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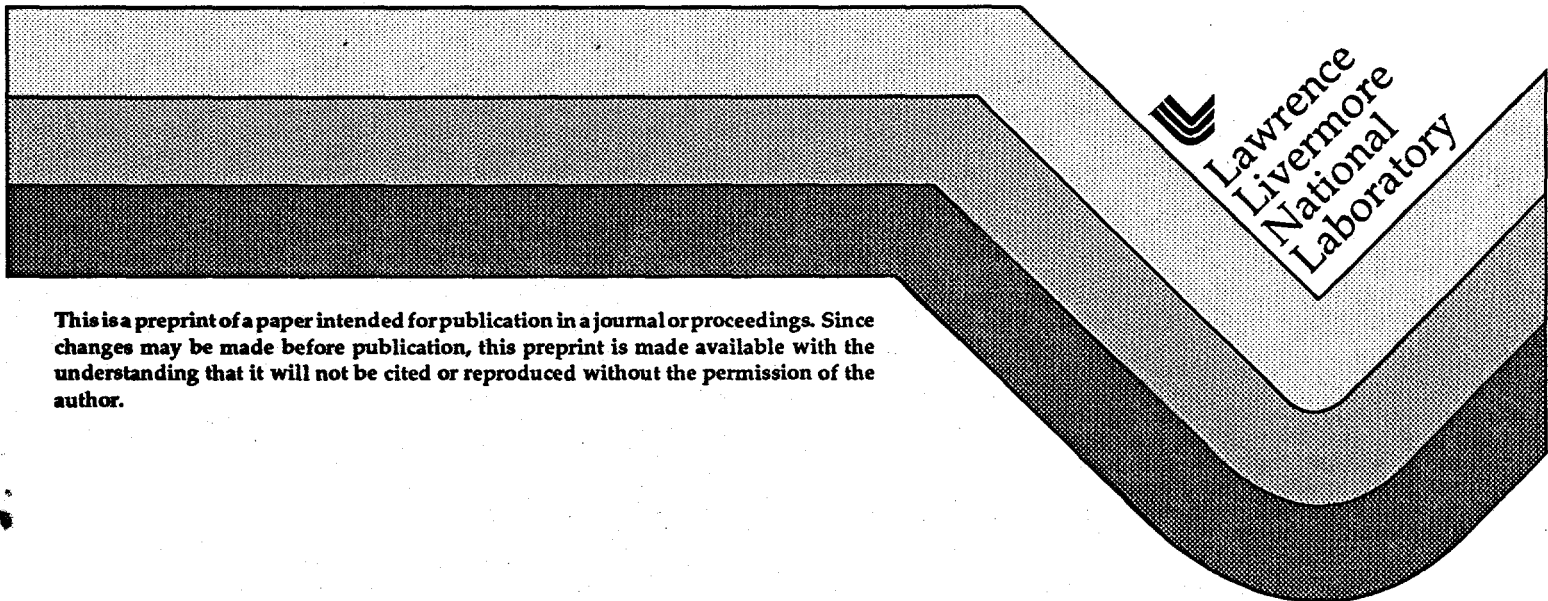
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Frequency Response Characteristics and Response Spectra of Base-Isolated and Un-Isolated Structures

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FREQUENCY RESPONSE CHARACTERISTICS AND RESPONSE SPECTRA OF BASE-ISOLATED AND UN-ISOLATED STRUCTURES*

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ABSTRACT

The transmissibility of seismic loads through a linear base-isolation system is analyzed using an impedance method. The results show that the system acts like a "low-pass" filter. It attenuates high-frequency loads but passes through low-frequency ones. The filtering effect depends on the vibration frequencies and damping of the isolated structure and the isolation system. This paper demonstrates the benefits and design principles of base isolation by comparing the transmissibilities and response spectra of isolated and un-isolated structures. Parameters of typical isolated buildings and ground motions of the 1994 Northridge earthquake are used for the demonstration.

1.0 INTRODUCTION

The seismic base-isolation system is gaining acceptance as an effective means for protecting a structure from earthquake loads. The benefit of a seismic base-isolation system can be explained in various ways. One common explanation is that the isolation system shifts the fundamental vibration frequency of an isolated structure from a frequency range of high earthquake excitations to a frequency range of low excitations (Skinner, Robinson, and McVerry 1993). Thus, the isolated structure vibrates under significantly lower earthquake excitations, resulting in a significantly lower response than the un-isolated structure. The explanation is straightforward and effective. However, to demonstrate the complete benefits and possible limitations of the technology, it is necessary to examine further the behavior of isolated structures and the possible effects of various system parameters on the behavior. Therefore, this paper analyzes, in the frequency domain, the seismic transmissibility and response of a linear structure isolated at its base with a linear isolation system. The frequency-domain solution is used because it provides a

greater insight into the cause and effect of dynamic behavior than the time-domain solution.

Representing a seismic excitation with its Fourier transform and an isolated structure with an equivalent linear lumped parameter model, the study examines the transmissibility of earthquake motions through a base-isolated structure using an impedance method. The analysis results show that an isolation system is an effective "low-pass" filter of seismic loads if the system is adequately designed with proper damping and flexibility. Adequate damping is required to control possible resonant vibration at the fundamental or the first fixed-base vibration frequency of the isolated structure. Sufficient flexibility is needed to lower and separate the fundamental vibration frequency of the isolated structure from those of the upper structure and of the dominant seismic loads. An adequately designed, effective base-isolation system can significantly reduce the transmitted seismic loads for frequencies higher than the fundamental vibration frequency of the isolated structure. Thus, a base-isolation system protects both the isolated upper structure and all its contents from the high-frequency seismic loads.

The possible effects of dampings, upper-structure vibrations, and seismic loads on the function of a base-isolation system are studied. The protective ability of a base-isolation system is demonstrated by comparing the transmissibilities and response spectra of isolated and un-isolated structures subject to an earthquake excitation.

Sections 2.0 and 3.0 describe the analysis models and method used for the study. Section 4.0 discusses the analysis results and demonstrates the effects of isolation, damping, and vibration on the behavior and response of isolated structures. Section 5.0 highlights the significant findings and identifies basic principles and criteria for the design and analysis of isolated structures.

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2.0 ANALYSIS MODELS

Figure 2.1 depicts the two basic analysis models used for this study: a single-degree-of-freedom (SDOF) model and a multiple-degree-of-freedom (MDOF) models. Both linear lumped parameter models are made of lumped masses, linear elastic springs and linear viscous dampers (or dashpots). The motion of each model is confined to only one direction, either the vertical (axial) or the horizontal (lateral) direction. In the horizontal case, the springs and dampers in Fig. 2.1 represent shear springs and dampers which respond only to horizontal forces and motions. Similarly, in the vertical case, the same elements represent, instead, axial springs and dampers which respond only to vertical forces and motions. The horizontal case simulates a structure isolated for horizontal earthquake loads, while the vertical case simulates an isolation for vertical loads. The mathematical formulations of the two cases are identical. Therefore, the present analysis and conclusions are equally applicable to horizontal and vertical isolations. At present, almost all seismically isolated facilities are designed for horizontal isolation only.

In the SDOF model of an isolated structure in Fig. 2.1, the upper structure (the structure above the isolation layer) is represented by the lumped mass and the isolation system is by the spring and the damper. The SDOF model is commonly used to explain seismic base isolation. Its results are used as the basis for equivalent static design analysis of isolated structures. However, the model does not include the flexibility of the upper structure and, therefore, cannot be used to analyze the vibrational response of the upper structure and its effect on the performance of the isolation system. Accordingly, the MDOF model is used here for this purpose.

The MDOF model represents a typical base-isolated building, which has a multi-story upper structure resting on a layer of relatively soft isolators (isolation layer). Similar to the SDOF model, the isolation layer is represented by a spring and damper located between the upper structure and the foundation. The upper structure of the MDOF model has six identical stories, each represented by a lumped mass supported by a spring and a damper.

Similar to the SDOF model, the MDOF model is also a simplified model of an isolated building. Most buildings do not have identical stories; the lower stories are usually stiffer, because they carry higher loads. However, the use of identical stories simplifies the analysis but does not alter the conclusion of this study.

Most actual isolators and isolation layers have nonlinear and hysteretic force-deformation characteristics. However, in a limited load range, the nonlinear effects are small and the isolation layer can be simulated by the linear model used here, provided the spring simulates the average stiffness of the isolation layer and the damper simulates the energy dissipation of the layer. Rigorously speaking, the results and conclusions of the present analysis are applicable only to linear systems since it uses the linear assumption. Nevertheless, past research in shock and vibration isolation has shown that linear and nonlinear isolation systems show similar general behaviors (Crede and Ruzicka 1988). Thus, the results of this study may also be helpful for

understanding the behavior of a general isolation system other than the linear system.

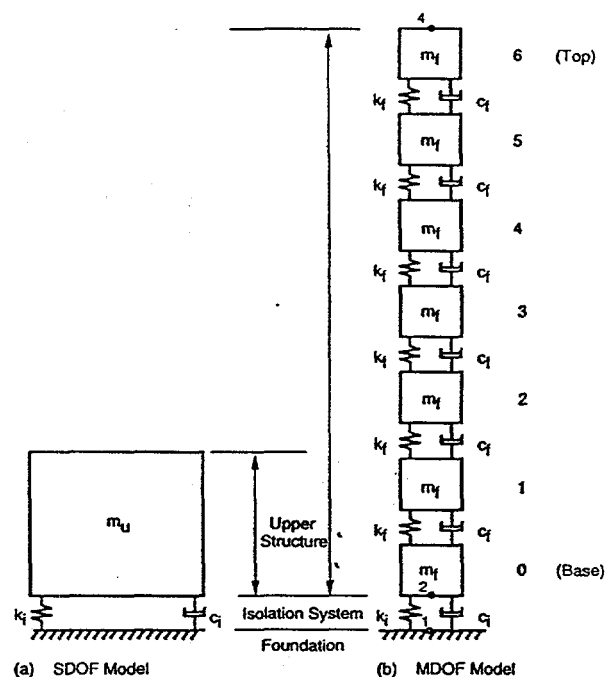


FIGURE 2.1 ANALYSIS MODELS

Table 2.1 lists all SDOF and MDOF models analyzed for this study. The SDOF and MDOF models are intended to be equivalent. Accordingly, corresponding SDOF and MDOF models have identical upper-structure mass, isolation spring, and damper. However, the upper-structure flexibility and damping of the two models cannot be made equivalent, because these properties cannot be simulated in the SDOF model.

The viscous damping coefficients of the dampers used in the analysis models are set to produce the desired modal dampings listed in Table 2.1 for the upper structure and the isolated structure. Table 2.1 also lists the dynamic amplification factor (DAF) corresponding to each of the modal dampings. A modal damping ζ corresponds to a DAF of $1/(2\zeta)$. The DAF is used to determine whether or not the selected viscous damping coefficient is sufficient to provide the desired modal damping. If the damping is adequate, the ratio of the maximum response of the structure to the input earthquake motion should equal the DAF, when the structure is excited by a sinusoidal earthquake motion of the modal frequency.

The modal information listed in Table 2.1 for each structure refers to the fundamental or the first fixed-base vibration mode of the structure. The information for the upper structure is determined using the upper structure of the MDOF model with its base (lumped mass #0) fixed, while the information for the isolated structure is obtained using the SDOF model. The viscous damping set for the first mode can cause a significantly higher damping for a higher mode. Therefore, the damped structure model used here may respond to earthquake excitations like a single-mode model. However, this behavior of the model would

not invalidate the conclusion of this study, as long as the interpretation of the result does not assume that only the first mode is responding.

The present study uses only one upper-structure model but three isolation systems. The upper-structure model has a fundamental fixed-base vibration period of 0.65 sec. and the three

isolation systems provide three fixed-base vibration periods of 1, 2, and 3 sec. for the isolated structure. These vibration periods are similar to those of existing isolated buildings in California (Sommer and Trummer 1993). The 5% and 15% modal dampings used for the upper structure and the isolated structure, respectively, are also typical values (Coats 1982).

TABLE 2.1 ANALYSIS MODELS

Structure	Model Type	Isolation System		Upper Structure			Complete structure				
							1st fixed-base vibration mode				
							DOF	Freq. cps	Period sec	Damp. %	DAF
		k_i	c_i	m_f	k_f	c_f					
Un-isolated	MDOF	-	-	1.00	1610.00	0.00	6	1.54	0.65	0	
Un-isolated	MDOF	-	-	1.00	1610.00	20.95	6	1.54	0.65	5	10.0
Isolated	SDOF	276.35	13.19	7.00	-	-	1	1.00	1.00	15	3.33
Isolated	SDOF	69.09	6.60	7.00	-	-	1	0.50	2.00	15	3.33
Isolated	SDOF	30.71	4.40	7.00	-	-	1	0.33	3.00	15	3.33
Isolated	MDOF	276.35	13.19	1.00	1610.00	20.95	7				
Isolated	MDOF	69.09	6.60	1.00	1610.00	20.95	7				
Isolated	MDOF	30.71	4.40	1.00	1610.00	20.95	7				
Isolated	MDOF	69.09	0.00	1.00	1610.00	20.95	7				
Isolated	MDOF	69.09	6.60	1.00	1610.00	20.95	7				
Isolated	MDOF	69.09	6.60	1.00	1610.00	0.00	7				
Isolated	MDOF	69.09	6.60	1.00	1610.00	20.95	7				

Note: The un-isolated structure is identical to the upper structure of the isolated structure.

The units of k_i , c_i , m_f , k_f , and c_f are immaterial, because the solution depends only on the modal frequencies and dampings.

3.0 ANALYSIS METHOD

The method used for the present analysis is an impedance method, which has been previously applied by one of the authors for a study of the general behavior of shock spectra obtained in shock testing (Mok 1970). Impedance methods solve dynamic problems of linear systems in terms of the Fourier transform of the excitation and response time histories (Hixson 1988). The relationship of a Fourier transform and the corresponding time history is as follows:

$$A(p) = \int_0^{\infty} a(t)e^{-pt} dt \quad (3.1)$$

and

$$a(t) = \frac{1}{2\pi j} \int_{-j\infty}^{j\infty} A(p)e^{pt} dp \quad (3.2)$$

where p equals $j\omega$; j is the square root of -1, and ω is the (circular) frequency.

In these equations and this paper, an upper case letter denotes the Fourier transform of a dynamic response and the corresponding lower case is the response (time history). Thus, the letter A represents the Fourier transform of the acceleration, a . Similarly, U , V , and F are the Fourier transforms of u , v , and f , the corresponding displacement, velocity and force time histories, respectively. Equations (3.1) and (3.2) show that a Fourier transform is a function of the purely imaginary number, p . Thus, in general, the value of a Fourier transform is a complex number consisting of a real and an imaginary part.

In impedance methods, the relation between two responses, R_2 and R_1 can be expressed in the general form:

$$R_2(p) = T_{21}(p) R_1(p) \quad (3.3)$$

Similar to R_2 and R_1 , T_{21} is a function of the variable p . T_{21} is called in general a transfer function but can have other names. In the case where R_2 is a velocity and R_1 is a force, T_{21} can be called a mobility. The inverse of a mobility is an impedance. If R_2 and R_1 give the same response at two different locations, T_{21} can be called the transmissibility of the response from location 1 to location 2.

The present study examines the transmissibility of acceleration (A), velocity (V), and displacement (U) across a base-isolation system; that is, from a point below the isolation system like the ground or foundation, to a point above the isolation system at the base, the top, or a location on the upper structure. The transmissibility of acceleration, T_{21} , from location 1 to location 2 in Fig. 3.1 is simply the ratio of the acceleration at location 2 (A2) to the acceleration at location 1 (A1):

$$T_{21} = \frac{A_2}{A_1} \quad (3.4)$$

The transmissibilities of velocity and displacement are similarly defined. The transmissibilities of acceleration, velocity and displacement are identical for an elastic system. This result is because the acceleration, velocity, and displacement of an elastic system return to their initial values at the end of an earthquake. Using this information and the definition of Fourier transform (Eq. 3.1), the Fourier transforms of the acceleration, velocity, and displacement (A, V, and U, respectively) of an elastic system can be shown to have the following relations:

$$A = pV \quad (3.5)$$

$$V = pU \quad (3.6)$$

These equations can in turn be used in Eq. 3.4 to confirm the above conclusion that the transmissibilities of acceleration, velocity, and displacement are identical. Therefore, the present study needs to examine only one transmissibility between each pair of locations in the isolated structure.

In general, the transmissibility varies with the location in the isolated structure, and the transmissibilities at more than one point are needed to provide a complete description of the transmission process. In this study, the transmissibilities (T_{41} and T_{21}) at the top (location 4) and at the base of the upper structure (location 2) in Fig. 2.1 are analyzed. The results presented in Section 4 show that the two transmissibilities provide sufficient information and understanding of the transmission process.

The equations for obtaining the transmissibilities, T_{41} and T_{21} are derived from an analysis of the basic two-component system shown in Fig. 3.1. In the system, each component (I or II) represents a general structure which may be simple or complex.

The equations and the solutions for this system can be expressed in terms of four mobility properties for each of the two components. The four mobility parameters describe the frequency response characteristics of each component as a separate and independent unit. The following equations define the four mobility parameters, M_{11} , M_{12} , M_{21} , and M_{22} of Component I:

$$M_{11} = \left. \frac{V_1}{F_1} \right|_{F_2 = 0} \quad (3.7)$$

$$M_{22} = \left. \frac{V_2}{F_2} \right|_{F_1 = 0} \quad (3.8)$$

$$M_{12} = \left. \frac{V_1}{F_2} \right|_{F_1 = 0} \quad (3.9)$$

$$M_{21} = \left. \frac{V_2}{F_1} \right|_{F_2 = 0} \quad (3.10)$$

For component II, the mobility parameters, M_{33} , M_{44} , M_{34} , and M_{43} are similarly defined. The subscript equation attached to the end of each of Eqs. 3.7-3.10, e.g. $F_2 = 0$ in Eq. 3.7, defines the boundary condition under which each mobility parameter is defined. Thus, Eq. 3.7 states that the mobility parameter M_{11} equals the velocity at location 1 (V_1) divided by the force at location 1 (F_1) when no force is applied at location 2. The mobility parameters M_{12} and M_{21} should be equal for a bilateral system where forces can be transmitted equally well in both directions (from 2 to 1 as well as from 1 to 2). The structure studied here is such a system.

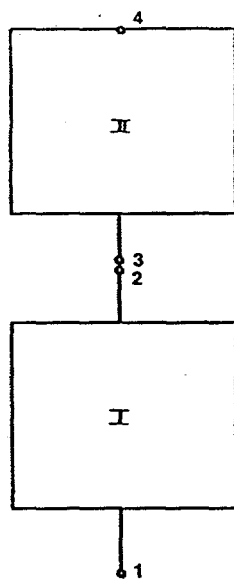


FIGURE 3.1 A TWO-COMPONENT MODEL FOR IMPEDANCE ANALYSIS

The equations for the solution of T_{41} and T_{21} in the two component system in Fig. 3.1 are:

$$V_1 = M_{11} F_1 + M_{12} F_2 \quad (3.11)$$

$$V_2 = M_{21} F_1 + M_{22} F_2 \quad (3.12)$$

$$V_2 = V_3 \quad (3.13)$$

$$F_2 = -F_3 \quad (3.14)$$

$$V_3 = M_{33} F_3 + M_{34} F_4 \quad (3.15)$$

$$V_4 = M_{43} F_3 + M_{44} F_4 \quad (3.16)$$

$$F_4 = 0 \quad (3.17)$$

Eqs. 3.11-3.12 and 3.15-3.16 are the results of the definitions of the mobility parameters (Eqs. 3.7-3.10). Eqs. 3.13-3.14 simply state that Components I and II are connected: the velocities must be continuous (Eq. 3.13) and the forces must be balanced (Eq. 3.14) at the interface of the two components. Eq. 3.17 simply states the force-free boundary condition at the top of Component II.

Solving Eqs. 3.11-3.17 yields the following general expressions for the transmissibility T_{41} and T_{21} :

$$T_{21} = \frac{V_2}{V_1} = \frac{M_{21} M_{33}}{M_{11} (M_{22} + M_{33}) - M_{12} M_{21}} \quad (3.18)$$

$$T_{41} = \frac{V_4}{V_1} = \frac{M_{21} M_{43}}{M_{11} (M_{22} + M_{33}) - M_{12} M_{21}} \quad (3.19)$$

The results show that the transmissibility is affected by the properties of both components (I and II). Mok (1970) has shown that transfer functions including transmissibilities have peaks and valleys at various frequencies due to vibration of the connecting components at those frequencies. Using similar reasoning as presented in Mok (1970), the transmissibilities T_{21} and T_{41} given in Eqs. 3.18-3.19 can be shown to have a valley near a fixed-base vibration frequency of Component II, and have a peak near a fixed-base resonant vibration frequency of the combined system (Components I and II together). Since an isolation system is significantly more flexible than the upper structure, the fixed-base vibration frequency of the isolated structure should be near a free vibration frequency of the upper structure. Accordingly, one can expect that the transmissibilities T_{21} and T_{41} have valleys near the fixed-base vibration frequencies and peaks near the free vibration frequencies of the upper structure. The results presented in Section 4 support this expectation.

Using Eqs. 3.11-3.17, the mobility parameters of the combined system (I and II) can be obtained according to the mobility definitions given in Eqs. 3.7-3.10:

$$M_{11c} = \left. \frac{V_{1c}}{F_{1c}} \right|_{F_{4c}=0} = \frac{M_{11} (M_{22} + M_{33}) - M_{21} M_{12}}{M_{22} + M_{33}} \quad (3.20)$$

$$M_{41c} = \left. \frac{V_{4c}}{F_{1c}} \right|_{F_{4c}=0} = \frac{M_{21} M_{43}}{M_{22} + M_{33}} \quad (3.21)$$

In these equations, the subscript c indicates a quantity belonging to the combined system (Components I and II together). M_{11c} and M_{41c} are, therefore, mobility parameters of the combined (two-component) system. If the combined system is now used as Component II in another two-component system (Fig. 3.2, next page), M_{11c} and M_{41c} will be the M_{33} and M_{43} of the new Component II, respectively. Thus, M_{11c} and M_{41c} of the new two-component system in Fig. 3.2 can be obtained by inserting the M_{33} and M_{43} of Component II in Fig. 3.2 and M_{11} , M_{21} , M_{12} , and M_{22} of Component I into Eqs. (3.20) and (3.21). By repeating the process, M_{11c} and M_{41c} of a multiple-component system like the upper structure of the MDOF model shown in Fig. 2.1 can be obtained in terms of the mobility parameters of the components in the system. After the mobility parameters of the upper structure of the MDOF model are found, the transmissibilities at the base and the top (T_{21} and T_{41}) of the isolated upper structure can be found using Eqs. (3.18) and (3.19).

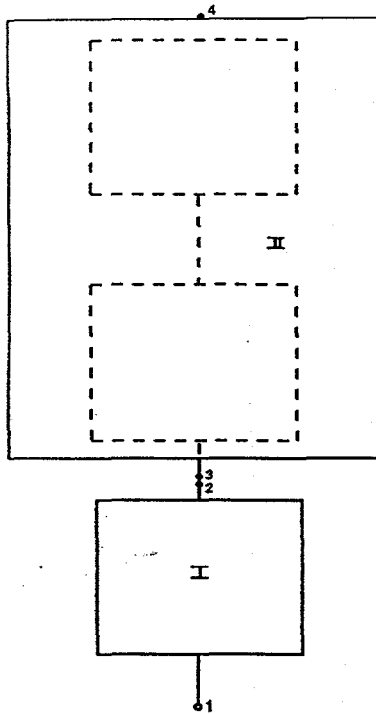


FIGURE 3.2 A THREE-COMPONENT SYSTEM ANALYZED AS A TWO-COMPONENT SYSTEM

For this calculation, M_{11} , M_{12} , M_{21} , and M_{22} are the mobility parameters of the isolation system which consists of the lumped mass #0, the isolation spring, and the isolation damper.

To evaluate the transmissibilities, the mobility parameters (M_{11} , M_{12} , M_{21} , etc.) must be expressed in terms of the masses, spring constants, and damping coefficients of the model. Since the basic building block of the analysis models is a single-degree-of-freedom system like the SDOF model shown in Fig. 2.1, the relationships for the SDOF model will suffice for the purpose. Mok (1970) has given the required relationships:

$$M_{11} = \frac{c + [c^2 - k(p m + k/p)] / p m}{c^2 - (k/p)^2} \quad (3.22)$$

$$M_{22} = M_{12} = M_{21} = \frac{1}{p m} \quad (3.23)$$

where m , k , and c are the mass, the spring constant, and the damping coefficient of the SDOF system, respectively.

An IBM-PC computer program was written to facilitate the described transmissibility analysis. Numerical results generated by this program are reported in the next section.

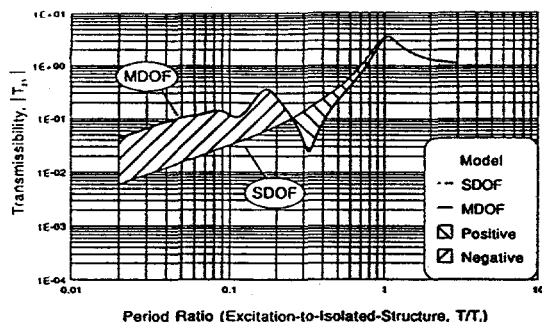
4.0 ANALYSIS RESULTS

Figs. 4.1.1 and 4.1.2 (next page) show the magnitude of the transmissibilities obtained using the SDOF and MDOF models depicted in Fig. 2.1. The magnitude of a transmissibility is the square root of the sum of the squares of the real and imaginary parts of the transmissibility. Fig. 4.1.1 presents the transmissibility from the foundation to the base of the upper structure (T_{21}) and Fig. 4.1.2 the transmissibility from the foundation to the top of the upper structure (T_{41}) of the two models. T_{41} and T_{21} of the SDOF model are identical, because the motion of the upper structure in this model is represented by a single degree of freedom.

In Figs. 4.1.1 and 4.1.2, a transmissibility magnitude $<$, $=$, or $>$ 1.0 indicates that the amplitude of the seismic load will be attenuated, unchanged, or amplified, respectively, when the load is transmitted from the foundation to the upper structure through the isolation system. The transmissibility of the SDOF model shows that the isolation system behaves almost like an ideal low-pass filter. Except in a small range of periods near the fixed-base vibration period of the isolated structure, the system does not affect the amplitude of a seismic load whose period (frequency) is longer (lower) than the fixed-base vibration period (frequency). However, for seismic loads whose period (frequency) is shorter (higher) than the fixed-base vibration period (frequency) it produces an amplitude attenuation which increases monotonically with decreasing period (increasing frequency) of the seismic load. In the vicinity of the fixed-base vibration period, the transmitted load is amplified due to the resonant vibration of the entire isolated structure. As shown later in Section 4.3, this amplification can be lowered by increasing the damping in the isolation system.

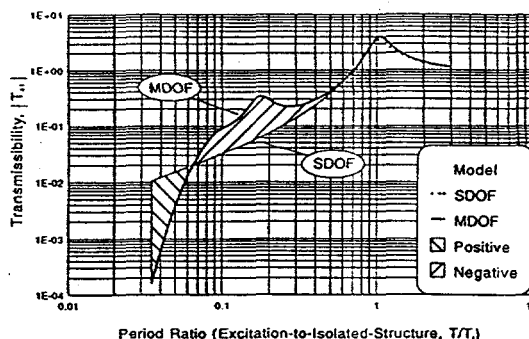
Figs. 4.1.1 and 4.1.2 show that the transmissibilities of the SDOF and MDOF models are very similar in the range of long periods (low frequencies). The similarity, however, disappears in the range of short periods (high frequencies), where the two models show significant differences in transmissibility. The differences mainly reflect the influence of the natural vibrations of the upper structure, since the two models differ only in the modeling of the upper structure, and the SDOF model does not simulate the vibrations. The vibration effects are analyzed in the next section.

Fig. 4.1.1 Vibration effect on transmissibility of isolated structure
Comparison of $|T_{21}|$ of SDOF and MDOF models



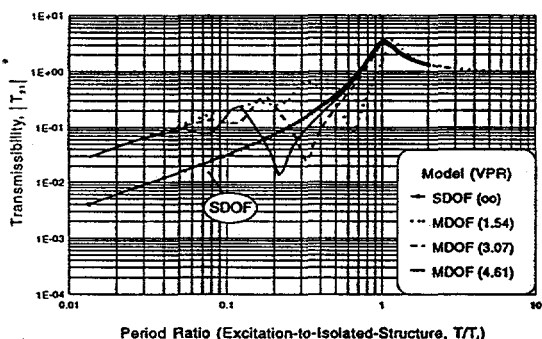
The transmissibility is from the ground (Pl.1) to the base (Pl.2) of the upper structure
Isolated structure: fixed-base vibration period (T_1), 2 sec; damping, 15%
Upper structure of MDOF model: fixed-base vibration period, 0.65 sec; damping 5%

Fig. 4.1.2 Vibration effect on transmissibility of isolated structure
Comparison of $|T_{41}|$ of SDOF and MDOF models



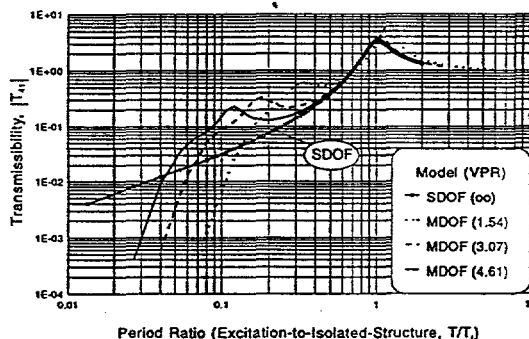
The transmissibility is from the ground (Pl.1) to the top (Pl.4) of the upper structure
Isolated structure: fixed-base vibration period (T_1), 2 sec; damping, 15%
Upper structure of MDOF model: fixed-base vibration period, 0.65 sec; damping 5%

Fig. 4.2.1 Vibration effect on transmissibility of isolated structure
Comparison of $|T_{21}|$ for various isolated-structure-to-upper-structure-vibration-period ratios (VPRs)



The transmissibility is from the ground to the base of the upper structure
Isolated structure: fixed-base vibration period (T_1), 1 to 3 sec; damping, 15%
Upper structure of MDOF model: fixed-base vibration period, 0.65 sec; damping 5%

Fig. 4.2.2 Vibration effect on transmissibility of isolated structure
Comparison of $|T_{41}|$ for various isolated-structure-to-upper-structure-vibration-period ratios (VPRs)



The transmissibility is from the ground to the top of the upper structure
Isolated structure: fixed-base vibration period (T_1), 1 to 3 sec; damping, 15%
Upper structure of MDOF model: fixed-base vibration period, 0.65 sec; damping 5%

4.1 Effect of Upper Structure Vibrations

The transmissibilities of the MDOF model shown in Figs. 4.1.1 and 4.1.2 do not decrease monotonically with decreasing period as the transmissibility of the SDOF model does. Significant fluctuations of the transmissibilities of the MDOF model appear in the range of periods shorter than the first fixed-base vibration period of the upper structure. As suggested in Section 3, these fluctuations are expected to exist as the result of natural vibrations in the structure. Furthermore, the peaks of the fluctuations should be located near the free-base vibration periods and the valleys should be near the fixed-base vibration periods of the upper structure.

Figs. 4.1.1 and 4.1.2 show that the vibrations of the upper structure have an overall negative effect on the load-attenuation ability of the isolation system. The comparison of the MDOF and SDOF results in Fig. 4.1.1 shows that the transmissibility T_{21} can be increased five fold from 0.07 to 0.35 (or the attenuation decreased 80%) by the upper-structure vibration at the first free-base or free vibration period of the upper structure ($T/T_1 \approx 0.18$).

The effect of the upper-structure vibrations on the transmissibility is further demonstrated in the results shown in Figs. 4.2.1 and 4.2.2. Fig. 4.2.1 presents the transmissibility T_{21} , and Fig. 4.2.2 presents T_{41} , obtained using the MDOF model for three isolated structures. The three structures have identical upper structures but different isolation systems. Each has a different flexibility so that the isolated structures have different fundamental fixed-base vibration periods of 1, 2, or 3 seconds, while the fundamental fixed-base vibration period remains at 0.65 seconds. Therefore, each of the three isolated structures has a different isolated-structure-to-upper-structure vibration period ratio (VPR). The transmissibilities of the three isolated structures are shown in Figs. 4.2.1 and 4.2.2 as the MDOF results for three different VPRs: 1.54, 3.07, and 4.61. The figures also compare the MDOF results of the isolated structures to the corresponding results from the SDOF model. The SDOF results are identical for the three isolated structures when the results are presented as a function of the excitation-to-isolated-structure vibration period ratio (T/T_1). Comparing the MDOF and SDOF results in Figs. 4.2.1 and 4.2.2 shows that the MDOF results approach the SDOF

results as the value of VPR increases, or as the fundamental fixed-base vibration period (frequency) of the isolated structure becomes farther separated from the vibration periods (frequencies) of the upper structure. Therefore, the negative effects of the upper-structure vibration on the transmissibility can be effectively reduced by decreasing the vibration frequency of the isolated structure or using a more flexible isolation system.

The SDOF model is the basis for equivalent static design analysis methods for isolated structures. The model is also often used to demonstrate the potential benefits of seismic base isolation. The present findings on the possible effects of upper-structure vibrations suggest that the use of the SDOF model for these purposes would be inappropriate and may be imprudent, if the vibration period of the isolated structure is not significantly longer than the first fixed-base vibration period of the upper structure. The results in Figs. 4.2.1 and 4.2.2 seem to confirm the common belief that in general the static analysis method can be used if the isolation period is more than three times the upper-structure vibration period (UBC 1991 and Buckle 1994). However, the precise requirement would vary with the earthquake input and the structural response. Constantino et al. 1993 have shown that the SEAOC and UBC static analysis procedure for isolated structures is adequate for predicting centroid displacement but not for distributing accelerations, stresses and interstory drifts in the flexible structures that they analyzed using a MDOF model and a dynamic analysis method. In general, the earthquake input and structural response that have significant higher-frequency components will be affected more by the upper-structure vibration.

4.2 Effect of Base Isolation

The transmissibilities of the un-isolated upper structure were also obtained to demonstrate the effect of base isolation. The same MDOF upper-structure model of the isolated structure (Fig. 2.1) was used by eliminating the isolation spring and damper and attaching the first floor mass directly to the foundation or ground. Figs. 4.3.1 and 4.3.2 compare the obtained transmissibilities of

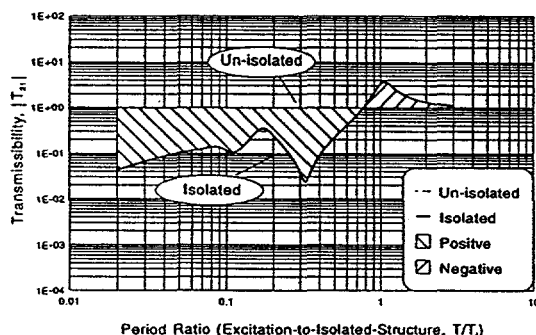
the isolated and un-isolated structures. The transmissibility T_{21} between the foundation and the base of the un-isolated structure has the identical value of 1.0 for all periods (frequencies), because the base of the un-isolated structure, being rigidly attached to the foundation, moves together with the foundation. The transmissibility T_{41} between the foundation and the top of the un-isolated structure shows a large increase near and at the fixed-base vibration period of the upper structure.

The shaded areas in Figs. 4.3.1 and 4.3.2 identify the positive and negative effects of isolation on the transmissibility. The positive effect is the large reduction of transmissibility in the range of short periods or high frequencies. The negative effect is the appreciable increase of transmissibility in periods near the fixed-base vibration period of the isolated structure.

The greatest positive effect of isolation is a nearly 50-fold reduction of transmissibility appearing at the first fixed-base isolation frequency of the un-isolated structure. The greatest negative effect is a nearly 4-fold increase of transmissibility occurring at the fixed-base frequency of the isolated structure. Therefore, the positive effect is about 12.5 (50/4) times the negative effect. Both the damping and flexibility of the isolation system contribute to the larger positive effect. Since the dampings of the isolated structure (15%) is 3 times that of the un-isolated structures (5%), the damping contributes at least 3 of the 12.5 times higher positive effect. Therefore, only about 4 of the 12.5 times higher positive effect is attributable to the flexibility of the isolation system.

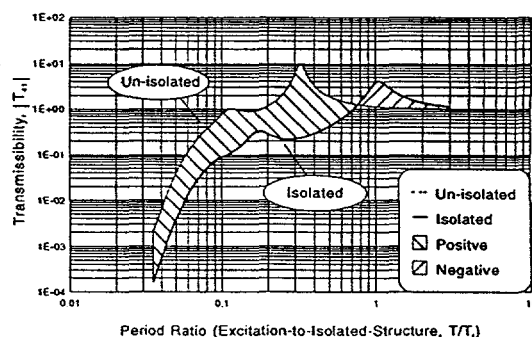
Another difference between the positive and negative effects is the consequence of the effects. The positive effect of isolation reduces the response of the first fixed-base vibration mode of the upper structure, whereas the negative effect increases the response of the rigid-body mode of the upper structure. A higher response of the rigid-body mode would produce greater strains and stresses in the isolation system but not in the upper structure. However, a higher response of the fixed-base vibration mode of the upper structure would produce the opposite consequences.

Fig. 4.3.1 Isolation effect on transmissibility of structure
Comparison of $|T_{21}|$ of isolated and un-isolated structures



The transmissibility is from the ground to the base of the structure
Isolated structure: fixed-base vibration period (T_i), 2 sec; damping, 15%
Upper structure: fixed-base vibration period, 0.65 sec; damping 5%

Fig. 4.3.2 Isolation effect on transmissibility of structure
Comparison of $|T_{41}|$ of isolated and un-isolated structures



The transmissibility is from the ground to the top of the structure
Isolated structure: fixed-base vibration period (T_i), 2 sec; damping, 15%
Upper structure: fixed-base vibration period, 0.65 sec; damping 5%

Accordingly, a base-isolation system protects a structure by exchanging a large reduction of the harmful response for a small increase in inconsequential response of the structure. The next section examines how damping can be used to control the negative effect of base isolation.

4.3 Effect of Isolation Damping

The damping coefficient c_i of the dashpot in the isolation layer of the MDOF model in Fig. 2.1 was varied to study the effect of isolation damping on the transmissibility of isolated structures. While the isolation damping was varied, the damping of the dashpots in the upper structure was kept at a constant, corresponding to a 5% damping of the first fixed-base vibration mode of the upper structure.

Figs. 4.4.1 and 4.4.2 present the results of this study for two isolation modal dampings, 0% and 15%. The results show that the damping can effectively reduce the high transmissibility at or near the fixed-base vibration period of the isolated structure. The damping, however, can also cause an increase in transmissibility at short periods (high frequencies). The increase of transmissibility increases with decreasing period (increasing frequency) but at a very small rate. Therefore, the small increase in transmissibility at short periods (high frequencies) may be ignored in determining the proper damping for the isolation system. The required damping can be set solely by the desired transmissibility and response at the fixed-base vibration frequency of the isolated structure. As shown in Section 4.5, the

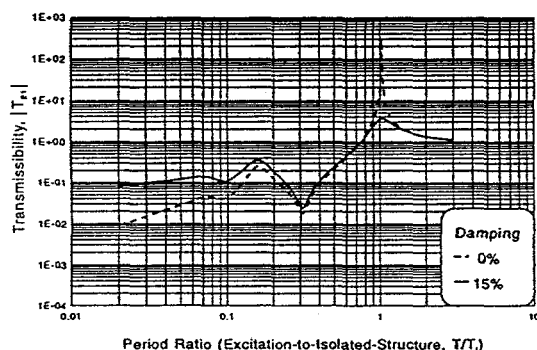
displacement response of an isolated structure can be large at the fixed-base vibration period (frequency) of the structure. The present result suggests that adding damping to the isolation system is a way to control it. The method, however, has limitations: (1) The transmissibility can never be made less than 1.0 by adding damping, (2) the damping cannot increase indefinitely without serious degradation of the isolation benefits at short periods (high frequencies).

4.4 Effect of upper-structure damping

The damping coefficient c_f of the dashpots in the upper structure of the MDOF model in Fig. 2.1 was varied to study the effect of upper-structure damping on the transmissibility of isolated structures. While the upper-structure damping was varied, the damping of the isolation layer was kept at a constant, corresponding to a 15% damping for the fixed-base vibration mode of the isolated structure.

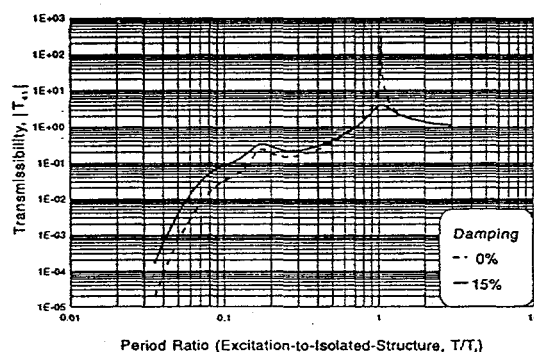
Figs. 4.5.1 and 4.5.2 (next page) present the results of this study for two upper-structure modal dampings, 0% and 5%. The results show that the damping helps to reduce the large variations of transmissibility caused by the resonant vibrations occurring near the fixed-base and free vibration frequencies of the upper structure. However, the upper-structure damping does not appear to have appreciable effect on the transmissibility at the fixed-base vibration period of the isolated structure. Thus, the upper-structure damping contributes mainly to the suppression of the resonant vibrations of the upper structure.

Fig. 4.4.1 Isolation damping effect on transmissibility of isolated structure
Comparison of $|T_{11}|$ of isolated structure with various isolation dampings



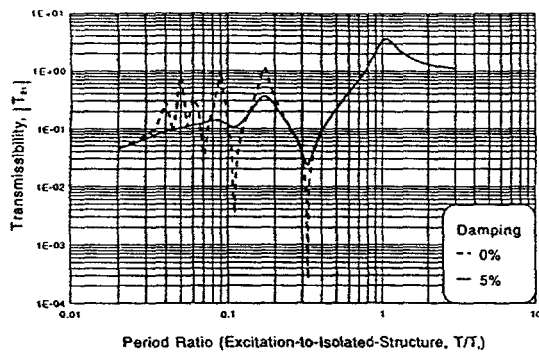
The transmissibility is from the ground to the base of the structure
Isolated structure: fixed-base vibration period (T_1), 2 sec; damping, 0 or 15%
Upper structure: fixed-base vibration period, 0.65 sec; damping 5%

Fig. 4.4.2 Isolation damping effect on transmissibility of isolated structure
Comparison of $|T_{11}|$ of isolated structure with various isolation dampings



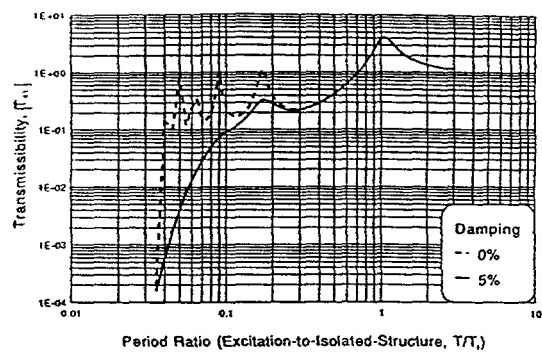
The transmissibility is from the ground to the top of the structure
Isolated structure: fixed-base vibration period (T_1), 2 sec; damping, 0 or 15%
Upper structure: fixed-base vibration period, 0.65 sec; damping 5%

Fig. 4.5.1 Upper-structure damping effect on transmissibility of isolated structure
Comparison of $|T_{11}|$ of isolated structure with various upper-structure dampings



The transmissibility is from the ground to the base of the structure
isolated structure: fixed-base vibration period (T_1), 2 sec; damping, 15%
Upper structure: fixed-base vibration period, 0.65 sec; damping 0 or 5%

Fig. 4.5.2 Upper-structure damping effect on transmissibility of isolated structure
Comparison of $|T_{11}|$ of isolated structure with various upper-structure dampings



The transmissibility is from the ground to the top of the structure
isolated structure: fixed-base vibration period (T_1), 2 sec; damping, 15%
Upper structure: fixed-base vibration period, 0.65 sec; damping 0 or 5%

4.5 Response Spectra of Upper Structure

Past research shows that the Fourier spectrum is related to the response spectrum for zero damping; therefore, it is possible to extend the present study to demonstrate the benefits of base isolation using response spectra of the upper structure.

Trifunac and associates suggest that the acceleration Fourier amplitude spectrum can be used as the relative velocity response spectrum for zero damping (Trifunac and Lee 1973 and Trifunac 1976). Similarly, Rubin and others have demonstrated that the acceleration Fourier (amplitude) spectrum can be treated as the pseudo velocity response spectrum for zero damping (Rubin 1961, Kelly and Richman 1969). To demonstrate these findings, Fig 4.6 compares the Fourier spectrum and the undamped velocity spectra of a 1994 Northridge earthquake acceleration record. The results were obtained from the processed data by Darragh et al. (1994) of the California Strong Motion Monitoring Program for a horizontal component of the ground acceleration recorded at the University of California at Los Angeles (UCLA) station. The record has some significance for seismic base isolation, because the recording station is located very near the UCLA Kerckhoff Hall which is a reinforced concrete building being seismically retrofitted with a base-isolation system.

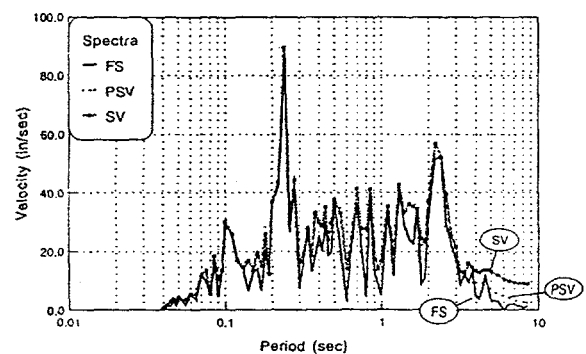
Fig. 4.6 shows: (1) The pseudo velocity response spectrum (psv) and the relative velocity spectrum (SV) nearly coincide except in the range of very long periods (very low frequencies). This result agrees with the observation made by Newmark and Hall (1976). (2) The upper envelope of the acceleration Fourier spectrum (FS) closely matches (in general, slightly lower than) that of the velocity spectra, although the lower envelope is significantly below the velocity spectra. (3) In the long-period range where the pseudo velocity and relative spectra are clearly different, the acceleration Fourier spectrum is closer to the pseudo velocity spectrum than to the relative velocity spectrum.

Based on the above analysis of the results in Fig. 4.6, the acceleration Fourier spectrum was used as the undamped pseudo-velocity response spectrum in the present study, and the following procedure was used to obtain the response spectra for a location in the structure: First, the acceleration Fourier spectrum

for the location was obtained by multiplying the ground acceleration Fourier spectrum by the transmissibility from the ground to the location (e.g., T_{21} or T_{41}). Then, the acceleration Fourier spectrum for the location was used as the undamped pseudo velocity response spectrum for the location. Last, the undamped pseudo acceleration response spectrum and the undamped relative displacement response spectrum for the location were derived from the velocity spectrum using the well-known relationships among the three response spectra. The relationships given in Newmark and Hall (1976) are identical to the relationships given in Eqs. 3.5 and 3.6, among the Fourier spectra of displacement, velocity, and acceleration. Newmark and Hall (1976) also pointed out that the undamped pseudo acceleration response spectrum and the undamped absolute acceleration spectrum are the same over the entire period (frequency) range.

Fig 4.6 Comparison of Fourier and response spectra

1994 Northridge earthquake, UCLA Grounds CHN 3, 360° horizontal



Data from Darragh et al. (1994): FS, acceleration Fourier spectrum;
PSV & SV, pseudo-velocity and relative-velocity response spectra for zero damping

Figs. 4.7.1 - 4.8.2 present the undamped response spectra obtained from the 1994 Northridge UCLA ground acceleration Fourier spectrum using the previously described procedure. Figs.

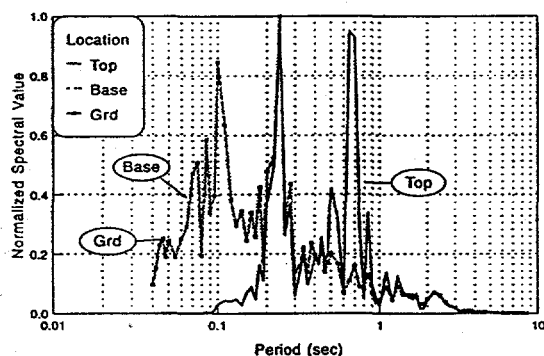
4.7.1 and 4.8.1 are the acceleration and displacement response spectra for the un-isolated MDOF upper structure shown in Fig. 2.1. Figs. 4.7.2 and 4.8.2 are the same response spectra of the same structure after the structure has been isolated with a base-isolation system. Each of the spectra in the figures are normalized by the corresponding peak ground spectral value for convenient comparison. A quick review of the spectra for both the isolated and un-isolated produces the following general differences between the responses of isolated and un-isolated structures:

- (1) The displacement and acceleration response spectra of the isolated structure do not appear to vary appreciably from

the base to the top of the upper structure, whereas the spectra of the un-isolated structure show significant differences between the base and the top of the structure.

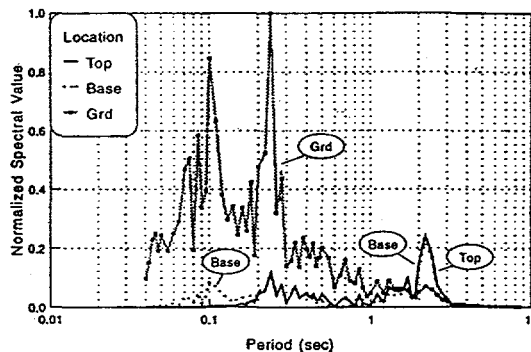
- (2) The overall acceleration response spectra of the isolated structure appear to be significantly lower than that of the ground and of the un-isolated structure. However, the same impression does not seem to hold for the displacement response spectra.

Fig 4.7.1 Acceleration response spectra of un-isolated structure
1994 Northridge earthquake, UCLA Grounds CHN 3, 360° horizontal



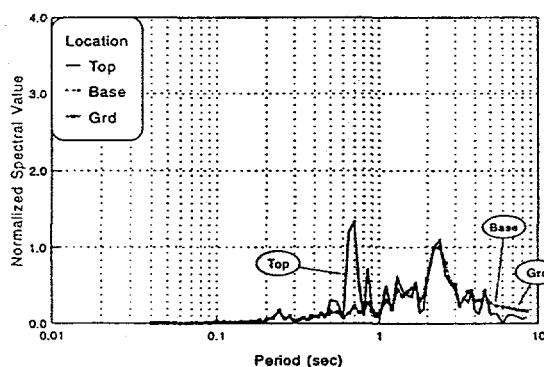
Spectra are absolute acceleration for zero damping & normalized by the peak ground spectral value
Un-isolated structure: fixed-base vibration period, 0.65 sec; damping, 5%

Fig 4.7.2 Acceleration response spectra of isolated structure I
1994 Northridge earthquake, UCLA Grounds CHN 3, 360° horizontal



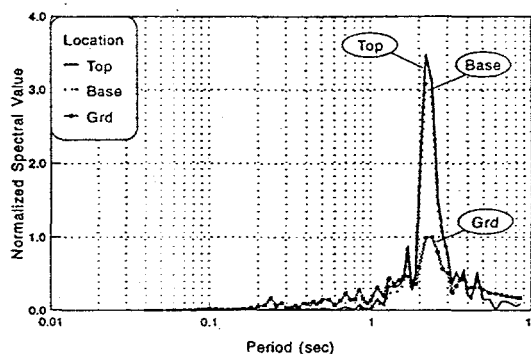
Spectra are absolute acceleration for zero damping & normalized by the peak ground spectral value
Isolated structure: fixed-base vibration period, 2 sec; damping, 15%
Upper structure: fixed-base vibration period, 0.65 sec; damping, 5%

Fig 4.8.1 Displacement response spectra of un-isolated structure
1994 Northridge earthquake, UCLA Grounds CHN 3, 360° horizontal



Spectra are relative displacement for zero damping & normalized by the peak ground spectral value
Un-isolated structure: fixed-base vibration period, 0.65 sec; damping, 5%

Fig 4.8.2 Displacement response spectra of isolated structure I
1994 Northridge earthquake, UCLA Grounds CHN 3, 360° horizontal



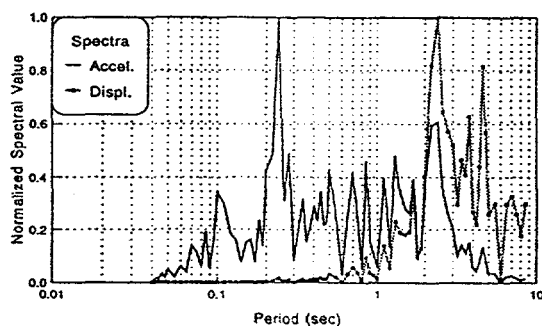
Spectra are relative displacement for zero damping & normalized by the peak ground spectral value
Isolated structure: fixed-base vibration period, 2.0 sec; damping, 15%
Upper structure: fixed-base vibration period, 0.65 sec; damping, 5%

A careful analysis of the results in Figs. 4.7.1 - 4.8.2 reveals that the impressions are the combined result of the following factors:

- (1) The response of the isolated structure is dominated by the fixed-base vibration mode of the isolated structure in which the upper structure moves like a rigid body. On the other hand, the response of the un-isolated structure is dominated by the fixed-base vibration mode or modes of the upper structure in which the structure moves like a cantilever.
- (2) The isolation system acts like a low pass filter, which attenuates transmitted ground motions whose periods are shorter than the fixed-base vibration period of the isolated structure.
- (3) Ground-acceleration components of significant amplitude are located at shorter periods relative to the dominant components of the ground displacement.
- (4) The dominant vibration period (the first fixed-base vibration period) of the un-isolated structure is located within the period range of the dominant acceleration components, whereas the dominant fixed-base vibration period of the isolated structure is located within the period range of dominant displacement components.

The first two factors were described earlier, and the last two factors are discussed here. Factor #3 is a natural consequence of Eqs. 3.5 and 3.6. Fig. 4.9 shows the Northridge ground

Fig 4.9 Comparison of Fourier spectra
1994 Northridge earthquake, UCLA Grounds, CHN 3, 360° horizontal

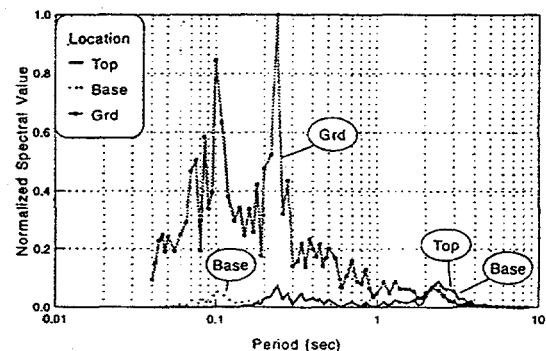


Acceleration spectrum from Darragh et al (1994)
Displacement spectrum derived from acceleration spectrum using Eqs.(3.5) & (3.6)
Each spectrum is normalized by its peak spectral value

acceleration Fourier spectrum used for this study and the displacement Fourier spectrum obtained using the two equations. The figure clearly shows that the acceleration components of significant amplitude are scattered in a higher period range than the dominant displacement components (0.2–2.5 sec. vs. 2–5 sec.). The first fixed-base vibration period of the un-isolated structure of 0.65 sec. is within the period range of significant accelerations, and the fixed-base vibration period of the isolated structure of 2 secs. is within the period range of significant displacements.

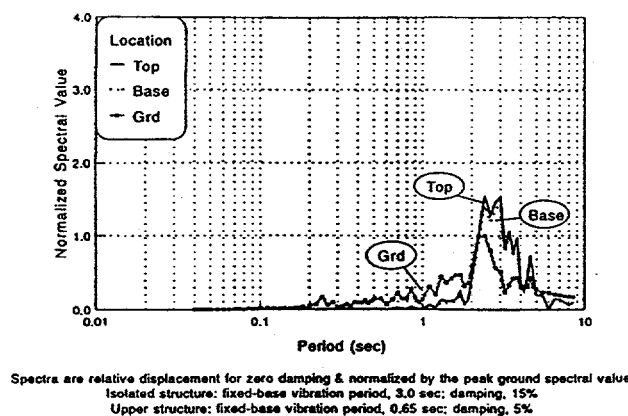
To demonstrate that the displacement response of an isolated structure can also be reduced (like the acceleration) by using a more flexible isolation system, the foregoing analysis of the isolated structure was repeated using a more flexible isolation system that lowered the fixed-base vibration frequency of the isolated structure to 3 sec. from the original 2 sec. Figs. 4.10.1 and 4.10.2 present the acceleration and displacement spectra of this new isolated structure, respectively. The results show that the new structure has significantly lower displacement response, though the new vibration period of 3 sec. is only slightly below the period of the highest displacement component (about 2.3 sec.) but not out of the range of the significant displacements. Unfortunately, in practice the flexibility of an isolation system cannot be increased indefinitely. A minimum flexibility is required to resist normal lateral loads like wind. Besides, there exists a persistent doubt that existing earthquake ground motion records may not adequately describe the possible maximum earthquake motions at long periods (low frequencies). Local soft soil and fault conditions can amplify the earthquake motion.

Fig 4.10.1 Acceleration response spectra of isolated structure II
1994 Northridge earthquake, UCLA Grounds CHN 3, 360° horizontal



Spectra are absolute acceleration for zero damping & normalized by the peak ground spectral value
Isolated structure: fixed-base vibration period, 3.0 sec; damping, 15%
Upper structure: fixed-base vibration period, 0.65 sec; damping, 5%

Fig 4.10.2 Displacement response spectra of isolated structure II
1994 Northridge earthquake, UCLA Grounds CHN 3, 360° horizontal



5.0 SUMMARY AND CONCLUSIONS

The transmissibility and response of linear isolated and un-isolated structures under seismic excitations have been analyzed and compared. The following are the major findings:

- A base-isolation system acts like a low-pass filter in transmitting seismic loads to the upper structure; it attenuates the short-period (high-frequency) loads but does not affect the long-period (low-frequency) ones. The period (frequency) separating the two different transmission behaviors is the fundamental fixed-base vibration period (frequency) of the isolated structure. Below the vibration period (above the frequency), the transmissibility is less than 1.0 and decreases with decreasing period (increasing frequency). Above the vibration period (below the vibration frequency), the transmissibility equals 1.0.
- The transmissibility and response of an isolated structure, however, can increase significantly near and at its fixed-base vibration period (frequency) due to the resonant vibration of the structure. The vibration and the resulting increase of transmissibility and response can be reduced by adding damping to the isolation system.
- Resonant vibrations of the upper structure of an isolated structure can also cause the transmissibility to increase substantially and fluctuate widely with the period (frequency) in the period (frequency) range near and below (above) the first fixed-base vibration period (frequency) of the upper structure. Adding damping to the upper structure can reduce the fluctuations but not the general increase of transmissibility. The general increase can only be reduced by further separating the fixed-base vibration periods (frequencies) of the upper structure and the isolated structure. The needed separation can be

achieved by stiffening the upper structure or softening the isolation system.

- Under the same ground excitation, the dynamic response of a structure with base isolation can be significantly lower and more uniformly distributed than the response of the same structure without base isolation. Accordingly, base isolation can be an effective means for providing uniform protection to all contents and equipment in a structure.

The findings of this study have suggested the following guidelines for the design and analysis of isolated structures.

- A base-isolation system must be sufficiently flexible to cause the fixed-base vibration period (frequency) of the isolated structure to be significantly longer (lower) than the first fixed-base vibration period (frequency) of the upper structure and the periods (frequencies) of the dominant earthquake excitations. In general, the periods (frequencies) of the dominant accelerations are the shortest (highest) and those of the displacements are the longest (lowest), with the velocities between them.
- A base-isolation system must also carry sufficient damping to suppress possible large displacement of the upper structure caused by the resonant vibration response of the isolated structure. The large displacement can also be reduced by increasing (lowering) the vibration period (frequency) beyond the dominant period (frequency) range of the displacement.
- The fixed-base vibration period of the isolated structure should be greater than 2 to 3 times the fixed-base vibration period of the upper structure to avoid significant degradation of the isolation effectiveness due to the vibrations of the upper structure.
- If the effect of the upper-structure vibrations on a response is expected to be appreciable, the analysis of the response should be carried out using a dynamic analysis and an appropriate MDOF model for the upper structure. An equivalent static method based on an SDOF model of the isolated structure would not be adequate for this situation. Different responses may have different analysis requirements, because they may have different frequency contents and thus may be affected differently by the vibration of the upper structure. The displacement response is usually less affected by the vibration effects than the acceleration, force and stress responses.
- The analysis method used for this study can be applied as a simplified method for preliminary response analysis of linear isolated structures.

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title Frequency Response Characteristics and Response Spectra of Base-Isolated and Un-Isolated Structures

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session Seismic, Shock, and Vibration Isolation—1995

division

abstract

The transmissibility of seismic loads through a linear base-isolation system is analyzed using an impedance method. The results show that the system acts like a "low-pass" filter. It attenuates high-frequency loads but passes through low-frequency ones. The filtering effect depends on the vibration frequencies and damping of the isolated structure and the isolation system. This paper demonstrates the benefits and design principles of base isolation by comparing the transmissibilities and response spectra of isolated and un-isolated structures. Parameters of typical isolated buildings and ground motions of the 1994 Northridge earthquake are used for the demonstration.