PARAMETRIC STUDY OF INELASTIC RESPONSE TO SOME EARTHQUAKES RECORDED IN SOUTHERN EUROPE

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SUMMARY

The main results of an extensive parametric study of inelastic response to three different groups of European accelerograms and to the group of standard Californian records are presented by means of mean inelastic response spectra. It has been found that the main features of the European and Californian earthquakes are quite similar, except for the Friuli earthquake, where the seismotectonic elements of the geologic structures seem to be different. The scaling of the ground motion to spectral intensity has been proved to reduce considerably the scatter in response spectra in comparison with the scaling to peak ground acceleration and only slightly in comparison with the scaling to peak ground velocity. The influence of different hysteretic behaviour, simulating predominantly the flexural behaviour without the strength degradation, has been found to be small in the majority of cases. Relative displacements are in the period range 0.8 - 2.5 s practically independent of the strength and of the hysteresis rule and only slightly dependent on the normalized earthquake. In the predominant period range the input energy seems to be a convenient parameter governing design. The spectrum of the normalized input energy is nearly constant in that range for strength levels provided by the code design. Furthermore, it is practically independent of the damping and of the hysteresis. The value of normalized energy varies noticeably for different input motions indicating a better method of scaling, presumably including the duration of strong motion, is to be found.

SCOPE AND OBJECTIVE OF THE STUDY

Three main objectives of the study were:

(a) The comparison of the characteristics of strong motion records in Southern Europe with the characteristics of well known Californian records;

(b) The evaluation of the methods for scaling input motions;

(c) The parametric study of inelastic response to earthquakes. In the study the input motion and the most important structural parameters were varied: strength, initial stiffness (period), hysteretic behaviour, and damping.

The results of such an analysis are easily represented by means of response spectra. These spectra usually plot, as a function of the period, displacements or displacements ductility factors required for a specified level of strength parameters. Recently it has been widely recognized that the maximum displacements lack one important feature: they do not reflect the cumulative fatigue-type damage. To study this possibility it is convenient to introduce response parameters which are related to the energy. Different complementary parameters have been proposed (i. e. [3]). In our investigation, among others, the normalized input energy has been used.

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SELECTION OF EARTHQUAKE RECORDS

Three different groups of strong-motion records obtained during recent earthquakes in Southern Europe (Friuli, North. Italy 1976; Montenegro, Yugoslavia 1979; Campania, South. Italy 1980) were used in the study. The main characteristic of the Friuli earthquakes is the short duration of the strong ground motion (less than 5 s). The predominant periods of all records are rather narrow-banded from 0.1 to 0.5 s. Montenegro 1979 is a stronger earthquake. The duration of the strong ground motion is 10 - 15 s and the predominant periods of different records are in the whole range from 0.15 to 1.7 s. The records of the Campania earthquake give the evidence of multiple event occurence (three events in 70 s) resulting in a very long duration. The predominant periods of different records are similar to those of the Montenegro earthquake. Only the records with the maximum acceleration greater than 0.15 g in at least one direction were chosen. Because of relatively small number of such records and because of the lack of information of site conditions for some recording stations no attempt has been made to compute site dependent spectral shapes. Some details of the records are given in Table 1.

For the comparison a group of standard Californian accelerograms representative for severe ground motions at moderate epicentral distances was chosen.

The standard Caltech procedure was used for the correction of records. All accelerograms were band pass filtered between 0.1 - 0.33 and 25 - 27 Hz. The applied uniform cut-off periods are justified by the range of frequencies investigated in the study (0.4 - 10 Hz).

SCALING OF THE GROUND MOTION

Three different methods of scaling: (a) to peak ground acceleration a_{gmax}, (b) to peak ground velocity v_{gmax}, and (c) to spectral intensity of the 5 % damped pseudo velocity spectrum I_{PVS} have been analysed.

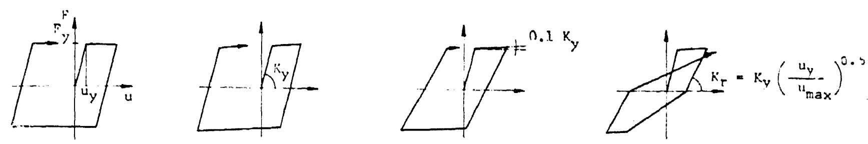
In Table 2 the mean coefficients of variation V for displacements and input energy are given for a pattern of the selected periods and strengths values. It has to be noted that some individual V for extreme periods (particularly 0.1 s) and strengths (0.2 and 5) are higher. In the mid-period range considered, the normalisation to a_{gmax} obviously yields the largest dispersion. As expected [2], the normalisation to spectral intensity reduces the dispersion. However, the differences between scaling to v_{gmax} or I_{PVS} are only slight. Due to the easier prediction of v_{gmax} in comparison with the spectral intensity of any kind, the scaling to v_{gmax} was chosen in the parametric study.

While the scaling to v_{gmax} is quite satisfactory for the displacements in the mid-period range (average V = 0.30 - 0.35), it appears that the duration of the ground motion has to be considered in computing such parameters as energy, the number of yield excursions or acumulated plastic deformations.

It was proved again (see [4]) that normalizing to v_{gmax} shows nearly constant V over the mid-frequency range, and is practically independent of the strength level. Furthermore, it was found that on the average the chosen hysteretic rule and damping have no important influence on V. However, it can be noted that V for the various registrations of the same earthquake in each European group is considerably greater than of different USA earthquakes. It is believed that this difference can be attributed predominantly to larger differences in soil conditions of the European stations considered in the study. The method of scaling to I_{PVS} leads to the similar observations than scaling to v_{gmax}.

STRUCTURAL SYSTEMS

One degree of freedom systems have been investigated. Various hysteresis models, simulating dominantly flexural behaviour, were used (Fig. 1):
(a) Elastoplastic model, (b) Bilinear model, (c) Bilinear model with unloading stiffness degradation ([5]), (d) Degrading stiffness Q model ([6]).



a) EPP Model b) B (10, 0) Model c) B (10, 0.5) Model d) Q (10, 0.5) Model

Fig. 1. Hysteresis models

The strenth parameter η which is defined as a ratio between the yield resistance F_y, divided by the mass of the system and by the peak ground acceleration

$$\eta = F_y/(m\ a_{gmax})$$

was varied. The value $\eta = 5$ was used to obtain elastic behaviour.

Mass proportional viscous damping was used. To study the effect of damping a considerable number of 2 % damped systems was investigated.

DISPLACEMENT SPECTRA

The displacements are presented by means of the mean displacement (Figs. 2 - 7) and displacement ductility (Figs. 14 - 16) spectra for different groups of earthquakes and different hystereses. All input motion were scaled to v_{gmax} = 50 cm/s (denoted by F1 in figures).

It is the most outstanding feature of displacement spectra that for the periods greater than approximately 0.8 s the maximum displacements are practically independent of:
(a) The strength level and hysteresis. Only a slight decrease of displacements is observed for lower strengths and it is greater for EPP and bilinear models than for the Q model.
(b) The group of accelerograms (Figs. 2,3,5). Only for the Friuli earthquake (Fig. 4) the displacements are noticeably lower.
The coefficient of variation is relatively small (see Table 2).

Concerning the regularity of curves the preliminary formula for the approximate estimation of the maximum relative displacement is proposed, which fits the mean values of the displacements for Montenegro, the U. S. A. and Southern Italy ground motions, while it is conservative for the Friuli records:

$$u_{max} = 0.16\ (T + 1)\ v_{gmax} \qquad \text{for } 0.8 \le T \le 2.5 \text{ s} \quad \text{and } \xi = 5\ \%$$

where u_{max} is the maximum relative displacement [cm], v_{gmax} is the peak ground velocity [cm/s], and T is the period of the structure [s]. The associated coefficient of the variation is about 30 per cent.

For stiffer structures, where displacements increase with the decreasing strength level, the influence of different hysteretic models is noticeable. The increase is the greatest for the EPP model. A decrease in damping results in an increase of displacements (compare Figs. 5 and 17, 15 and 18).

INPUT ENERGY SPECTRA

The input energy E_I, defined as the work of equivalent loading on relative displacements and equal to the sum of the hysteretic, damping, strain and kinetic energy, has been found practically independent of the damping coefficient (Figs. 11 and 19). Therefore it is considered a more appropriate parameter than the hysteretic energy, which has been also investigated. The normalized input energy

$$\overline{E}_I = E_I/(m\ a_{gmax})$$

is believed to be the most convenient for the presentation.

The mean spectra for various earthquakes scaled by v_{gmax} = 50 cm/s and for different hysteresis models are given in Figs. 8 - 13. The elastic spectra (η = 5) clearly reflect the predominant periods of earthquakes. The spectra for lower η values are higher than elastic spectra in the short period range (especially for Q hysteresis) and lower in the long period range of the considered period region. For η values, usually used in design (0.4 - 1.0), the spectra were found to be nearly constant in the vicinity of the predominant period range. In this range, the value of normalized input energy is not much dependent on the strength of the structure, on the hysteresis (Figs. 11 - 13), and on damping (Figs. 11 and 19). Considering these observations a preliminary formula for an approximate estimation of maximum input energy is proposed:

$$E_{Imax} = 0.7\ m\ a_{gmax}\ v_{gmax}$$

The peak ground velocity should be expressed in [cm/s] and the normalized input energy $E_{Imax}/(m\ a_{gmax})$ in [cm].

Unfortunately, in the contrast with displacements, the value of maximum energy varies noticeably for different ground motions (coefficient of variation is up to 0.76). It is believed that scaling by a factor involving duration of ground motion as a parameter would yield better results.

ACKNOWLEDGEMENTS

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Table 1: Data of strong-motion records

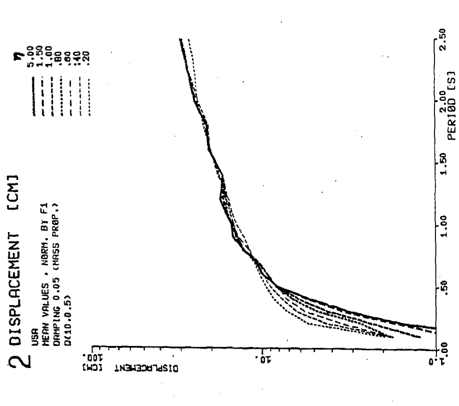
Gr.	Earthquake	Date	Mag. (1)	Depth [km]	Station	Record Ident.	Dist. [km] (1)	Soil Type (3)	Comp.	a_{max} [cm/s²]	v_{max} [cm/s]	I_{PVS} ξ=0.05 [cm]	Dur. [s] (4)
U. S. A.	Lower Calif.	1934	6.5		El Centro	(EERL) B024	58	1	S00W	159	19	54	25
									S90W	179	11	47	25
	Imp. Walley	1940	6.6		El Centro	A001	8	1	S00E	341	31	134	30
									S90W	213	27	114	30
	West Wash.	1949	7.1		Olympia	B029	20	2	N04W	158	18	75	25
									N86E	274	17	78	25
	Kern Coun.	1952	7.6		Taft	A004	56	1	N21E	152	13	58	50
			M_L=7.2						S69E	177	16	65	50
	San Fern.	1971	6.6		Castaic	D056	21	1	N21E	311	16	52	25
									N69W	262	28	79	25
FRIULI	Friuli 1976	05/11	M_L=6.3	7	Tolmezzo	(ENEL) 038	24	1	NS	342	20	72	15
									EW	310	32	83	15
	Friuli 1976	09/15 03H/15M	M_L=6.0	8	Forgaria	152	17	2	NS	254	10	28	15
									EW	210	9	29	15
	Friuli 1976	09/15 09H/21M	M_L=5.9	12	Forgaria	168	16	2	NS	299	23	51	15
									EW	323	22	72	15
					San Rocco	169	16	1	NS	136	12	47	15
									EW	228	17	56	15
MONTENEGRO	Montenegro	04/15 1979	M_L=6.7	10-30	Petrovac	(IZIIS) E58	29	2	NS	433	39	145	20
			M_S=						EW	299	25	78	25
			6.9-7.3		Ulcinj 1	E59	13	2	NS	279	39	159	25
									EW	234	46	184	25
					Ulcinj 2	E60	13	1	NS	165	17	74	25
									EW	214	25	124	25
					Bar	E61	11	2	NS	356	42	204	25
									EW	350	53	250	25
					Hercegnovi	E62	65	1	NS	211	14	55	25
									EW	225	12	45	25
SOUTH. ITALY	Campania	11/23 1980	M_L=6.5	10-20	Bagnoli	(ENEL) 621	(2) 22		NS	138	21	79	60
			M_S=6.9						EW	167	30	119	60
					Brienza	624	38		NS	210	12	41	60
									EW	155	9	34	60
					Sturno	629	37		NS	212	34	133	60
									EW	288	54	165	60
					Calitri	636	26		NS	150	25	112	80
									EW	170	27	114	80

(1) Data are different according to different sources. The magnitudes and distances of Calif. earthq. are taken from [7], the magnitudes M_L for Europ. earthq. from [1].
(2) Hypocentral distance
(3) Soil profile type: 1 = Rock and stiff soil sites, 2 = Others
(4) Duration of ground motion considered in the analysis

Table 2: Average coefficients of variations in per cents for displacement (u) and input energy (E_I)

	Method of scaling	Group of input motions: U. S. A.	Friuli	Montenegro	Southern Italy	All accel.	All accel except Friuli	Montenegro and S. Italy
u	v_g max	18	32	33	27	34	30	32
	I_{PVS}	17	27	28	25	28	-	-
	a_g max	33	51	55	48	65	-	-
E_I	v_g max	41	63	46	62	76	-	-
	I_{PVS}	34	59	44	54	70	-	-
	a_g max	56	85	65	74	105	-	-

All coefficients have been obtained for Q hysteresis.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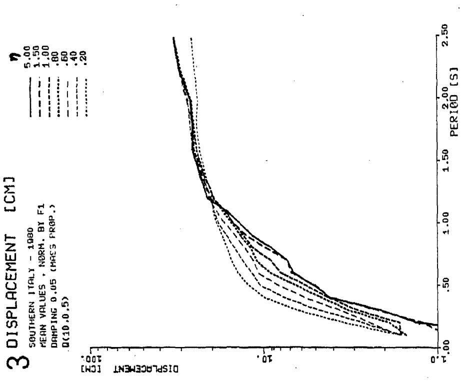
DISPLACEMENT [CM]
PERIOD [S]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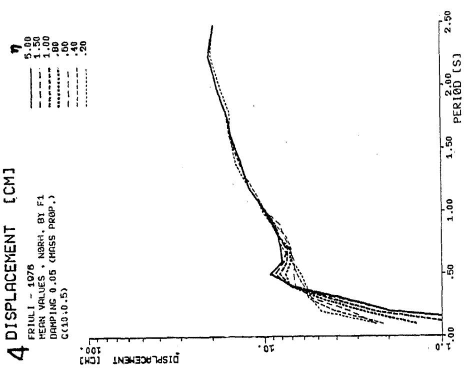
DISPLACEMENT [CM]
PERIOD [S]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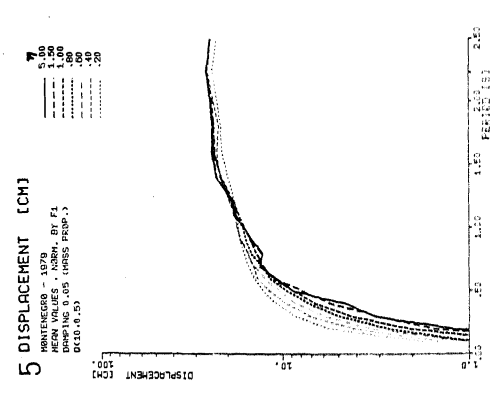
DISPLACEMENT [CM]
PERIOD [S]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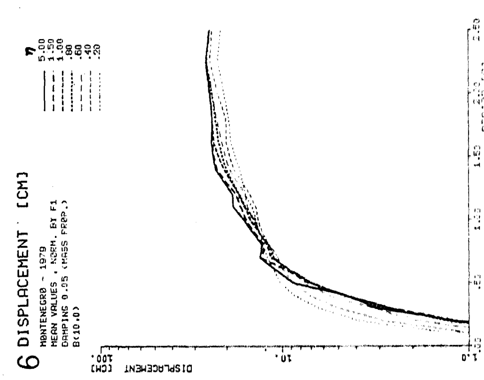
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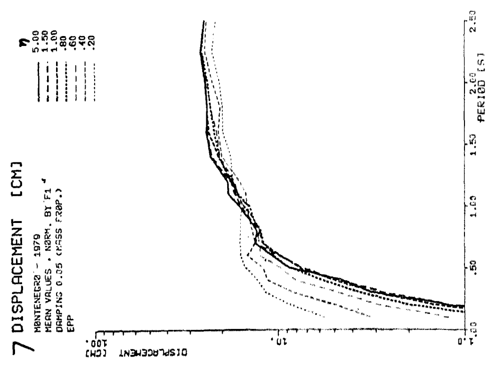
DISPLACEMENT [CM]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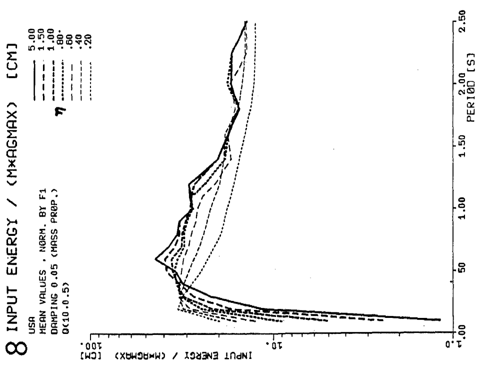
DISPLACEMENT [CM]
PERIOD [S]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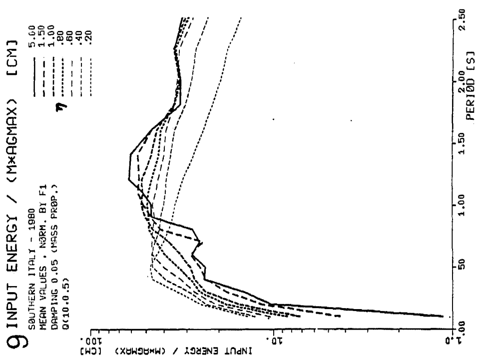
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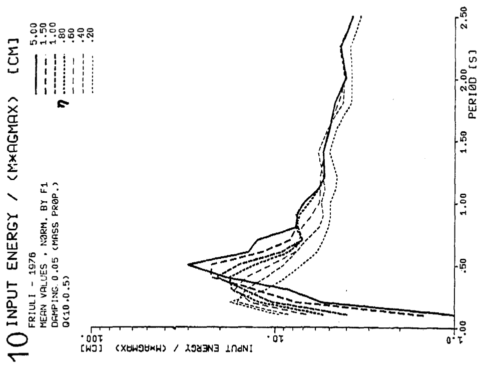
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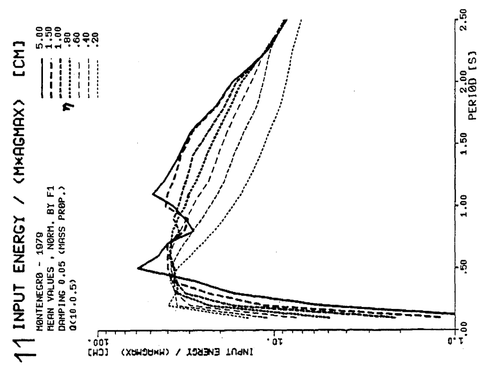
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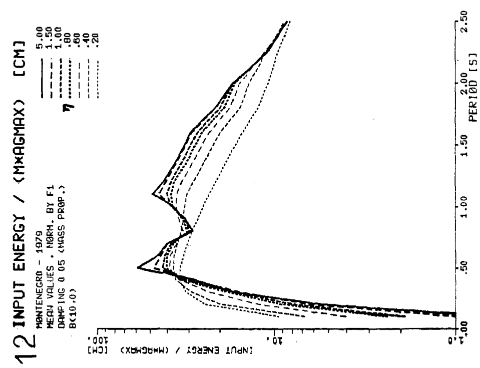
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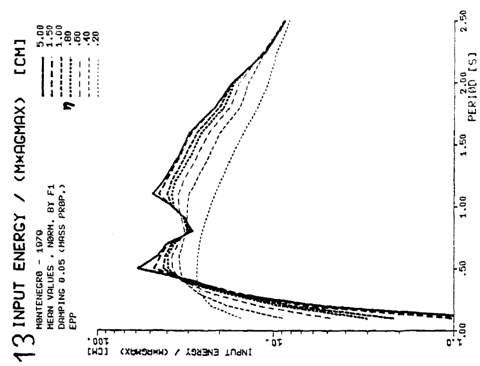
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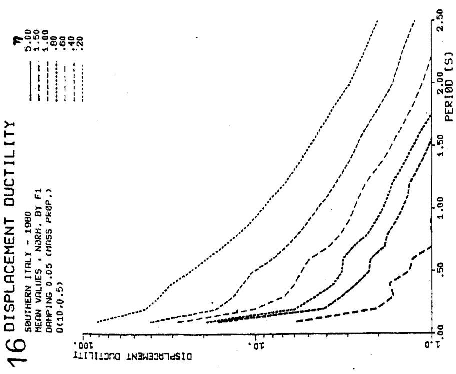
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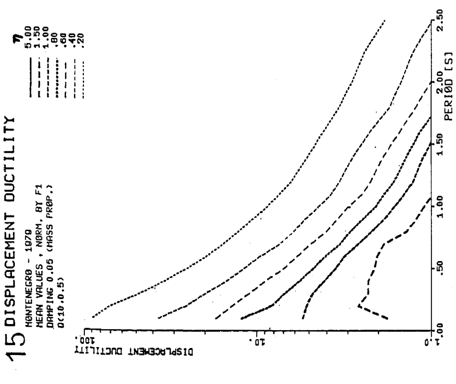
DISPLACEMENT DUCTILITY
PERIOD [S]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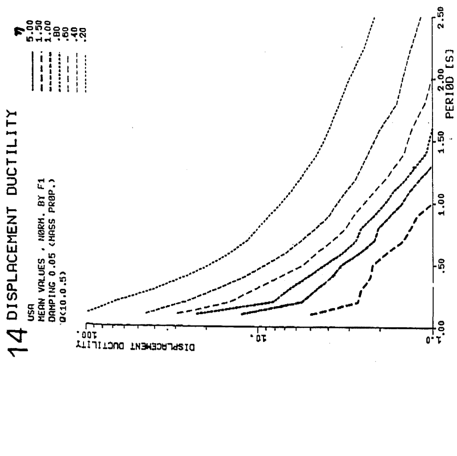
DISPLACEMENT DUCTILITY
PERIOD [S]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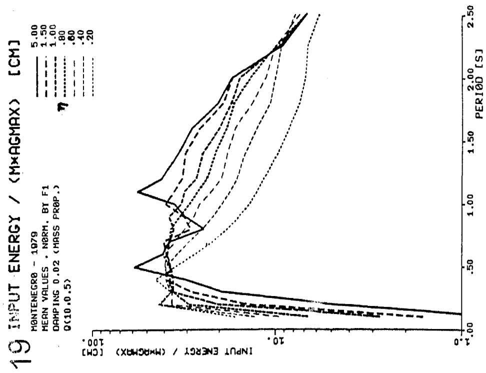
PERIOD [S]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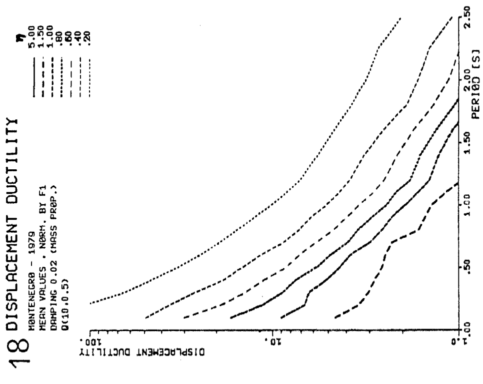
PERIOD [S]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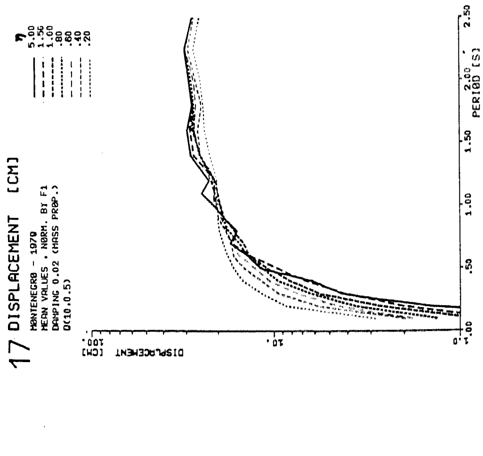
DISPLACEMENT DUCTILITY
PERIOD [S]


17 DISPLACEMENT [CM]
MONTENEGRO - 1979
MEAN VALUES , NORM. BY F1
DAMPING 0.02 (MASS PROP.)
Q(10.0.5)
η 5.00 1.50 1.00 .80 .60 .40 .20
DISPLACEMENT [CM]
PERIOD [S]