# Responses of an Isolation System with Distinct Multiple Frequencies

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ABSTRACT

Base isolation systems are generally designed with a single natural frequency. A major concern for these isolation systems is that, if the dominant frequency of a future earthquake is equal or close to the system's natural frequency, the ground motion will be greatly amplified because of resonance, and the superstructure would suffer severe damages. This paper presents an isolation system designed with two distinct frequencies. Its responses to different ground motions, including a harmonic motion, show that no excessive amplification will occur. Adoption of this isolation system would greatly enhance the safety of an isolated superstructure against future strong earthquakes.

## 1. INTRODUCTION

Base isolation has become popular in regions where earthquakes are frequent. In the last decade, different isolation systems have been installed in office buildings, emergency communication centers, nuclear power plants, and other essential facilities to increase the safety and reliability of the superstructure and its contents during and after earthquakes. Applications of base seismic isolation to different types of structures can be found, for example, in papers by Kelly (1986) and Izumi (1989).

Most isolation systems currently installed to structures have frequency of 0.5 Hz, which is lower than the high energy frequency range of 1 to 10 Hz of most earthquakes. The frequency range of seismic motion at a given site is dependent on a variety of variables such as the geology of the site and consequently is best described as random. Thus, seismic motion that has significant energy at or near the isolation frequency is a possibility. In fact, the 1985 Mexico City earthquake has dominant frequency of 0.5 Hz (Celebi et al. 1987). Should there be a structure in Mexico City isolated with frequency of 0.5 Hz, its responses to the 1985 earthquake there definitely will be much higher, due to resonance, than those of a similar structure without isolation.

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An ideal isolation system not only will reduce responses of the superstructure during anticipated earthquakes, it will also prevent the isolated structure to have excessive responses when it is subjected to unanticipated ground motions, including ground motions which are simple harmonic with frequency same as the isolation frequency. The system to be presented here is designed to have two distinct isolation frequencies. Should a future earthquake be stronger than the design earthquake or have dominant frequency equal or close to the primary isolation frequency of the system, it will shift, automatically and passively, to a different frequency, and no resonance and large amplification will occur. This new isolation system, therefore, provides the isolated structure with a greater safety assurance even against future earthquakes with characteristics different from known ones.

The system to be described here is effective in avoiding resonance or large amplification resulted from horizontal excitations and/or from vertical excitations. Since the horizontal performance of a system is of major interest in most seismic isolation studies, only the responses of the system to horizontal ground motions are presented.

## 2. THE SYSTEM

An isolation system designed with two distinct isolation frequencies is shown in Fig. 1. It consists of two sets of bearings, primary and secondary. Bearings which are rigidly coupled to both upper and lower mats are primary bearings. Primary bearings always support the structure and contribute to support stiffness in both vertical and horizontal directions. Bearings that are rigidly coupled only to one mat and may engage and disengage the other mat are secondary bearings.

For minor earthquakes and/or responses not exceeding the design limits, this system performs preciously as a conventional single frequency system with isolation frequency equal to the primary frequency $f_1$, while the secondary bearings serve as the fail-safe device, a feature very important for critical facilities such as nuclear power plants. The secondary bearings are activated automatically and passively when the design parameter(s) is exceeded such as due to resonance. Isolation frequency of the system is then shifted to a new frequency, $f_2$, which in this design is higher than primary frequency $f_1$, and thereby avoiding large amplification. At the same time, there could also be an increase in the damping ratio. Higher damping ratio means that the responses would be further reduced.

When the secondary bearings have been activated, isolation frequency of the system is shifted from the primary frequency $f_1$ to a new frequency, $f_2$. Isolation frequency will return to $f_1$ again when the responses are lower than the design limits. That the isolation frequency of the system alternates between $f_1$ and $f_2$ implies that "resonance" is unlikely to occur.

The prime functions of the secondary bearings are: to serve as the fail-safe mechanism when the responses are below the critical; and to shift the isolation frequency and damping ratio to higher values when the responses exceed the critical. In addition, the presence of the secondary bearings offers protection to the primary bearings by alleviating the loadings exerted by severe ground motions to the primary bearings. Failure modes such as overturning and tearing of the primary bearings are greatly reduced. As long as both the primary and secondary bearings remain elastic, the isolation system and, therefore, the superstructure will center themselves, or will return to their initial positions at the end of each seismic ground motion.

Responses of a structure shown in Fig. 2 incorporated with either a single frequency system or a system with two distinct frequencies have been studied to demonstrate the effectiveness of the latter. Both real earthquake time history and harmonic ground motion have been used as the input motion to the structure which is simulated by the four-mass model shown in Fig. 3. Isolation frequency $f_1$ and damping ratio $r_1$ of the primary bearings are taken to be 0.5 Hz and 5%, respectively. If the secondary bearings have the same mechanical properties as the primary bearings, the new isolation frequency $f_2$ and damping ratio $r_2$ of the system will be, respectively, 0.71 Hz and 7.1%.

## 3. RESPONSES TO REAL EARTHQUAKE TIME HISTORY

The ground motion considered is the S00E component recorded at El Centro of the 1940 Imperial Valley earthquake. Dominant frequency of this time history is above 1 Hz as shown in Fig. 4. When the simulated structure of Fig. 3 is incorporated with a system characterized with a single isolation frequency of 0.5 Hz and a damping ratio of 5%, its responses to the time history of Fig. 4 with peak acceleration scaled to 0.3 g yield maximum acceleration and relative displacement between upper and lower mats of 0.14 g and 0.43 ft., respectively (Case 1, Table I). That the maximum acceleration is less than one half of the input peak acceleration clearly indicates the effectiveness of base seismic isolation.

The same structure is now isolated with a system which has both primary and secondary bearings where, for simplicity, each group of bearings is assumed to have the same mechanical properties as the single frequency isolation system. When the secondary system is activated, both the stiffness and the damping coefficient are doubled, resulting new isolation frequency and damping ratio of 0.71 Hz and 7.1%, respectively. If the secondary system is designed to be activated when the relative displacement between the upper and lower mats exceeds 0.3 ft., peak responses of the same structure to the same ground motion of Fig. 4 are summarized by Case 2 of Table I. Although maximum acceleration is again significantly less than the peak input acceleration of 0.3 g, some of the peak responses of this case are slightly higher than when a single isolation system is used.

That some of the peak responses from the multi-frequency isolation systems are higher than those from a single frequency system is not unexpected. When the isolation frequency changes from 0.5 Hz to 0.71 Hz, the system becomes stiffer, resulting larger load being transmitted to the superstructure. Furthermore, the ground motion of Fig. 4 has higher spectral acceleration at 0.71 Hz than at 0.5 Hz, another factor which contributes to the higher responses in Case 2 than in Case 1.

Responses of isolation systems with other secondary bearings have also been investigated, and the results are summarized in Cases 3 and 4 of Table I. In Case 3, the secondary bearings will increase the stiffness of the entire isolation system but not the damping coefficient. Increasing stiffness while damping coefficient remains unchanged will yield smaller damping ratio. The secondary bearings of Case 4, on the other hand will increase the damping coefficient but not the stiffness. Peak responses from these two cases in Table I seems to indicate that, when the isolation frequency is much lower than the dominant frequency of the input ground motion, increasing damping coefficient is more effective in reducing the peak responses than increasing stiffness. The situation will be different when the dominant frequency of the ground motion is near the isolation frequency as shown by the results of the following section.

If the time history of the Fig. 4 is the only type of earthquakes the superstructure will encounter, results of Table I indicate that an isolation system with (primary) frequency of 0.5 Hz is a satisfactory design to achieve the goal of reducing the responses of the superstructure. The major advantage of multi-frequency isolation systems is to assure the safety and serviceability of the superstructure against future earthquakes which are either stronger than the design basis earthquake, or have characteristics different from known ones. Should a structure isolated with a system with a single isolation frequency of 0.5 Hz be subjected to the 1985 Mexico City earthquake, the results definitely will be disastrous.

## 4. RESPONSES TO HARMONIC GROUND MOTION

A major concern for a structure isolated with a single frequency system is when the dominant frequency of a future earthquake coincides with the isolation frequency. Since the 1985 Mexico City earthquake is observed almost as a harmonic motion with frequency of 0.5 Hz, it will be of interest to investigate the responses of an isolated structure to harmonic ground motion.

The same structure of the previous section incorporated with base seismic isolation with a single frequency of 0.5 Hz and damping of 5% is now subjected to a harmonic ground motion. The ground motion has peak acceleration of 0.3g and frequency of 0.5 Hz, same as the isolation frequency. Responses of the structure simulated by Fig. 3 show that maximum acceleration reaches 2.9g, indicating that the ground motion is amplified almost 10-fold. Maximum relative displacement between the upper and lower mats exceeds 9 ft. (Case I, Table II). These large responses are the direct result that the isolated structure is resonating with the ground motion.

When the isolation system is replaced by a system with two distinct frequencies, responses of the superstructure will be drastically reduced because resonance will no longer occur. If the secondary bearings again have the same characteristics as the primary bearings as in the previous section, while the critical relative displacement is taken to be 1 ft., response of the superstructure to the same harmonic ground motion yield maximum acceleration and relative displacement of 1.12g and 2.3 ft., respectively (Case 2, Table II). When compared to the results of Case 1 where single isolation frequency system is used, the multi-frequency system reduces maximum acceleration by a factor of 2.5, and the maximum relative displacement by 4.

As in Table I, Table II also includes responses from systems where the presence of the secondary bearings will only double either the stiffness or the damping coefficient, but not both. These results indicate that double either the stiffness or the damping coefficient alone is not as effective as Case 2 in reducing the responses. In the responses where frequency of the harmonic ground motion coincides with the primary frequency, doubling the stiffness (Case 3) yields peak responses lower than doubling the damping coefficient (Case 4), even when the damping ratio in Case 4 is much higher than in Case 3.

## 5. CONCLUSION

A simple isolation system with two distinct isolation frequencies has been shown to be able to enhance the reliability and safety of the superstructure even when a future earthquake with dominant frequency coincides with the (primary) isolation frequency. Furthermore, the system proposed here is fail-safe and also will reduce the failure potential of the primary bearings. With such an isolation system, seismic base isolation could even be extended to sites with soft soil properties where isolation systems with a single low isolation frequency are generally not considered effective or appropriate.

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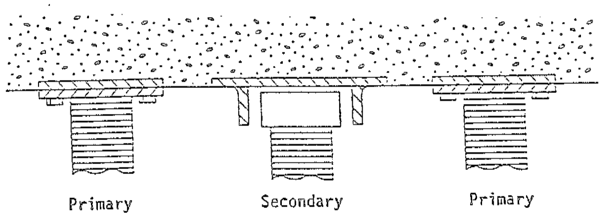


Fig. 1. An Isolation System with Two Distinct Isolation Frequencies.

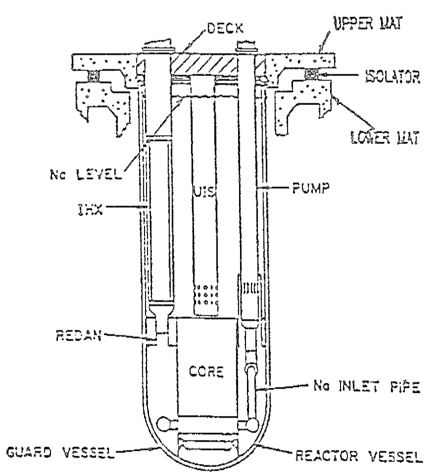


Fig. 2. Schematic of a Nuclear Reactor with Seismic Isolation.

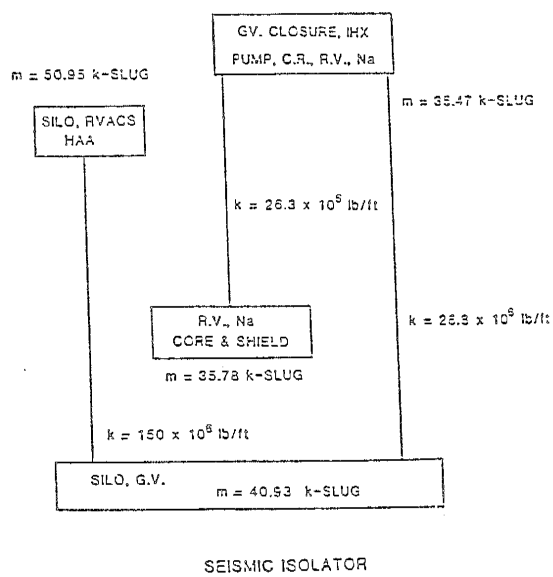


Fig. 3. Analysis Model for an Isolated Reactor

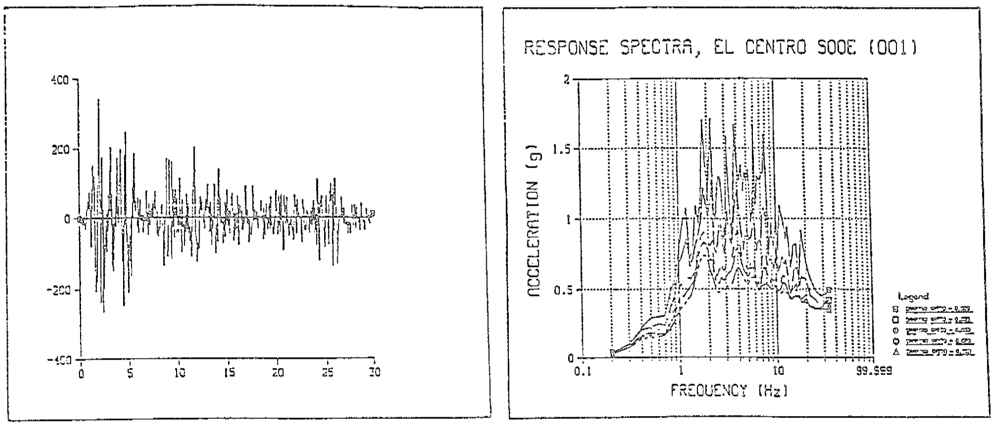


Fig. 4. Acceleration Time History and Response Spectra, 1940 Imperial Valley Earthquake Recorded at El Centro.

Table I: Responses to the 1940 Imperial Valley Earthquake Recorded at El Centro

| Case | | Max. Acc. (g) | Max. Rel. Disp. (ft.) | Max. Shear (% of Struc. Wt.) |
|---|---|---|---|---|
| 1 | $f_2$ = 0 <br> $r_2$ = 0 | .14 | .43 | 13 |
| 2 | $f_2$ = .71 Hz <br> $r_2$ = 7.1 % | .16 | .36 | 16 |
| 3 | $f_2$ = .71 Hz <br> $r_2$ = 3.5 % | .17 | .40 | 16 |
| 4 | $f_2$ = .5 Hz <br> $r_2$ = 10 % | .12 | .38 | 12 |

(a) Primary frequency $f_1$ and damping ratio $r_2$ are .5 Hz and 5%, respectively

(b) $f_2$ and $r_2$ are the frequency and damping ratio, respectively, when both the primary and secondary bearings are responding.

(c) Secondary bearings are activated when the maximum relative displacement between the upper and lower mats exceeds 0.3 ft.

Table II: Responses to a Harmonic Ground Motion with Frequency of .5 Hz

| Case | | Max. Acc. (g) | Max. Rel. Disp. (ft.) | Max. Shear (% of Struc. Wt.) |
|---|---|---|---|---|
| 1 | $f_2$ = 0 <br> $r_2$ = 0 | 2.86 | 9.37 | 291 |
| 2 | $f_2$ = .71 Hz <br> $r_2$ = 7.1 % | 1.12 | 2.31 | 113 |
| 3 | $f_2$ = .71 Hz <br> $r_2$ = 3.5 % | 1.28 | 2.61 | 130 |
| 4 | $f_2$ = .5 Hz <br> $r_2$ = '10 % | 1.53 | 4.95 | 155 |

(a) Primary frequency $f_1$ and damping ratio $r_1$ are .5 Hz and 5%, respectively.

(b) $f_2$ and $r_2$ are the frequency and damping ratio, respectively, when both the primary and secondary bearings are responding.

(c) Secondary bearings are activated when the maximum relative displacement between the upper and lower mats exceeds 1.0 ft.