EFFECTS OF NEAR-FIELD PULSE-LIKE GROUND MOTIONS ON TALL BUILDINGS

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ABSTRACT

Response of tall buildings to near-field ground motions with distinct low-frequency pulses can differ dramatically from, for example, the response to the 1940 El Centro ground motion. For the same peak ground acceleration (*PGA*) and duration of shaking, ground motions with a pulse-like characteristic can generate much higher base shear, inter-story drifts and roof displacement in a high-rise building as compared to ground motions without the characteristic pulse. Also, the ductility demand is much higher and the effectiveness of supplemental damping is lower for pulse-like ground motions. This paper presents a simple interpretation of the response characteristics for two recorded and one synthetic near-field pulse-like ground motions.

Key words: Ground motion, Near source, Tall buildings

1. Introduction

Ground motions recorded at near-field stations located in the direction of fault rupture may contain a distinct low-frequency pulse in the acceleration time history. The response of structures to these ground motions can differ dramatically from, for example, the response to the 1940 El Centro ground motion, which does not contain the characteristic pulse. It has been implied (Iwan, 1997) that the pulse in the near-field ground motion travels through the building as a wave, and that the conventional techniques using the modal superposition method and the response spectrum analysis may not capture the effect of this pulse. The objectives of this paper are to gain insight into the response characteristics of near-field pulse-like ground motions, and to evaluate the applicability of conventional methods for the linear analysis of buildings subjected to pulse-like ground motions.

2. Near-Field Ground Motions

The following three near-field ground motions are studied in this paper:

1940 El Centro

The 1940 El Centro ground motion time history was recorded during a M6.9, strike-slip earthquake, at a soil site located roughly 8 km from the surface projection of the fault (Richter, 1958). The acceleration, velocity and displacement time histories of the North-South El Centro ground motion (e.g. Trifunac and Lee, 1978) are shown in Figure 1(a). For El Centro record, the peak ground acceleration is PGA = 0.32 g, peak ground velocity PGV = 36 cm/sec (14 in/sec), and the peak ground displacement PGD = 21 cm (8.4 in). The El Centro time history is one of the earliest recorded and most widely used near-field ground motion time histories. It does not contain a distinct pulse in the

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acceleration time history.

1979 Imperial Valley

Shown in Figure 1(b) are the plots of the 1979 Imperial Valley ground motion time history recorded at a soil site in S50W direction (Brady et al., 1980) during a M6.8, strike-slip earthquake. The site was located roughly 1 km from the surface projection of the fault. The *PGA* for this ground motion is only 37% higher than the El Centro ground motion. However, the *PGV* and *PGD* values are, respectively, 3 and 2.6 times the values for the El Centro ground motion. The Imperial Valley time history does contain a pulse in the acceleration time history, which translates into pulses in the velocity and displacement time histories.

Synthetic

The plots shown in Figure 1(c) are of a simulated ground motion time history for a soil site for a M7, blind-thrust event (Hall et al., 1995). The site is 15 km from the surface projection of the fault. Note that the acceleration time history has a wide pulse, which causes the ground acceleration to remain at its peak value for nearly 1 sec. This, in turn, causes ground velocity and displacement to attain very high values. The *PGA* for the synthetic ground motion is only 25% higher than the El Centro ground motion, but the *PGV* is nearly 4 times and the *PGD* nearly 9 times the El Centro ground motion.

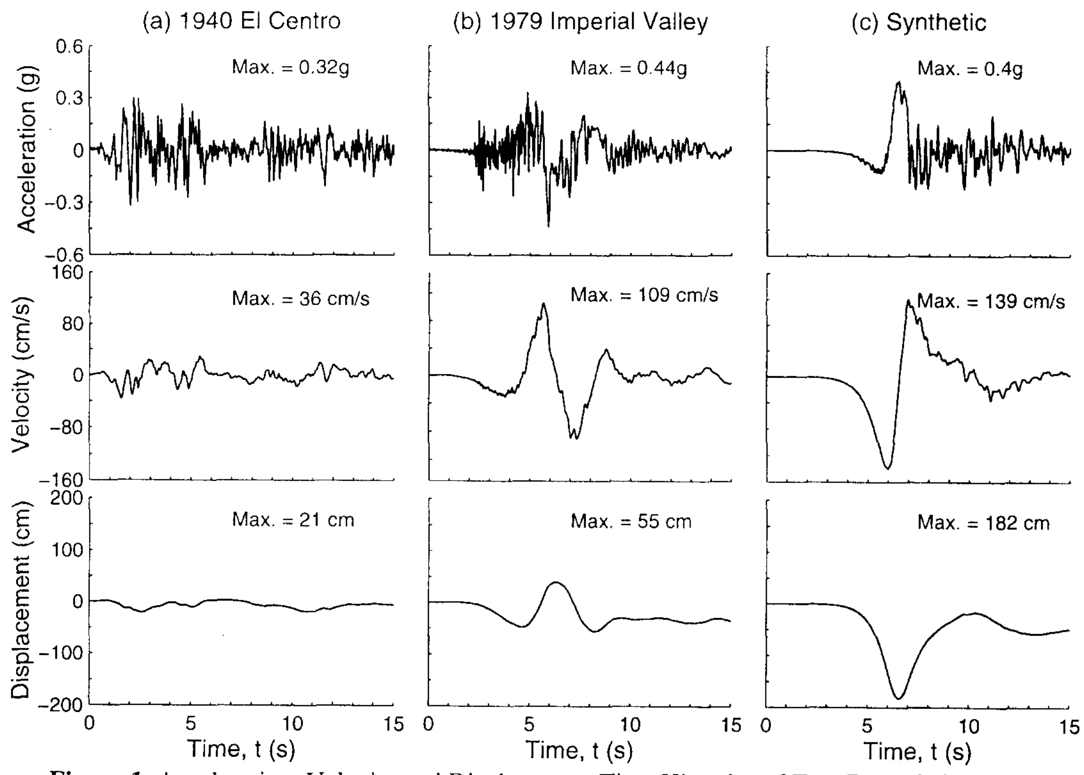

Figure 1. Acceleration, Velocity and Displacement Time Histories of Two Recorded and One Synthetic Near-Field Ground Motions

3. Elastic Response Spectrum

The tripartite plots of the 5% damped elastic response spectrum for the three ground motions are shown in Figure 2. In these plots, the natural period *T* is along the horizontal axis, pseudo spectral velocity *PSV* along the vertical axis, pseudo spectral acceleration *PSA* along the -45° axis, and the spectral deformation *SD* along the +45° axis. These quantities are related to each other as follows:

$$PSA\ x \left(\frac{T}{2\pi}\right)^2 = PSV\ x \left(\frac{T}{2\pi}\right) = SD$$

The time history values of *PGA*, *PGV* and *PGD* are shown in dashed lines in Figure 2. Note that the spectral amplitudes at short periods are sensitive to the value of *PGA*, those at long periods are sensitive to the value of *PGD*, and those in the intermediate range of period are sensitive to the value of *PGV*. This is not surprising because the frequencies in the ground motion that control the value of *PGA* also control the response of stiff (short period) systems while frequencies that control the value of *PGD* also control the response of flexible (long period) systems.

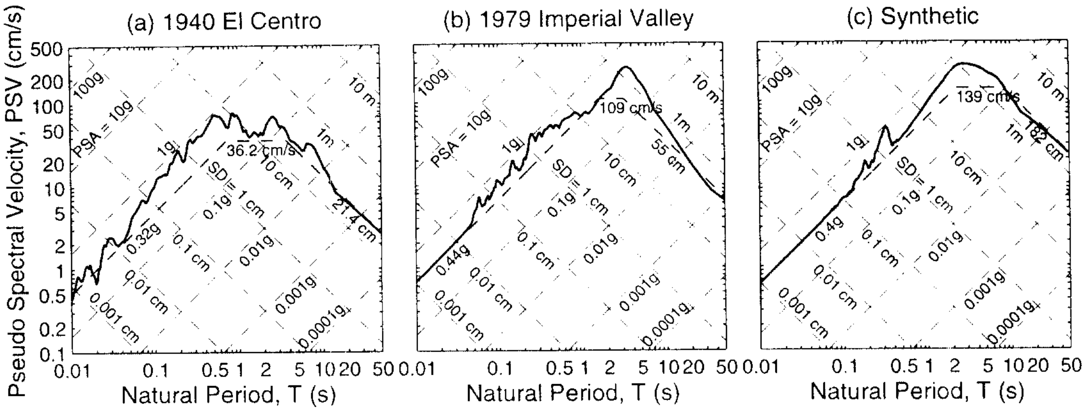

Figure 2. Tripartite Elastic Response Spectrum for Two Recorded and One Synthetic Near-Field Ground Motions (Damping = 5%)

4. Smooth Elastic Response Spectrum

The plots of the smoothed elastic response spectrum for the three ground motions are shown in Figure 3. In these plots, the middle region with constant pseudo spectral velocity is known as the velocity-sensitive region, the region to the left of it is known as the acceleration-sensitive region, and the region to the right of it is known as the displacement-sensitive region (Chopra, 1995). The widths of the various regions depend on the relative values of *PGA*, *PGV* and *PGD* while the spectral amplitudes in various regions depend on the actual values of *PGA*, *PGV* and *PGD*. Because the *PGA* values for the three ground motions are not significantly different, the peak spectral accelerations for the three ground motions are nearly the same. However, for the El Centro ground motion the acceleration-sensitive region extends only up to 0.5 sec, while this region for the Imperial Valley and the synthetic ground motions extends up to 2 sec. The rather wide acceleration-sensitive region for the Imperial Valley and the synthetic ground motions is due to the high *PGV/PGA* ratio: 0.25 sec for Imperial Valley, 0.35 sec for synthetic, and only 0.11 sec for El Centro.

In Table 1, the widths of the acceleration-sensitive regions for the three ground motion spectra are compared with the UBC 94 and UBC 97 spectra. Note that the acceleration-sensitive regions for the Imperial Valley and the synthetic ground motions are more than twice as wide as the widest acceleration-sensitive region recommended by UBC 94. Unlike UBC 94, UBC 97 does have a provision to widen the acceleration-sensitive region in the near-field, but even in the extreme case the acceleration-sensitive region for the UBC 97 spectrum falls significantly short of that for the Imperial Valley and the synthetic ground motions.

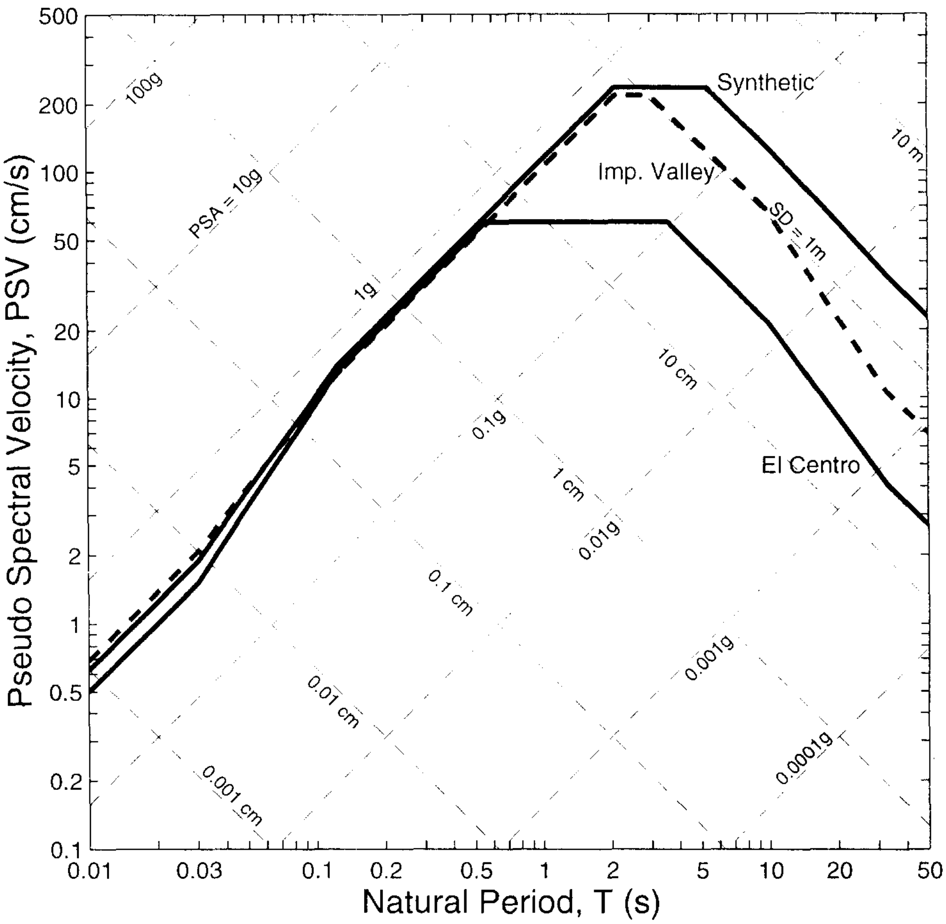

Figure 3. Smooth Elastic Response Spectrum for Two Recorded and One Synthetic Near-Field Ground Motions (Damping = 5%)

5. Effects of High PGV/PGA Ratio

Structures behave in a stiff or flexible manner depending on whether they are in the acceleration-sensitive region of the ground motion spectrum or outside of it. The increase in the *PGV/PGA* ratio widens the acceleration-sensitive region which, in turn, causes more and more systems to fall within the acceleration-sensitive region of the spectrum, and hence they behave as stiff systems. For example, a 15-story high-rise and a 3-story base-isolated building, both with a natural period of 2 sec, would be considered flexible for the El Centro ground motion but rather stiff for the Imperial Valley or the synthetic ground motions.

The widening of the acceleration-sensitive region causes more and more modes of vibration of a high-rise building to fall within the acceleration-sensitive region of the spectrum. This, in turn, increases the elastic base shear and inter-story drifts in a high-rise building.

It is well known that the effect of added damping is most pronounced in the longer-period part of the acceleration-sensitive region and throughout the velocity-sensitive region of the spectrum (Chopra, 1995). With an increase in the *PGV/PGA* ratio, the velocity-sensitive region is pushed to longer periods. Therefore, for many low- to medium-rise buildings, the added damping would be less beneficial for the Imperial Valley or the synthetic ground motions than for the El Centro ground motion.

The ductility demand μ is highest in the acceleration-sensitive region and lowest in the displacement-sensitive region of the spectrum for the same value of the force-reduction factor R (Chopra, 1995). Many systems that would be in the velocity- or displacement-sensitive regions for the El Centro ground motion would be in the acceleration or velocity-sensitive regions for the Imperial Valley and the synthetic ground motions. Ductility demand for these systems would increase significantly.

Table 1. Width of Acceleration-Sensitive Region for Different Ground Motions

Ground Motion	Width of Acceleration-Sensitive Region
1940 El Centro	0.5 sec
1979 Imperial Valley	2.0 sec
Synthetic	2.0 sec
UBC 94 (Rock Site)	0.4 sec
UBC 94 (Soft Soil Site)	0.9 sec
UBC 97 (Rock Site in Zone 4, > 15 km from any Seismic Source)	0.4 sec
UBC 97 (Soil Site in Zone 4, < 2 km from Seismic Source A)	1.4 sec

6. Acceleration-Deformation Response Spectrum

The acceleration-deformation spectrum is a plot of the pseudo spectral acceleration *PSA* against the spectral deformation *SD*. Such plots are routinely used in static nonlinear (pushover) analyses. The acceleration-deformation spectra for the El Centro, the Imperial Valley and the synthetic ground motions are shown in Figure 4 for 20% damping. The natural period T in this plot is indicated by radial lines passing through the origin. A building with an effective natural period of 2.5 sec and effective damping of 20% would experience a 15 cm (6 in) deformation for El Centro, 44 cm (17 in) deformation for Imperial Valley, and 75 cm (30 in) deformation for the synthetic ground motion. For a base-isolated building, this deformation is concentrated across the isolators, whereas for a high-rise building undergoing nonlinear response, this deformation is distributed throughout the height of the building. The corresponding values of spectral acceleration (base shear coefficient) are 0.1 g for El Centro, 0.29 g for Imperial Valley and 0.48 g for synthetic ground motion.

From an acceleration-deformation spectrum it is rather easy to visualize the effect of period change on the base shear coefficient and the deformation demand. For the El Centro record, a period increase from 0.1 sec to 2 sec causes a significant reduction in spectral acceleration (or base shear) but a nominal increase in the spectral deformation. For the synthetic ground motion, on the other hand, a period increase from 0.1 sec to 2 sec does not result in a significant reduction in the base shear but causes a large increase in the deformation demand. Base isolation is therefore much less effective for the synthetic ground motion than for the El Centro ground motion.

7. Drift Spectrum

The drift spectrum was introduced by Iwan (1997) to illustrate the effects of near-field ground motions on high-rise buildings. It is a plot of the maximum shear strain at the base of a uniform shear beam versus the natural period of the shear beam, for a given ground motion and a fixed value of the damping ratio. The shear strain is an indirect measure of the story-drift ratio in a high-rise building. For the purpose of this study, it is considered more instructive to replace the uniform shear beam with a uniform shear building. For an assumed relationship between the number of stories and the fundamental natural period a plot can be generated between the number of stories and the maximum first-story drift. Note that for a uniform shear building, the maximum drift depends only on the assumed relationship between the number of stories and the building period, and on the value of the damping ratio. It does not depend on the actual story height.

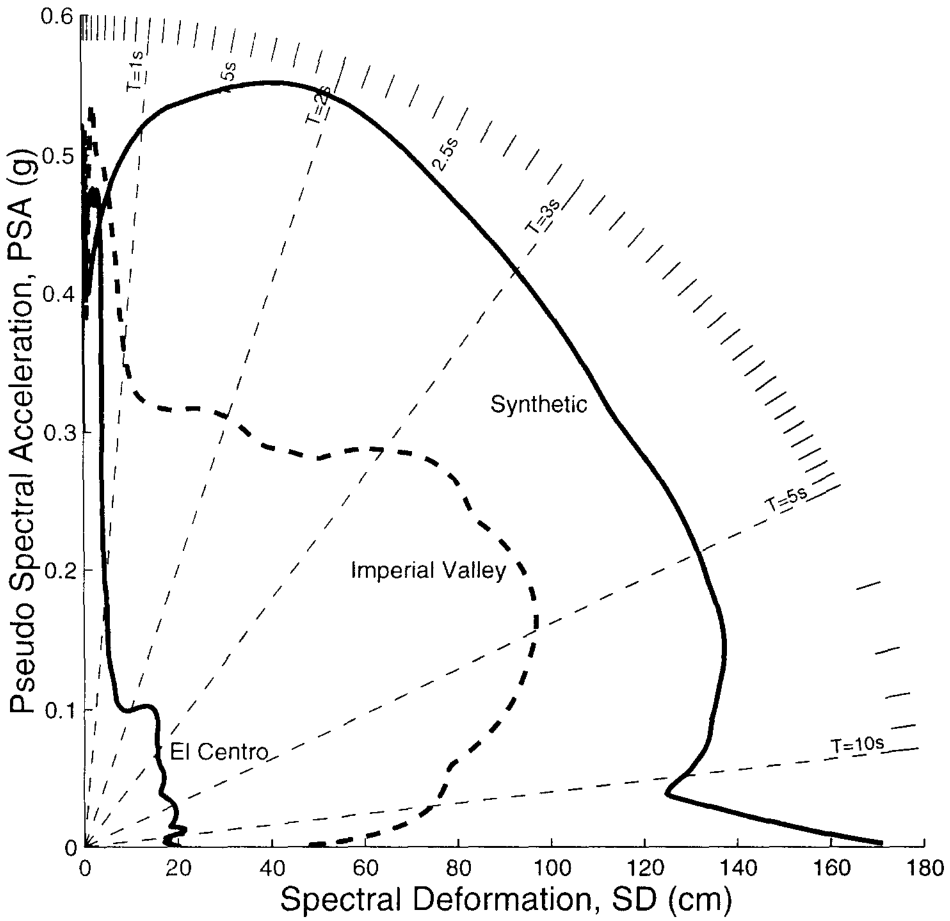

Figure 4. Acceleration-Deformation Response Spectrum for Two Recorded and One Synthetic Near-Field Ground Motion (Damping = 20%)

Shown in Figure 5 are the plots of 2% damped drift spectra for the El Centro, Imperial Valley, and synthetic ground motions. It is assumed that the fundamental building period T is related to the number of stories N by the relationship, $T = 0.15N$. Note that for all three ground motions, the story drift first increases with an increase in N and then decreases. For the El Centro ground motion, the increase in drift continues for up to a 5-story building. As the building height increases further, the fundamental mode and then the higher modes of vibration move out of the acceleration-sensitive region into the velocity and displacement-sensitive regions, thus, causing the base shear and, hence,

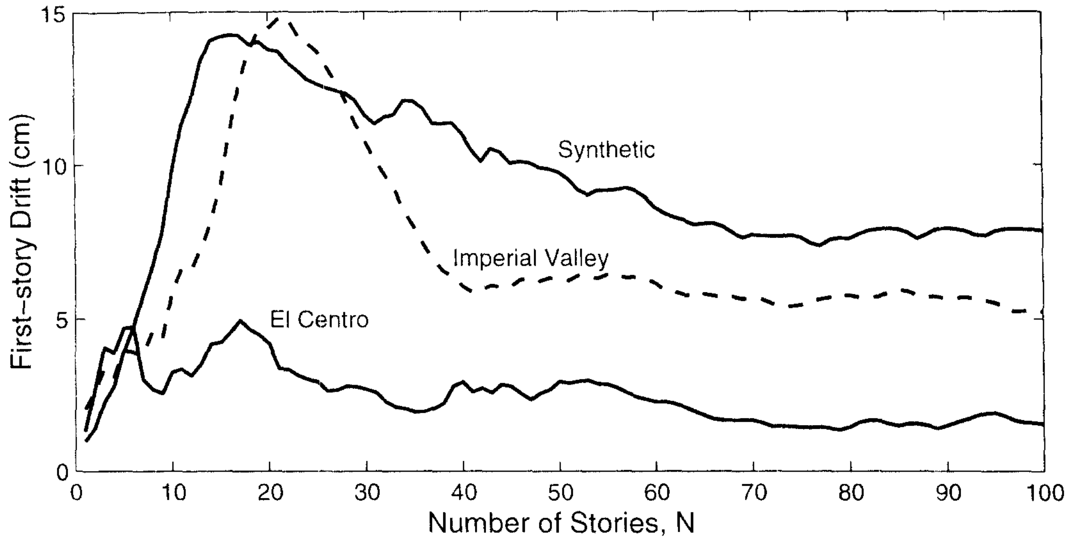

Figure 5. First-Story Drift in Uniform Shear Buildings of Different Number of Stories Subjected to Two Recorded and One Synthetic Near-Field Ground Motions (Damping = 2%, $T = 0.15N$ sec)

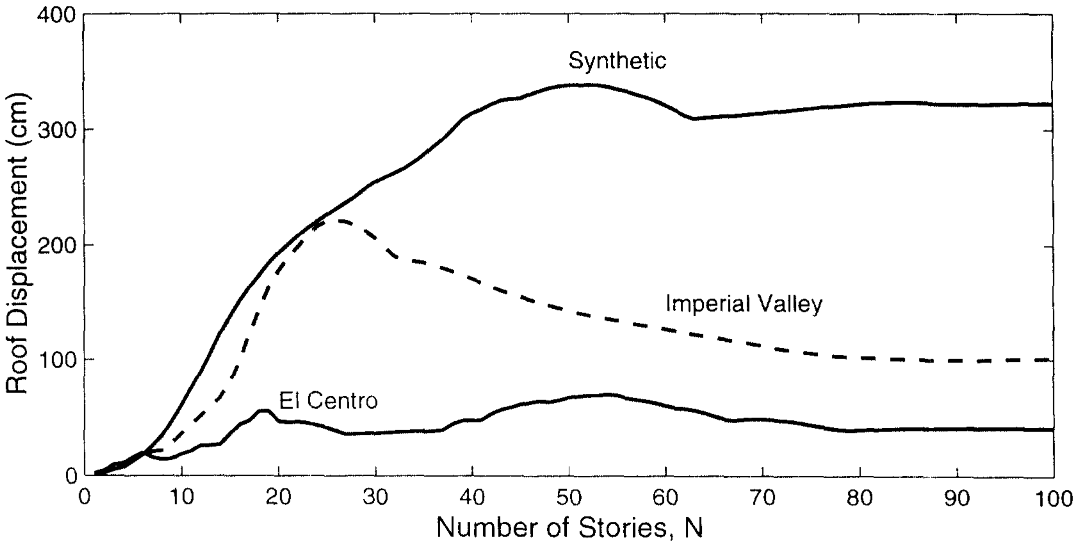

Figure 6. Roof Displacement in Uniform Shear Buildings of Different Number of Stories Subjected to Two Recorded and One Synthetic Near-Field Ground Motions (Damping = 2%, $T = 0.15N$ sec)

the story drift to reduce. For the Imperial Valley and the synthetic ground motions, the acceleration-sensitive region is so wide that even for a fairly tall building the fundamental mode of vibration remains within the acceleration-sensitive region of the spectrum. As a result, the increase in the first-story drift with number of stories continues much longer and the drift demand for high-rise buildings becomes substantially greater than that for the El Centro ground motion.

8. Roof Displacement Spectrum

Shown in Figure 6 are the plots of the roof displacement for uniform shear buildings of different number of stories subjected to the three ground motions. The displacement of the roof is dominated by the first mode of vibration of the building and is greatest when the first mode falls within the displacement-sensitive region of the spectrum. Because the synthetic ground motion spectrum is largest in the displacement-sensitive region, the roof displacement for the synthetic ground motion is significantly higher than that for the two recorded ground motions.

9. Conclusions

Peak values of ground velocity and displacement together with the peak value of ground acceleration provide significant insight into the response characteristics of near-field pulse-like ground motions.

Conventional analysis techniques such as the modal superposition method and response spectrum analysis not only provide valuable insight into the effects of near-field ground motions, but can accurately capture the response of systems subjected to pulse-like ground motions.

Ground motions with pulse-like characteristic tend to have higher *PGV/PGA* ratios, hence wider acceleration-sensitive region in their response spectra. This causes following effects on the response of structures:

1. Reduced apparent flexibility of high-rise and base-isolated buildings;
2. Reduced effectiveness of base-isolation;
3. Reduced effectiveness of supplemental damping;
4. Increased ductility demand; and
5. Increased base shear and inter-story drifts in high-rise buildings.

The effect of near-field pulse-like ground motions on high-rise buildings can be predicted from the shape of their elastic response spectra.

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