Modelling and Dynamic Analysis of Earthquake Isolation Structures

Wei LIU *

Department of Architectural Engineering, Hefei University, Hefei 230022, China

Abstract — Isolation technology of buildings from ground to protect them from earthquakes have great advantages compared with traditional seismic design method and has developed rapidly and is used widely at present. Based on structural dynamics analysis, the isolation structure is classified as two type: foundation isolation and floor isolation. In this paper, dynamic analysis and time history analysis of the isolation structures is derived to describe the dynamics response of the engineering structures from earthquakes. The dynamic equation is deduced, including single and multi-degree of freedom isolation systems. The dynamics analysis model and vibrated structure equations of the isolated floor are deduced and we discuss the advantages and application range of the floor isolation system. Finally, the principle of time history analysis of the floor isolation system is introduced and the anti-seismic performance of the floor isolation system is described.

Keywords - Isolation Structure; Time History Analysis; Vibrated Equation; Foundation Isolation; Floor Isolation

I.INTRODUCTION

The isolation floor of the isolation structures have two type layout, including foundation isolation system and floor isolation system. The foundation isolation system is that the isolation structures is placed in between foundation upper surface and structures bottom floor. The floor isolation system is that the isolation structures is placed in between floor and another floor[1]. The isolation floor is placed in the structures to decrease horizontal stiffness of the structures and the natural vibration period is longer to the structures is more softer. The destroy degree of the earthquake is change smaller and the response from the earthquake is smaller.

II.THE FOUNDATION ISOLATION SYSTEM

A. Dynamic Analysis of Single Degree of Freedom Isolation System

For the foundation isolation structures, because that the structures stiffness is uniform above the isolation structures, the horizontal stiffness of the isolation floor is smaller than the horizontal stiffness of upper structures. When earthquake happen, the isolation floor have most horizontal displacement because of smaller horizontal stiffness and the structures above the isolation floor have smaller displacement because of bigger horizontal stiffness[2]. When the earthquake happen, the structures above the isolation floor have only horizontal rigid body displacement, and floor displacement is smaller. The whole structures is see as single degree of freedom isolation structure, and Fig.(1) show us the single degree of freedom foundation isolation system model below.

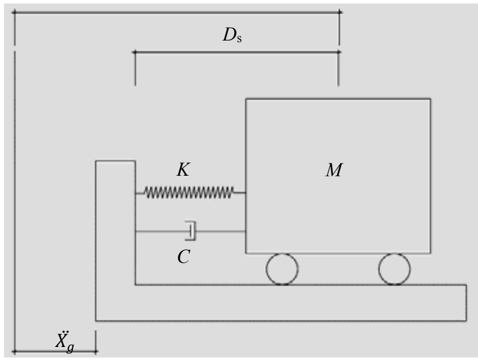

Fig.(1). Single degree of freedom of the foundation isolation

In Fig(1), $\ddot{X}_g$ is horizontal acceleration of the ground, D_s is displacement of upper structures relative to the isolation structures system, *M* is the mass of upper structures, *K* represent horizontal stiffness of the isolation structures system, *C* represent damping coefficient of the isolation structures system.

When earthquake wave spread to the engineering structures, the structures would appear acceleration response and the dynamics differential equation is shown by Eq.(1) below.

$$MX_s'' + CX_s' + KX_s = CX_g' + KX_g \tag{1}$$

Where, $\ddot{X}_s$ is acceleration of the upper structures, $\dot{X}_s$ is velocity of the upper structures, X_s is displacement of the

DOI 10.5013/IJSSST.a.17.47.22 ISSN: 1473-804x online, 1473-8031 print

upper structures. Assuming the natural frequency of the foundation isolation system is ω_n, damping ratio is ζ, the Eq.(1) is divided by mass matrix M, the Eq.(2) is gotten, and Eq.(2) is shown us below.

$$X_s'' + 2\zeta\omega_n X_s' + \omega_n^2 X_s = 2\zeta\omega_n X_g' + \omega_n^2 X_g \tag{2}$$

Where, $\omega_n = \sqrt{\frac{K}{M}}$, $\zeta = \frac{C}{2M\omega_n}$.

The acceleration of the structures is obtained by transfer function conception, and represent ratio of the isolation structures acceleration and ground acceleration. The ratio also represent isolation effect of the ground acceleration from the isolation structures. Assuming H is transfer function, attenuation ratio is R_a, Eigen frequency of the ground is ω, the acceleration of the ground is $\ddot{X}_g = e^{iwt}$, the acceleration of the structures with isolation structures is $\ddot{X}_s = He^{iwt}$. The transfer function is shown us by Eq.(3) below.

$$H = \frac{X_s''}{X_g''} = \sqrt{\frac{1+(2\zeta\omega/\omega_n)^2}{\left[1-(\omega/\omega_n)^2\right]^2 + (2\zeta\omega/\omega_n)^2}} \tag{3}$$

Acceleration attenuation ratio is shown us by Eq.(4) below.

$$R_a = \left|\frac{X_s''}{X_g''}\right| \tag{4}$$

The earthquake response is affected by the ground acceleration and the stiffness and damping of the isolation structures system. It meet the standard and safety requirements by controlling the maximum acceleration of the isolation structures system.

B. Multi-Degree of Freedom Foundation Isolation System

In practical engineering, the structures with the foundation isolation is mostly high and soft high-rise structures , and the high-rise structures have smaller story stiffness and have mostly shear deformation. Those structures is simplified as muti-degree of freedom system to be analysis. Because that the vertical stiffness of the isolation system is more than the horizontal stiffness of the isolation system, it is assumed that the structures have only the horizontal motion and ignoring the vertical motion. Fig.(2) show us calculation model of the isolation system below.

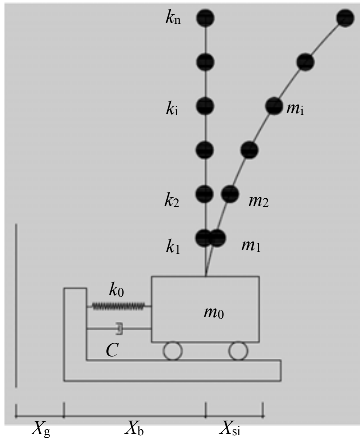

Fig.(2). Muti-degree freedom model of the foundation isolation system

In the Fig.(2), mi is the mass of every floor, ki is story horizontal stiffness, k0 is the horizontal stiffness of the isolation structures, C is the damping of the isolation floor.

The Fig.(2) show us story shear model of the foundation isolation system. Every story is basic element and dead load and live load are concentrated on a single mass to form the story shear model. The story shear model have some hypothesis below.

(1) the plane stiffness of floor is infinite.

(2) the horizontal members stiffness is infinite and can not appear vertical shear deformation.

(3) the vertical members can not appear axial deformation with horizontal loading.

(4) the story stiffness is only affected by the vertical member stiffness.

From the Fig.(2), the earthquake response of the story i is shown us by Eq.(5) below.

$$X_s = X_g + X_b + X_{si} \tag{5}$$

Base on D Alembert principle, the motion equation of the isolation system is shown us by Eq.(6) below.

$$m_0\left(X_b'' + X_g''\right) + \sum_{i=1}^{n} m_i\left(X_g'' + X_b'' + X_{si}''\right) + CX_b' + KX_b = 0 \tag{6}$$

The motion equation of the upper structures is shown us by Eq.(7) below.

$$[M]\{X_g''\}+[C]\{X_g'\}+[K]\{X_g\}=-\{X_g''+X_b''\}[M]\{1\} \quad (7)$$

Where $\ddot{X}_g$ is the acceleration of ground with earthquake, $\dot{X}_g$ is the velocity of the ground with earthquake and X_g is displacement of the ground with earthquake. $\ddot{X}_{si}$ the horizontal acceleration of the I story relative to base story of the engineering structures, $\dot{X}_{si}$ is the velocity of the I story relative to base story of the engineering structures, X_{si} is the displacement of the I story relative to base story of the engineering structures.

[M] is mass matrix and is shown us by Eq.(8) below. [K] is stiffness matrix and is shown us by Eq.(9) below. [C] is damping matrix and is shown us by Eq.(10) below[3].

$$[M]=\begin{bmatrix} m_1 & & & & \\ & \ddots & & & \\ & & m_2 & & \\ & & & \ddots & \\ & & & & m_3 \end{bmatrix} \quad (8)$$

$$[K]=\begin{bmatrix} k_1 & -k_1 & & & \\ \cdots & \cdots & \cdots & & \\ & -k_1 & k_i+k_{i+1} & -k_i & \\ & \cdots & \cdots & \cdots & \\ & & & -k_{n-1} & k_n \end{bmatrix} \quad (9)$$

$$[C]=\alpha[M]+\beta[K] \quad (10)$$

The constant α and β are gotten by Eq.(11) and Eq.(12) below.

$$\alpha=2\omega_i\omega_j\frac{\zeta_j\omega_i-\zeta_i\omega_j}{\omega_i^2-\omega_j^2} \quad (11)$$

$$\beta=\frac{\zeta_j\omega_i-\zeta_j\omega_j}{\omega_i^2-\omega_j^2} \quad (12)$$

Where ζ_i and ω_i are damping ratio and natural vibration frequency of the *i* mode, ζ_j and ω_j are damping ratio and natural vibration frequency of the *j* mode.

III. THE STORY ISOLATION SYSTEM

The story isolation system is that the isolation structures is placed the top of column above the foundation to decrease the earthquake response. The story isolation system is simple and economy to apply in reinforcement and reconstruction.

A. Advantage and Application Range of The Story Isolation System

Compared with the foundation isolation system, the story isolation system have many advantages below[4].

(1) when the story isolation system is applied, the displacement space can not be obligated for the story isolation system. The aseismic joint would be placed in the periphery of the upper building from the code and the aseismic joint width is more than 1.2 times of the maximum horizontal displacement of the isolation bearing with the rarely occurred earthquake. The horizontal isolated seam is placed between the upper structures and the ground.

(2) when the story isolation system is applied, the structures is more economy. When the foundation isolation system is applied, the thickness of 140mm floor is set above the isolation system and the stiffness and bearing capacity of the isolation system is more high to self-weight of the structures is very great. While the story isolation system don't need the floor, the self-weight of the structures is very light. Base on above content, the one floor cost is save by the story isolation system and the cost of the isolation bearing is decrease.

(3) the story isolation can decrease possibility of the structures overturning. The capacity of the isolation bearing is not good and the tensile stress of the isolation bearing is zero from the code. Because that the isolation story is higher position, the anti-overturning moment is more than overturning moment and the anti-overturning is increased.

(4) the construction is convenient. The soft pipe is applied in piping of the isolation structures and the soft pipe is constructed on the ground. While the structures is broken above the foundation to difficultly construct.

The story isolation system is applied in the following engineering structures[5][6].

(1) the engineering structures near sea and the engineering structures avoiding rust.

(2) for existing structures needing story adding, because that height and weight of the existing structures is increase, the existing structures can not meet demand of code and the story isolation system is applied in story adding to meet

DOI 10.5013/IJSSST.a.17.47.22 ISSN: 1473-804x online, 1473-8031 print

demand of bearing capacity and anti-seismic capacity.

(3) for important engineering structures, the story isolation system is applied to don't break the use of the engineering structures and the story isolation system is safety and practical.

(4) for the engineering structures with frame and tower, if the frame is bottom of the engineering structures, the story isolation system is placed on bottom of the structures.

B. Dynamics Analysis Model of The Story Isolation Structures

At present, the dynamic analysis model of the isolation structures have following models in design of the story isolation structures.

(1) the two mass model. The two mass model is that the structures above the isolation story is simplified as one mass and the structures below the isolation story is simplified as another mass. The two mass model is simple and is every easy to analysis influencing parameter of the story isolation structures.

(2) the three mass model. The three mass model is that the structures above the isolation story, the isolation story and the structures below the isolation story are simplified as one mass respectively.

(3) the muti-mass model. The muti-mass model is that the every floor of the structures is simplified as one mass, not including the isolation story. The muti-mass model can describe the dynamic response of the structures truly and is widely applied in the time history analysis.

C. The Vibrated Equation of The Story Isolation Structures

When analyzing the story isolation structures, many hypothesis are simplified following.

(1) the plane stiffness of the floor of the structures is infinite and the out-plane stiffness of the floor of the structures is infinitesimal.

(2) the mass of the floor is concentrated in every floor, when vibrating analysis.

(3) when the horizontal load is acting on the structures, the vertical members of structures ignore axial defomation.

(4) when the earthquake happening, the upper structures have only horizontal movement and the total horizontal displacement of the structures is appear in the story isolation system.

(5) the equivalent damping and stiffness of the isolation structures is approximatively equal to damping and stiffness of the story isolation device.

(6) the horizontal stiffness of isolation story is very small, while the horizontal stiffness of structures above isolation story is every large.

(7) when the structures is vibrating, the upper structures and bottom structures are in elastic station.

Because that the isolation story is placed in the structures, the stiffness and the damping of the isolation story is very different with upper structures and bottom structures. The structures above the isolation story system is similar to structures above the foundation isolation structures, while the structures below the isolation structures system is bore with upper structures and isolation story system.

The dynamic equation of the upper structures is Eq.(13) below.

$$\begin{aligned}&\left[M^{\mathrm{u}}\right]\left\{\mu_{\mathrm{u}}''\right\}+\left[C^{\mathrm{u}}\right]\left\{\mu_{\mathrm{u}}'\right\}+\left[K^{\mathrm{u}}\right]\left\{\mu_{\mathrm{u}}\right\}=\\&\qquad-\left[M^{\mathrm{u}}\right]\{I\}\left\{\mu_{\mathrm{b}}+\{R\}\left[\left\{\mu_{\mathrm{d}}''\right\}''+\left\{I_1\right\}\mu''g\right]\right\}\end{aligned}\tag{13}$$

The dynamic equation of the isolation story is Eq.(14) below.

$$\begin{aligned}&M_{\mathrm{b}}\mu_{\mathrm{b}}''+c_1\mu_{\mathrm{b}}'+k_1\mu_{\mathrm{b}}=\\&\quad-\{I\}^{\mathrm{T}}\left[M^{\mathrm{s}}\right]\left\{\{I\}\left[\mu_{\mathrm{b}}+\{R\}\left(\left\{\mu_{\mathrm{u}}''\right\}+\left\{I_1\right\}\mu_{\mathrm{g}}''\right)\right]+\mu_{\mathrm{s}}''\right\}\\&\quad-m_{\mathrm{b}}\{R\}\left(\left\{\mu_{\mathrm{u}}''\right\}+\left\{I_1\right\}\mu_{\mathrm{g}}''\right)-F_{\mathrm{b}}\end{aligned}\tag{14}$$

The dynamic equation of the bottom structures is Eq.(15) below.

$$\begin{aligned}&\left[M^{\mathrm{u}}\right]\left\{\mu_{\mathrm{u}}''\right\}+\left[C^{\mathrm{u}}\right]\left\{\mu_{\mathrm{u}}'\right\}+\left[K^{\mathrm{u}}\right]\left\{\mu_{\mathrm{u}}\right\}=-\left[M^{\mathrm{u}}\right]\{I\}\mu_{\mathrm{g}}''-\{R\}^{\mathrm{T}}\\&\left\{\left(\{I\}^{\mathrm{T}}M^{\mathrm{s}}\{I\}+m_{\mathrm{b}}\right)\left[\mu_{\mathrm{b}}+\{R\}\left(\left\{\mu_{\mathrm{u}}''\right\}+\left\{I_1\right\}\mu_{\mathrm{g}}''\right)+\{I\}^{\mathrm{T}}M^{\mathrm{s}}\left\{\mu_{\mathrm{s}}''\right\}\right]\right\}\end{aligned}\tag{15}$$

$$\left[M^{\mathrm{s}}\right]=\begin{bmatrix}m_{\mathrm{i+1}}&&&&\\&m_{\mathrm{i+2}}&&&\\&&\ddots&&\\&&&\ddots&\\&&&&m_{\mathrm{i+n}}\end{bmatrix}\tag{16}$$

$$[M^{u}]=\begin{bmatrix} m_1 & & & & \\ & m_2 & & & \\ & & \ddots & & \\ & & & \ddots & \\ & & & & m_n \end{bmatrix} \quad (17)$$

$$[K]=\begin{bmatrix} k_1 & -k_1 & & & \\ -k_1 & k_1+k_2 & -k_2 & & \\ & -k_2 & k_2+k_3 & -k_3 & \\ & & & \ddots & k_n \\ & & & -k_n & k_n \end{bmatrix} \quad (18)$$

$$[C]=\begin{bmatrix} c_1 & -c_1 & & & \\ -c_1 & c_1+c_2 & -c_2 & & \\ & -c_2 & c_2+c_3 & -c_3 & \\ & & & \ddots & c_n \\ & & & -c_n & c_n \end{bmatrix} \quad (19)$$

$$[R]=\{0 \quad 0 \quad \cdots \quad 1\} \quad (20)$$

Where M^{s} is the mass matrix of the upper structures, M^{u} is the mass matrix of the bottom structures. m_i is mass of every floor, K^{s} is the stiffness matrix of the upper structures, K^{u} is the stiffness of matrix of the bottom structures, k_i is stiffness of every floor, K_i is additional stiffness of the isolation story, C_i is additional damping coefficient of the isolation story. C^{s} is damping matrix of the upper structures, C^{u} is damping matrix of the bottom structures. C is damping matrix of orthogonal mode.

m_b is mass of the isolation story, $\{\ddot{\mu}_g\}$ represent movement acceleration of the ground, $\{\ddot{\mu}_s\}$ represent acceleration of the upper structures relative to the isolation story, $\{\dot{\mu}_s\}$ represent velocity of the upper structures relative to the isolation story, $\{\mu_s\}$ represent displacement of the upper structures relative to the isolation story. $\{\ddot{\mu}_u\}$ represent acceleration of the bottom structures relative to the ground, $\{\dot{\mu}_s\}$ represent velocity of the bottom structures relative to the ground, $\{\mu_u\}$ represent displacement of the bottom structures relative to the ground. $\{\ddot{\mu}_b\}$ represent acceleration of the isolation story relative to the story below the isolation story, $\{\dot{\mu}_b\}$ represent velocity of the isolation story relative to the story below the isolation story, $\{\mu_b\}$ represent displacement of the isolation story relative to the story below the isolation story.

F_b is the horizontal recovery force of the isolation device, including elastic-plastic recovery force and viscous damping force.

The dynamic equation of the total structures is shown us by Eq.(21) below.

$$[M^*]\{U^{*''}\}+[C^*]\{U^{*'}\}+[K^*]\{U^*\}+\{F\}=-[M^*]\{I^*\}\mu_g'' \quad (21)$$

Where, is $[M^*]$ is generalized mass matrix, $[C^*]$ is generalized damping matrix, $[K^*]$ is generalized stiffness matrix, $\{\ddot{U}^*\}$ is generalized acceleration matrix, $\{\dot{U}^*\}$ generalized velocity matrix, $\{U^*\}$ is generalized displacement matrix, $\{I^*\}$ is unit matrix, $\{F\}$ is load matrix.

IV. TIME HISTORY ANALYSIS OF THE ISOLATION STORY STRUCTURES

The time history analysis is that the differential equation is established with time and the dynamic response is gotten by integral form [7]. Whatever single degree of freedom system or multi-degree of freedom system, the dynamic equation of the structures is function with acceleration of the ground. The dynamic equation of the structures is not described only by time parameter, and the recovery force curve is also nonlinear, so the time history analysis is used now.

When time history analyzing, the acceleration curve is selected reasonably according to seismic grouping and site category and the earthquake response is simulated by integral form. The time history analysis is three types [8], including linear time history analysis, model analysis and nonlinear time history analysis.

V. CONCLUSIONS

In this paper, the two type isolation system are introduced including the foundation isolation system and the story isolation system. The single degree of freedom model and multi-degree of freedom model are proposed for the foundation isolation system and the vibrated differential equation are deduced to get acceleration, velocity and displacement.

The range and hypothesis of the story isolation system are introduced and the calculation model of the story isolation system are proposed. The time history analysis of the structures is introduced simply and the dynamic equation of the structures is deduced in the paper.

ACKNOWLEDGEMENTS

This work was supported by the Natural Science Foundation of the Anhui Education Institution of China (Grant

No. KJ2014A217) and Key projects of Anhui Province University outstanding youth talent support program (Grant No. gxyqZD2016273) and Major projects of research and Development Fund of Hefei University (Grant No. 16ZR02ZDA).

REFERENCE

[1] Architecture Institute of Japan, The Design of The Isolation Structures [M], Earthquake Press, 2006,pp.10-13.
[2] Niu Lijun, Seismic Research on Rubber Base Isolated Structures[D], Taiyuan University of Technology,2005,pp.30-35
[3] Zhang Ting, Study on Seismic Performance for Story Isolation Structures and Analysis of The Sensitivity for Isolaiton Bearing[D], Xian University of Technology,2010, pp.50-51
[4] Qi Ai, Lin Yuanteng, Zheng Guochen, Research on Working Mechanism of Story Isolation Structure, Earthquake Engineering and Vibration, 2006,vol. 26(4), pp.239-243
[5] Qi Ai, Zheng Guochen, Shaking Table Tests on Story-Isolation Structures Considering Parameter Optimization, Journal of Building Structures, 2009.vol. 30(2).pp.9-10
[6] Ran lipu, Analysis on Seismic Behavior of Tall Building with Podium Structures Under Story Isolation[D], Southwest Jiaotong University, 2008, pp.50-56
[7] Peng Junsheng, Luo Yongkun, Structures Dynamics[M], People's Communications Press, 2007, pp.43-46