OPTIMAL DESIGN AND CONTROL MECHANISM STUDY ON STORY ISOLATION SYSTEM

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ABSTRACT :

The story isolation system is a newly proposed isolation system, in which the flexible laminated rubber bearings are inserted between a floor and columns to reduce structural responses to earthquakes. In this paper, a story isolation system is modeled by a simple two degree of freedom model for theoretical study on the control mechanism of a story isolation system. A procedure to optimally design the isolator parameters of a story isolation system is put forward, based on the minimum base shear variance. The control mechanism of the story isolation system is systematically investigated for various location of isolation layer. Results demonstrate that the working mechanism of the story isolation system is changed from tuning frequency, isolation and energy dissipation to base isolation when the isolation layer is moved from roof to the bottom of the structure, corresponding to three zones: base isolation zone, mid-story isolation zone and tuning frequency zone. There exist an optimal damping level for the isolation layer in the tuning frequency zone and the base isolation zone. However, a higher damping level of the isolation layer results in a better performance in the mid-story isolation zone.

KEYWORDS: story isolation system, tuning frequency, energy dissipation, parameter optimization

1. INTRODUCTION

Seismic base isolation (Skinner et al.1993; Naeim and Kelly 1999) is a technique that mitigates the effects of an earthquake by essentially isolating the structure and its contents from potentially dangerous ground motion, especially in the frequency range where the building is most affected. Since the mature design theory is developed and the effectiveness of seismic isolation has been proved during the 1994 Northridge earthquake in USA and 1995 Kobe earthquake in Japan, the applications of seismic isolation systems to enhance the earthquake-resistant capability of buildings have become more and more extensive around the whole world (Zhou 1999).

The story isolation is a new development of isolation technique, in which the flexible laminated rubber bearings are inserted between a floor and columns to reduce the structural responses to earthquake excitations. As the location of the isolation layer has been lifted upon the ground, the story isolation system can prevent the rubber bearings of the isolated structure built near sea from being corrupted by the seawater and has no necessity to set enough separated space between the basement and surrounding soil for the large drift of the isolation layer, which must be considered for base isolation buildings according to the earthquake-resistant code in China. Furthermore, the story isolation system has provided a new way for seismic retrofitting of existing structures.

The effectiveness of the story isolation system has been investigated by many researchers using numerical finite element analysis (e.g. Xu et al. 2004; Shi et al. 2005). Qi (2004) summarized the state-of-the-art of the story isolation system about its applicable range, advantages, applications in pratical engineering, and some problems to be investigated. However, there are very few studies regarding the control mechanism of the story isolation system so far. In this paper, a story isolation system is modeled by a simple two degree of freedom model for theoretical study. A procedure to optimally design the isolator parameters of a story isolation system is put forward based on the minimum base shear variance. The control mechanism of the story isolation system is systematically investigated for various locations of isolation layer.

2. DYNAMIC ANALYSIS OF STORY ISOLATION SYSTEM

2.1. Two-DOF model for story isolation system

For simplicity, a simple 2-DOF model is developed to account for the working mechanism of a story isolation system, as shown in Fig.1. The motion of the superstructure is assumed to be a rigid-body translation due to the flexibility of the isolation layer, and the structure under the isolation layer is simplified to a single-DOF whose nature frequency of vibration is equal to the firs order mode of the original substructure.

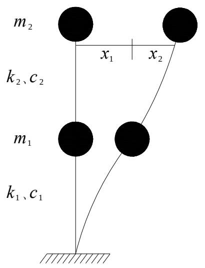


Fig. 1 Two-DOF model for story isolation system

Assumed that both the structure and the isolation layer are elastic, the equation of motion of the a two-DOF story isolation system can be expressed in the following form

$$\begin{cases} m_1\ddot{x}_1 + c_1\dot{x}_1 - c_2\dot{x}_2 + k_1x_1 - k_2x_2 = -m_1\ddot{x}_g \\ m_2\left(\ddot{x}_1 + \ddot{x}_2\right) + c_2\dot{x}_2 + k_2x_2 = -m_2\ddot{x}_g \end{cases} \tag{2.1}$$

in which, m_1、m_2 are the equivalent mass of substructure and the total mass of superstructure, respectively; k_1、k_2 are the equivalent stiffness of substructure and the lateral stiffness of isolation layer; c_1、c_2 are the equivalent damper of substructure and the damper of isolation layer; x_1、x_2 are the drift of the sub-DOF and super-DOF respectively; $\ddot{x}_g$ is the ground acceleration.

For the convenience of expression, the damping ratios of substructures can be defined as

$$\begin{cases} \zeta_1^2 = c_1 / 2\sqrt{k_1 m_1} \\ \zeta_2^2 = c_2 / 2\sqrt{k_2 m_2} \end{cases} \tag{2.2}$$

The natural frequencies of substructures are given by

$$\begin{cases} \omega_1^2 = k_1 / m_1 \\ \omega_2^2 = k_2 / m_2 \end{cases} \tag{2.3}$$

Here the mass ratio of the superstructure to the substructure is defined by

$$\mu = m_2 / m_1 \tag{2.4}$$

Similarly, the frequency ratio of the superstructure to the substructure can be written as

$$f = \omega_2 / \omega_1 \tag{2.5}$$

2.2 Dynamic behavior of story isolation system

Neglecting damping in Eqn. (2.1), the eigen equation of a story isolation system is given by

$$\begin{vmatrix} k_1 - m_1\Omega^2 & -k_2 \\ -m_2\Omega^2 & k_2 - m_2\Omega^2 \end{vmatrix} = 0 \tag{2.6}$$

where Ω is the nature frequency vector of the story isolation system. Substituting Eqn. (2.3)-(2.5) into Eqn. (2.6) and solving it gives

$$\Omega_{1,2}{}^2 = \left\{ \frac{1}{2}\left(1+f^2+\mu f^2\right) \mp \frac{1}{2}\left[1+2\left(\mu-1\right)f^2+\left(\mu+1\right)^2 f^4\right]^{\frac{1}{2}} \right\} \omega_1{}^2 \tag{2.7}$$

Let

$$\alpha_n = \Omega_n{}^2 / \omega_2{}^2 = \frac{\Omega_n{}^2}{f^2 \omega_1{}^2} \qquad n = 1,2 \tag{2.8}$$

The vibration mode vectors of story isolation system can be expressed in the following form

$$\left\{\phi^n\right\} = \left\{ \begin{matrix} 1 \\ 1-\alpha_n \end{matrix} \right\} \tag{2.9}$$

where the first vibration mode is the isolation mode, and the second mode is the structural mode, behaving as the vibration of substructure. Then, the modal mass participation ratio can be expressed as

$$\gamma_n = \frac{\left(\sum_{i=1}^{2} m_i \phi_i^n\right)^2}{(m_1+m_2)\sum_{i=1}^{2} m_i \phi_i^{n2}} = \frac{\left[u+\left(1-\alpha_n\right)\right]^2}{\left(1+u\right)\left[u+\left(1-\alpha_n\right)^2\right]} \tag{2.10}$$

which indicates the contribution of the first two modes on the seismic responses of a story isolation structure. In Eqn. (2.10), the modal mass participation ratio is only related with the mass ratio μ and the frequency ratio f .

3. PARAMETERS OPTIMIZATION OF STORY ISOLATION SYSTEM

Base shear is very important in earthquake resistant design of building structures. As for story isolation system, changing the stiffness and damping of isolators will shift the dynamic characteristic of the system and the distribution of the story shear in the system. In this paper, a procedure to optimally design the isolator parameters of the story isolation system is put forward based on the minimum base shear variance criterion, which can give consideration to performances of both the superstructure and the substructure.
The base shear of a two-DOF system is given by

$$F = \sum_{i=1}^{2} m_i \ddot{y}_i \tag{3.1}$$

where $\ddot{y}_1$、$\ddot{y}_2$ are the absolute accelerations of the substructure and the superstructure, respectively. Assumed that earthquake excitation to be a stationary stochastic process with zero mean, then the acceleration responses

$\ddot{y}_1$ and $\ddot{y}_2$ can also be considered as two statistically correlated stationary processes with zero mean. According to superposition principle of a stationary stochastic process, the first moment and the second moment of base shear are

$$< F >=< m_1\ddot{y}_1 > + < m_2\ddot{y}_2 >= 0 \quad (3.2\text{-a})$$

$$< F^2 >= m_1^2 < \ddot{y}_1^2 > + m_2^2 < \ddot{y}_2^2 > + 2m_1m_2 < \ddot{y}_1\ddot{y}_2 > \quad (3.2\text{-b})$$

where $<\cdot>$ represents a mean value of a variable. Let $S_{\ddot{x}_g}(\omega)$ represent the power spectral density function of seismic excitation and $H_{\ddot{y}_i}(\omega)$ represent the transfer function of the absolute acceleration response $\ddot{y}_i$, then the mean square value of the acceleration response and the mean value of product $\ddot{y}_1\ddot{y}_2$ can be evaluated as follows by stochastic vibration method

$$< \ddot{y}_i^2 >= \int_{-\infty}^{\infty} S_{\ddot{y}_i}(\omega) = \int_{-\infty}^{+\infty} S_{\ddot{x}_g}(\omega)\left|H_{\ddot{y}_i}(\omega)\right|^2 \mathrm{d}\omega \quad (3.3\text{-a})$$

$$< \ddot{y}_1\ddot{y}_2 >= \int_{-\infty}^{\infty} S_{\ddot{y}_1\ddot{y}_2}(\omega) = \int_{-\infty}^{+\infty} H_{\ddot{y}_1}(\omega)S_{\ddot{x}_g}(\omega)H^*_{\ddot{y}_2}(\omega)\mathrm{d}\omega \quad (3.3\text{-b})$$

In which, $S_{\ddot{y}_i}(\omega)$ is the power spectral density function of the acceleration response, $S_{\ddot{y}_1\ddot{y}_2}(\omega)$ is the cross-spectral density function, $S_{\ddot{y}_1\ddot{y}_2}(-\omega)$ and $S_{\ddot{y}_1\ddot{y}_2}(\omega)$ are a couple of complex conjugation functions.
With Laplace Transformation of Eqn. (2.1), the transfer function of the absolute acceleration response $\ddot{y}_i$ is given by

$$\begin{cases} H_{\ddot{y}_1}(\omega) = \Delta_1 / \Delta \\ H_{\ddot{y}_2}(\omega) = \Delta_2 / \Delta \end{cases} \quad (3.4)$$

where

$$\Delta_1 = \omega_1^2\omega_2^2 - (\omega_1^2 + 4\zeta_1\zeta_2\omega_1\omega_2)\omega^2 + \mathrm{i}(2\zeta_1\omega_1\omega_2^2\omega + 2\zeta_2\omega_1^2\omega_2\omega - 2\zeta_1\omega_1\omega^3)$$

$$\Delta_2 = \omega_1^2\omega_2^2 - 4\zeta_1\zeta_2\omega_1\omega_2\omega^2 + \mathrm{i}(2\zeta_1\omega_1\omega_2^2\omega + 2\zeta_2\omega_1^2\omega_2\omega)$$

$$\Delta = \omega^4 + \omega_1^2\omega_2^2 - [\omega_1^2 + (1+\mu)\omega_2^2 + 4\zeta_1\zeta_2\omega_1\omega_2]\omega^2 + \mathrm{i}2[\zeta_1\omega_1\omega_2^2\omega + \zeta_2\omega_1^2\omega_2\omega - \zeta_1\omega_1\omega^3 - (1+\mu)\zeta_2\omega_2\omega^3]$$

Defining the power spectral density function of the base shear for a two-DOF story isolation system as following

$$S_F(\omega) = S_{\ddot{x}_g}(\omega)m_1^2\left\{\left|H_{\ddot{y}_1}(\omega)\right|^2 + \mu^2\left|H_{\ddot{y}_2}(\omega)\right|^2 + 2\mu\,\mathrm{Re}[H_{\ddot{y}_1}(\omega)H^*_{\ddot{y}_2}(\omega)]\right\} \quad (3.5)$$

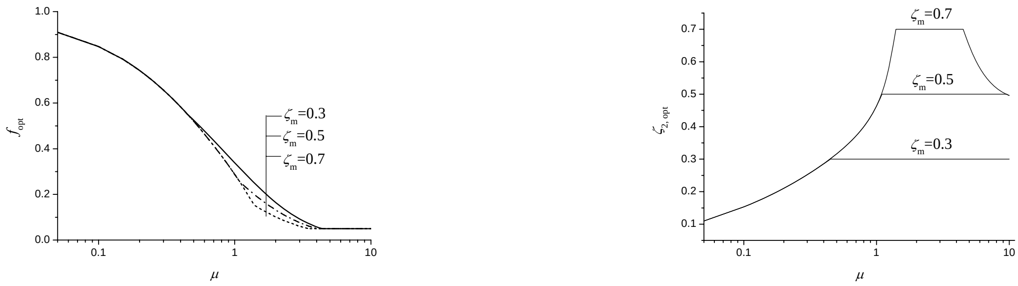
where, $\mathrm{Re}(\cdot)$ is the real part operation. The base shear variance is given by

$$\sigma_F^2 =< F^2 >= \int_{-\infty}^{+\infty} S_F(\omega)\mathrm{d}\omega \quad (3.6)$$

In order to get the minimal base shear of the story isolation system, the optimal isolator parameters such as frequency ratio f and isolator damping ratio ζ_2, can be solved by a nonlinear mathematical programming method

$$\begin{aligned} &\min_{f,\zeta_2} \quad \sigma_F^2 \\ &\text{s.t.:} \quad 0 \le \zeta_2 \le \zeta_{\mathrm{m}} \\ &\qquad\quad f_{\mathrm{l}} < f < f_{\mathrm{u}} \end{aligned} \tag{3.7}$$

In the above optimization process, supposing that the damping ratio of the substructure is 0.05 and the ground excitation is white noise. f_{l}, f_{u} are the lower limit and the upper limit of the frequency ratio, respectively. Here, the lower limit f_{l} can be assumed as 0.05 to avoid excessive drift of the isolation layer, and the upper limit f_{u} can be valued as 1 since the optimal frequency ratio of story isolation system is lower than 1 as usual. ζ_{m} is the upper damping ratio limit of the isolation layer in practical engineering.



(a) Optimal frequency ratio vs. mass ratio (b) Optimal damping ratio vs. mass ratio

Fig.2 Optimal parameter curves of story isolation system

Fig.2 shows the optimal isolator parameters for various ζ_{m}. It can be observed from Fig.2 (a) that as the mass ratio increases, the optimal value of frequency ratio is reduced rapidly. There exist two obvious inflexion points in each optimal frequency ratio curve for different upper bound of damping ratio, dividing the curve into three zones: base isolation zone, mid-story isolation zone and tuning frequency zone. The three zones can also be found in Fig.2 (b), whose control mechanism is quite different and will be investigated in the next section. In Fig 2(b), the optimal damping ratio of the isolation layer increases with the mass ratio before it reaches the upper damping limit, and then decrease for a larger mass ratio, regardless of the upper damping ratio limit.

4. CONTROL MECHANISIM OF STORY ISOLATION SYSTEM

As a rule, the main goal in use of base isolation in structures is to shift their natural period far from the frequency range where the energy content of the earthquake excitation is dominant. However, the control mechanism of the story isolation system is varied with the isolation level moved from roof to the bottom of the structure. In this section, a systematic investigation to the control mechanism is carried out combining the above optimization results and the base shear power spectrum of the system. Here ζ_{m} is assumed to be 0.5.

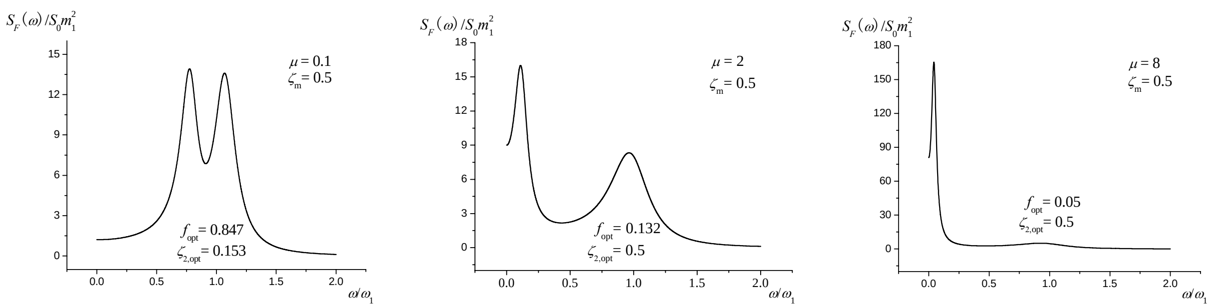
(1) When the mass ratio $\mu < 1$, the isolation layer is located at the upper portion of the structure. An optimal damping level exists for the isolation layer and two peaks are close to each other in the corresponding base shear power spectrum, as shown in Fig.3 (a). The control mechanism in this case is basically tuning frequency。

(2) When $1 \le \mu \le 4$, the isolation layer is located in the middle of the structure, in which case the optimum damping ratio in the isolation layer reaches its upper bound. Meanwhile, the peak base shear power spectrum appeared in the lower frequency region is much higher than the other one, and the frequency distance between both peaks is widened as compared with case 1, as shown in Fig.3 (b). This mass ratio zone can be defined as mid-story isolation zone, whose seismic reduction mechanism is a combination of both isolation and energy dissipation.

(3) The mass ratio $\mu > 4$ corresponds to the case that the isolation layer is located at the lower half of the structure. In this case, the optimal frequency ratio reaches its lower limit. That means the natural period of the structure in this case should be prolonged as possible as the isolator drift restriction is met. The optimal damping ratio of the isolation layer is converged to 0.5 with the increasing mass ratio, which is identical to that of the base isolation system (Ding, 1988). The story isolation system with $\mu > 4$ can be defined as base isolation zone because of their similar control mechanisms, and the base shear power spectrum of this story isolation system has only one obvious peak during its frequency region, as shown in Fig.3 (c).

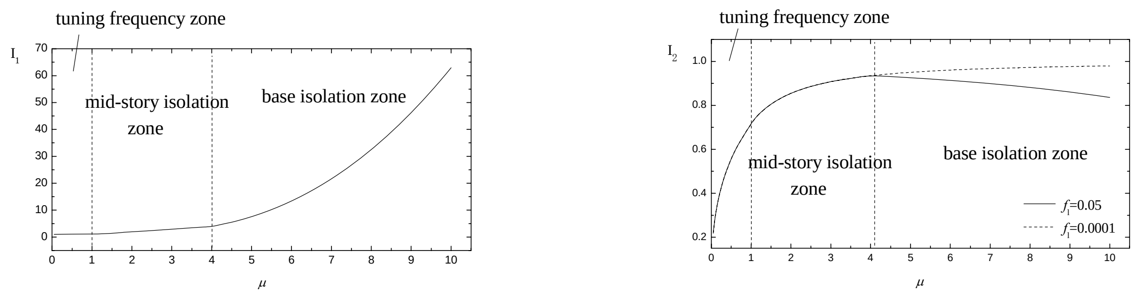
For convenience, the first two peak ratio of the base shear power spectrum is defined as I_1 and the frequency distance between both peaks is defined as I_2. Fig.4 shows the relationship of these two indices with the mass ratio. It is observed that the peak ratio I_1 is nearly kept constant of 1 in the tuning frequency zone and then ascends parabolically with the mass ratio. Meanwhile, the index I_2 is widened and converged to 1 for a small enough f_l (e.g. f_l=0.0001). As stated before, to limit the isolator drift and to avoid the extreme amplification of the acceleration response of the substructure, the value of f_l is selected to be 0.05 as a rule. Under this frequency ratio limit, the index I_2 descends slightly with increasing mass ratio when $\mu > 4$.

Substituting the optimized results of Eqn. (3.7) into Eqn. (2.10), the comparison of the first two modal mass participation factors with different mass ratio is graphically depicted in Fig. 5. The ratio of the first two modal mass participation factors γ_1/γ_2 rises linearly with mass ratio. In the tuning frequency zone whose mass ratio is relatively low, the first two modal mass participation factors are close to each other. As the location of the isolation layer moves down, the first modal mass participation factor increases whereas the second modal mass participation factor decreases. In the mid-story isolation zone, the ratio γ_1/γ_2 is ranged from 1.5 to 4. For the mass ratio $\mu > 4$, the first order modal mass participation factor of the isolation system is more than 80%, the structural response is dominantly contributed by the isolation mode and the earthquake energy is isolated from the sub-structure.



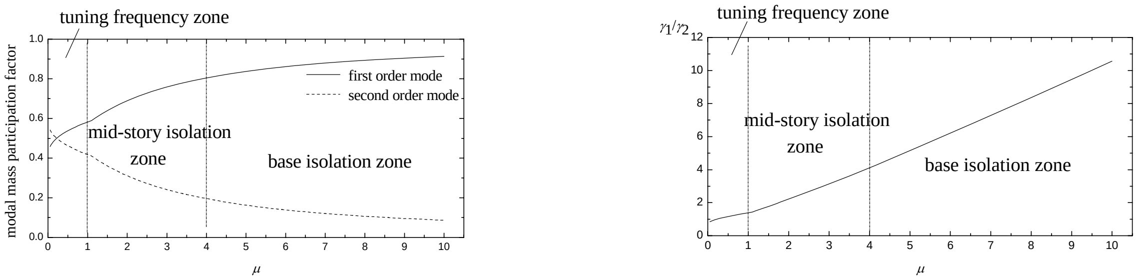
(a) $\mu = 0.1$ (b) $\mu = 2$ (c) $\mu = 8$

Fig.3 The power spectral density function of base shear for optimal isolator parameters



(a) wave peaks ratio I_1 (b) frequency distance between wave peaks I_2

Fig.4 Relationship between frequency spectrum characteristics of base shear and mass ratio



(a) first two modal mass participation factors (b) ratio of the mass participation factors

Fig.5 Relations between modal mass participation factor and mass ratio

5. CONCLUSION

In recent years, the story isolation system has been used more and more widely in the world for its great advantage compared to base isolation system. However, there are very few studies regarding the control mechanism of the story isolation system. In this paper, the minimum base shear criterion is proposed to optimally design the isolator parameters of the story isolation systems with different mass ratios, which can give consideration to the performances of both the superstructure and substructure. A systematic investigation to the control mechanism of story isolation system is carried out, which is significant to guild the application of the story isolation system in practical engineering to a certain extent. Results show that the control mechanism of the story isolation system is changed from tuning frequency, isolation and energy dissipation to base isolation when the isolation layer is moved from roof to the bottom of the structure, while the ratio of the first two modal mass participation factors is quite different. There exists an optimal damping ratio of the isolation layer in the tuning frequency zone and the base isolation zone, however in the mid-story isolation zone whose control mechanism is isolation and energy dissipation, the higher damping level results in a better control performance.

REFERENCES

Skinner, R. I., Robinson, W. H., and McVerry, G.H. (1993). An introduction to seismic isolation, Wiley, Chichester, England.

Naeim, F., and Kelly, J.M. (1999). Design of seismic isolated structures: From theory to practice, Wiley, Chichester, England.

Zhou, F. L. (1999). Progress of application and development in base isolation and passive energy dissipation for civil and industrial structure in P. R. China. *Proc. of the international post-SMiRT conference seminar*, Cheju, Korea, 31-40.

Xu, Z. G., Hu, M. Y. and Zhou, F. L. (2004). *Discussion on mid-story isolation of building. Earthquake Resistant Engineering and Retrofitting* **5**, 23-28. (in Chinese)

Shi, W. X., Sun, H. S. and Li, Z. G. (2005). High-position seismic isolation of press center at Shanghai international circuit. *Journal of Tongji University (Natural Science)* **33:12**, 1576-1580. (in Chinese)

Qi, A. (2004). State-of –the-art of story isolation system. *Earthquake Engineering and Engineering Vibration* **24:6**, 114-120. (in Chinese)

Ding, W. J. (1988). Vibration reduction theory, Tsinghua University Press, Beijing, China. (in Chinese)