Conf

ANL/CP--73489

DE92 004151

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1991

SEISMIC ISOLATION SYSTEMS DESIGNED WITH DISTINCT MULTIPLE FREQUENCIES*

by

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*Work performed under the auspices of the U. S. Department of Energy, Office of Technology Support Programs, under Contract No. W-31-109-ENG-38.

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June 13, 1991

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ABSTRACT

Two systems for seismic base isolation are presented. The main feature of these systems is that, instead of only one isolation frequency as in conventional isolation systems, they are designed to have two distinct isolation frequencies. When the responses during an earthquake exceed the design value(s), the system will automatically and passively shift to the secondary isolation frequency. Responses of these two systems to different ground motions, including a harmonic motion with frequency same as the primary isolation frequency, show that no excessive amplification will occur. Adoption of these new systems certainly will greatly enhance the safety and reliability of an isolated superstructure against future strong earthquakes.

I. INTRODUCTION

A great number of structures have been incorporated with different types of seismic base isolation systems in the last few years. One of the major functions of an isolation system is to filter out high energy of strong earthquakes. An isolation system is usually designed with a natural frequency lower than the dominate frequencies of anticipated earthquakes. Most strong earthquakes are observed to have high energy within the frequency range of 1 to 10 Hz. The favorable natural frequency for seismic base isolation systems, such as the systems used for the Foothill Law and Justice Center [1] and the William Clayton Building in Wellington, NZ [2], is of 0.5 Hz.

The dominant energy 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 natural frequency of the isolation system is a possibility. In fact, the dominate frequency of the 1985 Mexico City Earthquake is of 0.5 Hz [3]. Should there be a structure in Mexico City isolated with a system with isolation frequency of 0.5 Hz, its responses to the 1985 earthquake definitely will be much higher, due to resonance, than the responses of a similar building without isolation.

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 possible ground motions which are simple harmonic with frequency same as the isolation frequency. The systems to be presented here are designed to have two distinct isolation frequencies. Should a future earthquake be stronger than the design basis earthquake or have dominant frequency equal or close to the primary frequency of the system, it will shift, automatically and passively, to a different frequency and no resonance and large amplification will occur. These new isolation systems, therefore, provide the isolated structure with a greater safety assurance even against future earthquakes with characteristics different from known ones.

Two design concepts for base isolation systems are described in the following sections. In the first design, the system will shift its frequency from the primary to the secondary when the relative displacement exceeds the critical value; while the secondary frequency of the other design is activated by the critical shear force. Responses of a structure isolated by either of these systems to a real earthquake as well as to an harmonic ground motion are also presented.

II. DISPLACEMENT CONTROLLED SYSTEM

This system consists of two sets of bearings as shown in Figure 1. 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 when the design limit on the relative displacement between the upper and lower mats 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 could mean 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 relative displacement is lower than the design limit. That the 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 in this design 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.

III. FORCE CONTROLLED SYSTEM

The isolation system shown in Figure 2 also has two sets of bearings. In this design, both sets of bearings support the weight of the superstructure. The set which will be denoted as secondary has a pair of contact pads on top (or bottom) of the bearing as shown. One of the pads is anchored to a mat and the other to the bearing. For minor earthquakes, no relative motion between the pads will occur and the isolation system will function as a conventional system with a single (primary) isolation frequency.

When the horizontal shear force between the contract surface of the pads exceeds the design value, horizontal motion occurs between the pads and the secondary bearings are essentially disengaged. Again the system's frequency is shifted from the primary frequency f_1 to secondary frequency f_2. In this design, the secondary frequency f_2 is lower than the primary frequency f_1.

Although there could be reduction in damping when the secondary bearings become disengaged, lower frequency of the system (much less than 1 Hz, for example generally means less ground motion being transmitted to the superstructure, and therefore, avoiding large amplification. Once the horizontal shear force between the pads becomes lower than the design value, the isolation frequency returns to the primary value of f_1. Thus, as in the displacement activated system, the system will not oscillate a full continuous cycle at frequency f_2. No resonance, therefore, will occur for this system either.

Responses of a model simulating a nuclear reactor 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. 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 secondary frequency f_2 of the displacement activated (Figure 1) and force activated (Figure 2) systems are 0.71 Hz and 0.35 Hz, respectively. The damping ratios will also be different from their primary values once the secondary bearings are engaged or disengaged.

IV. RESPONSES TO REAL EARTHQUAKE

The ground motion considered is the SOOE component recorded at El Centro of the 1940 Imperial Valley earthquake. Dominant frequency of this time history is above 1 Hz. When a simulated structure 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 earthquake with peak acceleration scaled to 0.3g yield maximum acceleration of 0.14g. The corresponding maximum acceleration of the structure without isolation, on the other hand, is higher than the 0.3g input peak acceleration. The results clearly indicate the effectiveness of base seismic isolation.

The same structure is now isolated with a system which is either displacement controlled or force controlled. For simplicity, each group of bearings is assumed to have the same mechanical properties as the single frequency isolation system. The secondary system is designed to be activated either when the relative displacement between the upper and lower mats exceeds 0.3 feet for the displacement controlled system or, for the force controlled system, when the shear force transmitted through the sliding pads is larger than 5% of the weight of the superstructure.

Acceleration responses from these multiple frequency systems are plotted with the response from a single frequency system (Figures 3 and 4). Maximum accelerations when the new systems are used are also significantly lower than the peak input acceleration of 0.3g. In Figure 3, maximum acceleration from the displacement activated multiple frequency system is slightly higher than when a single frequency is used. That the peak acceleration from the displacement controlled isolation system is higher than that from a single frequency system is not unexpected, since the ground motion has higher spectral acceleration at 0.71 Hz than at 0.5 Hz.
If the superstructure considered here will only encounter earthquakes of the El Centro type, an isolation system with single frequency of 0.5 Hz is sufficient to reach the goal of reducing the responses of the superstructure, since the maximum response acceleration is less than half of the input peak acceleration The major advantage of the 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 become disastrous.

V. RESPONSES TO HARMONIC GROUND MOTION

A major concern for a structure isolated with a single frequency system is when the dominate 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 of investigate the response 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 simulated structure 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. 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 are 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 values are 1 ft. for displacement controlled system and 25% of the weight of the superstructure for the force controlled system, responses of the superstructure to the same harmonic ground motion yield maximum accelerations of 1.12g and 1.01 g, respectively, for the displacement and force activated systems (Figures 5 and 6). These accelerations are less than half of the maximum acceleration from the single isolation frequency system.

VI. CONCLUSIONS

Simple isolation systems with two distinct frequencies have 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. With such isolation systems, 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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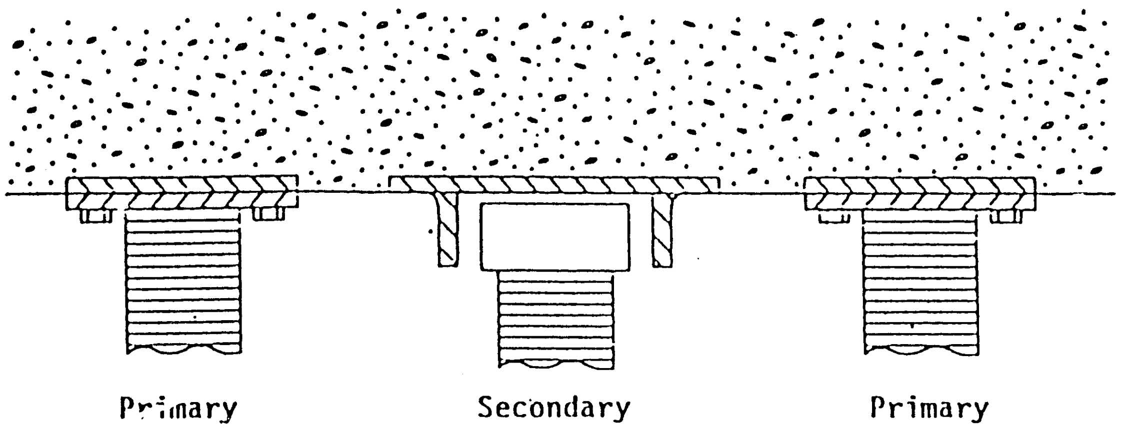

FIGURE 1 DISPLACEMENT CONTROLLED SYSTEM

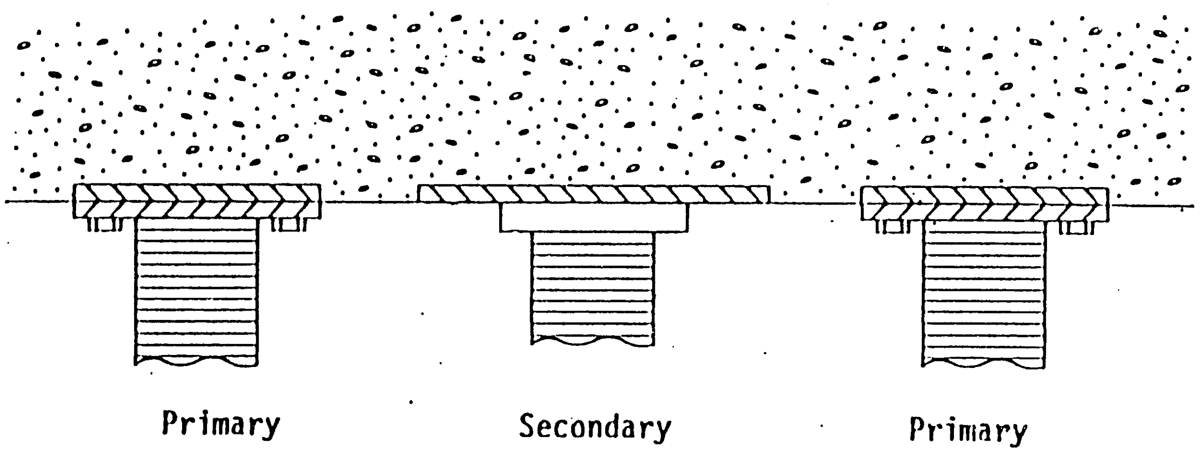

FIGURE 2 FORCE CONTROLLED SYSTEM

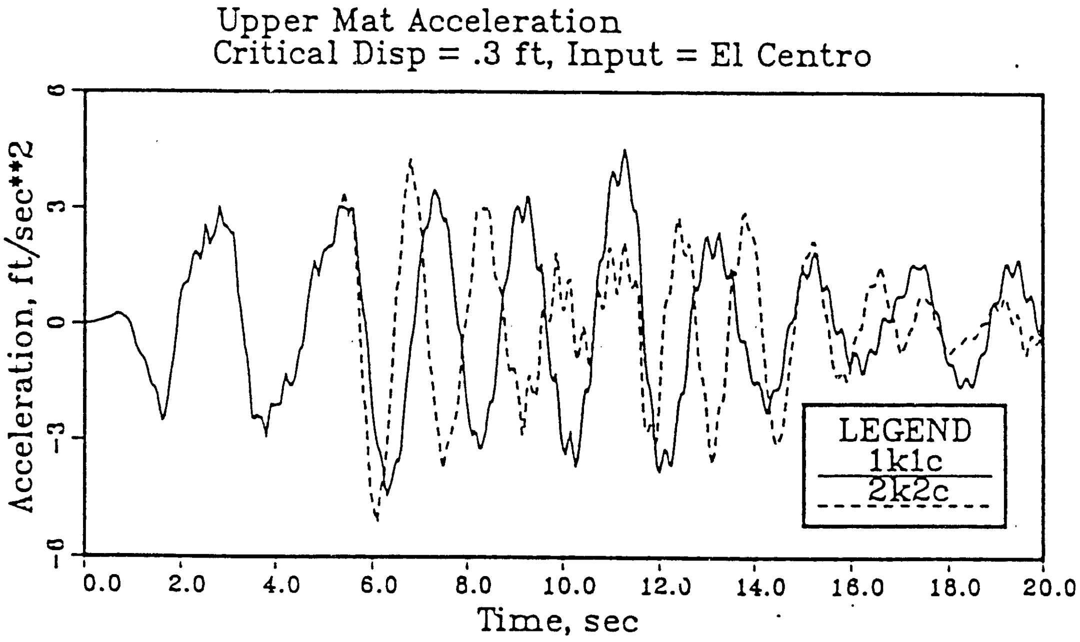

FIGURE 3 ACCELERATIONS FROM SINGLE FREQUENCY (IKIC) AND DISPLACEMENT CONTROLLED (2k2c) SYSTEMS, EL CENTRO EARTHQUAKE

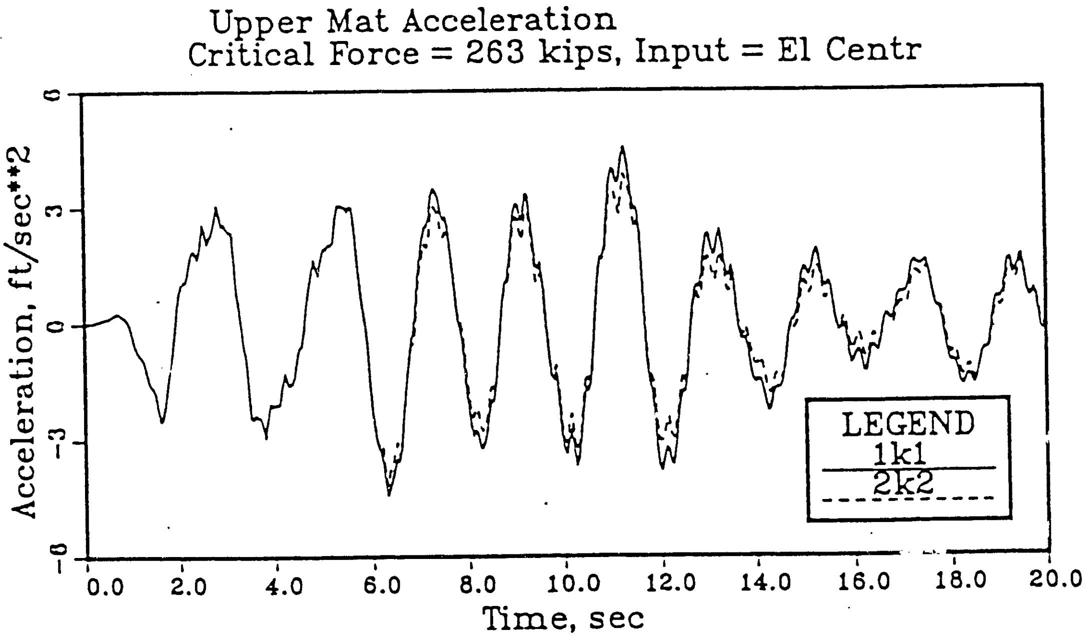

FIGURE 4 ACCELERATIONS FROM SINGLE FREQUENCY (IKI) AND FORCE CONTROLLED (2K2) SYSTEMS, EL CENTRO EARTHQUAKE

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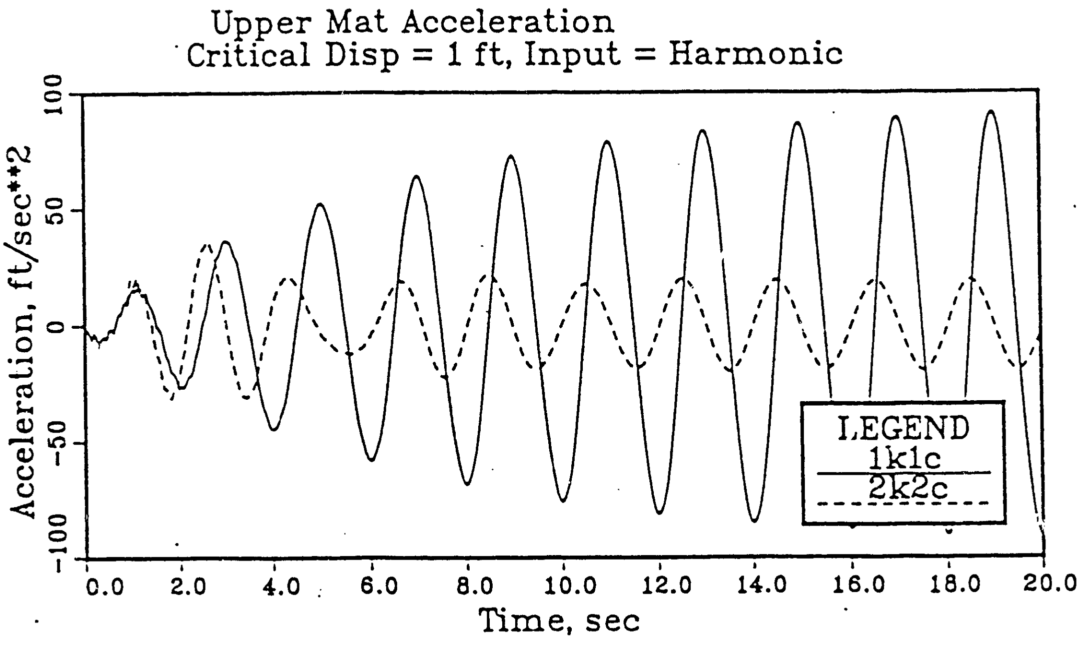

FIGURE 5 ACCELERATIONS FROM SINGLE FREQUENCY (IKIC) AND DISPLACEMENT CONTROLLED (2K2C) SYSTEMS, HARMONIC GROUND MOTIONS

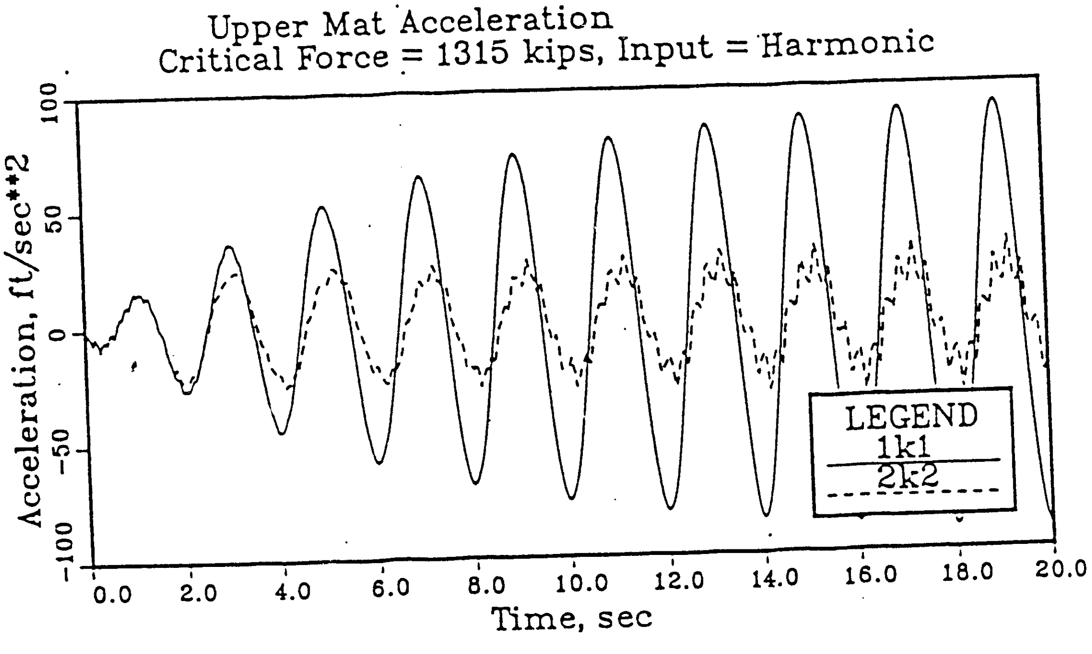

FIGURE 6 ACCELERATION FROM SINGLE FREQUENCY (1K1) AND FORCE CONTROLLED (2K2) SYSTEMS, HARMONIC GROUND MOTION

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