"DESIGN SPECTRA" AND THEIR APPLICATION IN ENGINEERING PRACTICE

P. G. Carydis [1] and J. M. Taflambas [2]

ABSTRACT

The aim of this paper is the presentation of the methods currently used, for the estimation of inelastic design response spectra, in order to evaluate the design forces that will restrict the demanded deformations of a structure in the limits of its available ductility. A comparison between the methods used is presented, to account for the reliability of each method and for the safety of design expected for different classes of strong motion records. Recently available methods, based on the estimation of the amount of hysteretic energy absorbed in a structure, are compared with methods evaluating displacement ductility demand. Special problems arising from near-field strong motions, affecting seriously the inelastic behaviour of structures, are regarded in accordance with the reliability of the methods used. Finally a brief presentation of points that may be subjects of future studies is given.

INTRODUCTION

As it is well known, structures are designed in order to withstand an amount of shaking, especially during severe ground motions, through inelastic deformations that the structure is designed to afford. These deformations must be limited below a certain value, which if exceeded results in the failure of a structure, either because it has exceeded its load bearing capacity, or because the amount of the inelastic deformations prohibits the repair of the structure for economic reasons. The ability of a structure to respond with limited inelastic deformations during a specified strong ground motion depends on the amount of the reduction of the elastic acceleration response spectrum which results to the inelastic design response spectrum for the estimation of the seismic forces of the structure.

The methods currently used for the estimation of the design seismic forces for structures with limited available ductility, belong to the following two categories:

a) Analytical methods for the evaluation of the demanded ductilities in order that a structure can effectively withstand a sample of severe ground motions. The use of these methods depends on the availability of a representative sample of earthquakes, expected at the site during the lifetime of the structure. This is not always possible, since strong motion

---

[1] P G Carydis, Profesor, Laboratory for Earthquaje Engineering, N T U.A , Polytechnic Campus, Zografos 157 00, Athens, Greece.

[2] J M Taflambas, Civil Engineer, Laboratory for Earthquake Engineering, N T U.A., Polytechnic Campus, Zografos 157 00, Athens, Grece.

records are not available to that extent, especially in what regards severe earthquakes in near-field zones. In order to compensate lack of data, methods for the construction of artificial accelerograms with defined characteristics are used, or methods based on random vibration theory, so that a probabilistic estimation of the inelastic behaviour of structures is carried out. These methods can give good results but they are time consuming and are not demanded for simple structures.

b) Methods based on the modification of smoothed linear elastic to inelastic design response spectra. These methods permit the estimation of design forces so that the demanded deformation is lower than specified limit state values. The usual methods are that of ATC recommendations [1] and the one proposed by NEWMARK & HALL [8].

METHODS FOR THE ESTIMATION OF INELASTIC DESIGN RESPONSE SPECTRA

ATC method [1]

This method follows the Applied Technology Council recommendations and is incorporated with slight modifications in the recent codes of various countries. The assumptions of the method are the following. The method uses a smoothed linear elastic acceleration response spectrum with constant spectral values for a range up to a certain period, with spectral amplification factors about 2.5. For further periods the spectral values are attenuated exponentially according to an inverse function of the natural period T. In ATC recommendations the spectral values are a function of Aa and Av, corresponding to the effective peak acceleration and effective peak acceleration as a derivative of the ground velocity. The definition of effective acceleration is still qualitative and is associated with a value lower than the peak ground acceleration corresponding to the damage effect of the strong motion. This is due to the fact that the peak ground acceleration usually has a high frequency content not exciting the structure and of no consequence on structural response. The effective ground acceleration is correlated with the part of the strong motion that releases the greatest percentage of input energy.

These assumptions are inherent in the construction of elastic design response spectra according to ATC and similar codes.

The modification of the elastic values, in order to approximate the inelastic design response spectrum, is effected by dividing the elastic spectrum by a factor R, common for the whole period range. The factor R incorporates the effect of the damping coefficient, as well as that of a specified ductility which permits for inelastic deformations as a result of the reduction of the design forces.

The most significant assumption of the method is that for every structural period the elastic and inelastic displacement spectral values coincide. This assumption is unreliable for low period structures and as a consequence the design forces for specified ductilities are underestimated.

NEWMARK & HALL method [8]

The second method used is the one presented by NEWMARK & HALL and is based on the analytical results of inelastic analysis of single degree of freedom systems. NEWMARK & HALL have evaluated a series of characteristics that command the values of inelastic spectra for single degree of freedom systems and for different ground motions. These basic observations are the following:

a) For periods greater than 0.5 sec the total inelastic displacement for different ductility factors ú remains the same.

b) For periods less than about 0.05 to 0.03 sec the maximum acceleration remains the same for all ductility factors. Between those period ranges exists a transition zone.

According to these observations the construction of inelastic design response spectra is done as follows. For periods greater than 0.5 sec displacements are the same for all ductility factors permitting the use of a constant reduction factor for the elastic spectrum equal to ú. For periods between 0.125 and 0.5 sec, at which range the acceleration values remain constant, the best relation between elastic and inelastic values is given by the principle of the same amount of hysteretic energy being absorbed in both elastic and inelastic systems. The reduction factor of that range of the elastic spectrum is equal to $(2\mu\text{-}1)$, which is the ratio between elastic and inelastic maximum displacements, allowing for equal energy absorption. Between 0.03 and 0.125 sec there is a transition zone. Below 0.03 sec, acceleration remains constant for all ductility factors.

The evaluation of the smoothed elastic spectrum is done with spectral amplification factors multiplied with the ground motion parameters for different damping coefficients. The value of the ground velocity is estimated from the ground acceleration assuming a relationship of V/A=120 cm/sec/g for firm soil conditions or 90cm/sec/g for rock.

MEASURES OF INELASTIC BEHAVIOUR BASED ON ENERGY ABSORPTION

The displacement ductility is only one of the indices that account for the inelastic response of a structure. In the case of repeated cycles of deformation reversal, ductility indices are proposed that are measures of the greatest inelastic excursion, of the permanent displacement at the end of the excitation or of the absorbed hysteretic energy [7]. Other indices proposed estimate a number of equivalent cycles as the ratio of the total hysteretic energy absorbed during the excitation to that absorbed during a monotonic loading with the same maximum inelastic displacement [10].

All these indices try to account for the energy absorption demand, in an effort to proceed with structural design methods combining a variety of measures of inelastic behaviour, since a structural failure can be caused either by unacceptably large deformations, or repeated cycles of smaller amplitude, which can reduce significantly the seismic load bearing capacity. In the first case displacement ductility remains the crucial index. In the last case, an index accounting for the hysteretic energy absorption is needed. A proposal for such an index, estimated from elastic response spectra, has been recently presented by KUWAMURA & GALAMBOS [5].

Energy absorption index by KUWAMURA & GALAMBOS [5]

The aim of this method is the construction of a smoothed absorbed energy spectrum, considering as energy absorption mechanisms both hysteresis and damping. The ratio berween total and hysteretically absorbed energy is given approximately, considering the damping of the structure and the ratio of the cumulative plastic deformation to that of the yield limit. The basic assumptions of the method are the following:

a) The total absorbed energy Et is insignificantly affected by the plastic strength of the structure.

b) Et is not affected by the spring characteristics simulating the structural stiffness.

c) Et is not affected by the damping coefficient.

d) Et/M is independent of the mass M and is affected by the natural period of the structure.

e) An equivalent velocity Ve can be estimated so that $Et=0.5MVe^2$ and its spectrum is very close to that of pseudovelocity.

The construction of the equivalent velocity spectrum is done as follows.If To is the predominant period of the strong motion and Ie the Arias Integral of the square of ground accelerations, then the equivalent velocity Veo for To is equal to Veo=0.5 (Ie To). The spectrun shape is given by the following relationships:

For $T>To/1.2$ $Ve = 1.2\ Veo\ T/To$
$T>To/1.2$ $Ve = Veo$

With the above method, the equivalent velocity spectrum is compiled for each strong motion record and the amount of hysteretically absorbed energy is estimated.

RELIABILITY OF THE ABOVE METHODS FOR DIFFERENT CLASSES OF STRONG MOTIONS

Results for medium distance strong motions

The greatest percentage of available strong motion records have been recorded at medium epicentral distances. For this class of records the ATC method gives acceptable results for the medium period range and further. For small periods, especially less than 0.4 sec, the displacement ductility demand is unacceptably larger than the specified values and the results are unreliable [6]. This is due to the assumption of the ATC method using a constant reduction factor for the whole period range. The NEWMARK & HALL method by changing the reduction factor, starting with a value equal to 1 for very small periods, gives acceptable results even in that range, assuming that very stiff structures must be designed elastically. For the same class of strong motions the equivalent velocity spectrum proposed by KUWAMURA and GALAMBOS can be justly accepted as the envelope of the equivalent velocity values estimated analytically, when the yield limit is estimated from a NEWMARK and HALL inelastic design spectrum.

These observations are not justified in the case of near-field strong motions.

Characteristics of near-field strong motion records

The precision and reliability of the above referred methods is tested in the case of near-field strong ground motions. From the small sample of this class of records the following characteristics were observed:

a) The near-field accelerograms contain severe large period acceleration pulses, considered crucial for structures with natural period less than the duration of the pulses [6,2].

b) Depending on the duration of the severe pulses, the relation between ground velocity and acceleration V/A may be greater than 120 cm/sec/g and can approximate values of 250 cm/sec/g, resulting in expected ground velocities much greater than those of medium distance strong motions [6,2].

c) In the case of near-field accelerograms the peak ground acceleration can be accepted as the effective acceleration because it coincides with the large period pulses. Methods for the estimation of Aa, show that the ratio of peak to effective acceleration is close to 1.2 [9].

d) The time function of the Arias Integral Ie presents, at the time span corresponding to the long duration severe pulses, a steeply rising portion. The time derivative of this portion is a measure of the rate at which energy input is accumulated into a structure. According to Housner [4], the rate of that energy release and the corresponding time span can be used for a two component definition of the intensity of ground shaking. This amount of energy is absorbed through damping and hysteretic deformation. The occurrence of the intense energy release corresponds to the greatest inelastic excursions, that will develop in the structure, and the demanded ductility. It is also correlated with the effective acceleration [8,9].

e) For this class of strong motions special attention must be given to the use of spectral amplification factors. The amplification factors [8,3] are given as a ratio of spectral acceleration values to the peak ground acceleration. For most earthquakes, effective acceleration values are smaller than peak values so that the amplification factor for the effective acceleration can be larger than the usual ones. Since the effective acceleration which is the crucial parameter for structural response is close to the peak acceleration for near-field earthquakes, the expected spectral amplification can be larger than usual.

f) Compared with the velocity and Fourier spectra of medium epicentral distance earthquakes, the spectra of near-field strong motions present a larger dispersion around the predominant period. The effect of that dispersion on the inelastic behaviour is that it causes a more rapid change of the initial stiffness and period of the structure.

Results for near-field strong motions

Although the method proposed by NEWMARK & HALL appears to be much more reliable than that of ATC, for near-field strong motions values severely exceeding the specified ductilities may appear in two ranges of the spectrum. For periods greater than 0.4 sec, this phenomenon is due to the assumption that ground velocity can be estimated from ground acceleration through a factor of 120 cm/sec/g. The use of this factor which may underestimate ground velocity, gives smaller spectral values for the medium period range where spectral pseudovelocity is assumed to remain constant. An underestimated elastic response spectrum causes unacceptably large ductility demand which can be corrected, if the values assumed are replaced by the actual ground velocities [6,2].

In the range of periods smaller than 0.4 sec the method gives unreliable results even with the actual V/A relationship, especially for values of ú greater than 3. This may be due to the underestimation of the actual spectral amplification factors by those usually proposed.

As a matter o fact, the large ductility demands analytically calculated do not realize to that extent in structures exposed to severe ground motions. The reduction of these values is due to the fact that analytical results are based on the minimum strength of materials, to the conservatism of minimum code requirements resulting in overstrength of structural members, to the contribution in the absorption of energy by the monstructural elements and finally to phenomena like soilstructure interaction.

Regardless of all these, the ponts referred must be taken into account, and the methods used by the design engineer must be approached with the knowledge of their weaknesses and uncertainties. The class of strong motions expected during the lifetime of the structure must always be considered beforehand.

RECOMMENDATIONS FOR FURTHER STUDIES

A good measure for the estimation, of whether the most critical inelastic index for a given earthquake is the displacement ductility or the accumulated absorbed energy because of repeated inelastic deformation reversals, is the time function of the Arias Integral Ie. The shape of the time function Ie (t) correlates well with that of the input energy in a structure. This convergence is much better with the time function of the absorbed energy through hysteresis or damping or their sum. According to that observation, if the time function of Ie presents a steeply rising portion, the association with the absorption of hysteretic energy permits to assume that, at the same time span, a system absorbs energy at a rate which accounts for large inelastic deformations and the demanded ductility. On the other hand a function of Ie that does not present time spans of steeply rising portions gives the impression of hysteretic energy absorbed through repeated low amplitude cycles, in which case the most crucial index appears to be that of energy absorption.

A future study must be that of the numerical correlation between the steep portions of the Arias Integral, the effective acceleration and the spectral amplifications factors. These parameters affect the displacement ductility demand for structures with natural period lower than the duration of the severe ground motion pulses. The two component estimation of the Intensity of ground motions proposed by Housner is based on the same logic. The same approach can be used for the normalization of strong ground motions regarding displacement ductility demand. The usual normalization methods, as spectrum intensity and Fourier energy account for the energy absorption during the excitation and not for displacement ductilities which are closely correlated with the steep portions of the Arias Integral, the acceleration spectrum and the effective acceleration.

An analysis example is presented for two strong motion accelerograms. The first is the El Centro N-S with a peak ground acceleration of 342 gal. The second is the Kalamata Trans component, recorded in Southwestern Greece in September 1986 at an epicentral distance of 15 km, with a peak ground acceleration of 290 gal. The two accelerograms are shown in Fig. 1. In Figs. 2 and 3, the power and velocity spectra are presented as measures of input energy. The ratio of input energy for El Centro and Kalamata is about 1.2 with which the second record should be scaled in order to have the same energy content as El Centro. This can be seen from the values of the spuare root of the Arias Integral at the end of the excitation in Fig. 4. The relation is reversed in what regards the steep rising portions of Ie and the acceleration spectra in Figs. 5 and 6, where the values for Kalamata are slightly higher than those of El Centro. The peak acceleration for Kalamata is lower than El Centro, but seems to be closer to the effective acceleration which is correlated with the steep rising portion of Ie. The larger spectral amplification factors that are presented for Kalamata can be due to the difference of ratio between peak and effective acceleration for the two records.

In Figs. 7 and 8, the ductility demand spectra for the two records are presented according to the ATC and the NEWMARK and HALL methods, with spectral amplification factors 2.80 for El Centro and 3.10 for Kalamata. The results are as expected, according to the previous comparison of the methods. In Fig. 9 the ductility spectra for the two methods are given for Kalamata with spectral amplification factor 3.50. In that case demanded and specified ductilities are very close. In Figs. 10 and 11 the equivalent velocity spectra corresponding to the cases of Figs. 7 and 8 are presented. The ratio of input energy for the two records is the same as previously referred. The approximation proposed by KUWAMURA and GALAMBOS improves significantly in the lower period range in the case of an inelastic design spectrum according to NEWMARK and HALL. In Fig. 12 the equivalent velocity spectra are presented for the case of Fig. 8.

As a result of the analysis performed, it seems that El Centro has a larger energy input but Kalamata causes larger ductility demand, especially in the lower period range. These observations are closely related with the time function of the relative Arias Integrals.

Finally, for the estimation of the spectrum of absorbed energy it is better to use the Fourier spectrum, considering maximum velocities during the free vibration, after the end of the excitation. Free vibration velocity is a measure of the energy remaining in the system, which, otherwise, would be absorbed by damping and hysteresis.

LIST OF SYMBOLS

A	peak ground acceleration
Aa	effective ground acceleration
Av	effective ground acceleration as a velocity derivative
Et	total absorbed energy
Ie	Arias Integral
M	system mass
R	ATC reduction factor
To	predominant period of strong motion
V	peak ground velocity
Ve	equivalent velocity
Veo	equivalent velocity for To
μ	displacement ductility factor

REFERENCES

1. Applied Technology Council, U.S. Dept. of Commerce, "Tentative Provisions for the Development of Seismic Regulations for Buildings", NSF Publication 78-8, NBS Special Publication 510, Washington, D.C., June, 1978.

2. Bertero V.V., Herrera R.A. and Mahin S.A., "Establishment of Design Earthquakes Evaluation of Present Methods", Proceedings, International Symposium on Earthquake Structural Engineering, August 1976, pp 551-580.

3. Carydis P.G., "Features of Greek Strong Motion Records and Response Spectra", Proceedings of the Symposium on the Analysis of Seismicity and on Seismic Risk, Liblice, October 1977.

4. Housner G.W., "Measures of Severity of Earthquake Ground Shaking", Proceedings of the U.S. National Conference on Earthquake Engineering, EERI, Ann Arbor, Mich., June 1975, pp 25-33.

5. Kuwamura H. and Galambos T.V., "Earthquake Load for Structural Reliability", Journal of Structural Engineering, Vol. 115, No. 6, June 1989, pp 1446-1462.

6. Mahin S.A. and Bertero V.V., "An Evaluation of Inelastic Seismic Design Spectra", Journal of Structural Division, ASCE Vol. 107, No St9, September 1981, pp 1777-1795.

7. Mahin S.A. and Lin J., "Construction of Inelastic Response Spectra for SDOF Systems", Earthquake Engineering Research Center, UCB/EERC-83/17, June 1983, Barkeley, California.

8. Newmark N.M. and Hall W.J., "Earthquake Spectra and Design", Earthquake Engineering Research Institute Monograph Series, Vol. 3, 1982.

9. Yang K.S., "An Evaluation of Strong Motion Records and a New Parameter A (95)", M.Sc. Dissertation, Civil Engg. Dept., Imperial College, London, 1984.

10. Zahrah T.F. and Hall W.J., "Earthquake Energy Absorption in SDOF Structures", Journal of Structural Engineering, Vol. 110, No. 8, August 1984, pp 1757-1772.

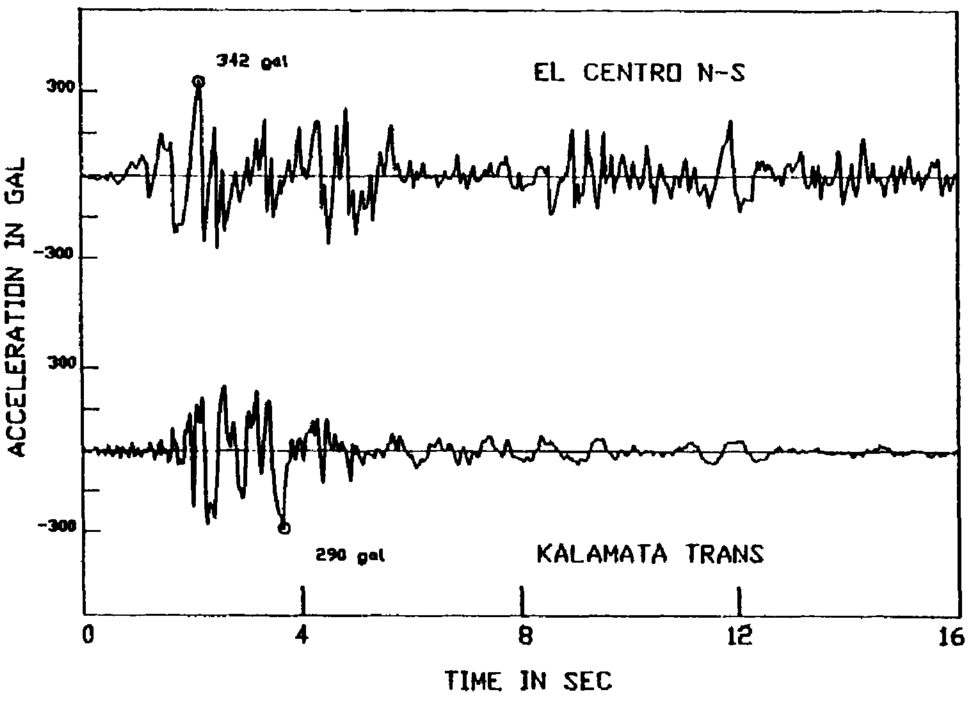

Fig. 1 Accelerograms of El Centro N-S and Kalamata Trans

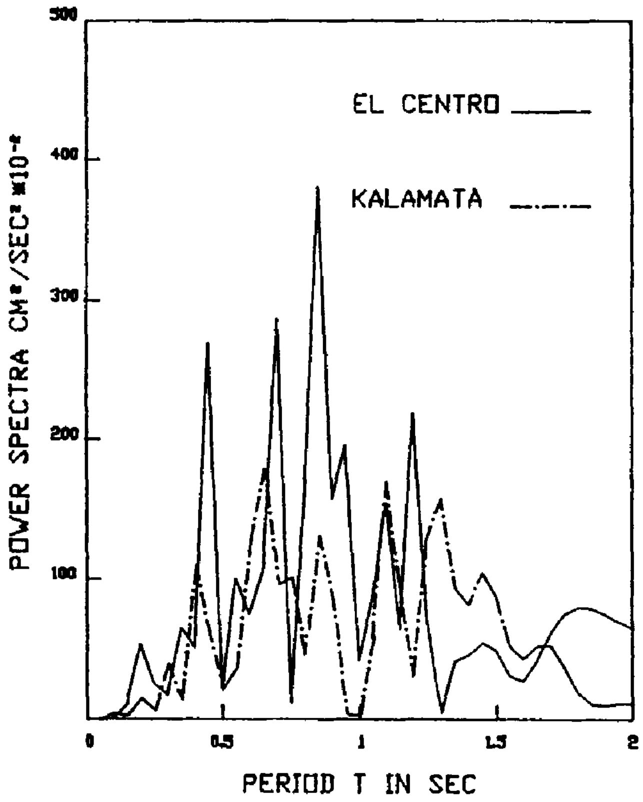

Fig. 2 Power spectra for Kalamata and El Centro

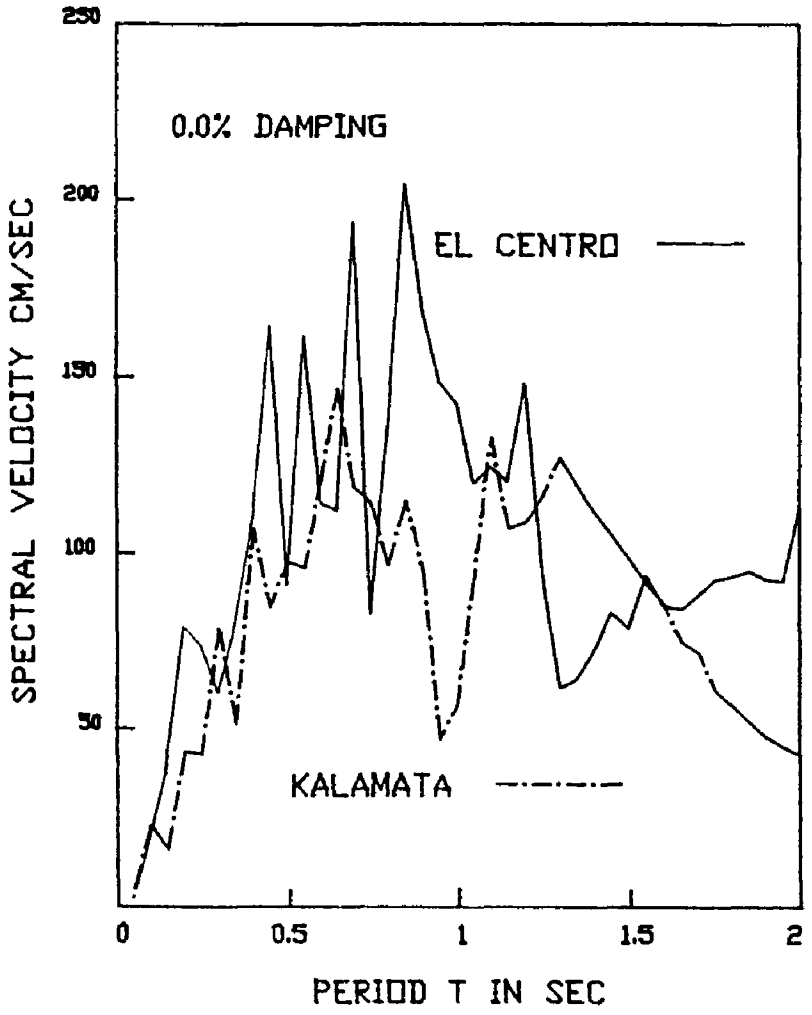

Fig. 3 Velocity spectra 0.% damping for Kalamata and El Centro

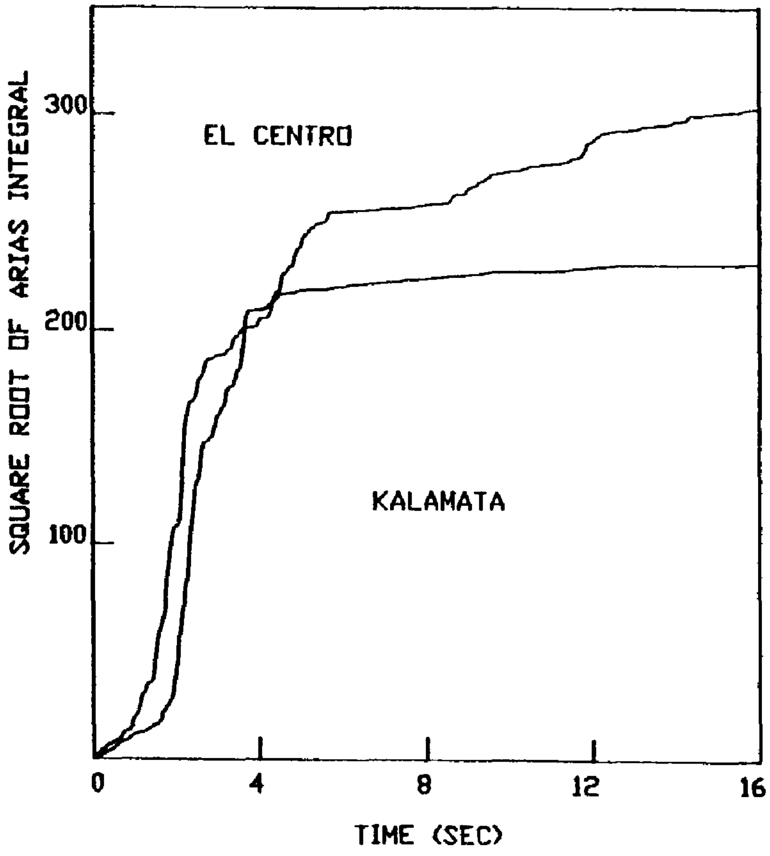

Fig. 4 Arias Integral Ie time histories for KALAMATA TRANS AND EL CENTRO N-S

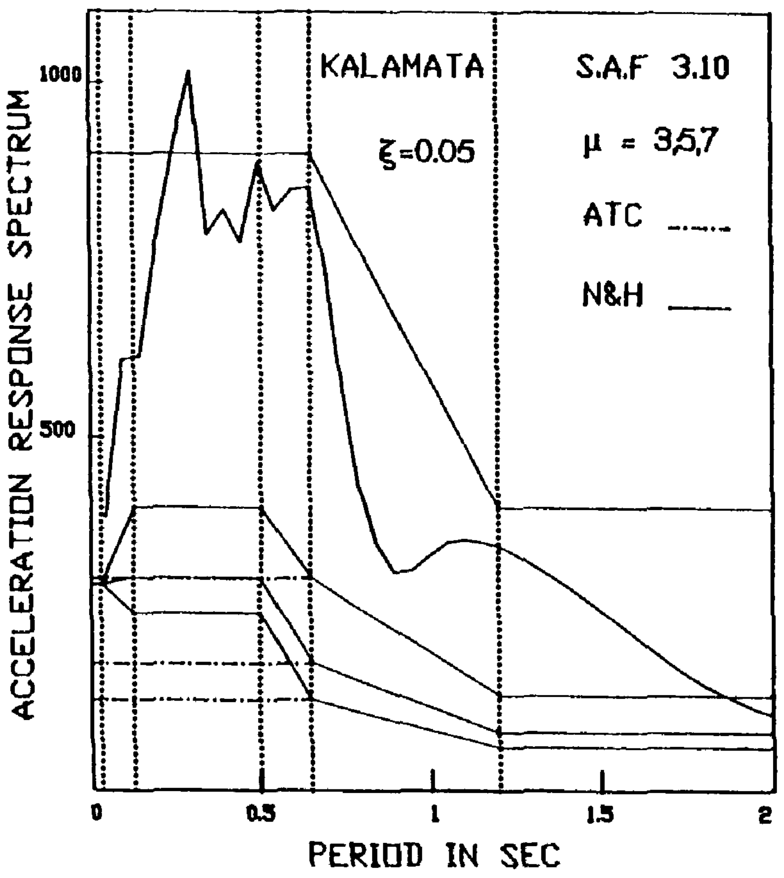

Fig. 5 Acceleration elastic and IDRS spectra for KALAMATA - ATC and N&H Method

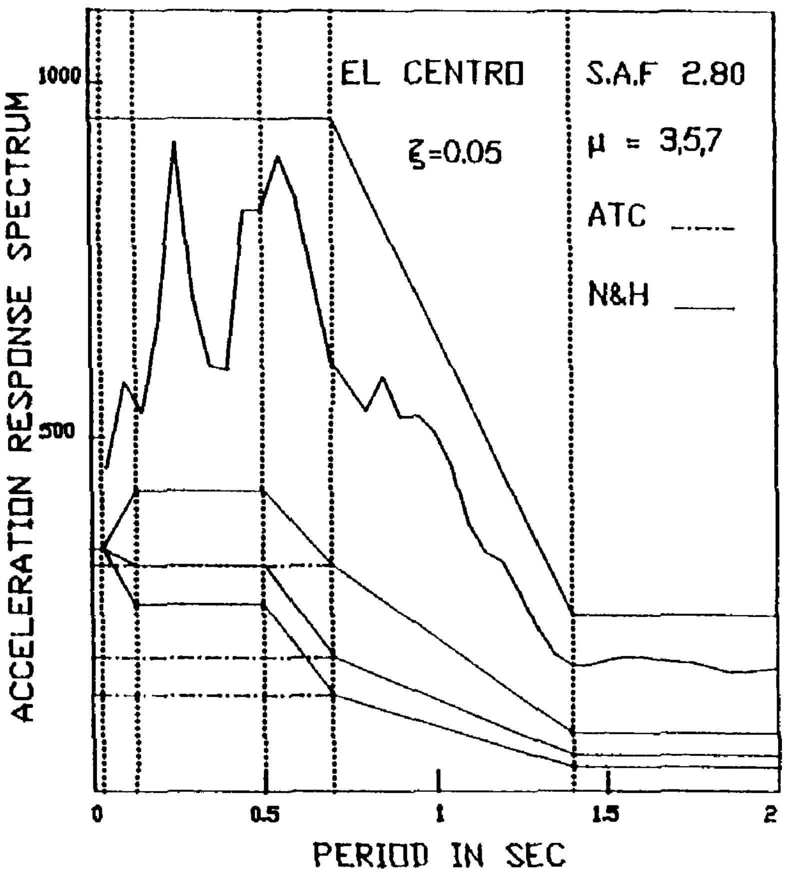

Fig. 6 Acceleration elastic and IDRS spectra for EL CENTRO - ATC and N&H Method

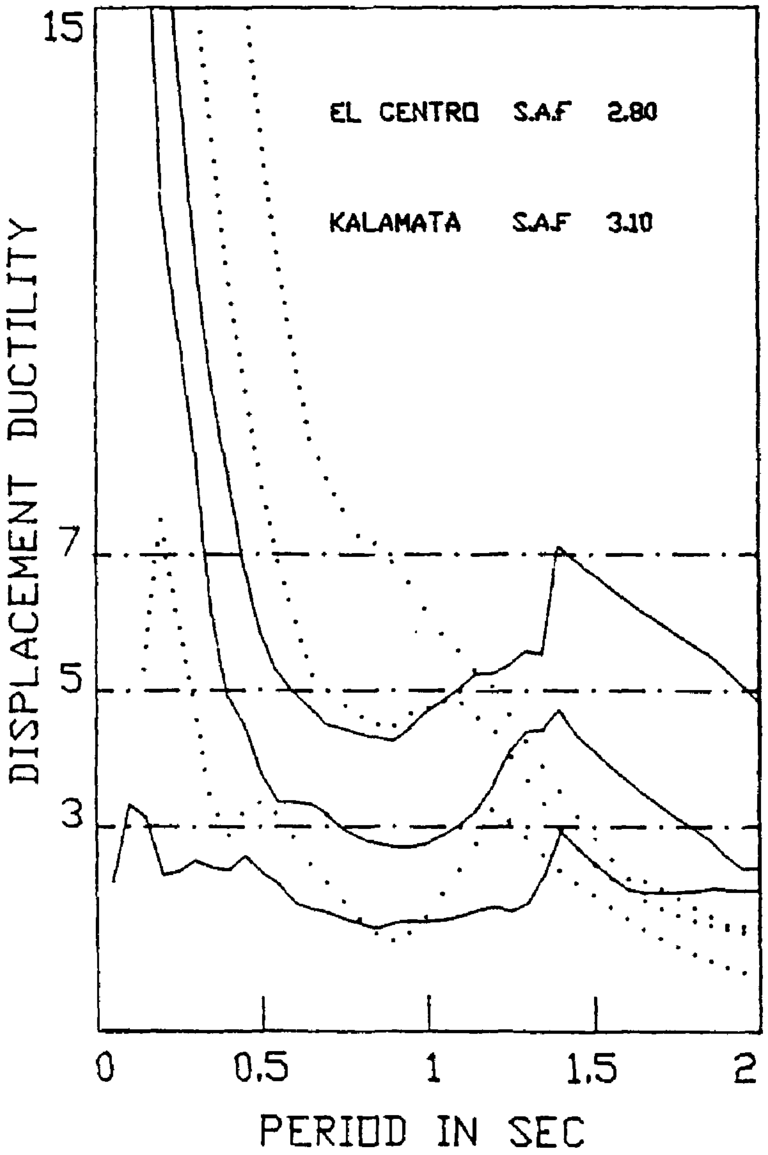

Fig. 7 Displacement ductilities using the ATC IDRS Method

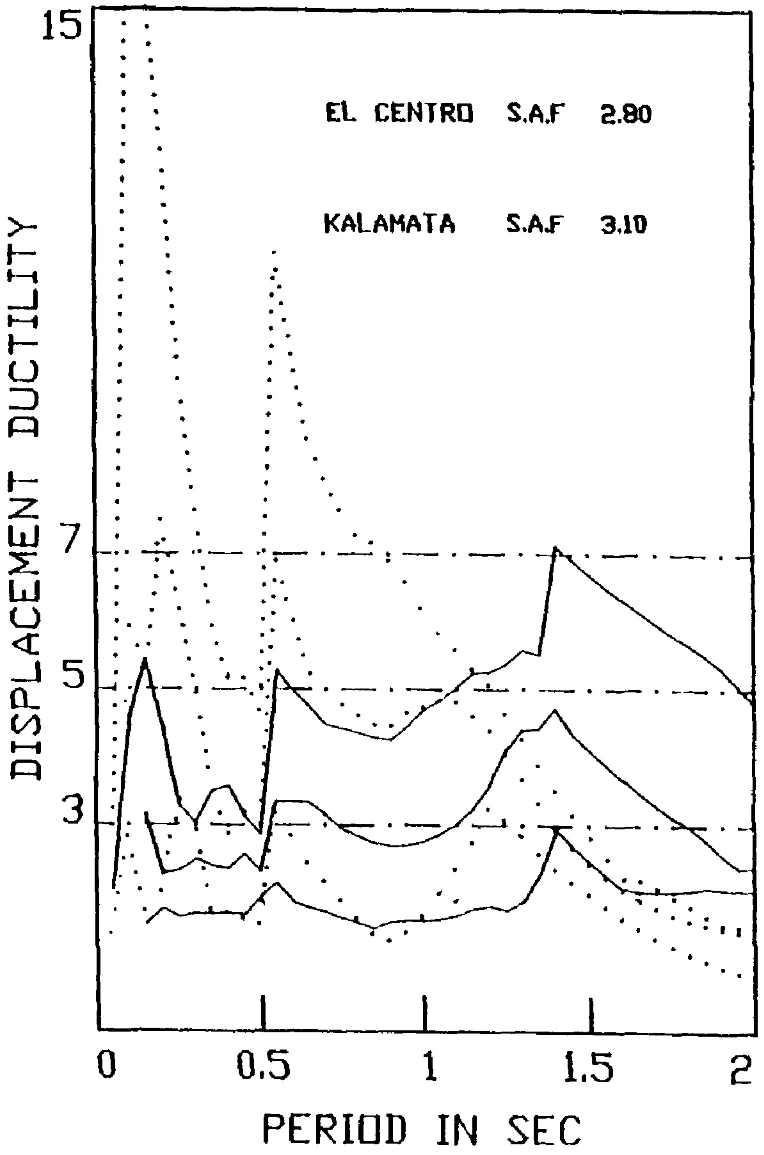

Fig. 8 Displacement ductilities using the N&H IDRS Method

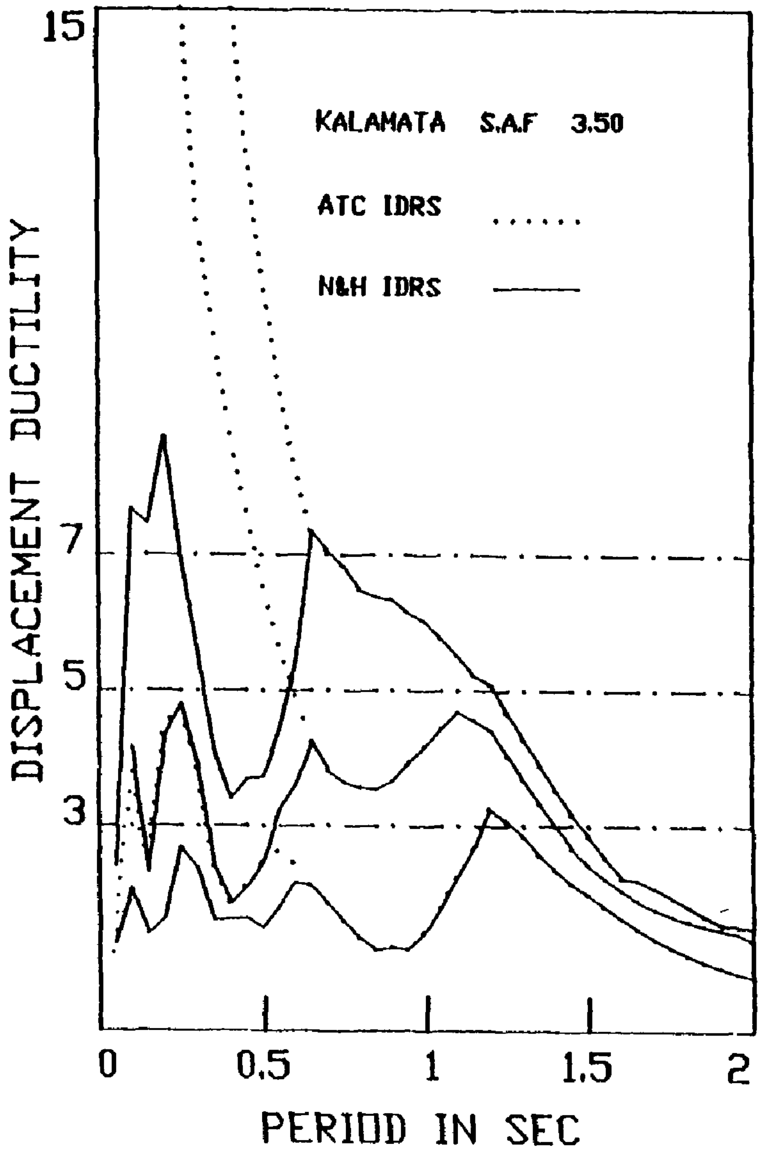

Fig. 9 Displacement ductilities using ATC, N&H IDRS Methods

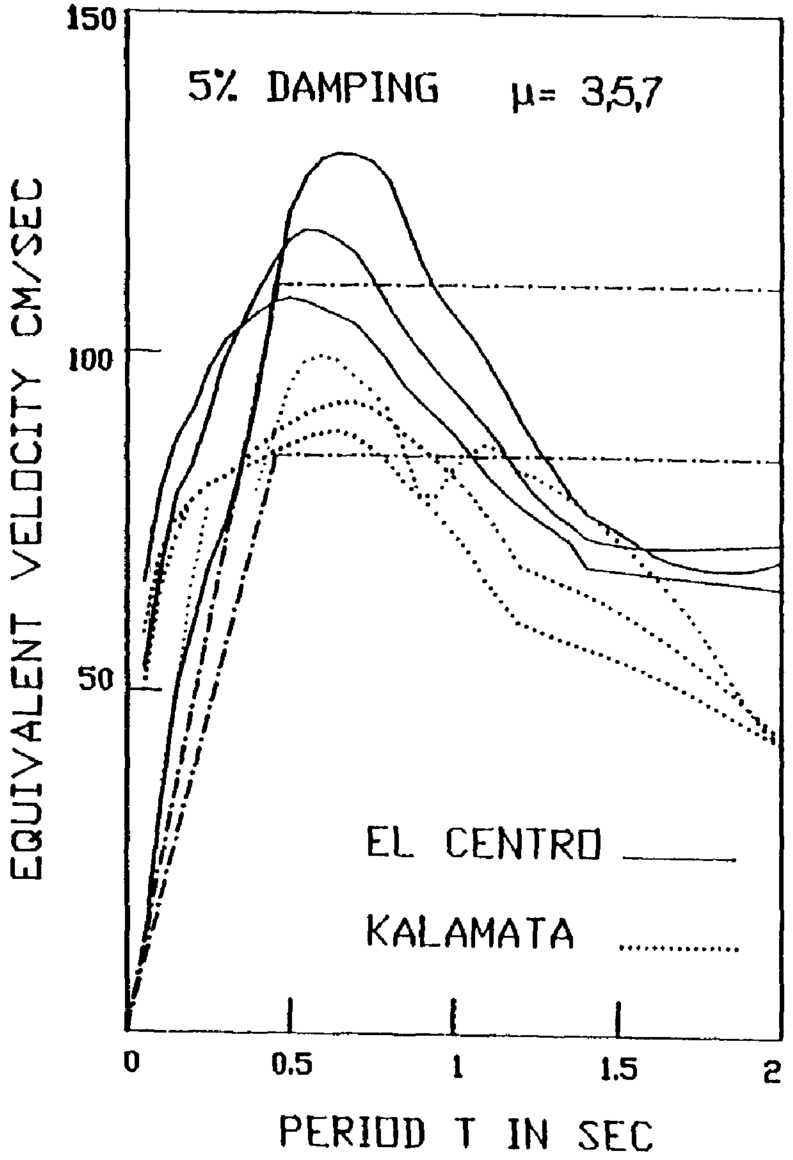

Fig. 10 Equivalent velocity spectra for ATC IDRS

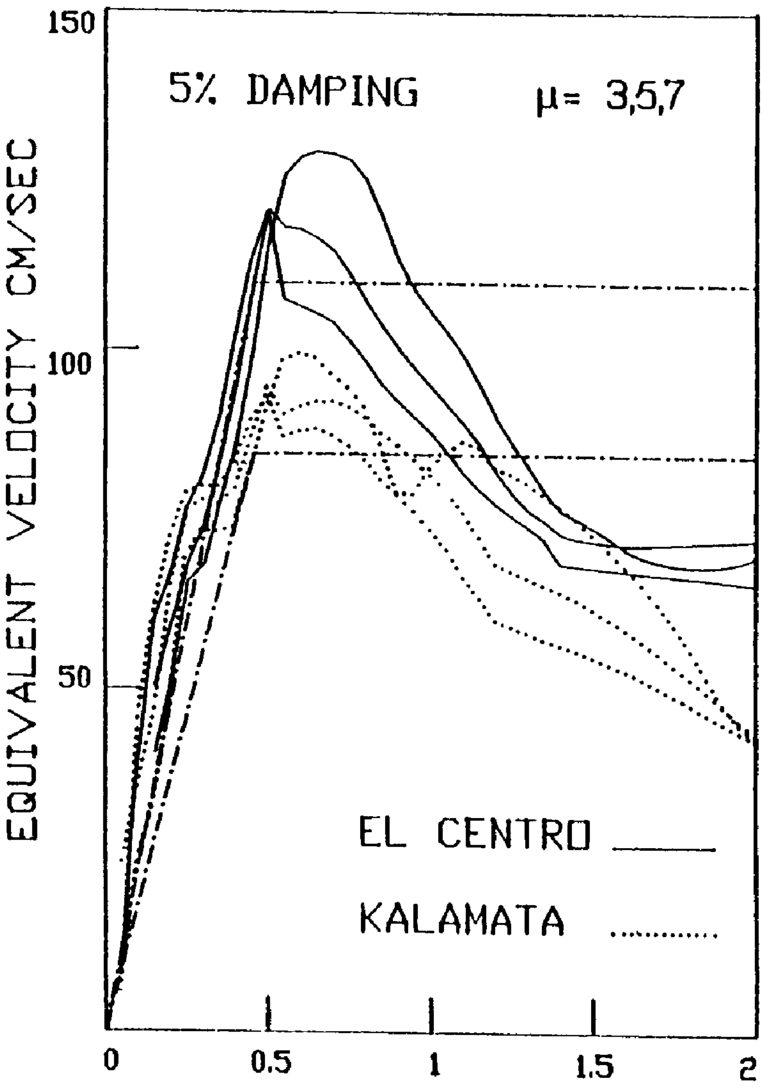

Fig. 11 Equivalent velocity spectra for N&H IDRS

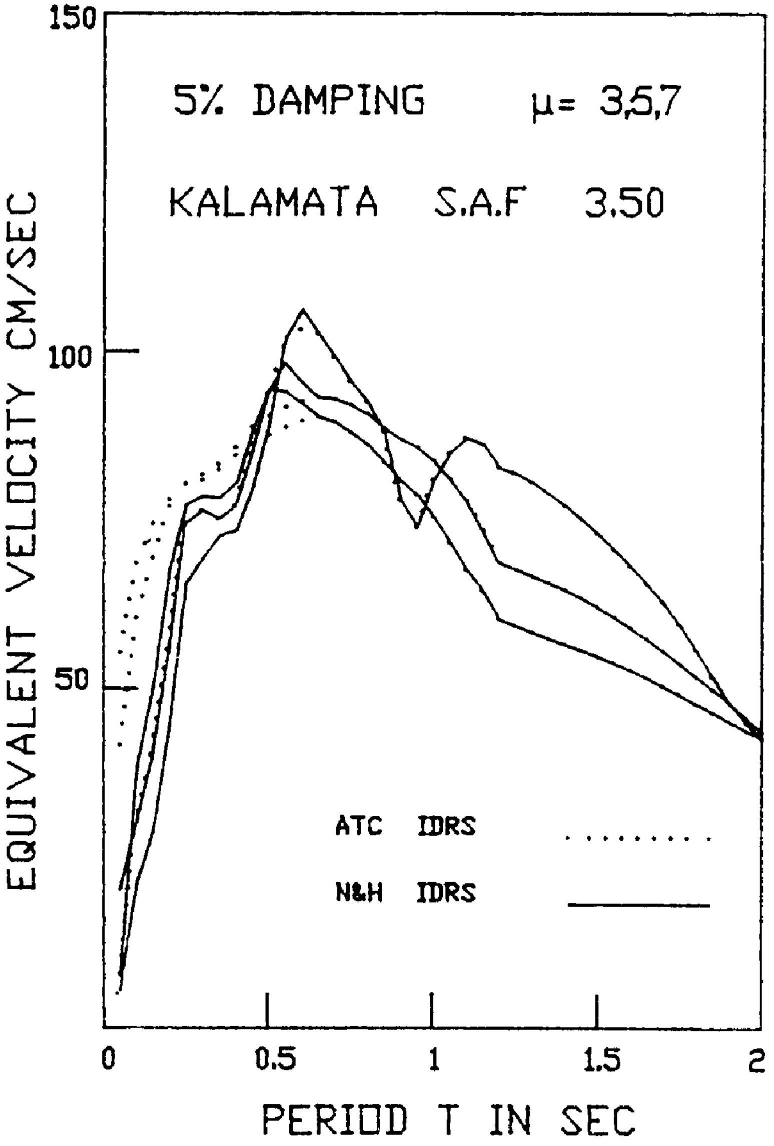

Fig. 12 Equivalent velocity spectra for ATC, N&H IDRS