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USE OF DESIGN SPECTRUM-COMPATIBLE TIME HISTORIES IN ANALYSIS OF STRUCTURES

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ABSTRACT

The increased use of nonlinear structural analysis techniques in the seismic resistant design of structures has created a need for ground motion time histories that model and represent the design ground motions. As it is common practice to specify ground motions in the form of design response spectra, it is desirable to have ground motions that are design spectrum compatible.

It is demonstrated that spectrum-compatible acceleration time histories may not represent real ground motion records from actual earthquakes. The process by which the records are generated distort the records in a manner that the corresponding velocity and displacement are not realistic. In addition, the energy content is greatly exaggerated by an order of magnitude across a very wide band of periods.

The use of spectrum-compatible time histories for analysis and design can lead to results that overpredict response and cause overly conservative design requirements to be met. The use of such time histories should be discouraged or used with extreme caution and understanding.

KEYWORDS

Design spectrum; response spectrum; time histories; dynamic analysis; nonlinear analysis; structural analysis

INTRODUCTION

The design and analysis of structures has matured to the point where it is very feasible to perform nonlinear analysis techniques to determine structural behavior for earthquake and other dynamic loadings. Such nonlinear techniques are absolutely mandatory for the analysis of seismically base isolated structures and structural systems using energy dissipation devices. For such analyses, a response spectrum is not sufficient to specify the dynamic input to the structure. Instead, acceleration-time histories representing the ground motions at the base of the structure are needed to define the dynamic input.

Although the number of actual strong ground motion accelerograms has increased dramatically with recent well-recorded earthquakes near urban areas, it is still difficult to match those recordings to design spectra that are specifically derived for a particular project. For this reason, analytical techniques have been developed to modify existing acceleration-time histories so as to match a specified design response spectrum within a reasonable tolerance. These design spectrum compatible time histories (DSCTH), therefore, would have seem to have a natural attractiveness having the proper frequency domain content as the specified design spectrum.

This paper will demonstrate that design spectrum-compatible time histories may not represent realistic earthquake ground motions and that their use in design and analysis may have serious overly conservative consequences.

DESIGN SPECTRUM

It is a very common practice to use a site-specific "probabilistic seismic hazard analysis" (PSHA) to define the design spectrum at a particular site if there is sufficient information available regarding the possible seismic sources and their rates of activity. Because a PSHA analysis considers all possible earthquake sources in the region surrounding a site, the results represent the cumulative contribution of all the seismic sources to the risk for any given recurrence interval or specified level of risk. In effect, the PSHA generated design response spectrum will actually be an envelop of the expected response spectra of ground motions from multiple sources based on the cumulative risk for all seismic sources found to be significant.

Therefore, a site-specific PSHA-generated response spectrum will not represent the maximum response of a single degree-of-freedom structure to any single earthquake ground motion; in fact, a PSHA spectrum was never intended to represent any single ground motion. Thus to generate spectrum-compatible acceleration-time histories is neither a reasonable nor realistic proposition.

ILLUSTRATIVE CASE HISTORY

To illustrate the potential problems associated with spectrum-compatible acceleration-time histories, the results from a case history for a recent hospital project in California are presented. The project was a seismic base isolation of a new hospital building and nonlinear dynamic analyses were required to investigate the behavior of the isolation system and the building superstructure for two levels of ground motions. These ground motions corresponded to those motions having a 10 percent probability of being exceeded in 50 years, referred to as the Design Basis Earthquake (DBE), and those motions having a 10 percent of being exceeded in 100 years, referred to as the Maximum Capable Earthquake (MCE). The recurrence intervals of the DBE and MCE events are about 475 and 950 years, respectively. For each of the design levels, a design spectrum was generated. The design spectrum for the MCE event for 5% structural damping is shown in Figure 1.

Three recorded sets of orthogonal paired horizontal ground motion acceleration-time histories from actual earthquakes were made spectrum-compatible for each of the DBE and MCE events. The design spectrum-compatible time histories (DSCTH) were manipulated in the frequency domain to be spectrum-compatible. The DSCTH records were originally generated using a proprietary computer program, which will be referred to herein as Method 1. Another set of DSCTH records was computed using an independent technique in the public domain known as WES-RASCAL (Silva and Lee, 1987), which will be referred to as Method 2. Using the two methods, the same horizontal ground motion records were used as the "seed" time histories to generate the DSCTH records. The two methods use different iterative procedures that involve the scaling of Fourier amplitudes of the processed signal to match the corresponding amplitudes of the target acceleration response spectrum. For both methods, convergence was assumed when the ratio of the response spectra areas (signal to target) was less than 2 percent, and the average error on all frequencies was less than 5 percent.

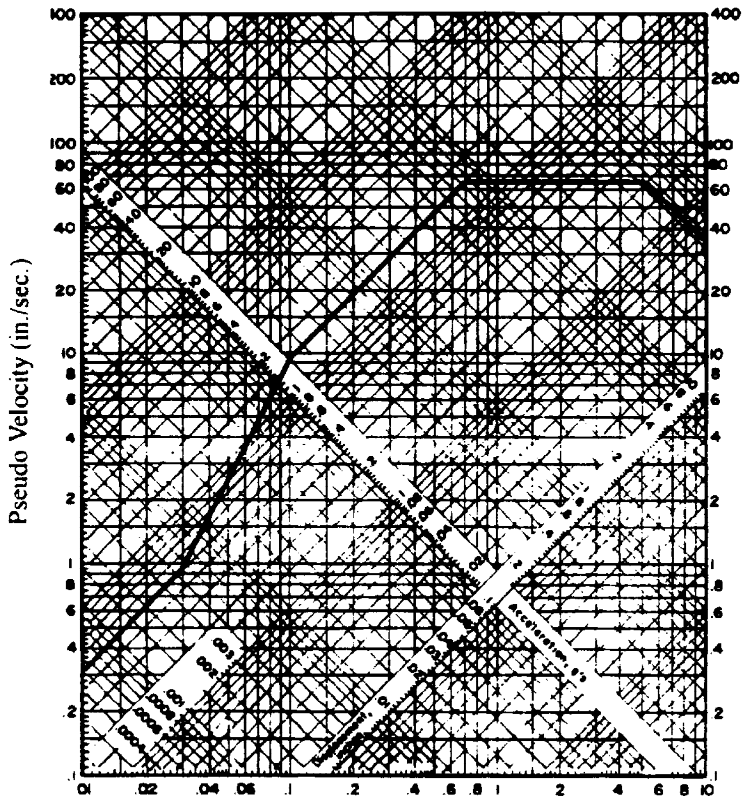

Fig. 1. MCE Design Spectrum for 5% Damping.

From the analysis of the 24 some different DSCTH records generated by the two methods, the acceleration response spectra of the all the spectrum-compatible records match the specified target response spectrum (as given in Figure 1) very well. For example, one of the "seed" records chosen was the Taft accelerogram from the 1952 Kern County, California earthquake. The DSCTH accelerogram for the S69E component, as generated by Method 1, is shown in Figure 2; the corresponding acceleration response spectrum for 5 percent damping is shown in Figure 3.

Method 2 was also employed to generate DSCTH records. The DSCTH accelerogram for the same Taft S69E component is shown in Figure 4 and the corresponding acceleration response spectrum for 5 percent damping is shown in Figure 5.

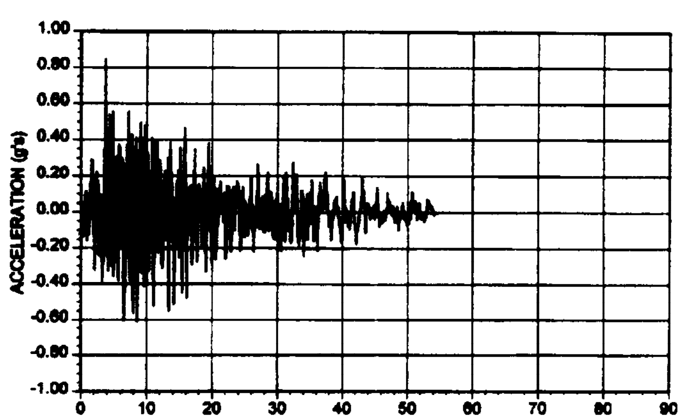

Fig. 2. DSCTH accelerogram for S69E component of Taft record using Method 1.

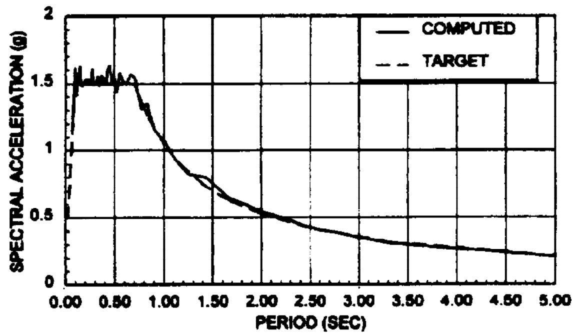

Fig. 3. DSCTH acceleration response spectrum (5 percent damping) of S69E component of Taft record using Method 1.

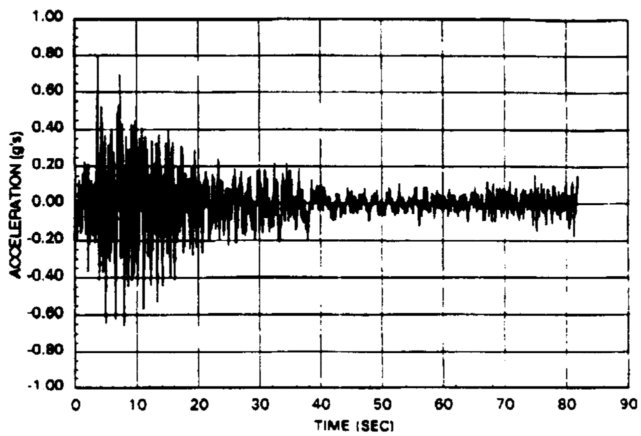

Fig. 4. DSCTH accelerogram for S69E component of Taft record using Method 2.

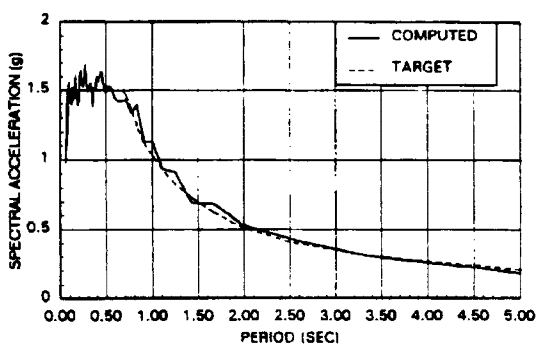

Fig. 5. DSCTH acceleration response spectrum (5 percent damping) of S69E component of Taft record using Method 2.

Having the goodness of fit to the target spectrum as shown in the example above can lull one into a sense of false security as one proceeds into the dynamic analysis of a structural system. Consider the DSCTH accelerogram based on the "seed" from the 140 degree component of the 1979 Imperial Valley Bonds Corner record as shown in Figure 6; Method 2 was used for this example. Figures 7 and 8 show the velocity and displacement time histories obtained by integration and double integration of the DSCTH accelerogram, respectively.

The displacement records obtained by double integration of all 24 DSCTH components produced unrealistic and physically impossible results as illustrated by Figure 8. For the example, the ground displacement starts at zero displacement, but never crosses the zero displacement line after the ground motion begins and shows a permanent offset of about 400 cm at the end of the record. Clearly, this is not a realistic displacement produced by an earthquake; this record is representative of the other 23 DSCTH components. It could be argued that this record could be corrected by base line and slope correction, however, such corrections could endanger the compatibility with the design spectrum.

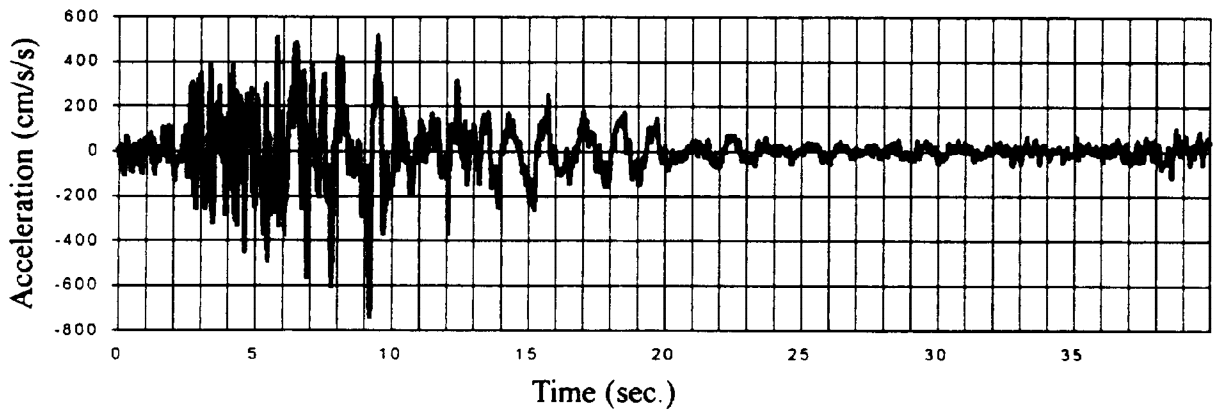

Fig. 6. DSCTH accelerogram for 140 degree component of Bonds Corner Record

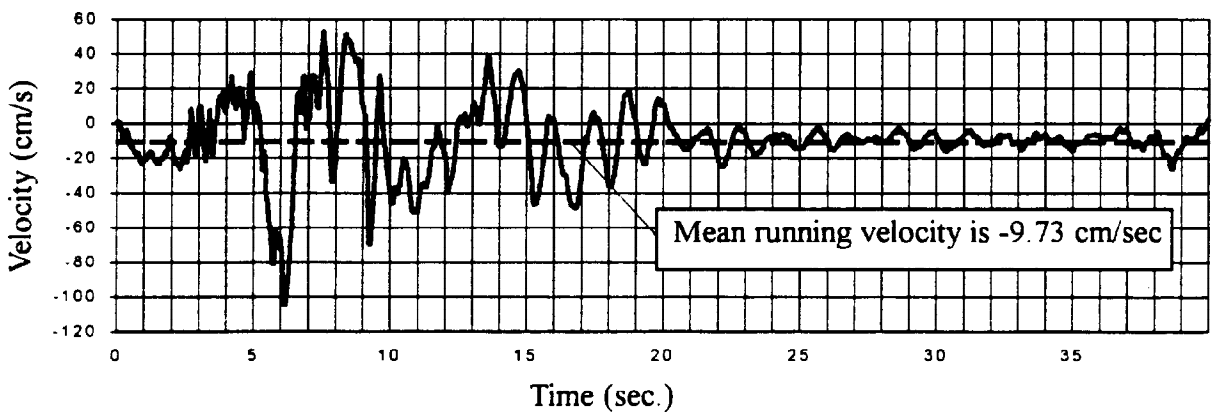

Fig. 7. Velocity time history determined by integration of DSCTH accelerogram from Bonds Corner

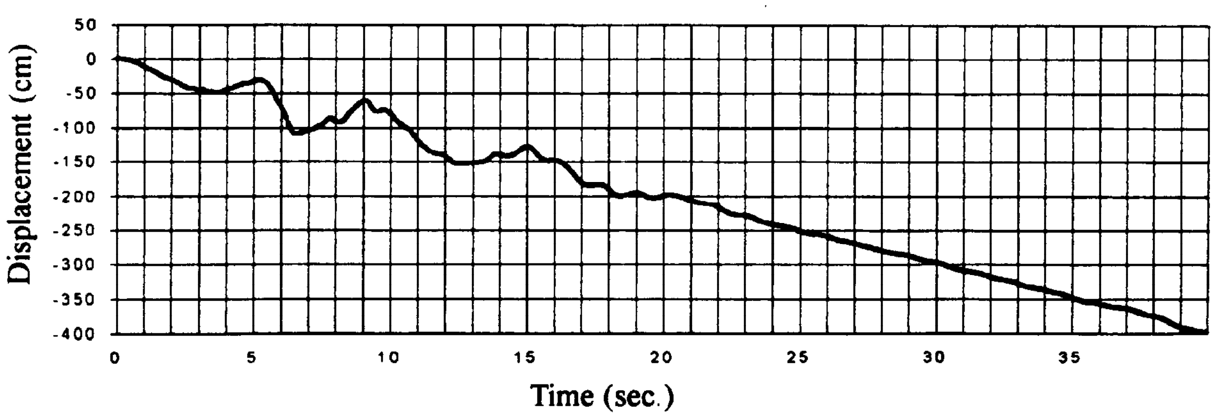

Fig. 8. Displacement time history determined by double integration of DSCTH accelerogram from Bonds Corner.

It should be noted that Figure 7 shows the velocity time history has a mean running velocity of -9.73 cm/sec; however, Method 2 presents a very reasonable displacement time history corresponding to this accelerogram. The reader should note that Method 2's best estimate for displacements is obtained by successive manipulation of the record before and after each integration step. For this example, the mean running velocity of -9.73 cm/sec is subtracted from the velocity record to obtain the baseline corrected velocity shown in Figure 9. Integration of this modified velocity record gives the displacent record shown in Figure 10 which has a mean running displacement of -6.84 cm. Method 2 then subtracts this mean running displacement to obtain the final displacement record as shown in Figure 11. While the displacement record shown in Figure 11 is much more realistic than the record shown in Figure 8, it does not have a proper initial boundary condition (i.e., the ground displacement does not start from zero).

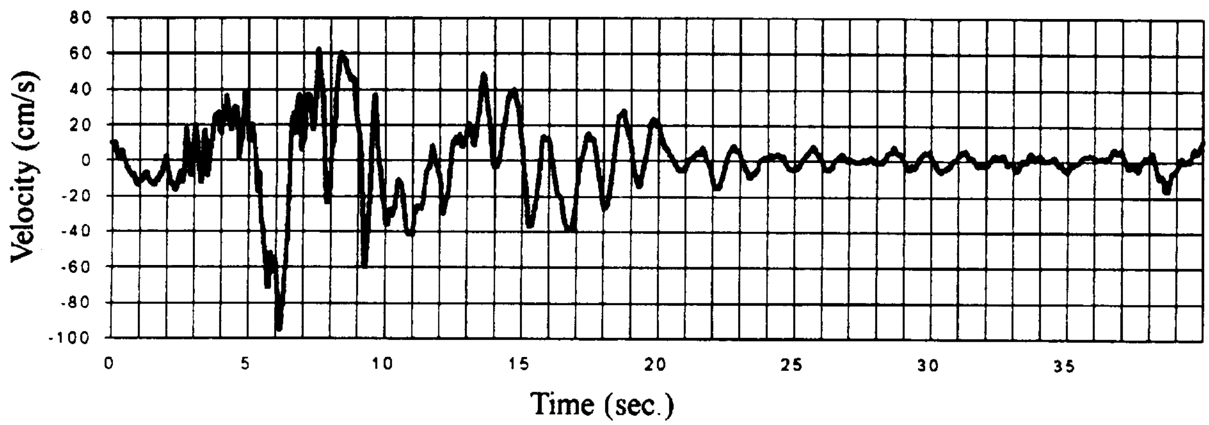

Fig. 9. Baseline corrected velocity time history.

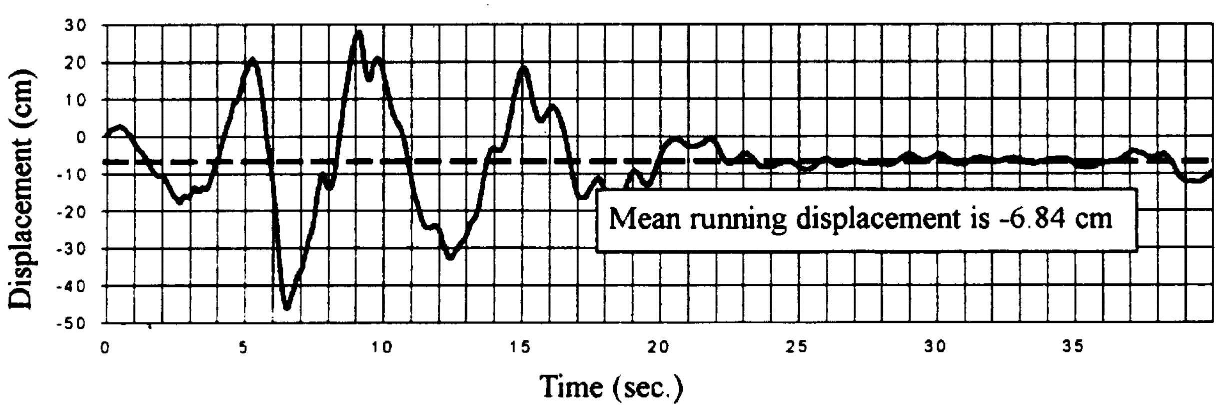

Fig. 10. Displacement time history obtained by integration of baseline corrected velocity time history.

Despite the manipulations of the velocity and displacement time histories, structural dynamic models generally only use the design spectrum-compatible acceleration time histories as input and are totally blind to the cosmetic changes the velocity and displacement time histories are subjected to. These computer models will suffer from the shortcomings of the uncorrected velocity and displacement records as they will be obtained by direct integration, if needed.

Another important characteristic of DSCTH records is brought out in the input energy spectra. The input energy spectra exhibit high levels energy spread out over a very wide band of periods (Naeim and Lew, 1993). The input energy spectra of actual earthquake time histories has been investigated by Naeim and Anderson (1993) and the characteristically high and wide band energy spectra of DSCTH records is not seen in real earthquake records. Figure 12 shows that the energy content of DSCTH records is consistently higher than the seed records used as the basis for their development, sometimes by orders of magnitude. The 230 degree component of the 1979 Imperial Valley earthquake at Bonds Corner has the largest long period input energies of any California record (Naeim and Anderson, 1993) and the 360 degree component of the Sylmar County Hospital free field record from the 1994 Northridge earthquake has the largest input energy of California earthquakes between periods of 1.5 to 2.0 seconds (Naeim, 1994). It can be seen in Figure 12 that the energy spectra of DSCTH records are greatly exaggerated when compared with the largest energy input records known in California.

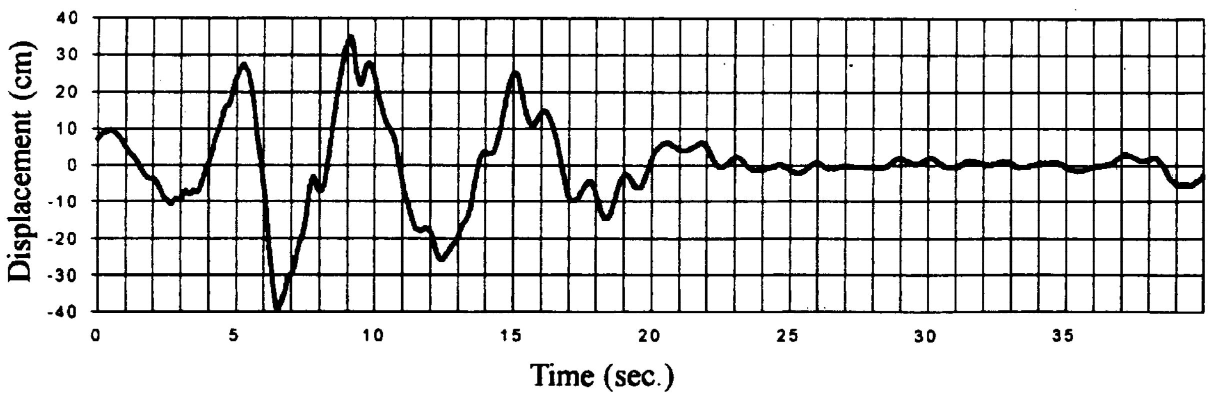

Fig. 11. Displacement time history obtained by shifting baseline of record shown in Fig. 10.

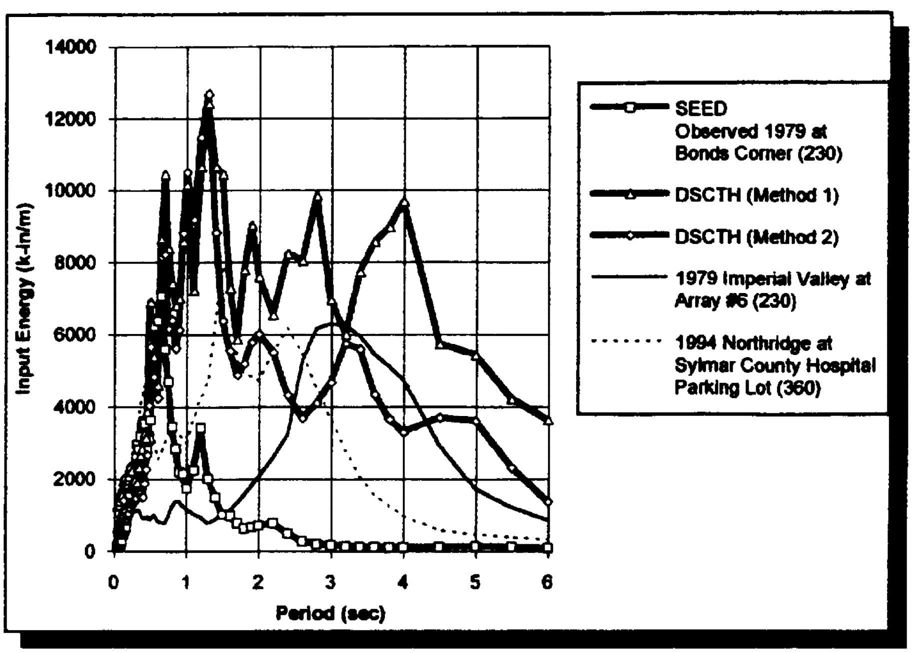

Fig. 12. Input energy spectra for actual and resulting DSCTH records from 230 degree component of the Bonds Corner accelerogram.

The average input energy spectra for all 24 real and DSCTH records are compared in Figure 13. It can be seen that the DSCTH records contain unrealisticly high energy contents across the entire period range. The energy content of the DSCTH records exceed their real counterparts by an order of magnitude.

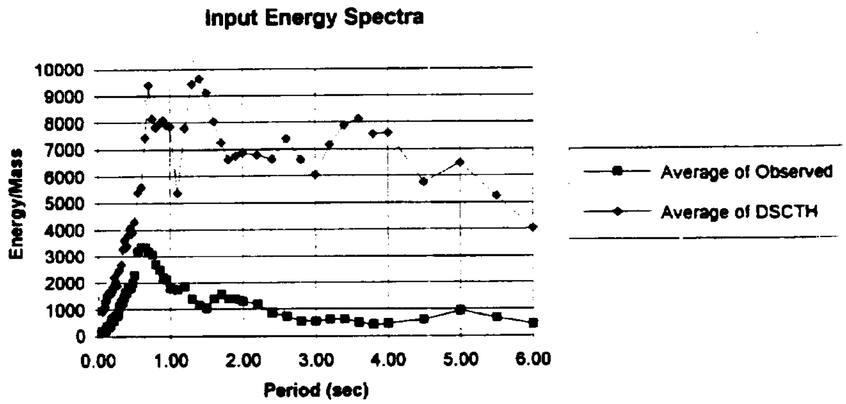

Fig. 13. Comparison of energy contents of real records and their DSCTH counterparts.

IMPLICATIONS FOR ANALYSIS AND DESIGN

The use of DSCTH records in the analysis and design of structures has serious implications. The attractiveness of spectrum-compatible acceleration time histories can be far outweighed by the undesirable velocity and displacement characteristics of the records and the unrealistic energy contents across the broad band of periods. The use of DSCTH records can lead to unnecessarily overconservative designs (Naeim and Lew, 1993 and 1995). When applied to special systems such as seismic isolation systems where the design events are extreme events, an overly conservative designed system may lead to undesirable behavior during earthquake events that are not as extreme.

It is suggested that actual time histories be used for analysis and design. These records should not be manipulated in the frequency domain, but should be adjusted arithmetically in the time domain to match the desired spectral characteristics at the periods of most interest, or within a limited range around the period of interest.

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