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On the Use of Design Spectrum Compatible Time Histories

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ABSTRACT

To a designer of a nonlinear structure, there is nothing more attractive than a real or fictitious ground motion time history whose response spectrum matches the target design spectrum. Frequency-domain scaled, design spectrum compatible time histories (DSCTH) are widely used in analysis and design of special structures, particularly seismic-isolated buildings. Their use has been even mandated by some code provisions. At the first glance, it seems that DSCTH records furnish designers of earthquake resistant structures with a consistency and compatibility bridge between the two very different worlds of elastic and inelastic response. Closer examination, as presented in this paper, reveal however that there are significant potential problems associated with uncontrolled use of DSCTH records in seismic design. It is shown that the use of design spectrum compatible time histories can lead to exaggeration of displacement demand and energy input. This in turn can distort the expected performance of the structure when subjected to design earthquake ground motions.

INTRODUCTION

With increased usage of nonlinear analysis techniques in the seismic design of structures, application of design spectrum compatible time histories (DSCTH) has become very popular. This is specially true in contemporary analysis and design of seismic-isolated structures.

The basic philosophical intent of seismic code provisions to provide a clear correspondence between the results obtained from response spectrum analysis and time-history analysis is perfectly logical. For example, the Uniform Building Code (ICBO, 1991, 1994) requires that:

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> *"Ground motion time histories developed for the specific site shall be representative of actual earthquake motions. Response spectra from time histories, either individually or in combination, shall approximate the site design spectrum . . . . . . "* [underlining by authors]

Some interpretations of this intent, however, will be shown by this paper to be very problematic. The following is one example of such an interpretation:

> *"If time history analysis is used, the input time histories ... should be scaled in the frequency domain such that their 5%-damped response spectrum essentially envelopes the site-specific spectrum and does not fall below the site-specific spectrum by more than 10% at any period... "* (OSHPD 1991, underlining is by authors)

We will demonstrate that such scaling of time-histories is inconsistent with the definition, purpose, and application concept of design spectra and may lead to unrealistic and physically incorrect (or impossible) ground motion time histories with serious practical implications.

DESIGN SPECTRUM AND DSCTH

Contemporary design spectra are often determined using a Probabilistic Seismic Hazard Analysis (PSHA). For the Design Basis Earthquake (DBE), the ground motions are at least those corresponding to a 10% probability of being exceeded in 50 years; for the Maximum Capable Earthquake (MCE) or Upper Bound Earthquake (UBE), the ground motions are at least those corresponding to a 10% probability of being exceeded in 100 years (previously 250 years). The recurrence intervals of DBE and UBE are about 475 and 950 years; respectively.

The PSHA analysis considers all possible earthquake sources in the region surrounding a site. If the result of the PSHA analysis is a site-specific design spectrum, it represents the cumulative contribution of risk from the seismic sources in the region for a given risk level. Thus the PSHA design spectrum represents an envelope of the ground motion levels based upon the cumulative risk for all seismic sources deemed to be significant. Since it is customary to include the dispersion in the ground motion attenuation relationship in the PSHA analysis, the predicted design spectrum values have an inherent conservatism built in.

Thus a PSHA-generated response spectrum does not and was never intended to represent the response of a single-degree-of-freedom structure to any single ground motion event. To the contrary, it is intended to envelop multiple events which correspond to a specified risk level. To generate an acceleration-time history to be spectrum compatible to a PSHA-generated design spectrum is neither reasonable nor realistic. This would be especially true if the seismic risk at a given site was due to several earthquake sources. Therefore, the resulting design spectrum compatible acceleration-time history will contain energy over the whole range of structural periods that is not seen in actual recorded time histories.

PROGRAM OF INVESTIGATION

Frequency-domain filtered DSCTH records for six pairs of horizontal ground motion time histories which were developed as a part of geotechnical investigations for a seismic-isolated hospital building and were reviewed and approved by the appropriate agencies (OSHPD and California Division of Mines and Geology) were selected. These records were generated using a proprietary computer program developed by Computech Engineering Services of Berkeley, California, hereafter refered to as *Method 1*). The authors recomputed these DSCTH records according to OSHPD 1991 requirements using an entirely independent technique referred to as *Method 2* (WES-RASCAL code by Silva and Lee, 1987). In both methods, the original horizontal ground motion records are used as "seeds" to generate DSCTH records. The target design spectrum is shown in Figure 1.

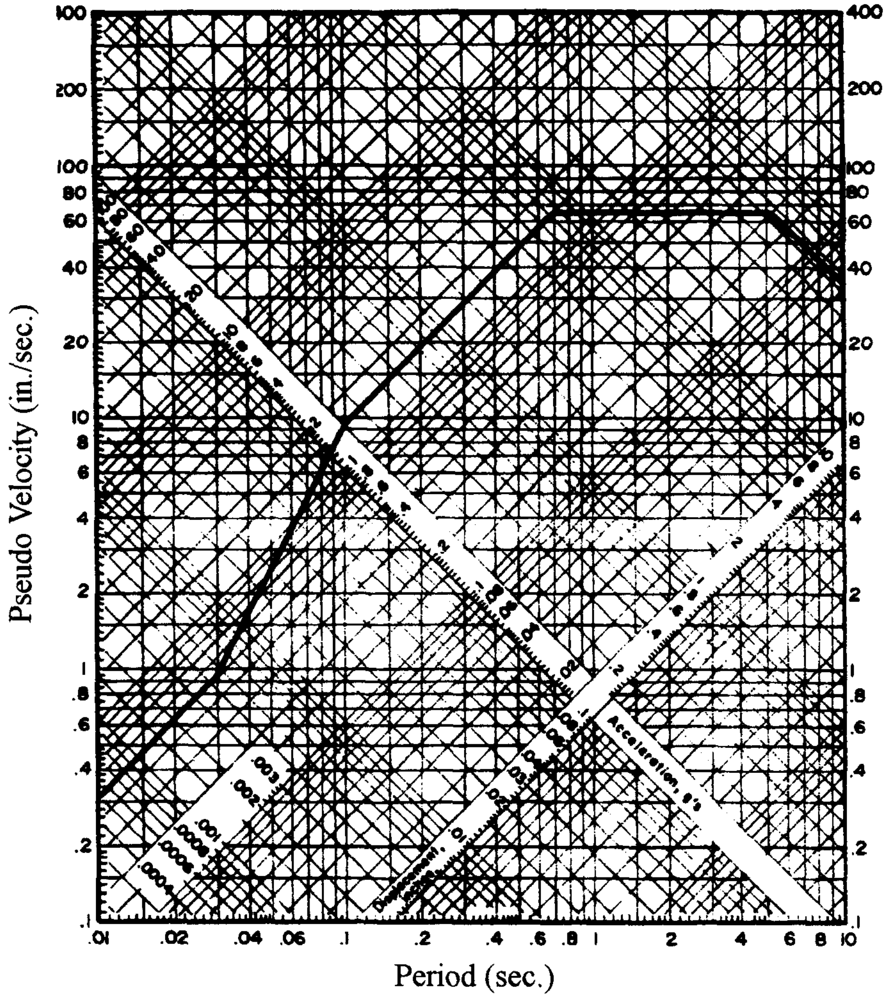


Figure 1 Target MCE design spectrum (5% damped).

The two methods use different iterative procedures that involve scaling the Fourier amplitudes of the processed signal to match the corresponding amplitudes in the target acceleration response spectrum. In both cases, convergence was assumed when the ratio of the response spectra areas (signal/target) was less than 2%, and the average error on all frequencies was smaller than 5%. These records were then applied in a detailed analysis of a typical seismic-isolated building structure.

ANALYSIS OF THE RECORDS

Our study of these 24 DSCTH records indicates that:

1. The acceleration response spectra of all 24 DSCTH records match the target design acceleration spectra remarkably well. For example, the DSCTH records generated based on the S69E component of the Taft record (1952 Kern County earthquake) to match the 5%-damped target design spectrum are shown in Figures 2 and 3.

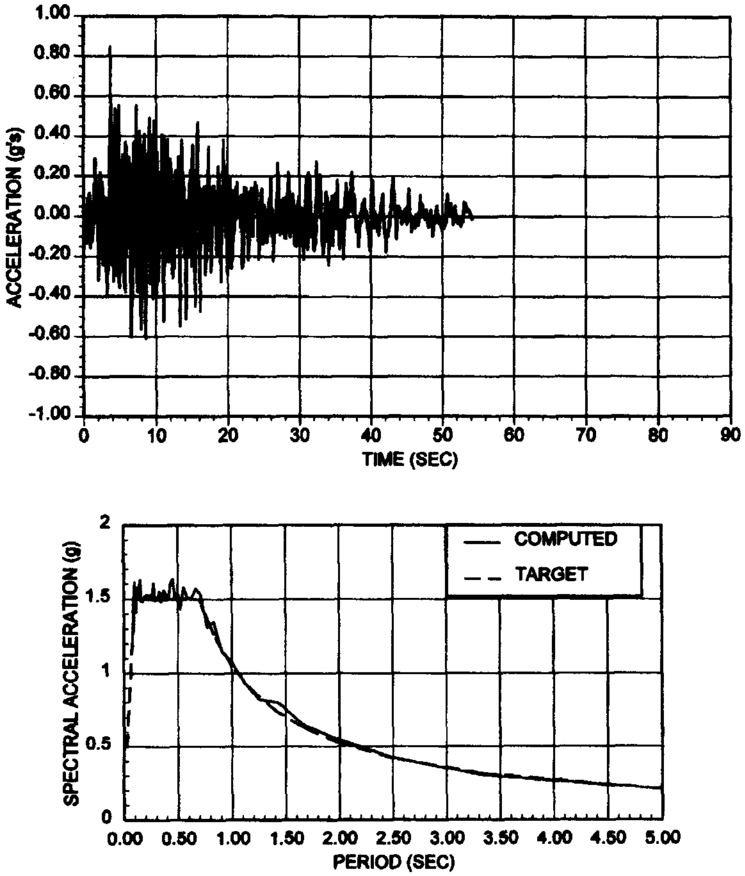


Figure 2 DSCTH accelerogram and response spectrum generated using *Method 1* based on the S69E component of the Taft record (1952 Kern County).

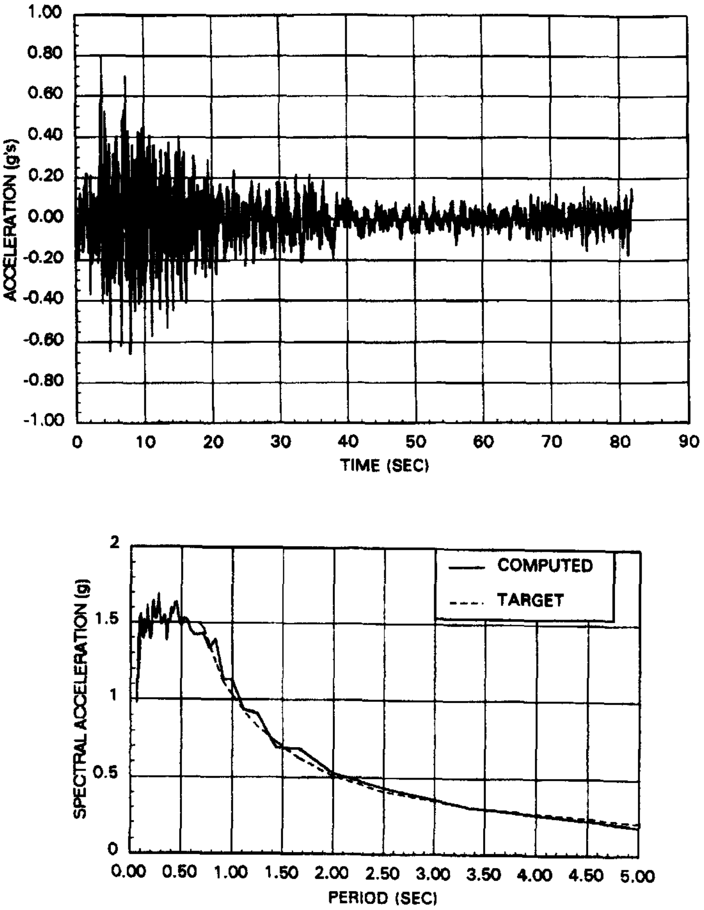


Figure 3 DSCTH accelerogram and response spectrum generated using *Method 2* based on the S69E component of the Taft record (1952 Kern County).

2. Displacement records obtained via direct double integration from all of the 24 DSCTH components produced very unrealistic and physically impossible results. For example, see Figure 4(c) showing displacements obtained for the DSCTH record based on the 140° component of the 1979 Imperial Valley Bonds Corner accelerogram. Notice that the ground displacement never crosses the zero line after the motion has been triggered and shows a permanent set of 400 cm (157 inches). Obviously such a displacement record cannot be produced by an earthquake or recorded by an accelerometer.

   One can argue that this record is in serious need for base-line and slope corrections. However, such adjustments may well endanger the sought after design spectrum compatibleness of the record. Figure 4(b) shows that the corresponding velocity record has a mean running velocity of -9.73 cm. The WES-RASCAL computer code reports a very reasonable displacement record for this accelerogram. The reader should note

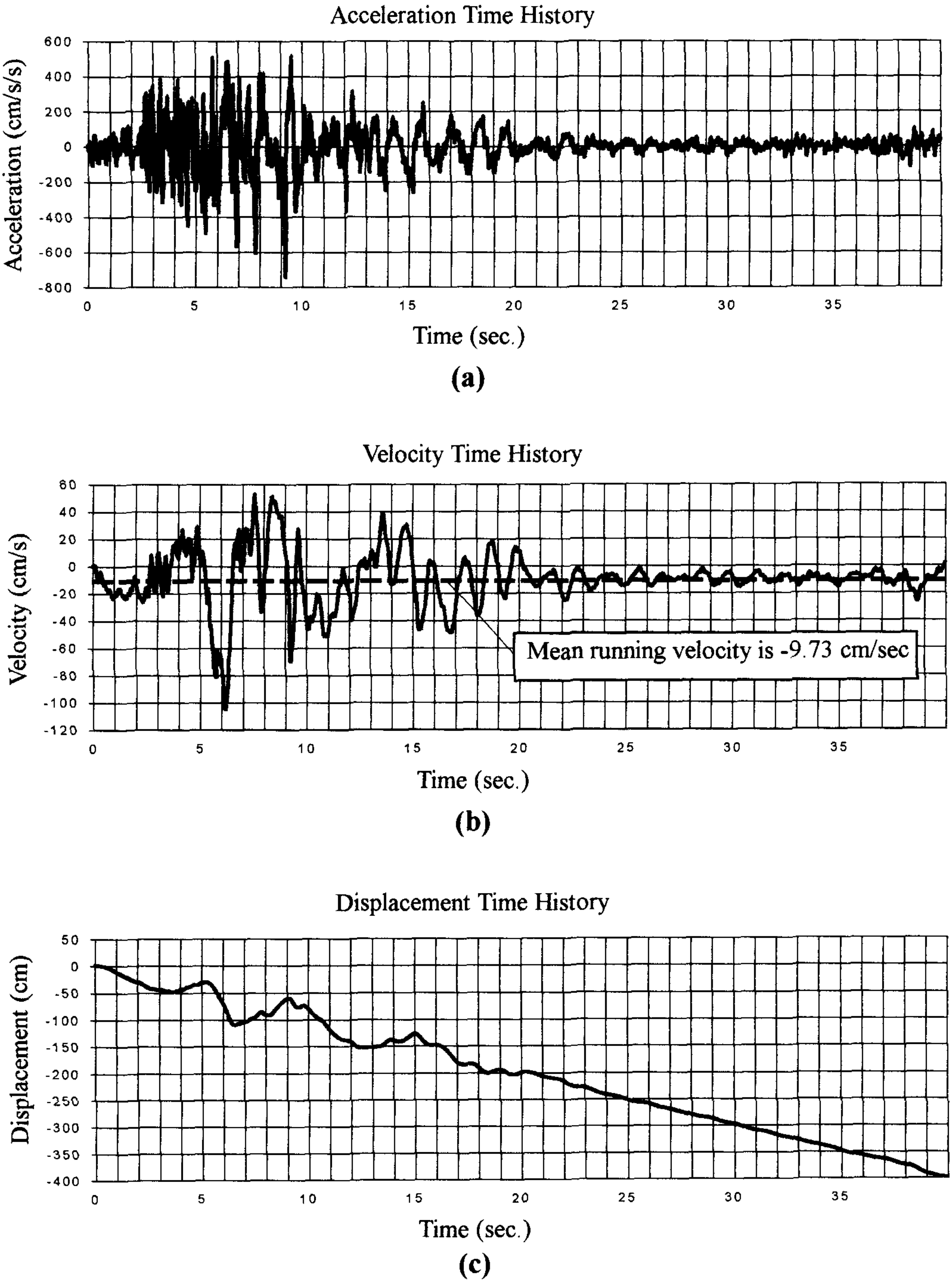
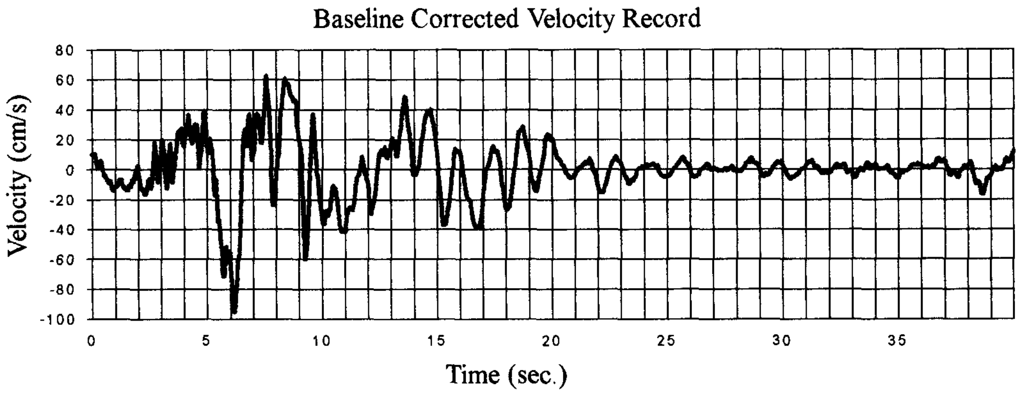
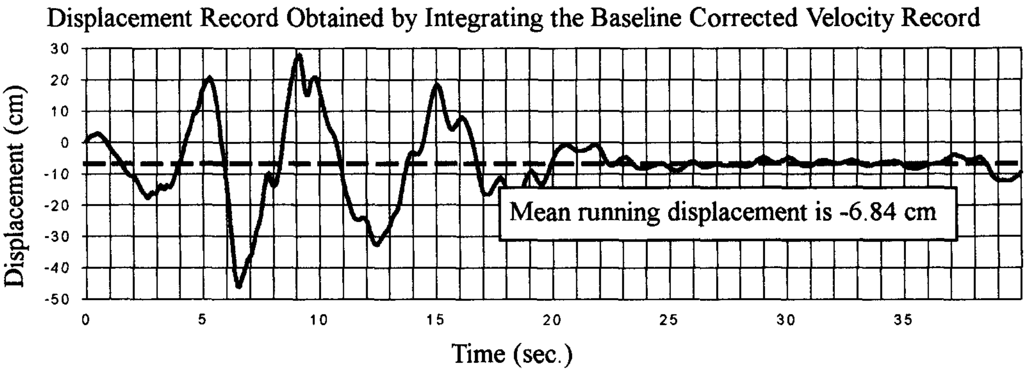


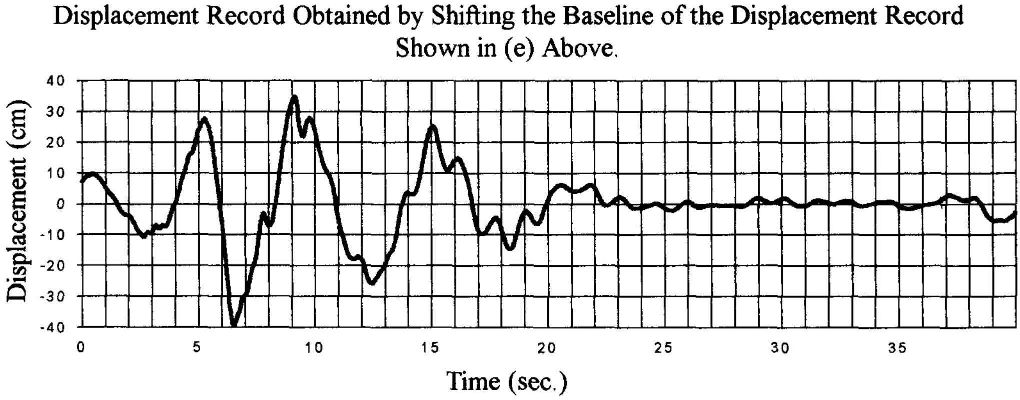
Figure 4 Typical velocity and displacements obtained for the 24 pairs of DSCTH acceleration records studied.


Baseline Corrected Velocity Record

(d)


Displacement Record Obtained by Integrating the Baseline Corrected Velocity Record

(e)


Displacement Record Obtained by Shifting the Baseline of the Displacement Record Shown in (e) Above.

(f)

Figure 4 (continued).

however, that WES-RASCAL's best estimate for displacements is obtained by successive manipulation of the record before and after each integration. For example, the mean running velocity of -9.73 cm/s is deducted from the velocity record to obtain the baseline corrected velocity shown in Figure 4(d). Integration of this modified velocity record yields the displacement record of Figure 4(e) which suffers from a mean running displacement of -6.84 cm. This mean running value is then deducted from the displacement record to obtain the final displacement record shown in Figure 4(f). Notice that while the displacement record shown in Figure 4(f) is certainly more realistic than that of Figure 4(c), it lacks proper initial boundary condition (the ground shaking does not start from rest).

The very serious issue to be faced is that the computer models used in analysis and design of structures are only exposed to the acceleration record of Figure 4(a). They are totally blind to the cosmetic changes to which the record is subjected to. Their estimates of velocity and displacement, when needed, come from direct integration of the acceleration record.

3. The input energy spectra of the DSCTH records (see Naeim and Lew, 1993) exhibit high levels of input energy spread over a very wide band of periods. Such behavior is not supported by observed data from real earthquake records (see Naeim and Anderson, 1993). As Figure 5 demonstrates, the energy content of DSCTH records is consistently higher than the real records used as the basis for their development (sometimes by orders of magnitude).

   The input energy spectrum for the 230° component of the 1979 Imperial Valley Array No. 6 record exhibits the largest long period input energies of any California record (Naeim and Anderson, 1993). Similarly 360° component of the 1994 Northridge at the Sylmar County Hospital Parking Lot exhibits the largest input energy of California records in ther period band of 1.50 to 2.0 seconds (Naeim, 1994). Energy spectra of these records are superimposed on the plots of Figure 5 to clearly demonstrate the exaggerated nature of energy spectra suggested by DSCTH records.

   The average input energy spectra for all real and DSCTH records are compared in Figure 6. It can be observed that when considered across the board, DSCTH records represent unrealistic energy contents which exceed the content of their real counterparts by an order of magnitude.

4. In most cases the overall distribution of energy across the various period bands show no resemblance to the real records used as seeds (see Figure 5).

5. The energy content of DSCTH records obtained by the two different methods may produce distinct input energy contents in certain frequency bands. For example, notice the large difference in input energies represented by the two methods at periods of about 2.5 seconds and 4.0 seconds in Figure 5. As will be demonstrated in the next section, these large differences in input energy, may result in vastly different estimates of design displacement demands for non-linear structures.

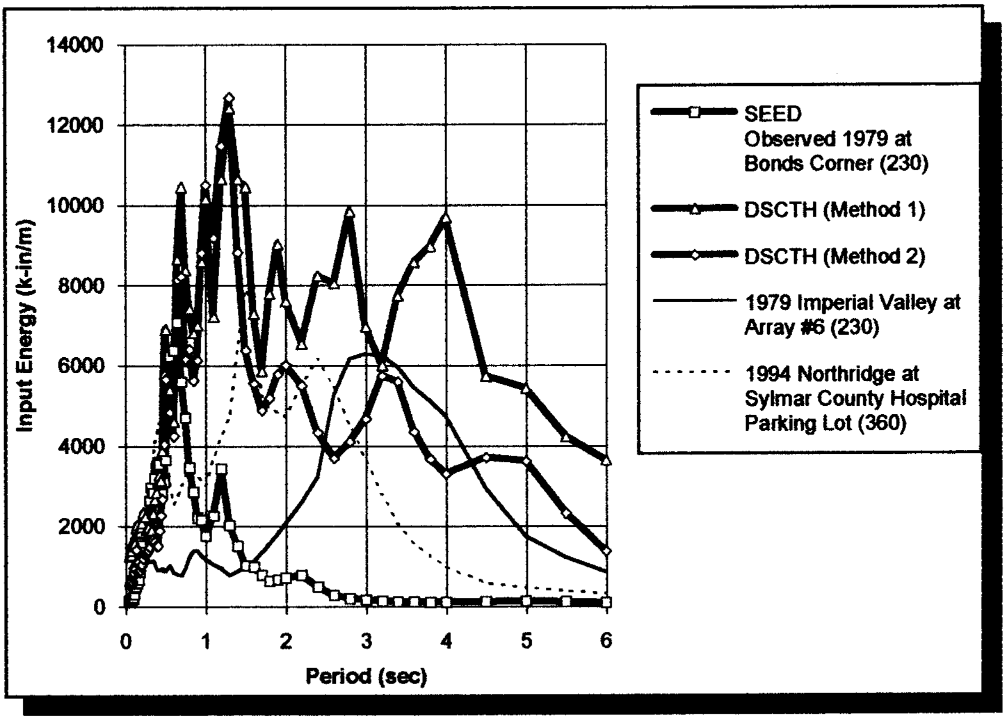


Figure 5 Input energy spectra for real (seed) and the resulting DSCTH records for the 230° component of the 1979 Imperial Valley at Bonds Corner.

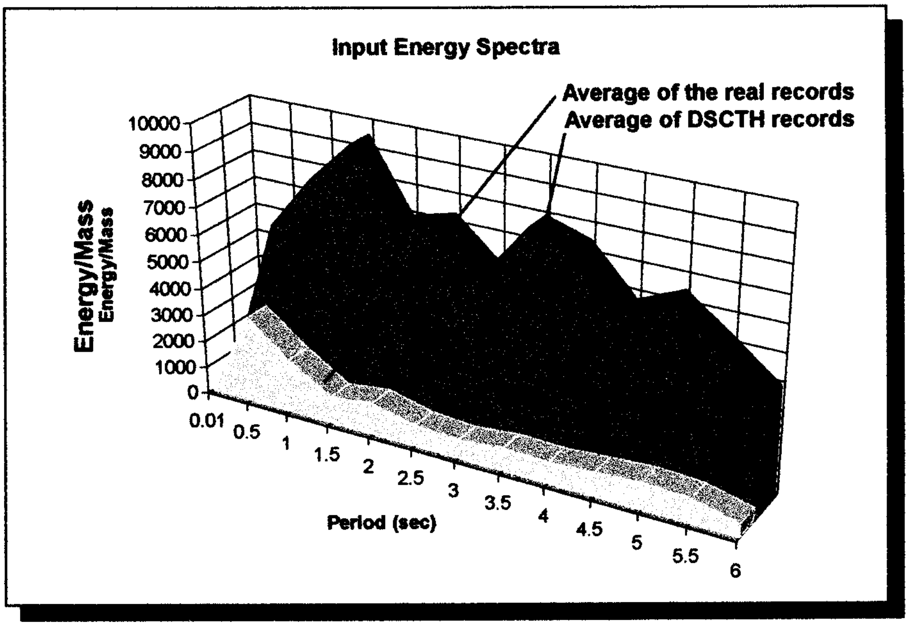


Figure 6 Comparison of energy contents of real records and their DSCTH counterparts.

6. As a result of the frequency filtering process, the DSCTH records obtained are very different in all characteristics from the real records which were used as seeds for their generation. Hence, this process has effectively eliminated the geologic, tectonic, and source characteristics that these records were initially selected to represent.

PRACTICAL IMPLICATIONS

Some practical implications of using frequency domain scaled DSCTH records are illustrated here by their application to a six-story seismic-isolated hospital building. The building is located in south central Los Angeles on an alluvium site which is only two miles away from the Newport-Inglewood fault. The site is also very close to the southern limits of the Elysian Park Fold and Thrust Belt. The target MCE design spectra is shown in Figure 1.

This is a very regular building in plan and elevation with a virtually square foot print of approximately 185 ft by 171 feet. There is a small notch at the south east corner of the plan. A foundation plan of this building is shown in Figure 7. The floor framing plan for the basement (top of the isolators) is shown in Figure 8. Plans for other floors are very similar in shape to the floor plan shown in Figure 8.

The building has a one story basement plus five stories above the grade. The lateral system for the first two levels (one below and one above the grade) consists of perimeter shear walls. The lateral system for the upper four levels consists of a series of chevron braced structural steel frames (see Figure 9). The foundations are composed of 24-inch-diameter, cast-in-place reinforced concrete piles. Pile caps have a thickness of up to six feet. Grade beams (16 inches wide, 24 inches deep) connect all pile caps.

Four alternative seismic isolation schemes were considered for this project. The seismic isolation system of these schemes consisted of 44 to 70 units of 40-inch-diameter high damping rubber (HDR) isolators supplemented by 8 to 12 units of special metal alloy friction sliders (FS) in some schemes. Typical force-displacement curves obtained from prototype testing of these devices are shown in Figures 10 and 11, respectively. The effective period of the isolated system varied from about 2.5 seconds for the 44HDR variation to about 1.5 seconds for the 70HDR+12FS variation. The target design spectrum (Figure 1) is matched in the period range of 1.0 to 4.0 seconds.

In this paper the results correspnding to the 70HDR+12FS scheme are presented. However, the same general observations apply equally well to other schemes (see Naeim and Lew, 1993).

The eigenvectors and eigenvalues of the "fixed-base" superstructure were computed using the ETABS computer program (Habibullah, 1992). These parameters were then used to model the superstructure in a series of 3D-BASIS (Nagarajaiah and others, 1991) nonlinear dynamic time history analyses to evaluate the response parameters of the seismic-isolated system.

The calculated displacement response of the building is summarized in Table 1, where the

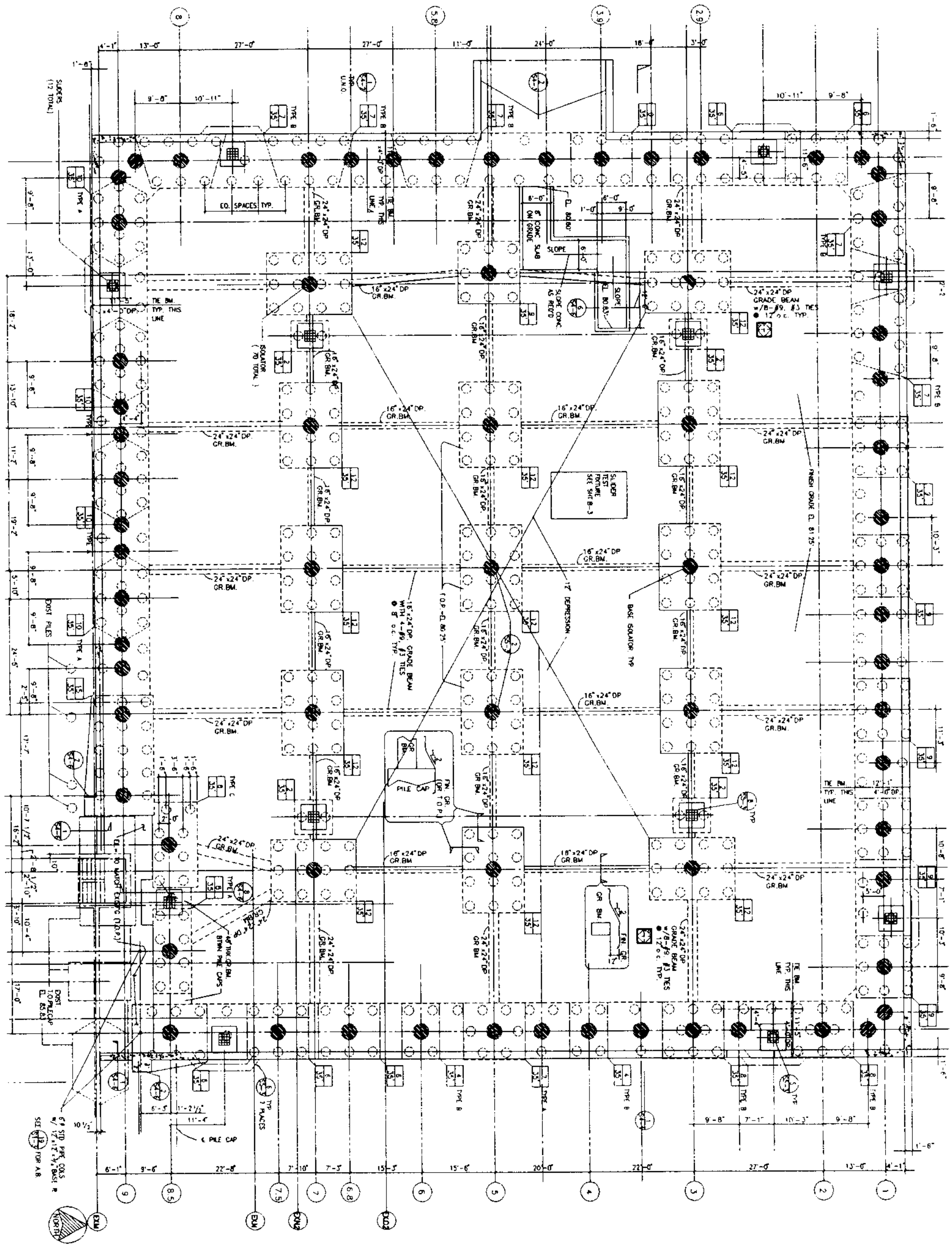


Figure 7 Foundation plan of the six story seismic isolated hospital building.

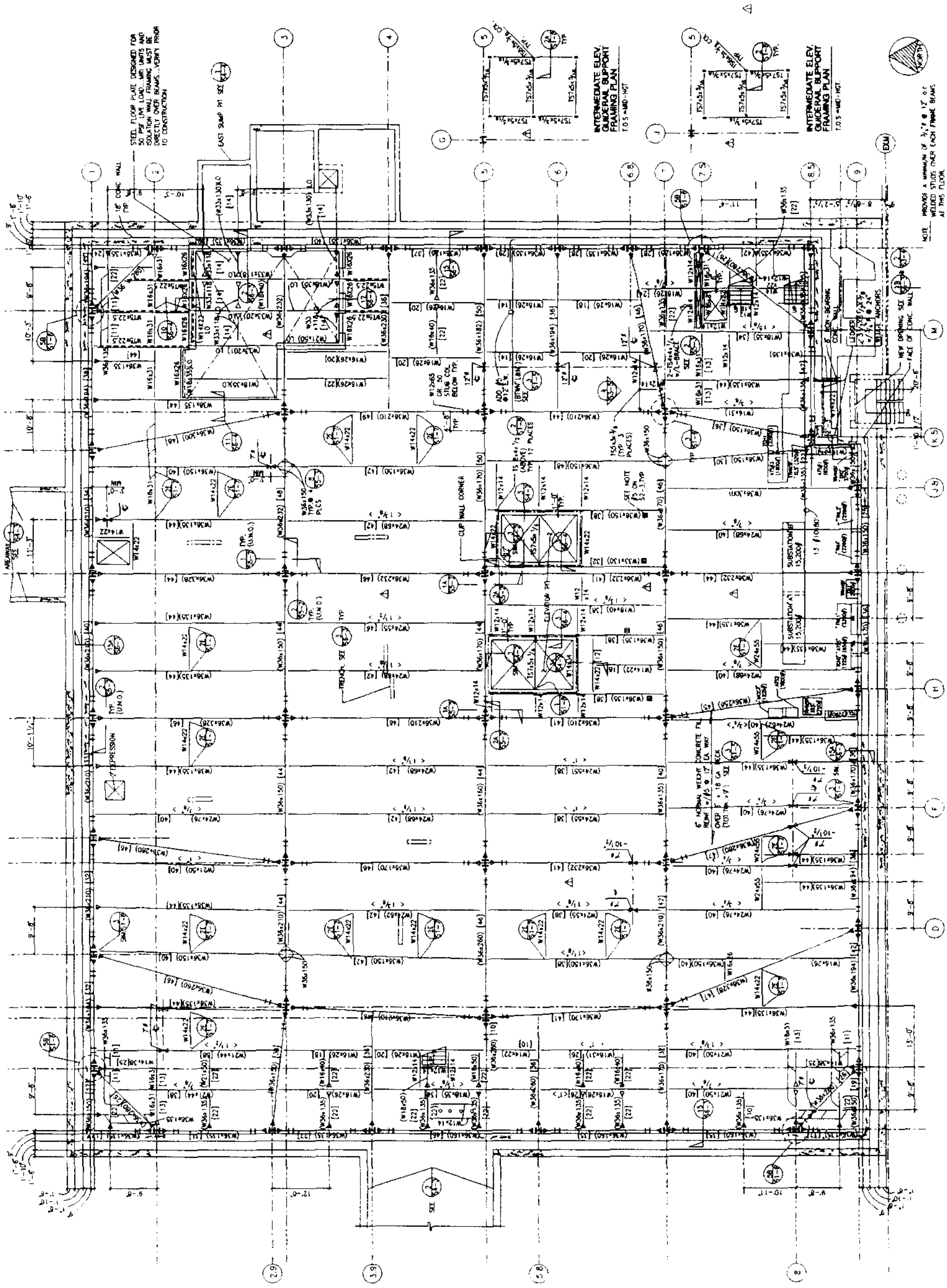


Figure 8 Floor plan for the diaphragm immediately above the isolation plane.

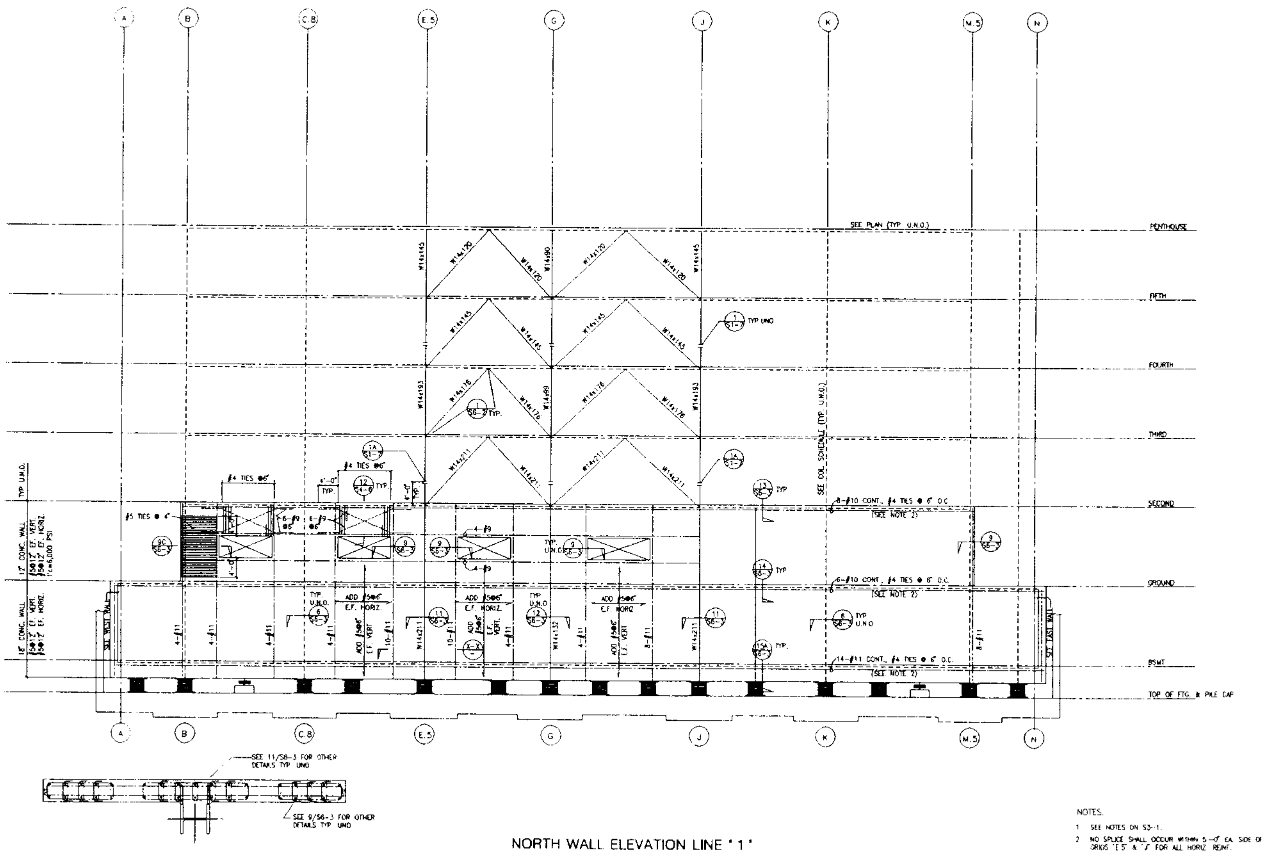


Figure 9 Elevation of a typical wall/braced-frame of the building.

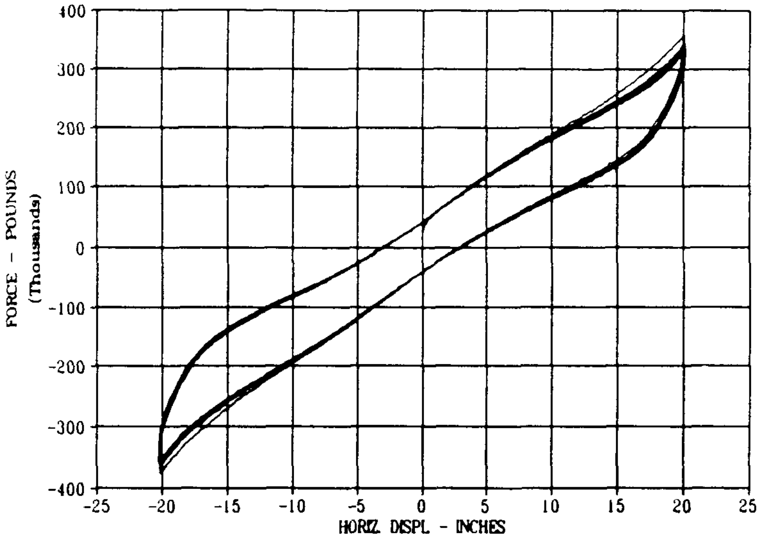


Figure 10 Typical force-displacement relationship for the high damping rubber isolators.

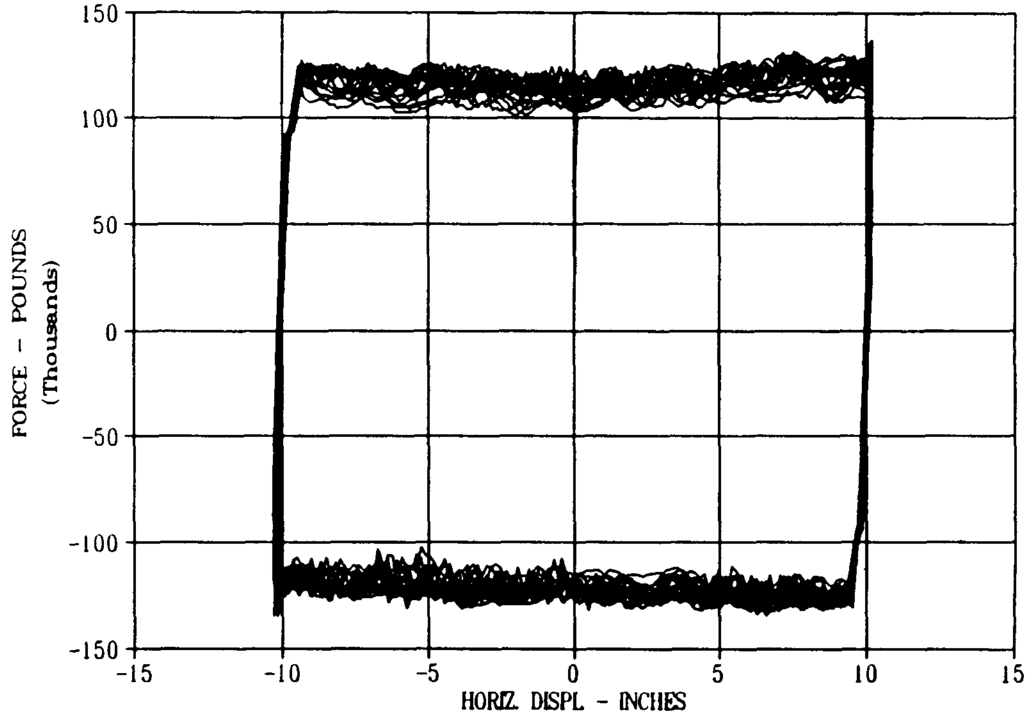


Figure 11 Typical force-displacement relationship for the friction sliders.

large differences between the results obtained by the two frequency-domain scaling procedures may be noticed.

TABLE 1 Maximum building displacement response at the isolation plane (inches).

Time-History Pair	Design Level	Real Pair	DSCTH (Method 1)	DSCTH (Method 2)
Imperial Valley (1979), Array #8	DBE	8.10	13.98	14.20
Imperial Valley (1979), Array #10	DBE	8.42	14.42	14.83
Loma Prieta (1989) at Corralitos	DBE	5.12	10.67	13.92
Kern County (1952) at Taft	MCE	2.33	23.71	28.93
Imperial Valley (1979) at Bonds Corner	MCE	4.49	21.33	18.06
Loma Prieta (1989) at Hollister, South & Pine	MCE	10.37	23.67	26.62

To further illustrate the problems associated with frequency-domain scaled DSCTH records, we amplified each individual pair in the time domain (by scaling the peak ground acceleration) so that the resulting response spectrum would equal or exceed the target design spectrum in period band of 1.0 to 4.0 seconds (in accordance with the UBC and OSHPD provisions discussed before).

For the 1952 Kern County at Taft pair, for example, the results can be summarized as follows:

1. The maximum displacement response when subjected to the unscaled horizontal components of the real record (100% in each direction) is 2.33 inches.
2. The maximum displacement response when subjected to the horizontal components scaled in time-domain to match or exceed the target design (348% scaling factor for each direction as calculated in Table 2) is 8.72 inches.
3. The maximum displacement response when subjected to frequency domain scaled DSCTH is 23.71 inches according to *Method 1* and 28.93 inches according to *Method 2*.

Notice that the results obtained by the above frequency-domain scaled DSCTH are between 271% and 332% larger than those obtained from the time-domain scaled DSCTH record and more than 10 times larger than what is indicated by application of the real record. Similar results were obtained for other time-history pairs. The reader is referred to Naeim and Lew (1993) for further details.

TABLE 2 Scaling a real pair to match or exceed target spectrum of Figure 1 over the period band of 1.0-4.0 seconds.

Period (sec)	1.30*Target SA (in/s/s)	1952 Taft C_1 (N21E) (in/s/s)	1952 Taft C_2 (S69W) (in/s/s)	3.48*SRSS(C_1, C_2)	1.30*Target SA is exceeded by
1.0	515	178	158	828	38%
1.2	429	142	143	701	39%
1.4	368	120	122	595	38%
1.6	322	103	163	672	52%
1.8	286	82	124	519	45%
2.0	258	62	84	365	29%
2.2	234	48	63	277	16%
2.4	215	37	60	246	13%
2.6	198	47	53	248	20%
2.8	184	45	46	225	18%
3.0	172	41	45	212	19%
3.2	161	38	39	189	15%
3.4	152	31	37	169	10%
3.6	143	26	33	147	3%
3.8	136	25	30	136	0%
4.0	129	26	26	129	1%

It is interesting to note that the Taft record, which in its pristine form showed the smallest displacement demand of all six real accelerogram pairs considered, has been transformed by the frequency domain spectrum matching process to a giant which controls the design of this structure.

Based on the above observations, the authors firmly believe that indiscriminate application of frequency-domain scaled spectrum-compatible time histories in seismic analysis and design of structures in general, and seismic-isolated buildings in particular should be discouraged. If DSCTH records have to be used for a particular application, serious attention should be given to the velocity and displacement characteristics of the DSCTH, as well as acceleration. This is a key requirement which is routinely ignored in practice. Furthermore, insisting on a very close match (i.e., 5% to10% tolerance) with a target spectrum over a relatively wide period band (i.e., 3.0 seconds), as required by the current siesmic design codes, may further increase the unrealistic characteristics of the DSCTH records obtained.

CONCLUSIONS

Potential problems associated with the uncontrolled use of frequency-domain scaled design spectrum compatible time-histories (DSCTH) in earthquake resistant design were illustrated. It was shown that frequency-domain scaled DSCTH are based on an erroneous understanding of the role of design spectra and can suffer from a multitude of major problems. They may represent velocities, displacements, and high energy content which are very unrealistic. The authors urge extreme caution in dealing with frequency-domain scaled DSCTH in the design of earthquake resistant structures.

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REFERENCES

California Office of Statewide Health Planning and Development (OSHPD), 1991, *An Acceptable Procedure for the Design and Review of California Hospital Buildings using Base Isolation,* Draft Revised April 26, 1991.

Habibullah, A. (1992), *ETABS — A Computer Program for Three Dimensional Analysis of Buildings,* User Manual, Computers and Structures, Inc., Berkeley, CA.

International Conference of Building Officials (1991, 1994), *Uniform Building Code,* Whittier, California.

Naeim, F., and J.C. Anderson (1993*), Classification and Evaluation of Earthquake Records for Design*, Report No. CE 83-08, Dept. of Civil Engineering, University of Southern California, July.

Naeim, F. and M. Lew (1993), *Design Ground Motion Criteria for Seismic-Isolated California Hospitals — Evaluations and Recommendations —*, Report No. 6980.68/93 John A. Martin and Associates, Inc., Los Angeles, October.

Naeim, F. (1994), "Implications of the 1994 Northridge Earthquake Ground Motions for The Seismic Design of Tall Buildings, *Str. Des. of Tall Bldgs,* 3(4), John Wiley and Sons.

Nagarajaiah, S., A.M. Reinhorn and M.C. Constantinou (1991), *3D-BASIS — Nonlinear Dynamic Analysis of Three Dimensional Base Isolated Structures: Part II,* National Center for Earthquake Engineering Research, NCEER-91-0005.

Silva, W.J. and Lee, K., 1987, *State-of-the-Art for Assessing Earthquake Hazards in the United States: WES RASCAL Code for Synthesizing Earthquake Ground Motions,* US Army Corps of Engineers, Washington D.C.