PROBLEMS IN PRESCRIBING RELIABLE DESIGN EARTHQUAKES

by

Vitelmo V. Bertero,[I] Stephen A. Mahin,[II] and Ricardo A. Herrera[III]

SYNOPSIS

Earthquake ground motion characteristics controlling the elastic and inelastic response of structures are shown to be fundamentally different. Limitations of present methods for specifying design earthquakes for buildings located near potential sources of a major earthquake are examined. In particular, the reliability of inelastic design response spectra derived directly from linear-elastic design response spectra is evaluated on the basis of the nonlinear dynamic response of single and multiple degree-of-freedom systems to near-fault accelerograms obtained during the San Fernando earthquake. Guidelines for prescribing inelastic design response spectra for near-fault sites and recommendations for further research are offered.

INTRODUCTION

To achieve an efficient aseismic design it is necessary to predict structural behavior for various critical combinations of loads and seismic excitations for each of a structure's limits of usefulness (limit states). While evaluation of all possible limit states in accordance with the philosophy of comprehensive design(1) is impracticable at present, satisfaction of the requirements for service and ultimate limit states is generally desirable and appears feasible. To prevent functional failure during relatively frequent seismic events (service limit states), structures should generally be designed to behave elastically. For unusually severe ground shakings, inelastic behavior up to the point of incipient dynamic collapse (ultimate limit states) may be tolerated. While analytical methods for predicting the mechanical behavior of structures are rapidly improving, considerable uncertainty remains regarding the characterization of design earthquakes. Resolution of this problem is complex because the critical ground motion varies according to the limit state considered.

The results of several studies(1,2) conducted to identify special problems encountered in prescribing design earthquakes for buildings located close to potential sources of major earthquakes are summarized in this paper. Methods currently used to specify design earthquakes, as well as some recent information regarding the characteristics of ground motions at near-fault sites, are reviewed and evaluated. The aseismic design implications of this evaluation are examined.

PRESENT METHODS OF PRESCRIBING DESIGN EARTHQUAKES

The ground motion experienced at a site is a complex function of the type and characteristics of the source mechanism, the nature of the intervening geological structure, and the topographical and soil conditions near the site. A usual design simplification is to consider only nonconcurrent action of horizontal ground translational components. It should be recognized that, for sites near the earthquake source, it may be necessary to base structural response evaluations on the simultaneous action of all six ground components(3) and to consider realistically the nonlinear soil-structure interaction.

I Professor of Civil Engineering, University of California, Berkeley.
II Assistant Research Engineer, University of California, Berkeley.
III Engineer, Capacete-Martin and Associates, San Juan, Puerto Rico; formerly Junior Specialist, University of California, Berkeley.

SERVICE LIMIT STATE DESIGN EARTHQUAKES. - Design earthquakes have been specified in terms of a building code zone, a site intensity factor, or more increasingly, an effective site acceleration.(4) However, for structures located at moderate distances from the source, it is generally agreed that one of the best ways to specify the service limit state design earthquake is by an average or smooth linear-elastic design response spectrum (LEDRS). Such a spectrum can be constructed by statistical analysis of elastic spectra obtained for appropriate real or simulated accelerograms, or by scaling the peak ground acceleration, velocity and displacement by spectral amplification factors statistically derived for various amounts of damping.(5) When only estimates of peak ground acceleration are available, it has been suggested that reasonable values for the peak ground velocity and displacement can be obtained by multiplying the ground acceleration (expressed as a fraction of gravity) by 122 cm/sec and 91 cm, respectively.(5)

ULTIMATE LIMIT STATE DESIGN EARTHQUAKES. - Design forces significantly lower than those derived from LEDRS for major earthquakes may be used in some cases by taking advantage of a structure's inelastic energy dissipation capacity. Preliminary ultimate limit state loads can be obtained using inelastic design response spectra (IDRS) derived by statistically evaluating the dynamic response of realistic nonlinear structural models to various appropriate ground motions.(6) Because of the complexities involved in such nonlinear dynamic analyses, a simpler method which derives IDRS by directly modifying LEDRS is more commonly used.(5) In this method, the LEDRS is modified using factors for a specified displacement ductility ratio. These factors were derived on the basis of analyses of elasto-perfectly plastic responses of single degree-of-freedom (SDOF) systems to several strong motion records obtained at moderate epicentral distances.(5) Caution should be exercised when applying this simplified method to sites subjected to significantly different types of ground motions, to multiple degree-of-freedom systems, or to systems with hysteretic behavior different from the assumed elasto-plastic idealization.(1,4,5)

CHARACTERISTICS OF NEAR-FAULT GROUND MOTIONS

Very little empirical data are available on ground motion characteristics, especially peak ground acceleration and velocity, for epicentral distances less than 15 km. Theoretical estimates of the upper limit for peak particle velocities range from 100-150 cm/sec.(5,7,8) Analytical studies based on simple two- and three-dimensional fault dislocation models (9,10) have indicated that the near-fault ground motions of the San Fernando earthquake were characterized by large ground velocity pulses. The Pacoima Dam (PD) record (which was the only accelerogram recorded in the area of heaviest shaking), and derived records for the base of the PD (i.e. the DPD record) and for the motion needed to produce the lower Van Norman Dan (VND) seismoscope trace, are shown in Fig. 1. These records contain severe, long duration acceleration pulses which resulted in unusually large incremental ground velocities (Fig. 1) and spectral velocities for periods greater than 0.8 sec. (Fig. 2). Such severe, long duration acceleration pulses can be directly related to the faulting process(9) and they have been detected in other near-fault accelerograms.(4)

RELIABILITY OF IDRS BASED ON LEDRS

The basic approach of deriving IDRS directly from LEDRS can seriously be questioned since the types of excitations that induce the maximum response in linear and inelastic systems are fundamentally different. In the case of a linear-elastic system, the critical dynamic excitation is of a periodic type having a frequency equal to that of the system; this induces an engineering resonance phenomenon. Since the largest dynamic amplification factor for an impulsive excitation is only 2, severe, relatively long duration acceleration pulses are not usually critical for elastic systems. On the other hand, the larger the intensity of the effective acceleration of a pulse with respect to the structure's yield strength, and the shorter the time to reach the peak acceleration and the longer the duration of the pulse relative to the fundamental period of the structure, the larger the inelastic deformations that will develop. Relatively short, periodic acceleration pulses are usually not critical for inelastic systems because, one yielding occurs, engineering resonance is depressed by the large energy dissipated by even small inelastic deformations.

Several nonlinear dynamic analyses of single and multiple degree-of-freedom systems were performed to assess the reliability of present methods of constructing IDRS from LEDRS for near-fault sites in view of possible severe, long duration acceleration pulses. For example, the actual ductility requirements for elasto-perfectly plastic SDOF systems with 5% viscous damping designed according to the IDRS in Ref. 5 for a desired ductility of four are shown in Fig. 3a for the El Centro and DPD records. While the maximum displacement ductilities required for the El Centro record are generally smaller than those predicted by the IDRS, ductilities required by the DPD record exceeded the specified value by factors as great as 2.2 for periods longer than 0.4 sec. IDRS based on ductility factors larger than 4 are even less reliable for near-fault motions.

Nonlinear analyses[1] of a ten-story, three-bay frame[2] designed using an IDRS for a ductility, μ, of four and with spectral velocities in the constant velocity range 31% higher than conventional values[5] also indicate that IDRS derived directly from LEDRS may not adequately define ultimate limit state design earthquakes. The frame's nonlinear response to records obtained at moderate epicentral distances was adequate[2], while not so for the DPD and VND records.[1] The response of the frame to near-fault records was characterized by a few large inelastic displacement excursions rather than by numerous intense oscillations, Fig. 4. The results in Fig. 4 also indicate that inelastic response cannot be reliably predicted by elastic analyses.

Derivation of IDRS directly from LEDRS implicitly assumes that increasing damping is as benefitial to the response of inelastic systems as it is to that of elastic systems. This is not the case, however. It has been found that the spectral amplification factors used to construct LEDRS[5] may significantly overestimate the effect of damping on inelastic response,[1] resulting in lower design forces than actually required to achieve a given μ. The typical effect of this is illustrated by Fig. 3b which shows that ductility requirements for elasto-perfectly plastic SDOF systems designed using suggested IDRS[5] for a μ of four increase with increasing values of the viscous damping ratio, ξ.

IMPLICATIONS FOR ASEISMIC DESIGN

LEDRS offer relatively simple and reliable methods for specifying design earthquakes for service limit states. At near-fault sites, however, ground spectrum shapes based on strong motion records obtained at moderate source distances may significantly underestimate the peak ground velocity and displacements. Realistic spectral shapes based on analyses of available near-fault records, or from theoretical predictions accounting for the faulting process and the nonlinear mechanical characteristics of a building's foundation media, should be used. To better define design earthquakes, strong motion instrumentation capable of recording all six ground motion components is needed at sites close to potential sources of major earthquakes.

DESIGN EARTHQUAKES FOR ULTIMATE LIMIT STATES. - Near-fault records can contain severe, relatively long duration acceleration pulses. Such pulses substantially increase the spectral velocity and, more importantly, the required seismic resistance coefficient, C_y, of buildings, particularly those with relatively long periods. To illustrate this, the values of C_y needed to limit ductility to four for the El Centro, DPD and VND records (normalized to 0.5g peak acceleration) are compared in Fig. 5 to current IDRS[5] and code values.[1] Unless the values of damping and ductility usually assumed in design can be substantially increased, structures located at near-fault sites must be designed for much higher forces than currently specified in codes. The IDRS requires sufficiently high C_y values in the short period range, while underestimating them for the near-fault records at periods greater than 0.5 sec.

Although structures can be detailed to accommodate the large ductilities that might result at near-fault sites if they were designed using current code or IDRS forces, this may not be desirable except for short period structures. The danger of underestimating design forces at near-fault sites is illustrated by the performance of the Olive View Hospital Main Building during the 1971 San Fernando earthquake.[1] Although this six-story reinforced concrete building, located near the fault rupture, had C_y values in excess of 0.3 (which would correspond to a ductility requirement of about 4 for 5% damping and peak ground acceleration of 0.5g), it suffered permanent drifts exceeding 75 cm and had to be demolished.

Since ultimate limit state design criteria are not only controlled by the energy dissipation capacity of the structural system but also by the deformations that can be tolerated due to economic, safety or stability considerations, selection of displacement ductility based on energy dissipation alone may not be a sufficient basis for establishing design earthquakes. In particular, the selection of a design ductility factor without regard to structural period or earthquake type (magnitude, source distance, duration, etc.) is inadequate. Furthermore, current IDRS do not give any indication of the total amount of inelastic action, or numbers and magnitudes of inelastic reversals which are essential for detailing critical regions. Comprehensive studies to determine more rational methods for establishing acceptable ductilities, particularly for flexible structures, are needed. Investigations are also needed regarding the economic impact of designing structures for either seismic resistance coefficients or design ductility ratios higher than those presently assumed.

Extensive research is also needed to fully characterize near-fault ground motions (particularly, duration of shaking and the number, sequence and features of intense, relatively long duration acceleration pulses). Misleading results can be obtained for near-fault sites if accelerograms characteristic of earthquakes with different magnitudes, source distances and soil conditions are used. For example, accelerograms obtained on soft soil at sites distant from the source often contain very long, but rather moderate acceleration pulses. Normalization of these records to larger peak accelerations, may be unrealistically severe for inelastic systems.

CONCLUDING REMARKS

Prediction of inelastic response on the basis of linear-elastic analysis, and correspondingly, direct derivation of IDRS from LEDRS, have been shown to be unreliable since the ground motion characteristics that control elastic and inelastic dynamic response are fundamentally different, and the effect of viscous damping is different. The reliability of simple relationships for constructing IDRS from LEDRS is expected to remain small even if more refined ground spectrum shapes for near-fault events and spectral amplification factors for yielding systems are developed. Thus, it may be preferable to obtain IDRS from a statistical analysis of the nonlinear dynamic response of SDOF systems with realistic hysteretic models to numerous types of ground motions. Nondimensional nonlinear response spectra, Fig. 6, can be developed for a particular record in terms of period, damping ratio, ductility and the parameter, η, defined as the ratio of the seismic resistance coefficient to the peak ground acceleration expressed as a fraction of gravity.(1) For given values of period, damping and peak ground acceleration, the seismic resistance coefficient required to limit the ductility to a desired value can be determined. Statistical analysis of such nonlinear spectra could lead to a better definition of the design earthquake which could explicity account for the variability of response.

It should be reiterated that design methods based on SDOF systems are only approximate guidelines for multiple degree-of-freedom (MDOF) systems. The seismic response of such systems designed using these methods should be thoroughly investigated to determine ways that IDRS obtained for SDOF systems should be modified for MDOF systems or to formulate new procedures for establishing design earthquakes for the inelastic design of MDOF systems.

ACKNOWLEDGMENTS

The financial support of the National Science Foundation is gratefully acknowledged.

REFERENCES

1. Bertero, V. V., Herrera, R. A. and Mahin, S. A., "Establishment of Design Earthquakes—Evaluation of Present Methods," Proc. of Int'l. Symp. on Eq. Str. Engng., St. Louis, August 19-21, 1976.
2. Bertero, V. V. and Kamil, H., "Nonlinear Seismic Design of Multistory Frames," Canadian Jnl. of Civ. Engng., Vol. 2, Ottawa, December 1975.
3. Rosenblueth, E., "The Six Components of Earthquakes," Jnl. of Struc. Div., ASCE, Vol. 102, No. ST2, 1976.
4. Newmark, N. M. and Rosenblueth, E., Fundamentals of Earthquake Engineering, Prentice-Hall, Inc., Englewood Cliffs, N.J., 1971.
5. Newmark, N. M. and Hall, W. J., "Procedures and Criteria for Earthquake Resistant Design," Bldg. Sci. Series 46, NBS, February 1973.
6. Murakami, M. and Penzien, J., "Nonlinear Response Spectra for Probabilistic Seismic Design of Reinforced Concrete Structures," Proc. of the U.S.-Japan Coop. Res. Prog. in Earthq. Engng., Tokyo, 1976.
7. Ambraseys, N. N., "Maximum Intensity of Ground Movements Caused by Faulting," Proc. of the 4th Wld. Conf. on Earthq. Engng., Vol. 1, Santiago, Chile, 1969.
8. Brune, J. N., "Tectonic Stress and the Spectra of Seismic Shear Waves from Earthquakes," Jnl. of Geophys. Res., Vol. 75, 1970.
9. Boore, D. M. and Zoback, M. D., "Two-dimensional Kinematic Fault Modeling of the Pacoima Dam Strong-motion Recording of the February 9, 1971, San Fernando Earthquake," BSSA, Vol. 64, No. 3, June 1974.
10. Trifunac, M. D., "A Three-dimensional Dislocation Model for the San Fernando, California, Earthquake of February 9, 1971," BSSA, Vol. 64, No. 1, February 1974.

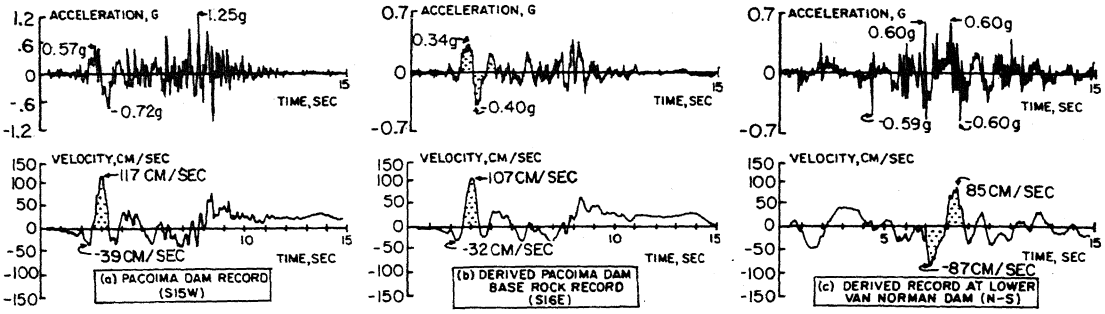


FIG. 1 NEAR-FAULT GROUND MOTION RECORDS OF THE SAN FERNANDO EARTHQUAKE

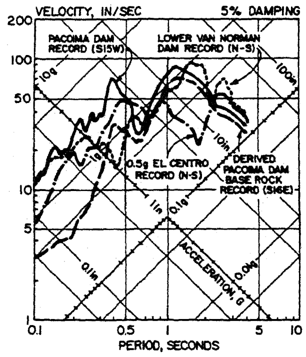
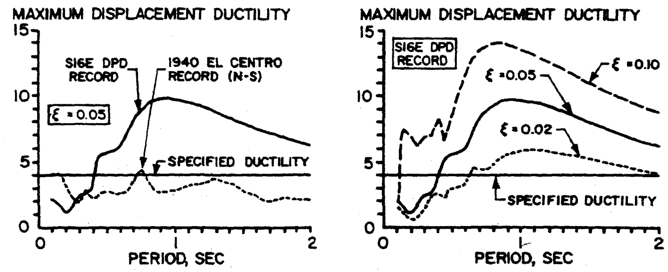


FIG. 2 RESPONSE SPECTRA



a. FOR DIFFERENT RECORDS

b. FOR DIFFERENT DAMPING RATIOS

FIG. 3 COMPARISON OF SPECIFIED AND REQUIRED DUCTILITIES

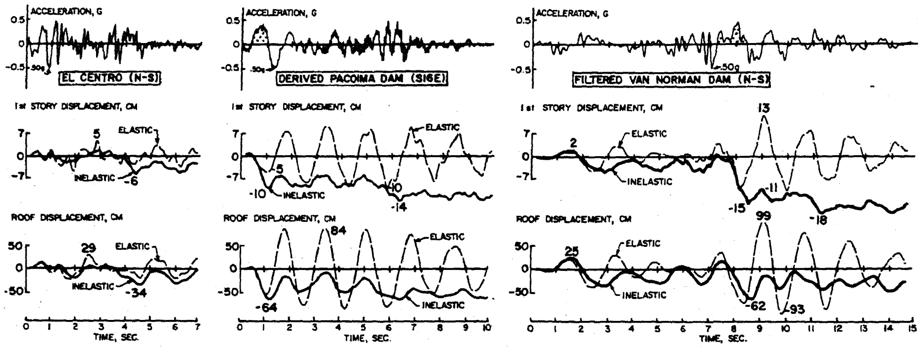
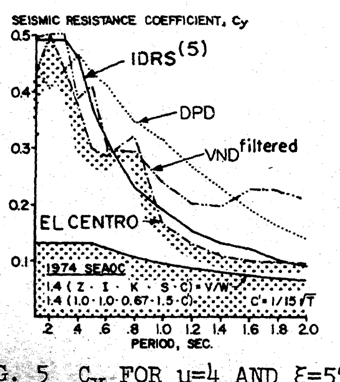


FIG. 4 RESPONSE OF 10-STORY FRAME TO DIFFERENT ACCELEROGRAMS



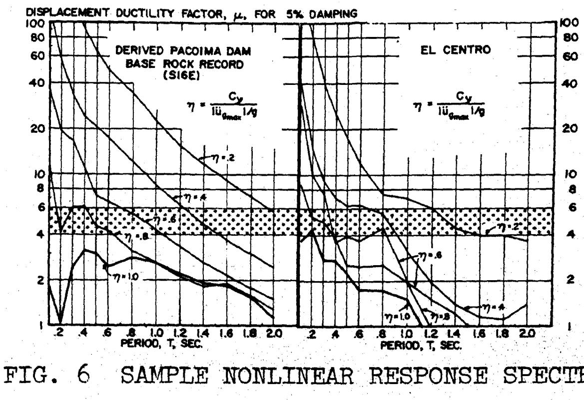


FIG. 5 C_y FOR $\mu=4$ AND $\xi=5\%$ FIG. 6 SAMPLE NONLINEAR RESPONSE SPECTRA