

## Velocity of seismic damage

G.Rodolfo Saragoni & Hector Díaz  
*University of Chile, Chile*

**ABSTRACT:** Important number of accelerograms of different earthquake types have been recorded in the world during last years. However only a very small number of them were obtained in epicentral zones or in zones affected by real damage. Only for these damaging records the evaluation of ductility demand have sense.

Using the destructiveness potential factor  $P_D$  a world group of 28 real damaging records is defined. This group of accelerograms considers El Centro 1940 (USA), Tokachi-oki 1968 (Japan), records of Chile and 1985 México earthquakes. Response of elastoplastic and stiffness degrading oscillators is evaluated for this group of damaging accelerograms for different natural periods.

Computation and comparison of ductility requirement, number of nonlinear incursion, velocity of incursion and energy distribution with time are done. Results show important difference in ductility requirement and nonlinear response between chilean accelerograms and the ones recorded in other seismic zones of the world due to the influence of the velocity of damage and the power of the acelerogram (energy per acceelerogram cycle).

### INTRODUCTION

In the last ten years an important number of accelerograms of different earthquakes types have been recorded in the world. However only a very small number of them were obtained in epicentral zones on in zones affected by real damage. Despite this situation nonlinear response spectra are computed from linear elastic response spectra for different ductility values for nondamagig accelerograms.

Furthermore nonlinear response of damaging and nondamaging records are averaged arriving to misleading conclusions, since nondamaging records are more numerous they control averaged values.

Uang and Bertero (2) veriefied that Araya and Saragoni's  $P_D$  correlates well with obervated damage at the accelerographic station for 8 accelerograms of very important earthquakes.

In this study a group of accelerograms obtained in the world in zones of Mercalli modified intensity (MMI) greater or equal to VII is considered.

This group of "damaging accelerograms" includes El Centro 1940, Tokachi-oki 1968 (Japan), records of 1985 Chile and 1985 Mexico earthquake. For the mexican

earthquake records in the epicentral zone as well as in the Mexico city are considered.

The scope of this study is to understand the nonlinear behavior in time of sigle degree of freedom elastoplastic and stiffness degrading oscillators only for real damaging records eliminating records which have been used in others studies corresponding to nondamaging records.

### DESTRUCTIVENESS POTENTIAL FACTOR AND DAMAGING ACCELEROGRAMS

Saragoni, Holmberg y Saez (3) have verified that the destructiveness potential factor  $P_D$  is a good measurement of the real damage since correlates very well with MMI values. Uang and Bertero (2) concludes that from the different parameters proposed by previous researchers to specify the damage potential (on Intensity) of a given earthquake ground motion do not correlate well. Of the parameters reviewed the destructiveness potential factor  $P_D$  proposed by Araya and Saragoni (1) correlates best with observed damage.

Saragoni et al.(3) found that the horizontal destructiveness potential factor  $P_D$  defined by

$$P_{DH} = P_{DXX} + P_{DYY} \quad (1)$$

is correlated with MMI through the following equation

$$MMI = 4.56 + 1.50 \log_{10} P_{DH} \quad (2)$$

In order to consider only damaging accelerograms the condition  $MMI > 7.0$  in Eq.(2) is imposed obtaining the condition for damaging accelerogram of  $P_{DH} > 42.33 \cdot 10^{-4} \text{ g sec}^3$ . Considering this condition for the four classic USA records El Centro 1934, El Centro 1940, Olympia 1949 and Taft 1952 indicated in Table 1 it is concluded that only El Centro 1940 is a damaging accelerogram. (Saragoni (4))

Table 1. Destructiveness Potential Factor for USA Classical Accelerograms

Station	Component	$P_D$ 10-4g sec <sup>3</sup>	$P_{DH}$ 10-4g sec <sup>3</sup>
El Centro	NS	48.32	
1940	EW	37.28	85.60
El Centro	NS	12.76	
1934	EW	9.58	22.34
Olympia	S80W	14.60	
1949	N10W	8.48	23.08
Taft	S69E	13.19	
1959	N21E	14.01	27.20

The condition  $P_{DH} \geq 42.33 \times 10^{-4} \text{ gsec}^3$  for damaging accelerograms will be reduced to  $P_D \geq 20 \times 10^{-4} \text{ g sec}^3$  for one accelerogram horizontal component. Under this condition a very reduced group of world accelerograms components become "damaging accelerograms". The group of damaging accelerograms to be considered in this study considers El Centro 1940, Tokachi-oki 1968 (Japan), records of 1985 Chile and Mexico earthquakes (epicentral as well as Mexico city records). The  $P_D$  values of these 28 damaging accelerogram are indicated in Table 2.

#### DISPLACEMENT DUCTILITY

Maximum relative displacement or displacement ductility is the structural parameter which is most widely used to evaluate the nonlinear performance of structures.

In this study the ductility requirement and nonlinear response are estimated for elastoplastic and stiffness degrading oscillators of 1 DOF of natural period  $T_n = 0.2, 0.3, 0.7, 1.0, 1.5, 2.0$  and  $2.5$  secs. For the viscous damping ratio only 0.05 value is considered due to the little influence in the nonlinear response.

The characteristics of the nonlinear models are indicated in Arazola et al. (5)

Figs. 1.1 and 1.2 show the spectra of ductility requirement for elastoplastic and stiffness degrading oscillators for the Lollole N10°E, Viña del Mar S20°S, Melipilla NS, El Centro 1940 NS, and Tokachi-Oki 1968. The spectra of ductility requirement are in order according with the  $P_D$  values, the Lollole N10°E spectrum is the envelope spectrum for the remaining spectra (Díaz and Saragoni (6)).

Table 2.  $P_D$  Values of damaging accelerograms

Record	$P_D$ 10 <sup>-4</sup> g sec <sup>3</sup>	$\nu$ cross/ sec	$\dot{u}_{max}$ cm/sec
Tlahuac Bombas EW (Mex)	1627.71	0.83	44.61
Tlahuac Bombas NS (Mex)	1250.92	1.07	64.10
Secret.Telec. EW. (Mex)	1221.32	1.43	61.47
Secret.Telec NS (Mex)	670.96	1.38	38.68
Central Abastos EW (Mex)	628.62	1.08	37.57
Central Abastos NS (Mex)	361.81	1.20	24.85
Tlahuac Deportv.EW (Mex)	232.00	1.75	36.06
Tlahuac.Deportv.NS (Mex)	225.71	1.69	34.90
Lollole N10E (Chi)	201.57	9.09	40.01
Viña del Mar S20W (Chi)	117.81	6.92	30.98
Llayllay N80W (Chi)	103.05	7.66	37.36
Lollole S80E (Chi)	80.29	9.81	22.94
Ventanas NS (Chi)	75.78	7.00	23.41
Llayllay S10W (Chi)	68.10	8.58	41.45
Viña del Mar N70W (Chi)	55.75	7.42	25.54
El Almendral N50E (Chi)	47.33	8.40	29.16
El Centro 1940 NS (USA)	46.21	6.59	33.40
El Almendral S40E (Chi)	46.71	7.12	16.67
Melipilla NS (Chi)	43.33	16.84	29.99
Papudo N40E (Chi)	39.63	8.56	12.31
Melipilla EW (Chi)	37.06	16.38	31.94
El Centro 1940 EW (USA)	36.34	6.27	36.90
Tokachi-Oki 1968 (Jap)	32.84	6.04	31.89
Iloca EW (Chi)	32.04	8.84	14.81
Ventanas EW (Chi)	30.79	9.40	24.78
Zacatula NS (Mex)	30.55	9.38	30.39
Iloca NS (Chi)	23.27	9.25	8.55
Zacatula EW (Mex)	20.74	9.03	13.96

Making the comparison of absolute acceleration response spectra among the same accelerograms important differences are found which are not observed in the ductility requirement spectra. Therefore nonlinear response spectra can not be obtained from elastic response spectra. Furthermore damaging capacity of accelerograms can not be forecasted from elastic response spectra (Saragoni.(4))

#### NUMBER OF NONLINEAR INCURSION

Considering the important differences between the intensity of zero crossings among

the 1985 Chile earthquake records, specially Melipilla NS with  $\nu_0 = 16.84$  cross/sec and Llolleo with  $\nu_0 = 9$  to 10 cross/sec, with Mexico City records  $\nu_0 = 1.4$  to 1.0 cross/sec, and El Centro 1940,  $\nu_0 = 6.27$  to 6.59 cross/sec and Tokachi-oki 1968,  $\nu_0 = 6.04$  cross/sec. It was considered important to compute the number N of nonlinear incursion for each type of oscillator. In Table 3 are indicated the number of nonlinear incursions for the elastoplastic oscillators with  $T_n = 0.2, 0.3, 0.7, 1.0, 1.5, 2.0$  and  $2.5$  sec. In Table 4 are given the same results for the stiffness degrading oscillator. From the results of Table 3 it is observed that the number of incursion for 1985 Chile earthquake are 2 to 3 times the 1940 El Centro NS accelerogram independent if the destructiveness potential value is greater or lower than the El Centro value. This situation is increased when the comparison is done with Tokachi-oki. This situation is almost identical for the stiffness degrading oscillators. The only case of similar values are the accelerograms of El Centro NS and Viña del Mar S20°W.

It is important to notice the big difference of number of nonlinear incursion between elastoplastic and stiffness degrading oscillator for the same record. The N values for elastoplastic are 10 times the stiffness degrading for almost all the records with the exception of Mexico City records which are 4 to 5 times only. It must be noticed that Zacatula records in the epicentral zone of 1985 Mexico earthquake have values similar to the Chilean records and the ratio of N values is also 10 times. The ratio between N values for Chile and Mexico epicentral records with respect to Mexico city records is around 10 times. This situation distribute the absorbed energy in the Chilean records in more cycles of nonlinear incursion than the Mexican city record. It is must be observed that the more damaging Mexico City records is not the SCT EW most used in the earthquake resistant study. The most damaging records is Tlahuac Bombas EW ( $P_D = 1627.71$ ) with  $\nu_0 = 0.83$  compared with the  $\nu_0 = 1.43$  of SCT EW gives an N value for SCT two times than Tlahuac Bombas EW. Therefore the damaging effect of

Table 3. Number of Nonlinear Incursions for Elastoplastic Oscillators

Record	PD $10^{-4} \text{gsec}^3$	$\nu_0$ Cross/ sec	PERIOD (sec.)							
			0.2	0.3	0.7	1.0	1.5	2.0	2.5	
Tlahuac Bombas EW (Mex)	1627.71	0.83	1	2	9	19	27	34	29	
Tlahuac Bombas NS (Mex)	1250.92	1.07	2	5	15	25	31	33	30	
Secret.Telec. EW (Mex)	1221.32	1.43	16	23	29	32	50	75	58	
Secret.Telec. NS (Mex)	670.96	1.38	1	8	26	35	52	78	56	
Central Abastos EW (Mex)	628.62	1.08	0	0	17	20	32	36	31	
Central Abastos NS (Mex)	361.81	1.20	0	0	11	12	25	42	38	
Tlahuac Deportv. EW (Mex)	232.00	1.75	1	3	26	40	35	47	33	
Tlahuac Deportv. NS (Mex)	225.71	1.69	2	3	19	20	23	39	27	
Llolleo N10E (Chi)	201.57	9.09	319	273	126	66	40	22	10	
Viña del Mar S20W (Chi)	117.81	6.92	200	150	158	89	33	8	4	
Llaylly N80W (Chi)	103.05	7.66	213	186	97	76	43	17	7	
Llolleo S80E (Chi)	80.29	9.81	239	265	117	62	15	1	0	
Ventanas EW (Chi)	75.78	7.00	216	189	134	149	43	9	1	
Llaylly S10W (Chi)	68.10	8.58	195	173	85	72	42	22	7	
Viña del Mar N70W (Chi)	55.75	7.42	220	137	141	66	20	3	0	
El Almendral N50E (Chi)	47.33	8.40	225	194	126	82	34	10	5	
El Centro 1940 NS (USA)	46.21	6.59	100	85	43	28	14	12	5	
El Almendral S40E (Chi)	46.71	7.12	185	166	145	83	16	2	0	
Melipilla NS (Chi)	43.33	16.84	321	210	58	30	15	8	6	
Papudo S40E (Chi)	39.63	8.56	214	326	17	4	1	0	0	
Melipilla EW (Chi)	37.06	16.38	327	216	58	39	17	13	9	
El Centro 1940 EW (USA)	36.34	6.27	111	102	30	29	16	11	9	
Tokachi-Oki 1968 (Jap)	32.84	6.04	66	126	43	44	19	23	25	
Iloca EW (Chi)	32.04	8.84	170	207	19	4	0	0	0	
Ventanas NS (Chi)	30.79	9.40	271	168	116	101	31	2	0	
Zacatula NS (Mex)	30.55	9.38	185	152	86	51	30	8	11	
Iloca NS (Chi)	23.27	9.25	145	270	20	5	11	0	0	
Zacatula EW (Mex)	20.74	9.03	179	163	60	47	11	4	0	

Table 4. Number of Nonlinear Incursions for

Stiffness Degrading Oscillators

RECORD		P	v <sub>o</sub>		PERIOD (sec.)								
			10 <sup>10</sup>	gsec	cross/ sec	0.2	0.3	0.7	1.0	1.5	2.0	2.5	
Tlahuac Bombas	EW	(Mex)	1627.71	0.83	1	2	6	8	7	12	12		
Tlahuac Bombas	NS	(Mex)	1250.92	1.07	2	7	8	10	9	8	6		
Secret.Telec.	EW	(Mex)	1221.32	1.43	8	10	10	11	15	8	8		
Secret.Telec.	NS	(Mex)	670.96	1.38	1	7	12	8	6	6	4		
Central Abastos	EW	(Mex)	628.62	1.08	0	0	9	7	7	8	9		
Central Abastos	NS	(Mex)	361.81	1.20	0	0	9	10	8	7	4		
Tlahuac Deportv.	EW	(Mex)	232.00	1.75	1	3	10	7	10	8	9		
Tlahuac.Deportv.	NS	(Mex)	225.71	1.69	2	3	9	9	8	9	8		
Llolleo	N10E	(Chi)	201.57	9.09	24	23	12	10	9	7	4		
Viña del Mar	S20W	(Chi)	117.81	6.92	10	10	11	5	4	2	2		
Llayllay	N80W	(Chi)	103.05	7.66	25	28	14	15	7	7	5		
Llolleo	S80E	(Chi)	80.29	9.81	27	21	12	10	3	1	0		
Ventanas	EW	(Chi)	75.78	7.00	24	27	12	10	5	1	1		
Llayllay	S10W	(Chi)	68.10	8.58	24	17	18	15	9	5	2		
Viña del Mar	N70W	(Chi)	55.75	7.42	12	12	9	4	6	1	0		
El Almendral	N50E	(Chi)	47.33	8.40	20	19	13	8	4	4	3		
El Centro 1940	NS	(USA)	46.21	6.59	8	9	7	6	4	5	3		
El Almendral	S40E	(Chi)	46.71	7.12	40	38	31	25	10	7	1		
Melipilla	NS	(Chi)	43.33	16.84	34	30	16	8	8	7	3		
Papudo	S40E	(Chi)	39.63	8.56	16	15	3	1	1	0	0		
Melipilla	NS	(Chi)	37.06	16.38	20	18	7	6	4	2	3		
El Centro 1940	EW	(USA)	36.34	6.27	7	6	6	5	2	2	3		
Tokachi-Oki 1968		(Jap)	32.84	6.04	9	6	3	5	5	8	4		
Iloca	EW	(Chi)	32.04	8.84	20	18	3	3	0	0	0		
Ventanas	NS	(Chi)	30.79	9.40	18	22	15	8	7	2	0		
Zacatula	NS	(Mex)	30.55	9.38	16	6	4	4	2	2	1		
Iloca	NS	(Chi)	23.27	9.25	14	15	3	1	1	0	0		
Zacatula	EW	(Mex)	20.74	9.03	13	14	7	3	1	1	0		

SCT EW record is distributed in a greater number of nonlinear incursion reducing its capacity of ductility demand.

Finally it is must be observed that there is a strong correlation between the  $v_o$  values and the N values. Therefore for greater  $v_o$  values the earthquake energy input is distributed in a larger number N of nonlinear incursions, reducing the displacement ductility as it is predicted by the destructiveness potential factor  $R_D$ .

#### INPUT POWER DEMAND

From the results of the previous section it is clear that the damaging capacity of an accelerogram measured by the  $P_D$  values measures the power of the accelerogram, i.e input energy demand per accelerogram cycle and the total duration of the record.

This results show that the input energy alone is not a measurement of the damaging capacity of an accelerogram, it is also important to know the number of nonlinear cycles that the energy will be distributed.

#### DAMAGE VELOCITY

In Table 5 the computation of the oscillator velocity in the greatest nonlinear incursion are indicated for elastoplastic structures. The oscillator velocity is expressed as a ratio of the maximum ground velocity  $U_{max}$ . It is was found that this ratio is always lower than 1.0. Therefore the velocity of the maximum nonlinear incursion is always lower than  $U_{max}$ , taking values between 0.65 to 0.90 in the period range 0.70 to 1.50 sec. for the Chilean records. The same values are obtained for the Mexico City records in the period range 1.5 to 2.5 sec. It is must be noticed that El Centro 1940 NS and Tokachi-oki give reduced values 0.50 to 0.60 in the period range 0.70 to 1.50 sec. Therefore the damage velocity V for Chilean and Mexico earthquakes in their corresponding period range is greater than the El Centro 1940 NS and Tokachi-oki for similar maximum ground velocity. Ratio  $VD/v_o$  is proportional to ductility displacement demand.

TABLA 5. Damage Velocity Expressed in Terms of Mximum

Ground Velocity Elastoplastic Oscillator.

RECORD			P <sub>D</sub> 10-4gs <sup>3</sup>	U <sub>smax</sub> cm/sec	PERIOD (sec.)							
					0.2	0.3	0.7	1.0	1.5	2.0	2.5	
Tlahuac Bombas	EW	(Mex)	1627.71	0.83	44.61	0.00	0.02	0.17	0.35	0.62	0.69	0.84
Tlahuac Bombas	NS	(Mex)	1250.92	1.07	64.10	0.03	0.06	0.30	0.45	0.56	0.58	0.60
Secret.Telec.	EW	(Mex)	1221.32	1.43	61.47	0.20	0.16	0.51	0.63	0.72	0.78	0.82
Secret.Telec.	NS	(Mex)	670.96	1.38	38.68	0.00	0.02	0.19	0.41	0.66	0.72	0.74
Central Abastos	EW	(Mex)	628.62	1.08	24.85			0.11	0.34	0.61	0.76	0.95
Central Abastos	NS	(Mex)	361.81	1.20	37.57			0.11	0.21	0.57	0.80	0.87
Tlahuac Deportv.	EW	(Mex)	232.00	1.75	36.06	0.01	0.05	0.29	0.44	0.72	0.96	0.95
Tlahuac.Deportv.	NS	(Mex)	225.71	1.69	34.90	0.01	0.07	0.24	0.53	0.79	0.86	0.97
Llolleo	N10E	(Chi)	201.57	9.09	40.01	0.53	0.65	0.77	0.72	0.77	0.62	0.60
Viña del Mar	S20W	(Chi)	117.81	6.92	30.98	0.34	0.53	0.85	0.88	0.90	0.88	0.53
Llayllay	N80W	(Chi)	103.05	7.66	37.36	0.47	0.57	0.64	0.77	0.81	0.69	0.42
Llolleo	S80E	(Chi)	80.29	9.81	22.94	0.50	0.65	0.99	0.95	0.73	0.41	
Ventanas	EW	(Chi)	75.78	7.00	23.41	0.27	0.40	0.82	0.90	0.87	0.60	0.45
Llayllay	S10W	(Chi)	68.10	8.58	41.45	0.34	0.49	0.66	0.74	0.72	0.51	0.52
Viña del Mar	N70W	(Chi)	55.75	7.42	25.54	0.31	0.36	0.36	0.93	0.77	0.47	
El Almendral	N50E	(Chi)	47.33	8.40	29.16	0.28	0.48	0.79	0.83	0.71	0.76	0.63
El Centro 1940	NS	(USA)	46.21	6.59	33.40	0.47	0.57	0.56	0.66	0.55	0.81	0.57
El Almendral	S40E	(Chi)	46.71	7.12	16.67	0.32	0.46	0.79	0.81	0.63	0.47	
Melipilla	NS	(Chi)	43.33	16.84	29.99	0.52	0.56	0.55	0.58	0.80	0.50	0.42
Papudo	S40E	(Chi)	39.63	8.56	12.31	0.69	0.84	0.59	0.67	0.65		
Melipilla	EW	(Chi)	37.06	16.38	31.94	0.56	0.55	0.75	0.74	0.76	0.59	0.54
El Centro 1940	EW	(USA)	36.34	6.27	36.90	0.21	0.36	0.49	0.42	0.48	0.62	0.79
Tokachi-Oki 1968		(Jap)	32.84	6.04	31.89	0.29	0.32	0.52	0.47	0.51	0.60	0.55
Ventanas	NS	(Chi)	30.79	9.40	24.78	0.27	0.35	0.69	0.78	0.68	0.30	
Zacatula	NS	(Mex)	30.55	9.38	30.39	0.34	0.50	0.73	0.69	0.63	0.51	0.70
Zacatuja	EW	(Mex)	20.74	9.03	13.96	0.38	0.45	0.76	0.93	0.88	0.77	

This knowledge requires to introduce the concept of input power demand. This result emphasizes the importance of the duration of the accelerogram pulses noticed by Bertero and Mahin (7).

energy for the chilean records is done through a larger number of plastic cycles but a lower velocity of damage. (Díaz and Saragoni (6)).

ABSORVED ENERGY

The study of the absorbed energy with time was analyzed for the same set of elastoplastic and stiffness degrading oscillators. The absorbed energy is distributed between plastic and viscous energy. The values of the plastic energy expressed in terms of the total absorbed energy are 0.6 to 0.8 for elastoplastic oscillators and 0.5 to 0.7 for stiffness degrading. From the comparison of the distribution of the plastic energy for El Centro 1940 NS and Viña del Mar S20°W, it is concluded that El Centro reaches the damage with quicker velocity in few cycles. Viña del Mar reaches the total plastic energy with lower damaging velocity. The 45% of the total plastic energy is reached for el Centro in 6 secs. For the Viña del Mar record is reached in 30 secs. This is due to the effect of the number of plastic cycles: 158 for Viña del Mar and 43 for El Centro. This makes that the absorbed

CONCLUSIONS

1. Nonlinear response study must be done only for damaging accelerograms with  $P_D > 20 \times 10^{-4} g \text{ sec}^3$
2. Ductility displacement spectra are in order according with the  $P_D$  values.
3. The number of nonlinear  $P_D$  incursions for 1985 Chile and México epicentral records are 2 to 3 times the 1940 El Centro 40 NS independent of the  $P_D$  value.
4. The number of nonlinear incursions for elastoplastic oscillators are 10 times the stiffness degrading. This ratio is reduced to 4 to 5 times for the Mexico records.
5. There are a strong correlation between intensity of zerocrossings  $\nu_0$  and the number of nonlinear incursions. Therefore for greater  $\nu_0$  values the earthquake energy input is distributed in a larger number of nonlinear incursions.
6. Energy alone is not a measurement of the damaging capacity of an accelerogram it is

also important to know the number of nonlinear incursions related with  $v_0$ . Therefore it is important to introduce the concept of input power demand, energy per accelerogram cycle.

7. Damaging velocity for Chilean and Mexican earthquake is greater than El Centro 1940

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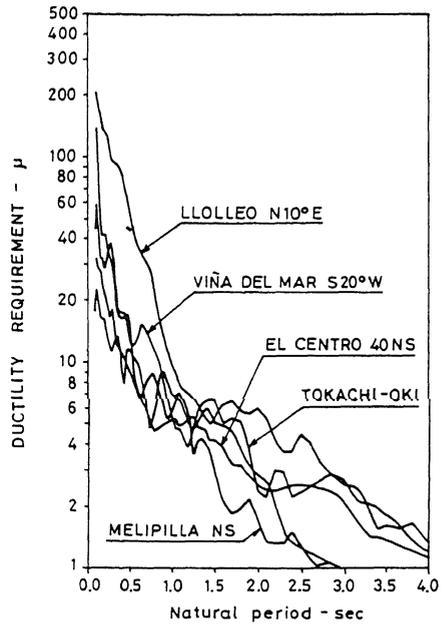


FIG. 1 DUCTILITY SPECTRA ELASTOPLASTIC OSCILLATOR

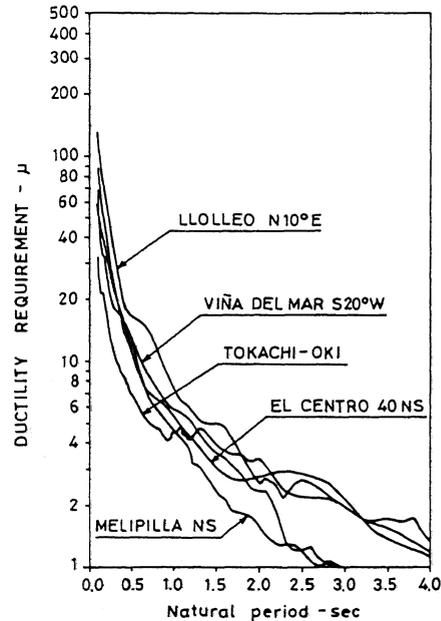


FIG. 2 DUCTILITY SPECTRA STIFFNESS DEGRADING OSCILLATOR