6th Canadian Conf. Earthquake Engineering / Toronto / 1991 / 6ème Conf. Canadienne Sismique

Nondeterministic inelastic response spectra

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ABSTRACT

The present study aims at generation of probabilistic inelastic response spectra using the analytical probability distributions of the strength and reduction factors. These spectra consists of constant ductility, constant strength, reduction factor and acceleration spectra. Elasto-plastic and stiffness degrading hysteresis models are used to generate these spectra for two ensembles of the artificial earthquakes for different confidence levels. It is concluded that for strength and reduction factors, the extreme value type I and II distributions are within 10% of the analytical distribution upto a confidence level of 85% beyond which the difference is 15%. The Weibull distribution does not give satisfactory results. It is shown that the elastic forces can be reduced upto a factor of 10 for confidence level of about 85%. For lower confidence levels, the reduction factors are about 24.

INTRODUCTION

Riddell and Newmark (1979) studied the statistical response of single degree of freedom systems subjected to ten real earthquakes and proposed amplification and deamplification factors to construct trapezoidal inelastic response spectra. Briseghella, Zaccaria and Guiffre (1982) also proposed reduction factors, that is, deamplification factors, to generate response spectra. Jain (1985) and Pal (1987) carried out statistical analysis and presented constant strength, constant ductility, reduction factor and inelastic spectra. These analyses were based on the assumption that the inelastic response follows Gaussian probability distribution.

This paper aims at the generation of probabilistic inelastic response spectra using the analytical probability distribution for viscously damped single degree of freedom systems. The amplification factors were determined by fitting trapezoidal lines to each accelerogram rather than to the mean normalized spectra of the ensemble since the variation in the knee periods was enormous. In this study, two ensembles of fifty records each were

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generated using the nonstationary shot noise modelling using the intensity curves shown in Fig. 1 (Murakami and Penzien 1975). Earthquake E1 was of 5 sec duration and peak ground accelerations varied between 0.15 g and 0.3 g. It simulates a shallow ground motion of magnitude 4.5 to 5.5. Earthquake E2 was of 30 sec duration and peak ground accelerations varied between 0.25 g and 0.4 g. It simulates a motion of magnitude 7 close to a fault.

A computer code IRS was written to generate the various response spectra and PDF was written to compute the various probability distributions. The equation of motion was integrated using a variable time step so as not to miss any peak or trough. The maximum time step was 0.01 sec. These inelastic spectra were generated using 27 values of strength factors ranging from 0.001 to 4. The displacement ductility ratios were 1,1.5,2,2.5,3,4.5, 6,7, and 8. The response was computed for fifty six values of the time periods ranging from 0.05 sec to 10 sec. A larger number of ordinates were selected in the shorter time period range since the response spectra is very sensitive to the system characteristics in this range.

AMPLIFICATION FACTORS

The trapezoidal lines were fitted to the elastic spectra and amplification factors were determined. The procedure of fitting the trapezoidal lines is adopted after Riddell and Newmark (1979) and is as follows :

(i) Initialize values of knee periods T_{av} and T_{vd}, where, T_{av} is the knee period at the junction of acceleration and velocity regions, and T_{vd} is the knee period at the junction of velocity and displacement regions.

(ii) Compute average values of acceleration, velocity and displacement for the spectral regions as follows :

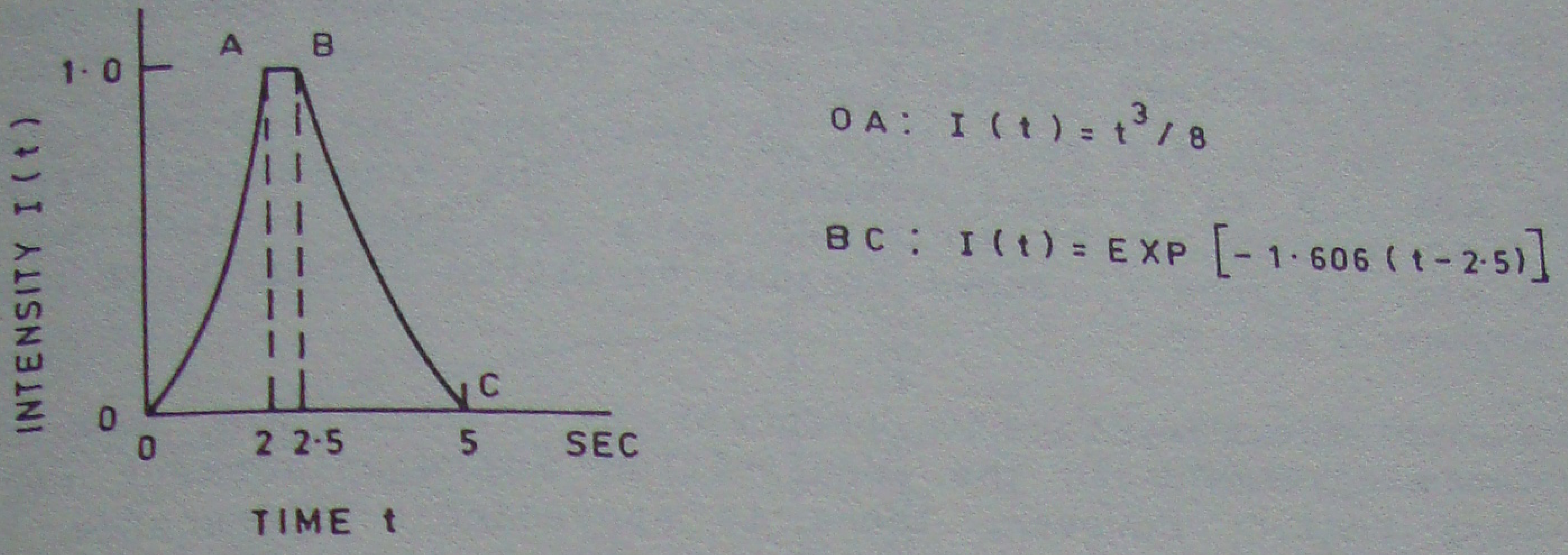
$$S_a^i = \frac{\int_{0.5}^{T_{av}^i} S_a(T)dT}{T_{av}^i - 0.05} \; ; \quad S_v^i = \frac{\int_{T_{av}^i}^{T_{vd}^i} S_v(T)dT}{T_{vd}^i - T_{av}^i} \; ; \quad S_d^i = \frac{\int_{T_{vd}^i}^{10} S_d(T)dT}{10 - T_{vd}^i} \quad (1)$$

where, subscript i denotes the ith iteration, T is time period, and values 0.05 and 10 are the smallest and largest time periods for the spectra.

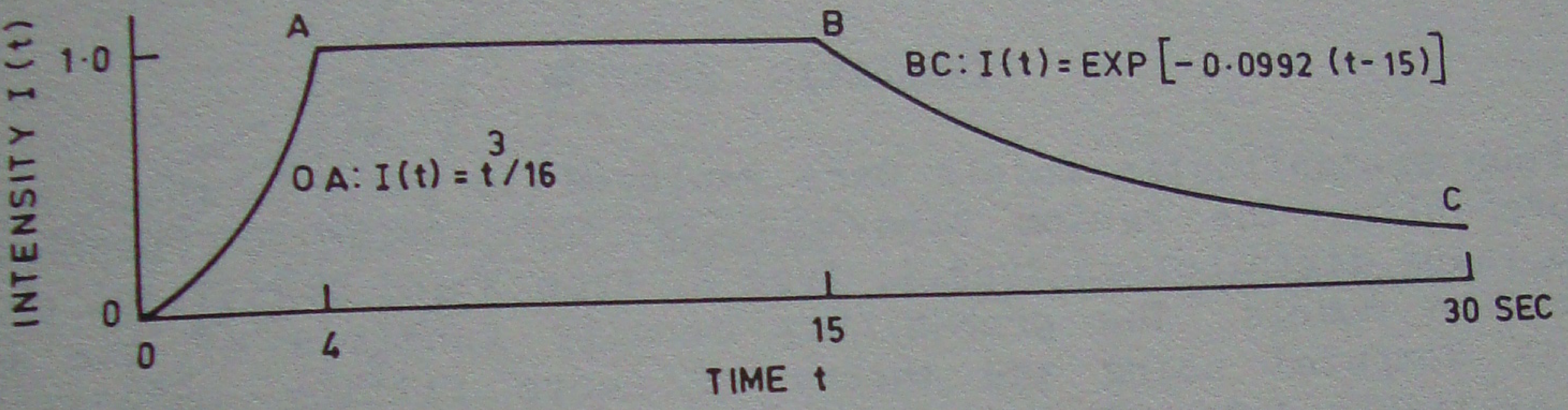
(iii) Compute new values of the knee periods using the relation as :

$$T_{av}^{i+1} = 2\pi \frac{S_v^i}{S_a^i} \; ; \qquad T_{vd}^{i+1} = 2\pi \frac{S_d^i}{S_v^i} \qquad (2)$$

(iv) Repeat steps (ii) and (iii) till $T_{av}^{i+1} = T_{av}^i$, and $T_{vd}^{i+1} = T_{vd}^i$ within a specified tolerance.



(a) EARTHQUAKE E 1



(b) EARTHQUAKE E 2

FIG.1 TIME INTENSITY FUNCTION CURVES FOR ARTIFICIAL EARTHQUAKES

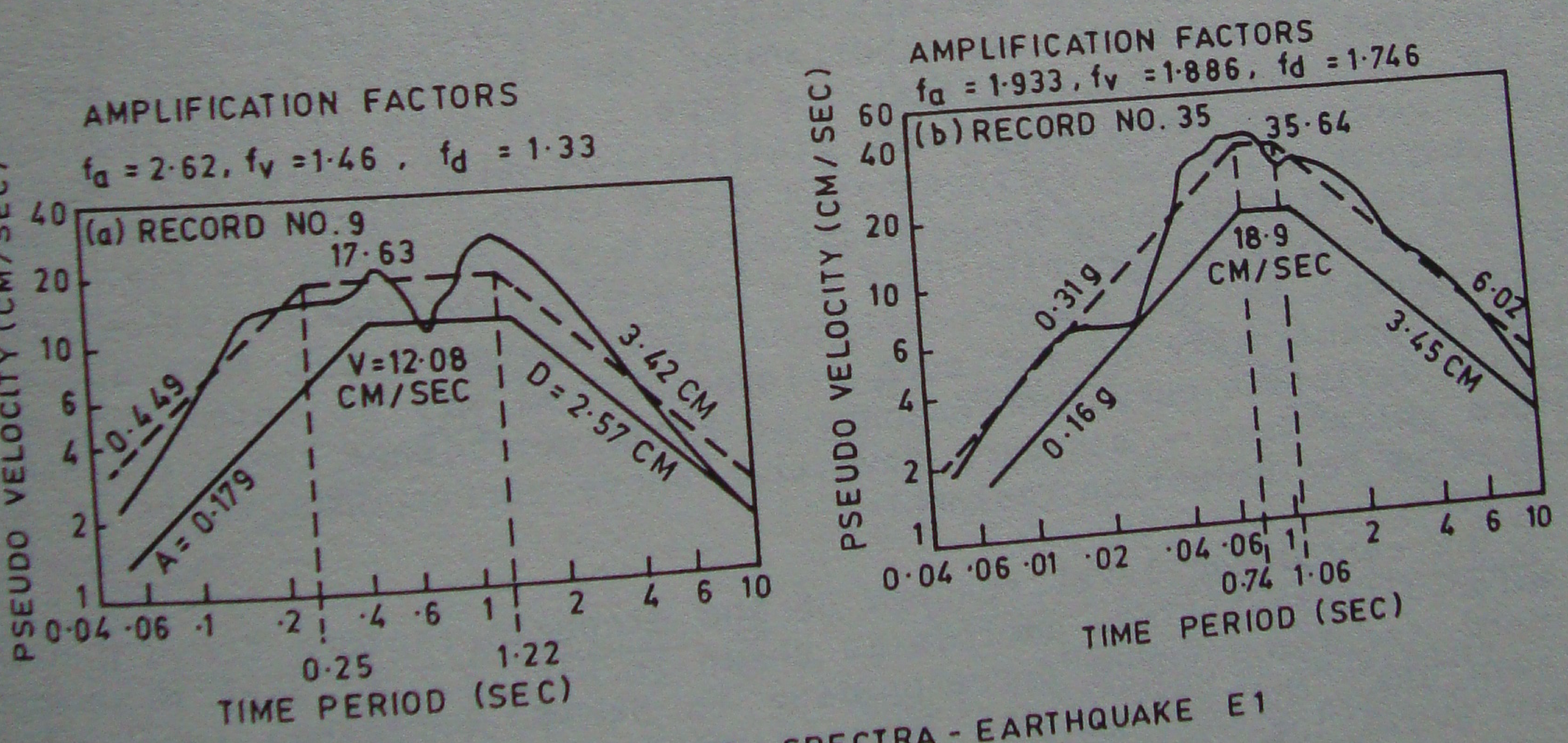


FIG.2 – ELASTIC RESPONSE SPECTRA - EARTHQUAKE E1

There was considerable dispersion in the knee period values. For earthquake E1, the knee period T_{av} varied from 0.2 sec to 1 sec, and T_{vd} varied from 0.4 to 1.7 sec. For E2 earthquake the values were 0.35 to 0.9 sec and 1.8 to 9 sec., respectively. The trapezoidal lines fitted to the mean spectra of E1 earthquake gave the knee periods as 0.31 sec and 0.95 sec. Figure 2 shows typical variation in the knee periods for record numbers 9 and 35.

The amplification factors proposed by Riddell and Newmark (1979) are in close agreement in the acceleration and displacement regions. In the velocity region, however, there is appreciable difference (Jain and Pal 1991). Riddell and Newmark obtained lower values in the velocity region because they used the mean spectra of ten records and amplification factors were computed by averaging the normalized spectra of each earthquake within each interval. This results in lowering the trapezoidal line in the velocity region. As the interval between the knee periods increases, the velocity region ordinates decrease. Figure 3 shows the distribution of amplification factors for different confidence levels.

INELASTIC SPECTRA

Four probabilistic models were employed to examine their suitability in representing the random behaviour of the inelastic response, viz : Extreme value distribution type 1, type 2, type 3 and analytical probability distribution models. The probability density function of the analytical model is computed using the theory of curve fitting and interpolation on the available data. More details can be seen in Pal (1989) and Siddal (1983).

Elasto-plastic and stiffness degrading hysteresis models were used to generate constant ductility, constant strength, reduction factor and inelastic response acceleration spectra. The stiffness degrading model is shown in Fig. 4 and its salient features are given elsewhere (Jain 1985). The various probability distributions of the strength factors are shown in Fig. 5. It can be seen that the type I and type II distributions are fairly close to the analytical distribution till about 85% confidence level beyond which the difference is quite large. Similarly, the various probability distribution for reduction factors are shown in Fig. 6. The type I and type II distributions are very close to the analytical distribution except in the lower confidence level range (less than about 20%) which is practically of not much relevance. It may be noted that mean + standard deviation curve corresponds to 84.1% confidence level for strength factors while mean - standard deviation curve corresponds to 84.1% confidence level for reduction factors.

The confidence level spectra of the strength factors for a ductility of 4 for different times periods is shown in Fig. 7. It also shows mean + standard deviation curve corresponding to 84.1% confidence level. It can be seen that the statistical curve is close to the probabilistic curve within about 10%. The probability distributions of the reduction factors for earthquake E1 and time period of 1.0 sec for all ductility ratios

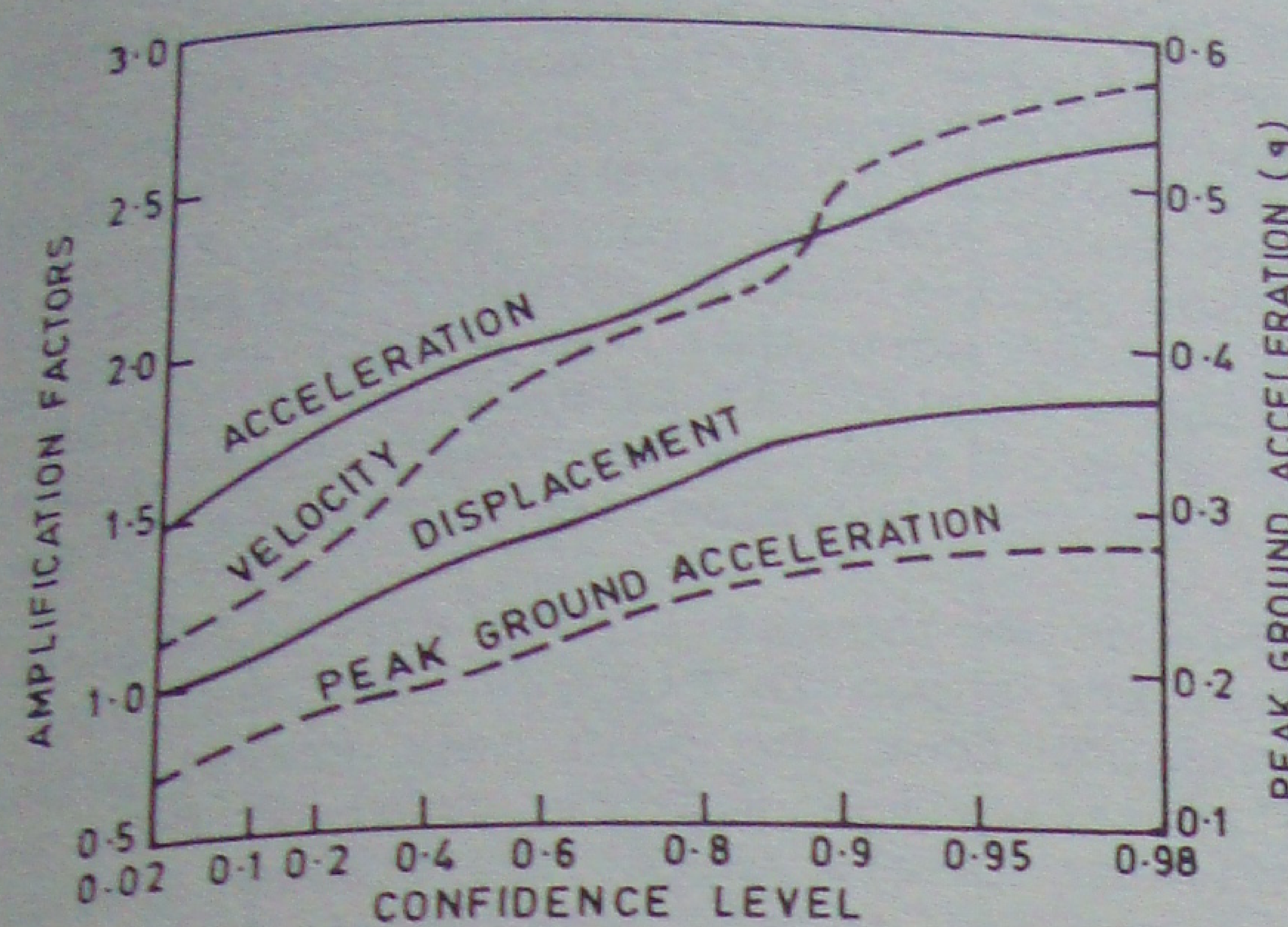


FIG. 3 AMPLIFICATION FACTORS FOR ELASTIC SPECTRA EARTHQUAKE E1

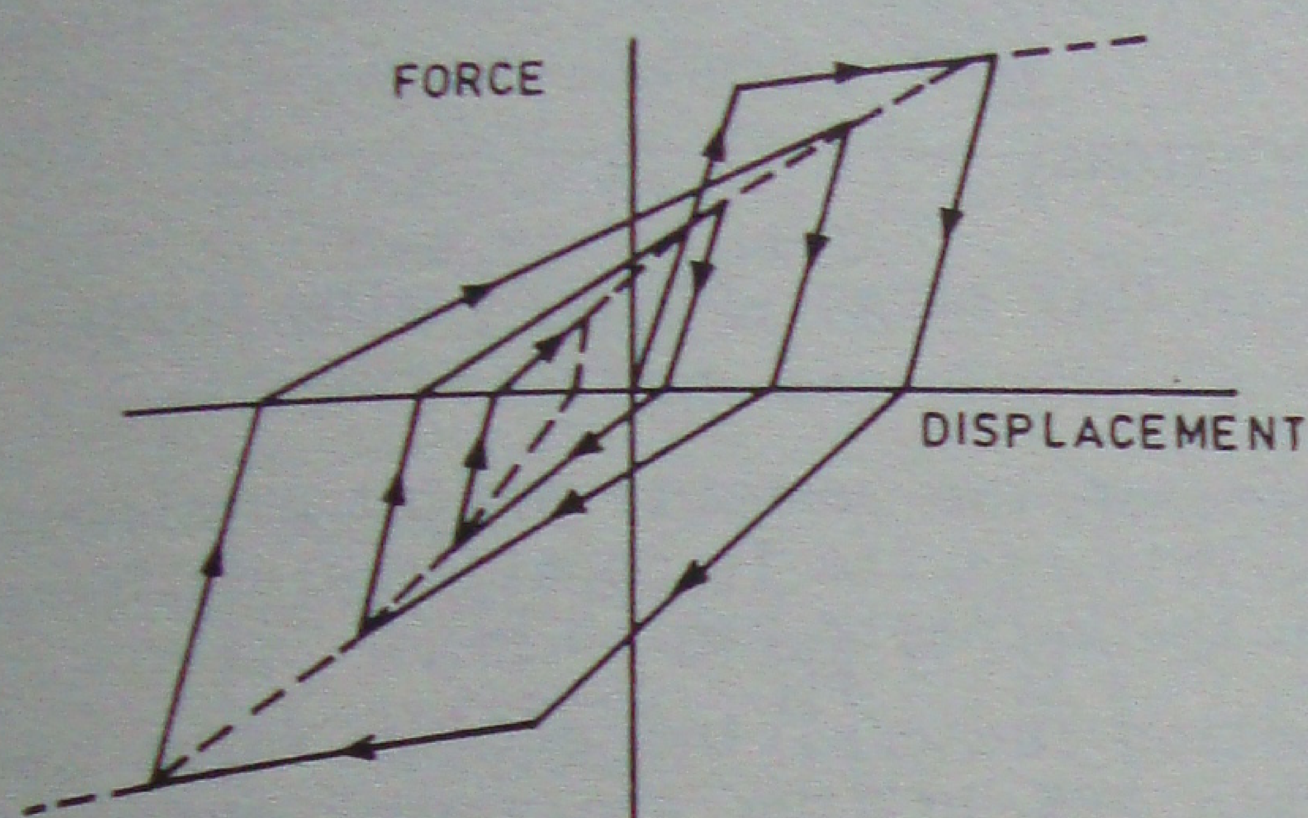


FIG.4- STIFFNESS DEGRADING MODEL

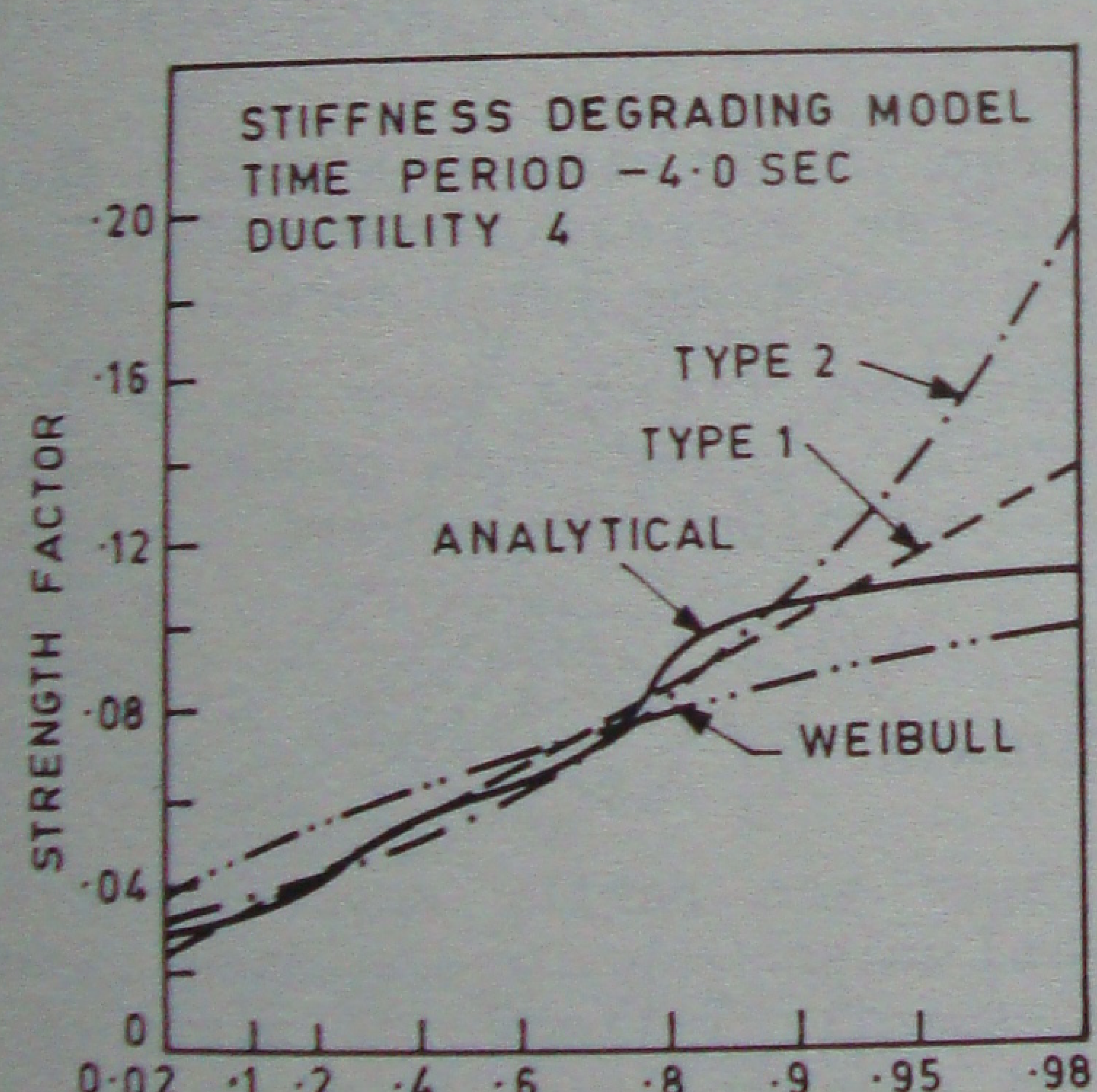


FIG.5 COMPARISON OF PROBABILITY DISTRIBUTION OF STRENGTH FACTORS - EARTHQUAKE E 2

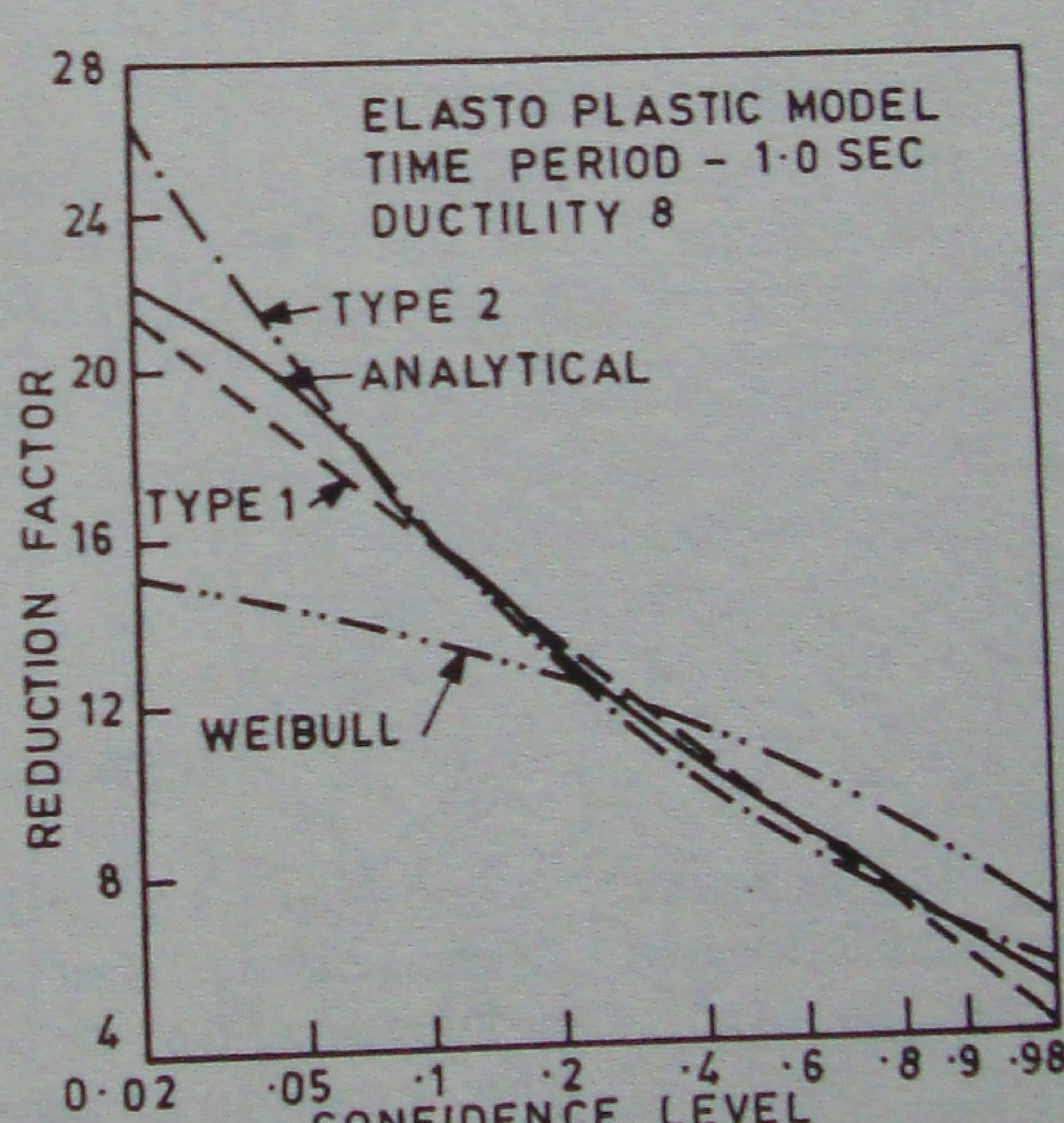


FIG.6. COMPARISON OF PROBABILITY DISTRIBUTIONS OF REDUCTION FACTORS - EARTHQUAKE E 1

and confidence levels are shown in Fig. 8. The type I distribution compares very well with the analytical probability distribution. For very low confidence levels, the reduction factors were as high as 24 (Fig. 6). For a confidence level of 85%, the reduction factors were up to 10 depending upon the ductility ratio, hysteresis model and the ground motion. Figure 9 shows confidence level spectra for the two hysteresis models for a ductility ratio of 4 and earthquake E1. It may be seen that the reduction factors decrease with the increase in confidence levels. It is because the inelastic acceleration spectra is inversely proportional to the reduction factors. Hence, the accelerations increase with the increase in confidence levels.

Inelastic acceleration spectra for earthquake E2 for different ductility ratios and 85% confidence level are shown in Fig. 10. The trapezoidal elastic response spectra can be obtained from the mean peak ground motion parameters by first applying the amplification factors obtained from the elastic analysis for different confidence levels to get the elastic spectra. Next, the reduction factors may be applied to the smoothened trapezoidal response spectra for different ductility ratios and confidence levels.

CONCLUSIONS

Based on the results presented in this paper, the following significant conclusions can be made :

1. The knee periods of each spectra of the ensemble varied considerably from those of the mean spectra. This results in considerable difference in the amplification factors in the velocity region.

2. For the strength and the reduction factors, the extreme value type I and II distributions are within 10% of the analytical probability distribution upto a confidence level of 85% beyond which the difference is about 15%. The Weibull distribution does not give satisfactory results.

3. The (mean + standard deviation) curve in the case of strength factors and (mean - standard deviation) curve in the case of reduction factors are within 15% of the respective 85% confidence level curves.

4. For 85% confidence level, the reduction factors vary up to 10 for various ductility ratios, hysteresis models and ground motions. For lower confidence levels, the reduction factors are as high as 24.

ACKNOWLEDGEMENTS

The research reported in this paper was partly supported by the University Grants Commission, New Delhi under the Career Award Scheme. The results and conclusions do not necessarily reflect the views of the sponsor. Much of the results summarized were obtained by Shri Pal in conjunction with his Ph.D. studies at the University of Roorkee. His originality and contribution to this effort are gratefully acknowledged.

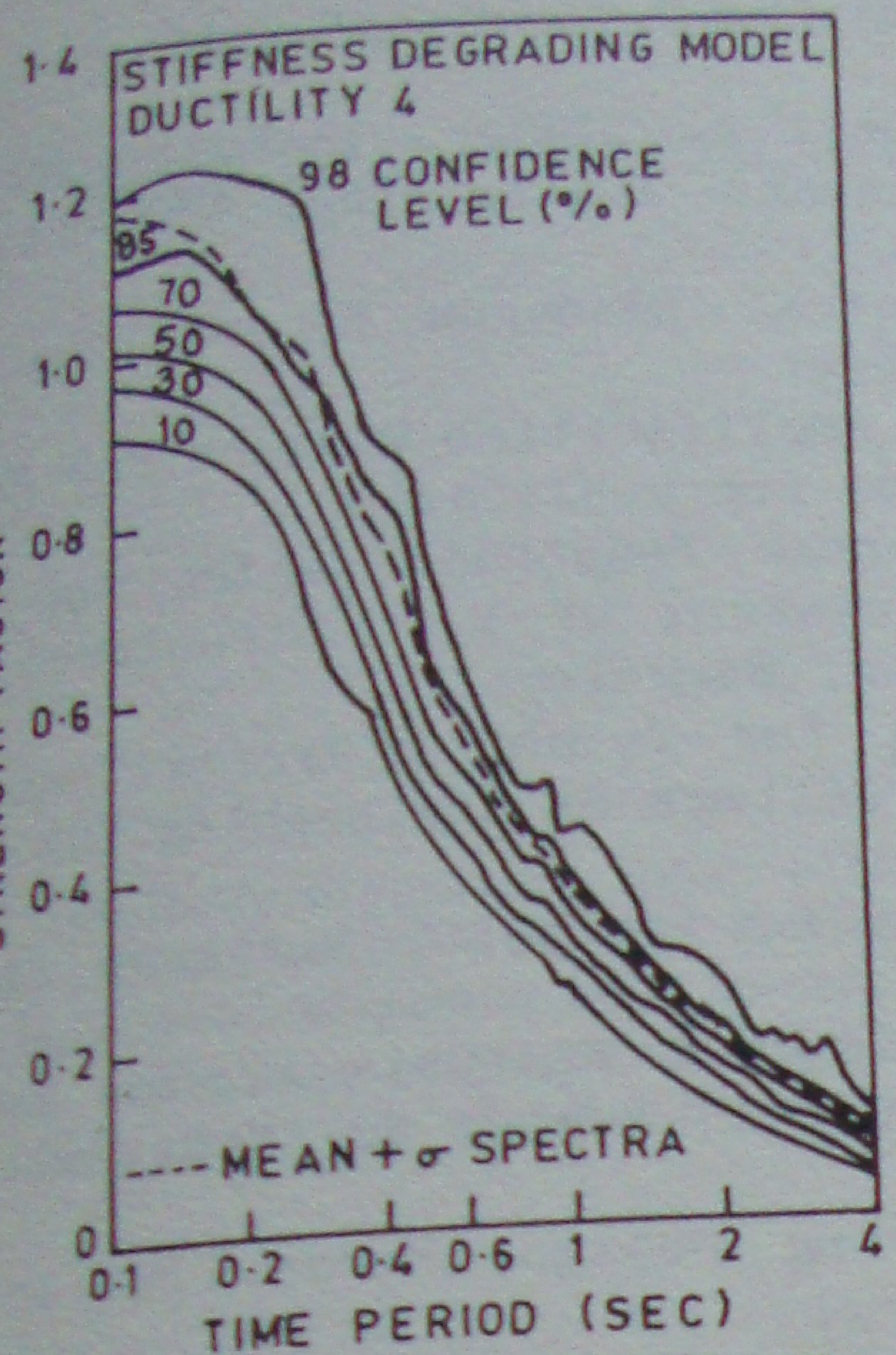


FIG.7 CONFIDENCE LEVEL SECTRA OF STRENGTH FACTORS - EARTHQUAKE E.2

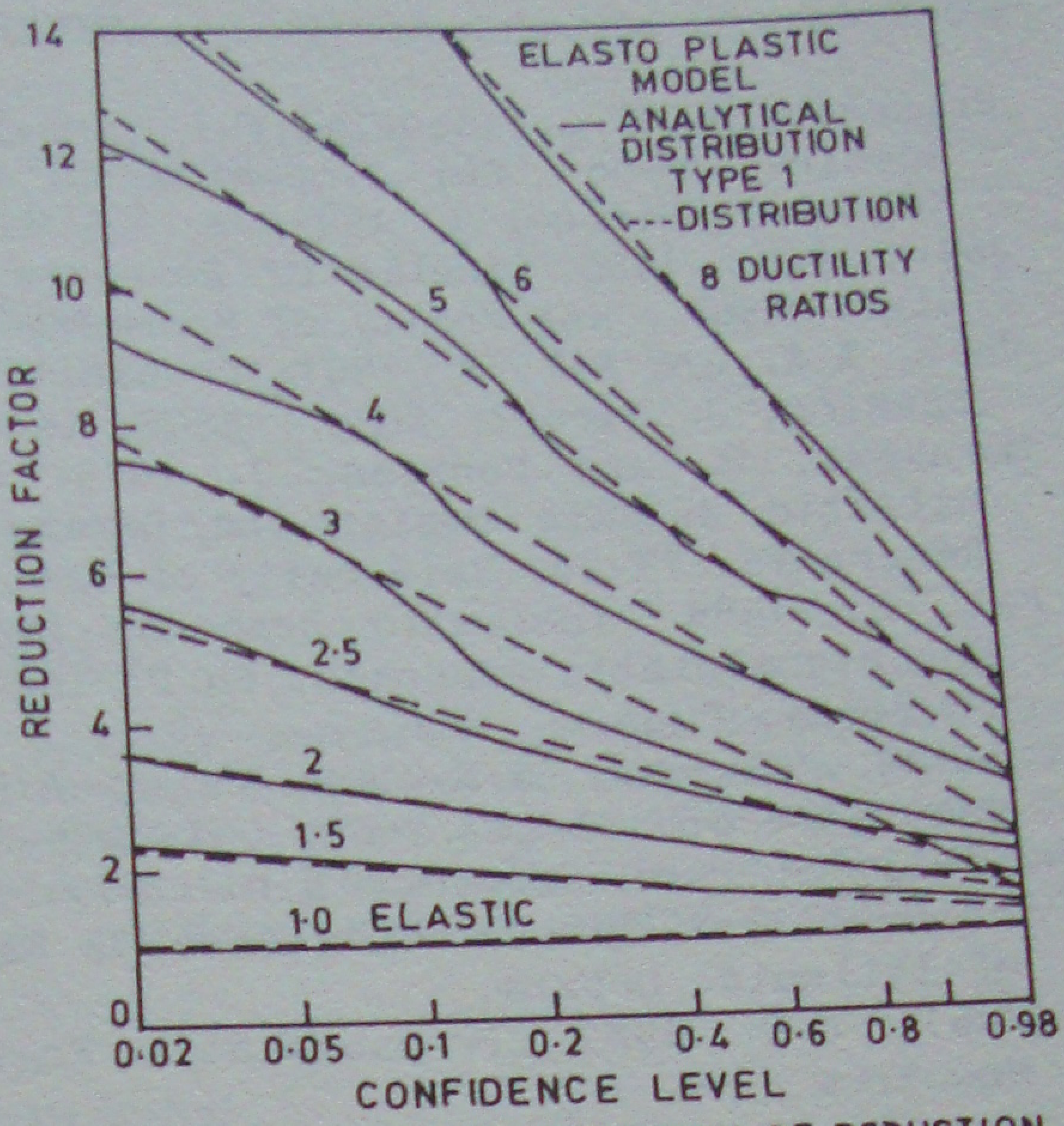


FIG.8 PROBABILITY DISTRIBUTION OF REDUCTION FACTORS - EARTHQUAKE E 1 (TIME PERIOD = 1·0 SEC)

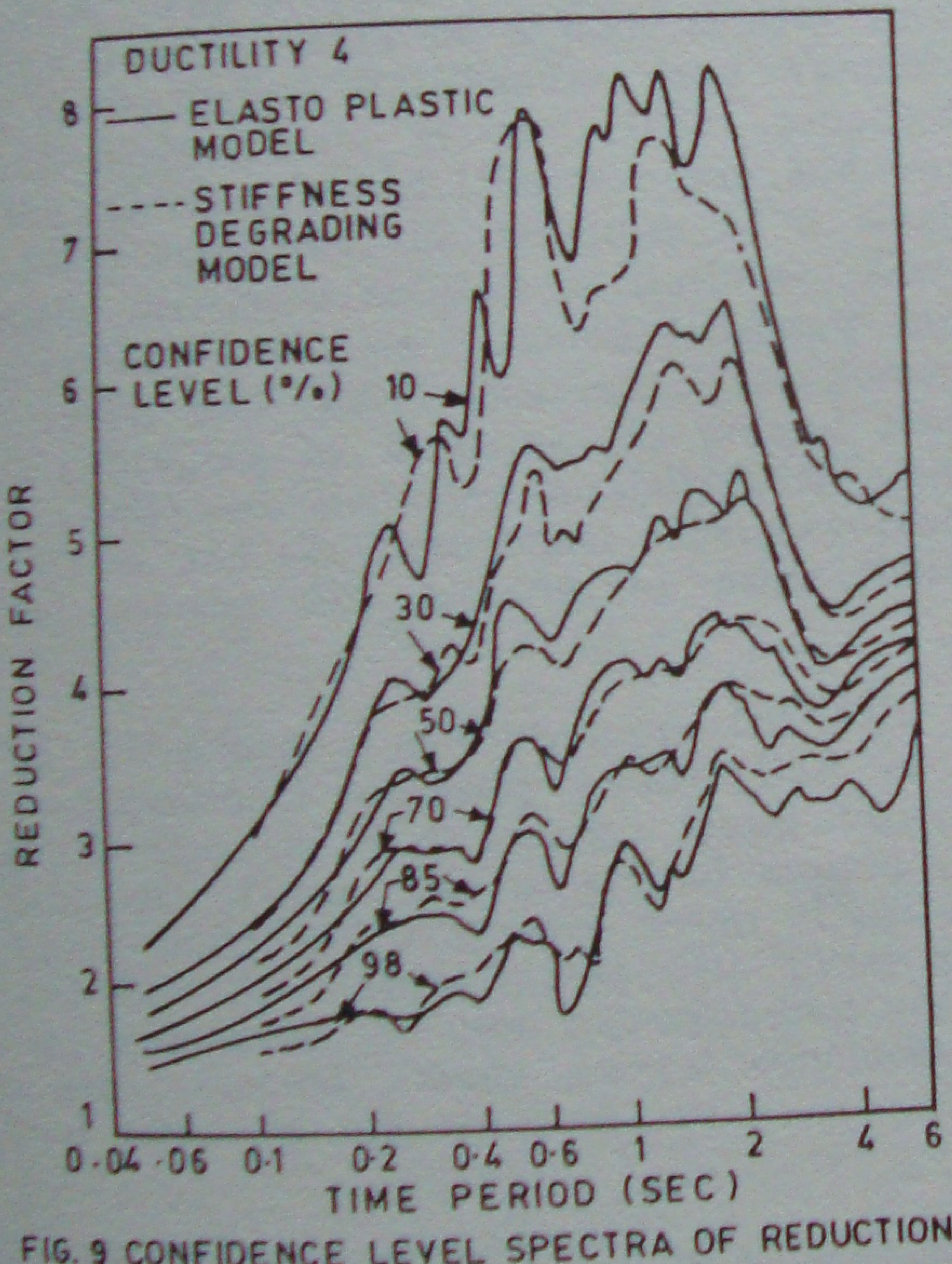


FIG. 9 CONFIDENCE LEVEL SPECTRA OF REDUCTION FACTORS - EARTHQUAKE E 1

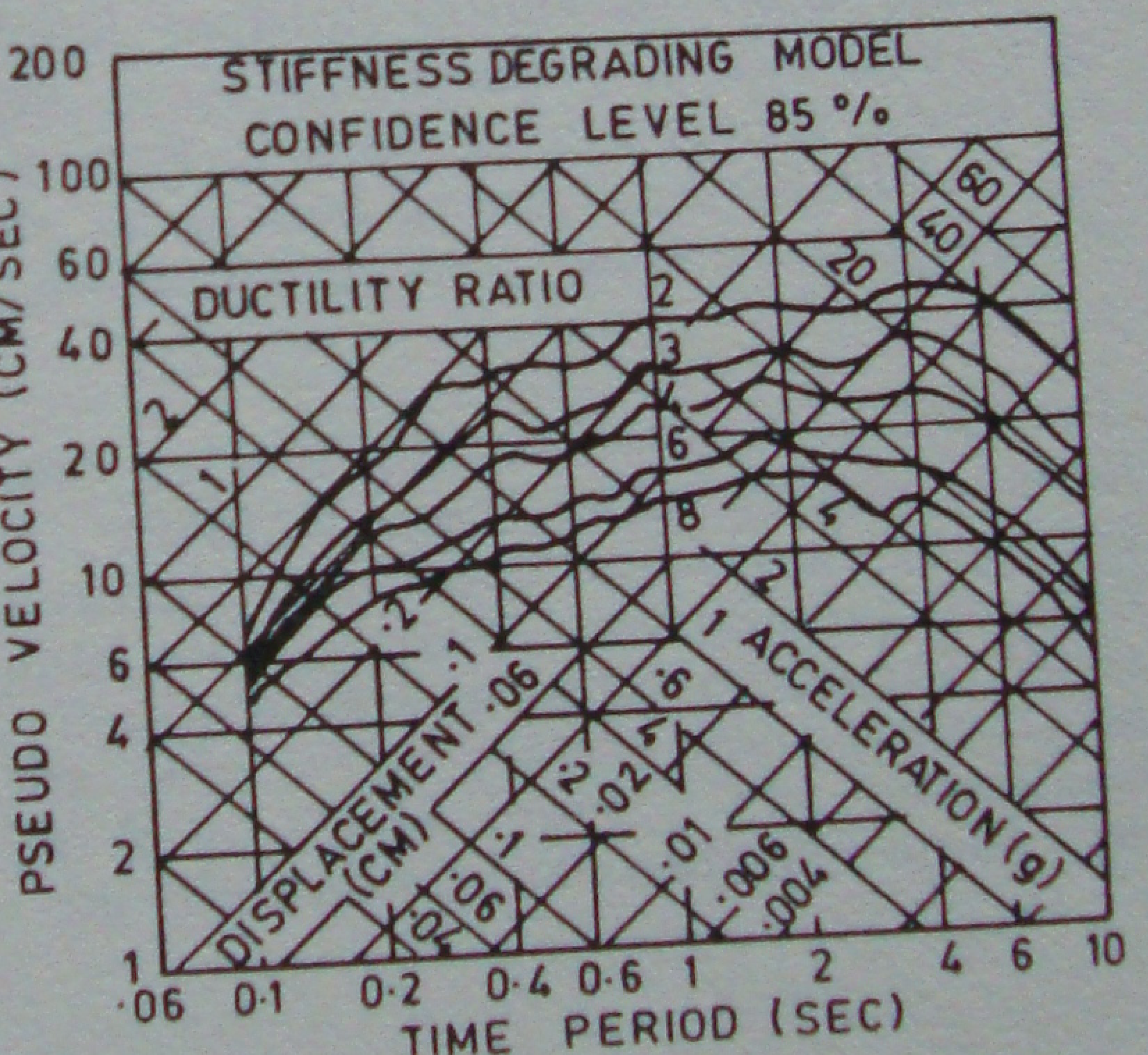


FIG.10 - INELASTIC RESPONCE SPECTRA FOR 85 % CONFIDENCE LEVEL-EARTHQUAKE E 2

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