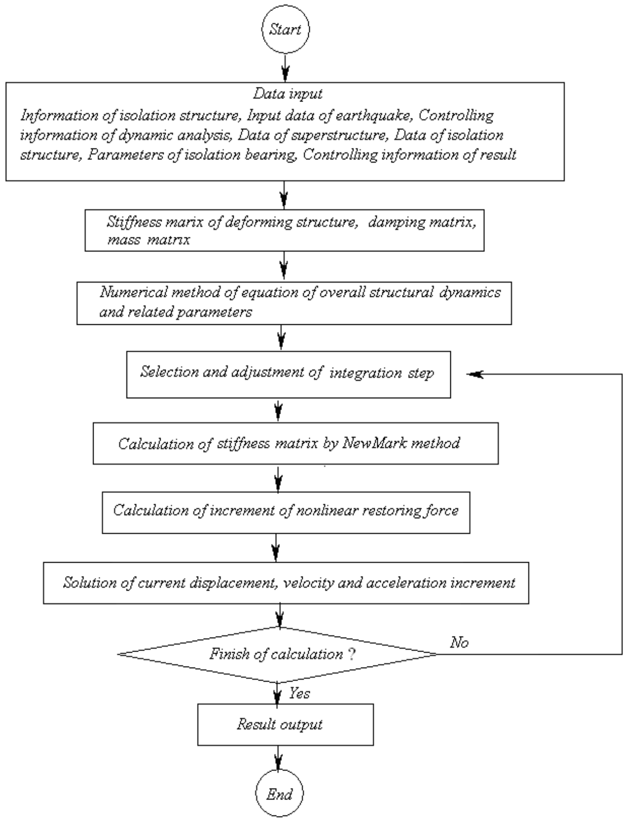


Fig. 4 Flow chart of dynamic response of horizontal base-isolated structure

IV. Analysis of Horizontal Base-Isolation

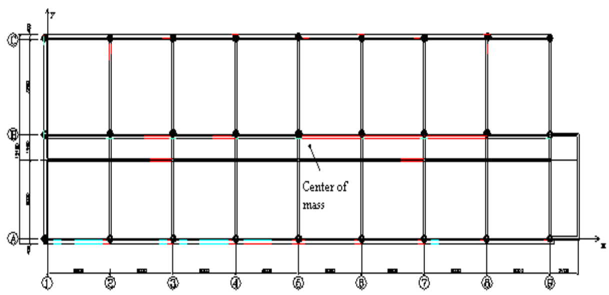


Fig. 5 Layout of floor plane and vibration isolation

The selected project is a six-storeyed residential building with reinforced concrete framework: rectangle plane, 3.0 m each storey height, 19.3 m structure height, 15.95 m structure width, and 1.21 ratio of height to width, 8 degree aseismatic intensity, Assessment of construction site. There are totally 27 rubber isolation bearings distributed under the ±0.000 floor. Among them, there are 10 GZY500V5A isolation bearings, 10 GZY600V5A isolation bearings and 7 GZY700V5A isolation bearings. The plane layout is shown in Figure 5. The mechanical property of lead rubber isolation bearing is shown in Table 1.

According to the requirement of earthquake wave, strong and moderate and small earthquakes are selected in this time history analysis. Three strong and small waves are selected which are 8l.1, 8l.2, 8l.3 and 8s.1, 8s.2, 8s.3. Among them, the third wave is the artificial wave, the others are the natural waves. The calculated result of the structure without isolation is the average of three waves. It is shown from the Table 2 that, the interlaminar shear ratio is 0.292, and the horizontal seismic reduction factor is 0.423. The interlaminar shear ratio is 0.273, and the vertical seismic reduction factor is 0.397.

The time history displacements of side-bearings and corner-bearings are shown in Table 3. And it can be obtained from Table 3 that, the adverse bearing in x direction is ①/C (GZY500V5A), the maximum displacement is 225.325mm, less than the horizontal displacement limitation (269.5mm), the adverse bearing in y direction is ①/C (GZY500V5A), and the maximum displacement is 235.6mm, less than the horizontal displacement limitation (269.5mm). So the layout of bearings can meet the requirement.

TABLE I
MECHANICAL PROPERTY OF LEAD RUBBER ISOLATION BEARING

Attribute / Model	Design bearing capacity (KN)	Horizontal deformation (50%)		Horizontal deformation (250%)		Total	Secondary shape factor
		Horizontal Stiffness (KN/mm)	Damping ratio (%)	Horizontal Stiffness (KN/mm)	Damping ratio (%)		
GZY500V5A	2800	2.75	27	1.37	13	10	5.30
GZY600V5A	4000	3.06	27	1.52	13	10	5.01
GZY700V5A	5600	2.78	23	1.57	9	7	5.00

TABLE II
RESULTS OF HISTORY ANALYSIS UNDER TREMOR

Layer Number		6	5	4	3	2	1
Average shear in x direction before isolation (KN)		1207.5	1921.8	2439.3	2884.8	3110.9	3420.0
Average shear in y direction before isolation (KN)		1131.8	1842.5	2442.6	2805.8	3212.3	3792.3
Shear in x direction after isolation (KN)	Using wave 8s.1	205.7	383.9	576.56	754.6	926.1	1089.2
	Using wave 8s.2	225.4	430.1	609.7	755.8	871.2	950.7
	Using wave 8s.3	157.9	325.2	493.9	653.7	812.6	960.3
	average	196.4	379.8	560.1	721.4	869.9	1000.1
Shear in x direction after isolation (KN)	Using wave 8s.1	202.6	386.1	580.5	759.9	928.7	1084.1
	Using wave 8s.2	250.6	456.5	613.9	748.4	852.1	974.9
	Using wave 8s.3	191.9	378.8	551.2	711.9	850.7	943.0
	average	215.1	407.1	581.9	740.1	877.1	1000.7
Interlaminar shear ratio (x direction)		0.163	0.198	0.230	0.250	0.280	0.292
Interlaminar shear ratio (y direction)		0.190	0.221	0.238	0.264	0.273	0.264

TABLE III
TIME HISTORY DISPLACEMENT OF SIDE-BEARINGS AND CORNER-BEARINGS

Displacement (m) \ Bearing number		Axis ①/C	Axis ⑨/C	Axis ①/A	Axis ⑨/A
x direction	Using wave 8l.1	230.942	229.535	229.557	228.008
	Using wave 8l.2	210.805	210.174	210.179	209.486
	Using wave 8l.3	234.228	233.526	233.532	232.762
	Average	225.325	224.411	224.43	223.42
y direction	Using wave 8l.1	234.5	226.0	234.5	226.0
	Using wave 8l.2	212.4	209.4	212.4	209.4
	Using wave 8l.3	259.8	250.5	259.8	250.5
	Average	235.6	228.6	235.6	228.6

V. RESULTS

Compared to the traditional seismic isolation system, the base-isolation system has an obviously lower horizontal seismic response. The value of structural horizontal seismic action reduces to 1/4-1/32, and the interlaminar shear of superstructure reduces to 1/14-1/23. The vibration mode of multilayer isolation structure is overall translation. After seismic isolation, the interlaminar displacement is small, and can be calculated as a single mass point system approximately.

Under the wind load and small earthquake, the isolation effect of the structure is not obvious. However, under the moderate and strong earthquake, the system has an obvious isolation effect.

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