EFFECT OF VARIOUS ENERGY DISSIPATION MECHANISMS IN SUPPRESSING STRUCTURAL RESPONSE

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SUMMARY

In this paper the efficiency of various dissipative mechanisms to protect structures from pulse-type and near-source ground motions is examined. Physically realizable cycloidal pulses are introduced, their resemblance to recorded near-source ground motions is illustrated, and their shaking potential is examined. It is found that the response of structures with low to moderate isolation periods is substantially affected by the high frequency fluctuations that override the long duration pulse, therefore the concept of seismic isolation is beneficial even for motions that contain a long duration pulse which generates the large recorded displacements and velocities. Dissipation forces of friction type are efficient in reducing displacement demands, although occasionally they are responsible for substantial permanent displacements. The study concludes that a combination of relatively low friction and viscous dissipation forces is attractive since base displacements are substantially reduced without increasing appreciably base shears.

INTRODUCTION

The dynamic response of a structure depends on its mechanical properties and the characteristics of the induced excitation. Mechanical properties which are efficient to mitigate the structure's response when subjected to certain inputs might have an undesirable effect during other inputs. Ground motions vary significantly from one another in amplitude, frequency content and duration. Those characteristics are influenced by source mechanism and travel path and modified by local geological and soil conditions. The ability to dissipate the induced energy is crucial to the earthquake resistance of a structure. Various energy dissipation mechanisms have been proposed to enhance structural response [ATC, 1993]. These energy dissipation mechanisms can be of various types such as viscous, rigid-plastic, elastoplastic, viscoplastic, or combination of them.

The challenge to provide seismic protection is the selection of appropriate mechanical properties that improve the response of a structure subjected to either high-frequency spikes or low-frequency pulses. Previous studies [Anderson and Bertero 1993, Hall et al. 1995] indicated that what makes near-source ground motions particularly destructive to some structures is not their peak ground accelerations but their long duration pulses. These indications challenged the concept of seismic isolation. In this chapter, the effect of various dissipation mechanisms in reducing the response of seismically isolated structures is investigated in detail. Different level of yield displacements, viscous forces and plastic forces are examined. It is shown that seismic isolation is an effective protection strategy provided that the appropriate energy dissipation mechanism is provided.

In this study the effect of various dissipation mechanisms in reducing the response of seismically isolated structure subjected to near-source ground motions is examined in detail. Selected near-source ground motions are presented and their resemblance to physically realizable cycloidal pulses is shown. A type-A cycloidal pulse approximates a forward motion and a type-B cycloid pulse approximates a forward-and-back motion; whereas, a type-C_n pulse approximates a recorded motion that exhibits n main cycles in its displacement history. The

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velocity histories of all type-A, type-B and type-C_n pulses are differentiable signals that result in finite acceleration values.

While the proposed cycloidal pulses capture many of the kinematic characteristics of the displacement and velocity histories of recorded near-source ground motions, in most cases the resulting accelerations are poor predictions of the recorded histories. This is because in many near-source ground motions there are high frequency fluctuations that override the long duration pulse. It is shown that the response of structures with low to moderate isolation periods is affected significantly by these high frequency fluctuations indicating that the concept of seismic protection by lengthening the isolation period is beneficial when the appropriate type of energy dissipation is provided. The paper concludes that a combination of relatively low values of friction and viscous damping results to an attractive design since displacements are substantially reduced without increasing appreciably base shears.

CLOSED FORM APPROXIMATION OF NEAR-SOURCE GROUND MOTIONS

In recent years, the quantity and quality of recorded strong-motion data have increased significantly. These data recognize the kinematic characteristics of the near-fault ground motions which contain large displacement pulses from 0.5 m to more than 1.5 m with peak velocities of 0.5 m/sec or higher. In some cases, the coherent pulse is distinguishable not only in the displacement and velocity histories, but also in the acceleration history. In other cases, acceleration histories recorded near the faults contain high-frequency spikes and resemble the traditional random-like signals; however, their velocity and displacement histories uncover a coherent long-period pulses with some overriding high-frequency fluctuations [Campillo et al. 1989, Iwan and Chen 1995].

The physics of the near-source ground motions is complicated. Some of their components have larger intensities with higher frequency in the direction of rupture propagation and some of their components have smaller intensities with lower frequency at the opposite direction. The rupture propagation toward a site at a rate closed to the shear wave velocity causes accumulation of the seismic energy and this result in a single long period pulse. The pulse represents the cumulative effect of the seismic energy radiating from the fault [Somerville and Graves 1993].

The fault parallel component of many near-source ground motion resembles a forward motion that can generate large permanent ground displacements of the order of 1.0 m or higher. In some cases, they can be approximated with type-A cycloidal pulses [Jacobsen and Ayre 1985, Makris 1997], which is defined as:

$$u_g^A(t) = \frac{v_p}{2} t - \frac{v_p}{2\omega_p} \sin(\omega_p t), \quad 0 \le t \le T_p . \tag{1}$$

On the other hand the fault normal component of many near-source records resembles a forward-and-back motion. They can be approximated with type-B cycloidal pulses [Makris 1997], which is defined as:

$$u_g^B(t) = \frac{v_p}{\omega_p} - \frac{v_p}{\omega_p} \cos(\omega_p t), \quad 0 \le t \le T_p , \tag{2}$$

where v_p is the velocity amplitude and $\omega_p = 2\pi / T_p$ is the circular frequency of the pulse. The type-A pulse reaches its maximum displacement, $u_{g,\max}^A = \pi v_p / \omega_p$, at the end of the forward pulse, while the type-B pulse reaches its maximum displacement, $u_{g,\max}^B = 2 v_p / \omega_p$, at $t = T_p / 2$. The report by Makris and Chang (1998) shows examples of recorded forward only and forward-and-back motions that can be approximated with the type-A and type-B pulses.

Not all near source records are type-A or type-B pulses. Figure 1 shows the acceleration, velocity and displacement time histories of the fault-normal component of the October 15th, 1979 Imperial Valley earthquake recorded at the El Centro Station Array #7. The ground displacement has a long-period pulse, which started at 3.4 sec and ended at 6.8 sec. The ground displacement consists of a main long period cycles. These near-fault ground motions, where the displacement history exhibits one or more long duration cycles, are approximated with type-C pulses. An n-cycle ground displacement is approximated with a type- C_n pulse, which is defined as

$$u_g^{c_n}(t) = -\frac{v_p}{\omega_p}\cos(\omega_p t + \varphi) - v_p t \sin(\varphi) + \frac{v_p}{\omega_p}\cos(\varphi)\,, \quad 0 \le t \le (n + \frac{1}{2} - \frac{\varphi}{\pi})T_p\,. \tag{3}$$

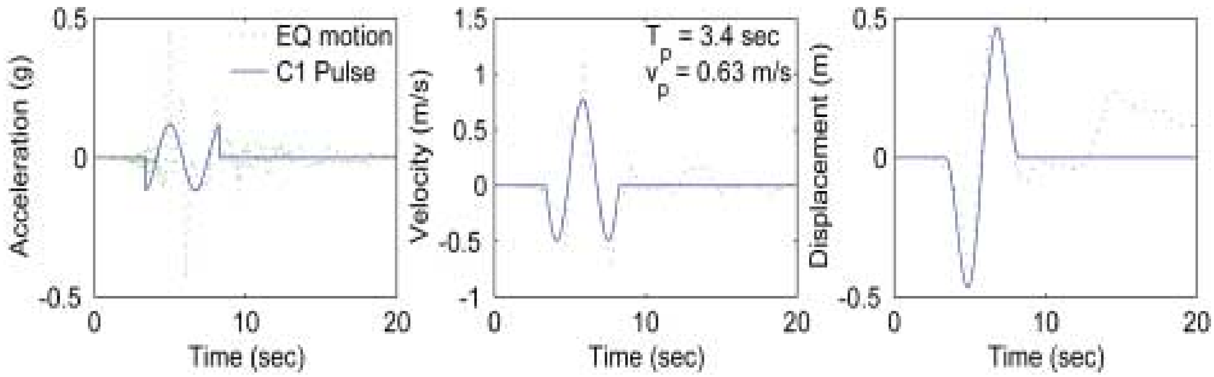

Figure 1: Acceleration, velocity and displacement histories of the 1979 Imperial Valley Earthquake, El Centro Array #7 – S50W and a cycloidal type- C_1 **pulse.**

A type- C_n pulse with frequency $\omega_p = 2\pi / T_p$ has duration $T = (n + 1/2 - \varphi/\pi)T_p$. In deriving these expressions, it is required that the displacement and velocity are differentiable signals. The value of the phase angle, φ, is determined by requiring that the ground displacement at the end of the pulse be zero. In order to have a zero ground displacement at the end of a type- C_n pulse; equation (3) is equal to zero when $t = (n + 1/2 - \varphi/\pi)T_p$, which gives

$$\cos[(2n+1)\pi - \varphi] + [(2n+1)\pi - 2\varphi]\sin\varphi - \cos\varphi = 0\,. \tag{4}$$

The solution of this transcendental equation gives the value of the phase angle φ. For example, for a type- C_1 pulse (n = 1), φ is equal to 0.0697π ; whereas, for a type- C_2 pulse (n = 2), φ is equal to 0.0410π. Figure 1 (left) plots a type- C_1 pulse (n = 1) with a pulse period, T_p = 3.4 s and a velocity amplitude, v_p = 0.63 m/s. The type- C_n pulse reaches its peak displacement, $u_{g,\max}^{C_n} = (2v_p / \omega_p)\cos(\varphi) - (v_p / \omega_p)(\pi - 2\varphi)\sin(\varphi)$, at $t = (1/2 - \varphi/\pi)T_p$ and peak velocity, $\dot{u}_{g,\max}^{C_n} = v_p + v_p \sin(\varphi)$, at $t = (3/4 - \varphi/(2\pi))T_p$. The velocity amplitude of the type-Cn pulse is slightly larger than v_p, which is the velocity amplitude of a type-A or a type-B pulse.

It is shown that while trigonometric pulses can capture many of the kinematic characteristics of the displacement and velocity histories recorded near the faults of strong earthquake, they do not capture the high frequency fluctuations shown on the acceleration records. This high frequency content affects the response and the results derived by considering smooth trigonometric pulses should be used with caution.

THE DISSIPATION MECHANISM OF PRACTICAL ISOLATION SYSTEMS

In addition to its restoring capability, an isolation system dissipates energy. The dissipation mechanism of practical isolation systems can be approximated with various macroscopic models: (1) viscous model (viscous fluid dampers); (2) rigid-plastic model (sliding bearings); (3) elastoplastic model (lead rubber bearings); (4) viscoplastic model (sliding bearings with viscous fluid dampers); (5) elastoviscoplastic model (elastomeric bearings with controllable fluid dampers).

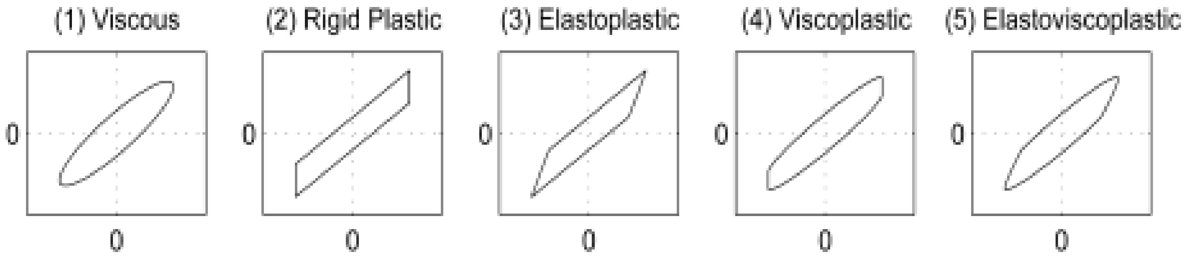

Figure 2: Idealizations of energy dissipation mechanisms of practical seismic isolation system.

Figure 2 shows the force-displacement loops of these five dissipation mechanisms. It is worth mentioning that the rigid plastic model is the limiting case of the elastoplastic model when the yield displacement becomes very small, whereas the rigid plastic model is also the limiting case of the viscoplastic model when the viscous component vanishes. Accordingly, the dissipative behavior of a sliding bearing is the limiting case of dissipative behavior of a lead rubber bearing with a very small yield displacement.

The dissipation force of these idealized macroscopic models can be expressed mathematically as

$$P(t) = C_b \dot{u}_b(t) + \alpha K_e u_b(t) + (1-\alpha) K_e u_y z(t)\,, \tag{5}$$

where C_b is the viscous damping coefficient of the isolation system, α is a parameter that controls the post yielding stiffness, K_e is some reference stiffness, u_y is the value of the yield displacement and z is a hysteretic dimensionless variable that is govern by the following equation.

$$u_y \dot{z} + \beta \dot{u}(t)|z|^n + \gamma |\dot{u}(t)| z |z|^{n-1} - A\dot{u}(t) = 0\,. \tag{6}$$

The model given by (5) and (6) is the Bouc-Wen model (Wen 1975) enhanced with a viscous term. In the equation (5), β, γ, n and *A* are dimensionless quantities that control the shape of the hysteretic loop. It can be shown that when *A* = 1, parameter K_e in equation (5) becomes the pre-yielding elastic stiffness and parameter becomes the ratio of the post to pre-yielding stiffness. Based on this observation parameter, *A* is set equal to one. For the special case of sliding bearings, the pre-yielding stiffness is very large and the yield displacement is close to zero so that the product, $K_e u_y$, is equal to a finite yield force, P_y.

Under ground excitation, $\ddot{u}_g(t)$, the equation of motion for a simple 2-DOF isolated structure can be expressed as

$$\begin{bmatrix} 1 & \gamma_m \\ 1 & 1 \end{bmatrix} \begin{bmatrix} \ddot{u}_b(t) \\ \ddot{u}_s(t) \end{bmatrix} + \begin{bmatrix} 0 & 0 \\ 0 & 2\zeta_s \omega_s \end{bmatrix} \begin{bmatrix} \dot{u}_b(t) \\ \dot{u}_s(t) \end{bmatrix} + \begin{bmatrix} \omega_b^2 & 0 \\ 0 & \omega_s^2 \end{bmatrix} \begin{bmatrix} u_b(t) \\ u_s(t) \end{bmatrix} + \begin{bmatrix} \dfrac{P(t)}{m_s + m_b} \\ 0 \end{bmatrix} = -\begin{bmatrix} \ddot{u}_g(t) \\ \ddot{u}_g(t) \end{bmatrix}, \tag{7}$$

where $P(t)$ is the dissipation force given by equation (5). The response of a 2-DOF isolated structure is computed by using a state-space formulation where the state vector of the system is $y(t) = < u_b(t), \dot{u}_b(t), u_s(t), \dot{u}_s(t), z(t) >^T$. The natural frequency of the fixed base superstructure is $\omega_s = \sqrt{K_s / m_s}$ and the isolation frequency is $\omega_b = \sqrt{K_b /(m_s + m_b)}$. Furthermore, the damping ratio of the superstructure is defined as $\zeta_s = C_s /(2 m_s \omega_s)$ and the damping ratio of the isolation system is defined as $\zeta_b = C_b /[(2(m_s + m_b)\omega_b]$. Because of the presence of the isolation system, the 2-DOF structure will primarily oscillate along its first mode.

PARAMETRIC STUDY

The scope of this parametric study is to provide information on the efficiency of various combinations of dissipation mechanism to suppress the earthquake response. Therefore, various levels of viscous damping and friction damping with different yield displacement (u_y = 0.2mm and u_y = 0.2mm) are consider. When viscous damping alone is considered in the spectra, the levels of viscous damping have been chosen to be ζ = 5%, 15% and 30%. In the case of seismically isolated structures, isolation systems with ζ = 15% are common; whereas, isolation damping, ζ = 30% is at the high end. The levels of friction selected are μ = 5%, 10% and 15%. The values of 5% and 10% are common on commercially available sliding bearings or lead rubber bearings. The value of μ = 15% was selected to illustrate the effects of high-value dry friction in civil engineering applications.

The seismic performance of a 2-DOF isolated structure equipped with various types of damping mechanisms in its isolation system is presented in Figure 3, where base displacement, base shear, interstory drift and superstructure acceleration spectra are plotted. The 2-DOF isolated structure is subjected to a type-C_1 pulse with $T_p^{c_1}$ = 3.4 sec and the fault normal component of the 1979 El Centro Array #7 record. While the base displacement spectra from the trigonometric pulse and the recorded motion reveal similar trends, the other spectra exhibit drastic differences at the low isolation period range. This is because the trigonometric pulse is clean from the high frequency fluctuations that the recorded acceleration contains (see Figure 1). Accordingly, cycloidal pulses should be used with caution when one is interested in evaluating seismic response. The yield displacement, u_y, in the first two column of Figure 3 is equal to 0.2 mm which represents the rigid-plastic dissipation mechanism. The yield displacement in the third column is equal to 20 mm which represents the elastic-plastic dissipation mechanism. The differences between a rigid-plastic and an elastic-plastic model that will reflect the behavior of a teflon sliding bearing and a lead rubber bearing respectively with the same yield force. It is shown that smaller yield displacement has most desirable performance but the difference is limited. Rigid-plastic behavior (sliding bearings) results to similar degree of response reduction as elastic-plastic behavior (lead rubber bearings) provided that both systems have the same yield force. By elongating the isolation period from the peak response range of the acceleration spectrum to the low response range, the isolated structure can reduce its base shear and superstructure acceleration at the expense of a larger base displacement. Viscous dissipation is effective to eliminate the resonance for the 2-DOF isolated structure with isolation period around 0.7 sec; whereas friction dissipation is effective to reduce the base displacement for isolation periods longer than 2 sec. An appropriate energy dissipation mechanism can alleviate this large base displacement and further reduce the base shear. Figure 3 shows that a combination of viscous and friction damping results in an attractive performance, since the effective reduction of displacements is accompanied by base shear lower than that resulting from friction dissipation alone.

Figure 4 summarized the effect of adding viscous and friction damping on the isolated structures with different flexibility. When none or a small amount of friction damping is involved in the isolation system, adding viscous damping is beneficial to suppress most of the responses. If the additional viscous damping exceeds a certain amount, the base displacement will be further reduced but the base shear and the superstructure responses may increase. Therefore, there is an optimum amount of additional viscous damping. When a large amount of friction damping is involved in the isolation system, adding viscous damping has minor effect on the maximum responses. This is observed by the nearly horizontal lines of the structural responses when is equal to 15%. By comparing the second and third column of Figure 4, the flexibility of the superstructure has a major influence on the interstory drift while fewer effects on the other spectral values. A low level of friction damping combines with a proper amount of viscous damping has the best performance in the superstructure response.

CONCLUSIONS

The efficiency of various dissipative mechanisms to protect isolated structures from pulse-type and near-source ground motion has been investigated in detail. It was first shown that under these motions the concept of equivalent linear damping has limited meaning since the transient response of a structure is more sensitive to the nature of the dissipation forces, rather then the amount of energy dissipated per cycle.

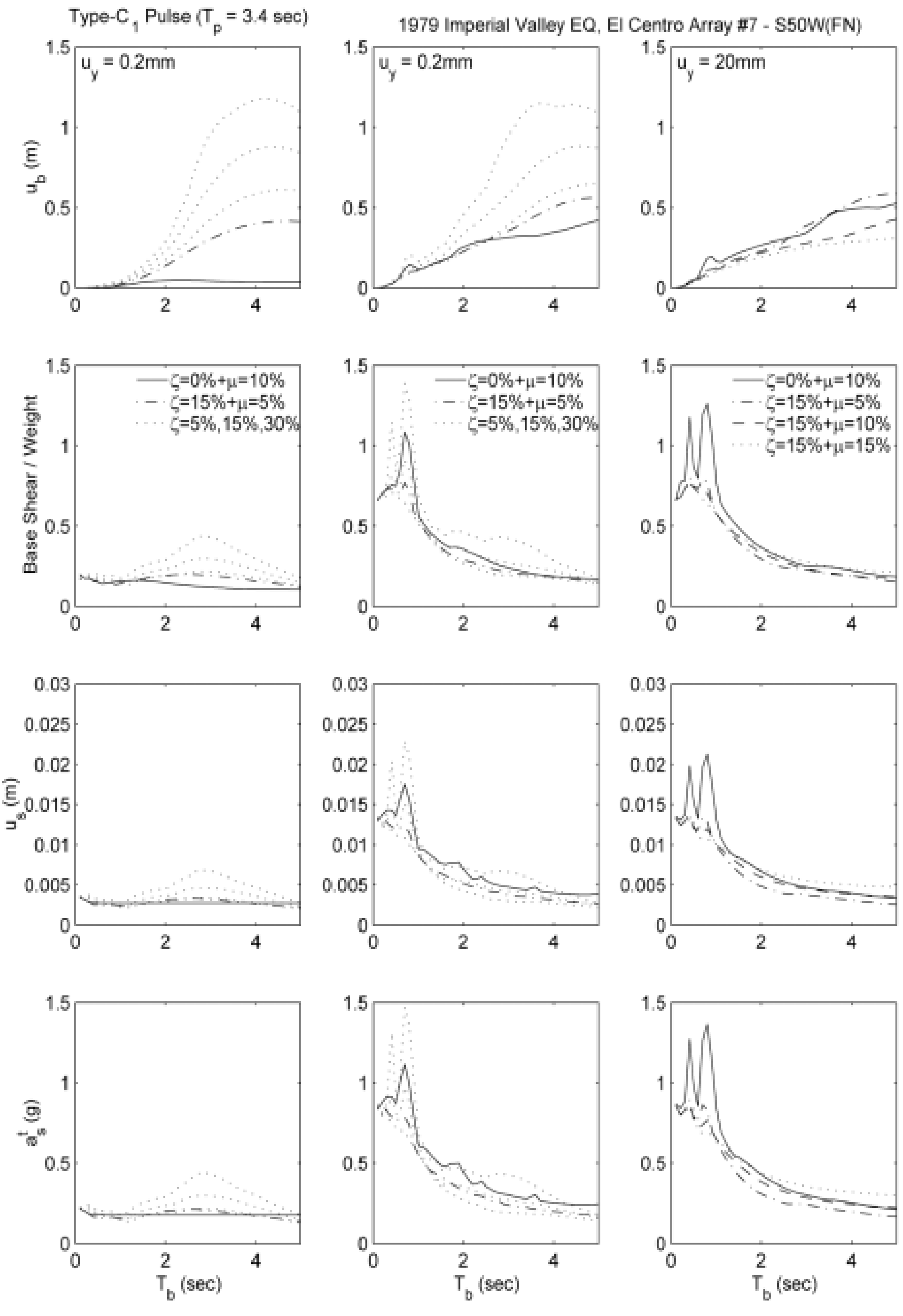

Figure 3: Base displacement, base shear, superstructure drift and total superstructure acceleration spectra of a 2-DOF isolated structure subjected to a type-C_1 pulse and the El Centro Array #7 record.

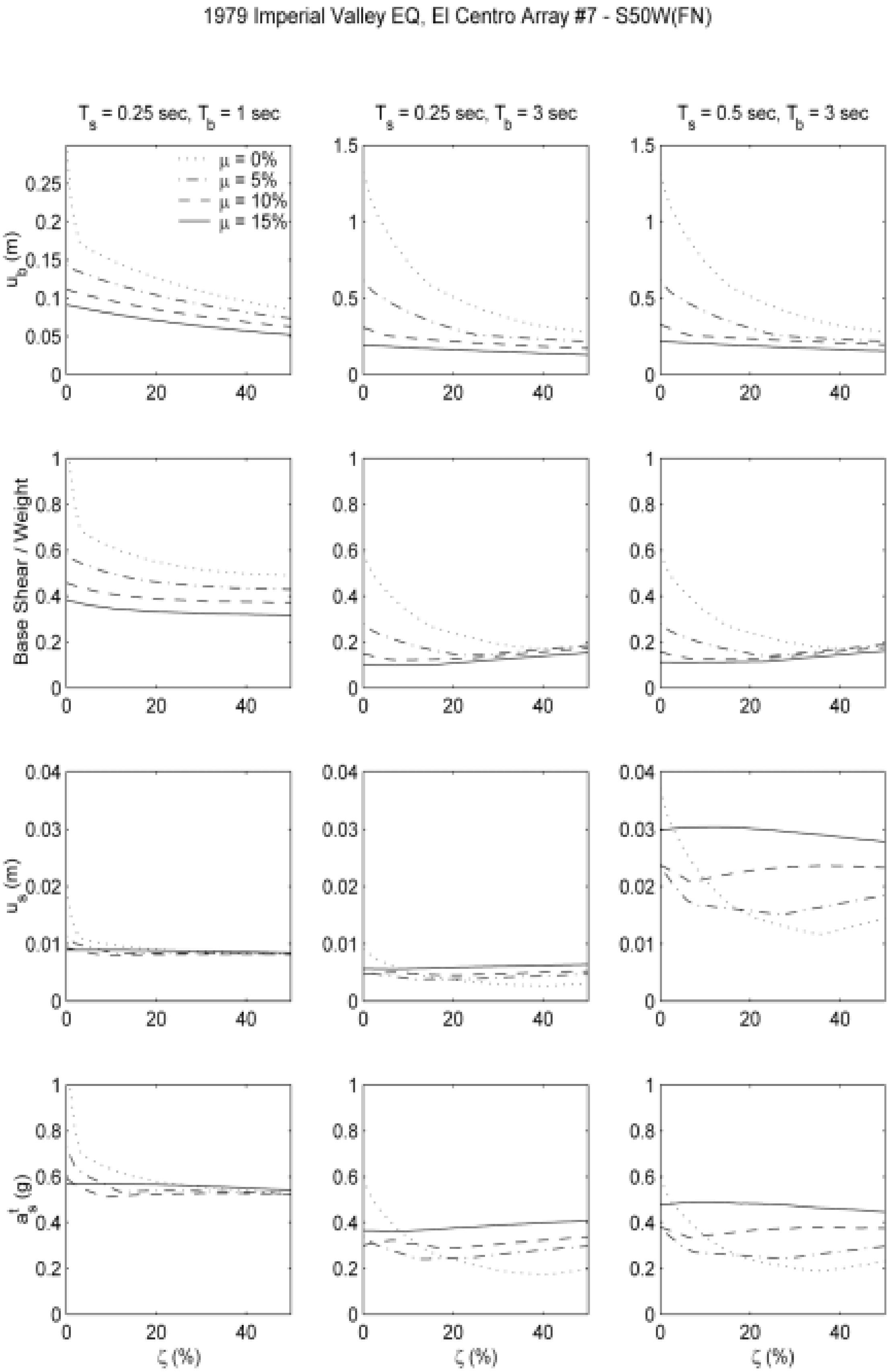

Figure 4: Base displacement, base shear, superstructure drift and total superstructure acceleration spectra of three different 2-DOF isolated structures subjected to the 1979 El Centro Array #7 record.

Physically realizable trigonometric pulses have been introduced and their resemblance to selected near-source ground motions was illustrated. It was found that the structural response due to ground motions recorded near the source resembles the structural response due to cycloidal pulses only when the structure is on the flexible side. The paper concludes that the response of structures with relatively low periods is substantially affected by the high frequencies that override the long duration pulse. Therefore, the concept of seismic isolation is beneficial even for motions that contain long velocity and displacement pulses. Even a low value of plastic (friction) damping (i.e. $\mu \approx 5$%-10%) removes any resonant effects that a long duration pulse has on a long period structure.

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