FLOOR RESPONSE SPECTRA CONSIDERING ELASTO-PLASTIC BEHAVIOUR OF NUCLEAR POWER FACILITIES

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Abstract

Floor response spectra (FRS) have been a major factor in the aseismic design of piping systems and of other mechanical equipments. The FRS are usually estimated using time-history responses of buildings whose dynamic characteristics are assumed to be linear.

However, under severe earthquake conditions the response analysis of buildings may more accurately be carried out using an elasto-plastic system.

The first object of this paper is to evaluate the elasto-plastic dynamic analysis the auxiliary building (A.B.) for the P.W.R. Power Plant. The nonlinear response of the structure is affected by the hysteresis curves of the structural members. In this paper, three hysteresis curves (Origin orientated type, Degrading tri-linear type and Slip type) are applied to the time-history response analysis of the A.B. The geometrical non-linearity of the soil rocking spring due to the separation of the foundation from the soil surface is also considered.

The second object is to discuss FRS obtained from elastic and elasto-plastic systems. The FRS are calculated from the time-history acceleration of the A.B. at selected floor level using a single-degree-of-freedom mass-spring-dashpot system with a specific damping ratio.

The three major parameters for this study are hysteresis curves, ground motions and input motion levels.

The three abovementioned hysteresis curves are based on shear force-deformation characteristics of reinforced concrete (RC) walls. The ground movements were produced by two simulated earthquakes and they provided the design ground response data. The input acceleration range was 300 - 1000 gal.

The results of responses to severe earthquakes were summarized as follows:

1. Due to the strong ground motion, the model structure response became partially nonlinear.

2. Response forces did not increase in proportion to the magnitude of the input motions.

3. The peak level and shape of FRS were affected by the characteristics of the hysteresis curve.

1. Introduction

Several concepts involving inelastic response spectra have been developed for use in the design of structures and mechanical equipments to resist earthquake motions.

Newmark proposed the modified inelastic design response spectra, which is developed from the elastic design spectra using a ductility factor (μ) and an idealized elasto-plastic resistance-displacement relationship of single mass spring system. (1), (2)

The nonstationarity due to the zero-starting condition and variation of intensity modulation function for ground motion is considered by Singh and Wen. (3)

Sato, Komazaki and Ohori attempted to extend the simple method of estimating a response spectrum based on the simulated spectrum for elastic multi-storied building sturcture. (4)

This paper discusses the Inelastic Floor Response Spectra (IFRS) obtained from elasto-plastic multi-storied building system and suggests the dynamic estimation model for the actual aseismic design of mechanical equipments under severe earthquake conditions.

The flow chart of this study is presented in Fig. 1.

2. Analytical Model

The Auxiliary Building (AB) of the PWR three-loop power plant is selected as the building structure for analysis. The 6-story AB is designed to resist 300 gals earthquake motions. The two upper stories are a braced steel frame structure and the lower four stories are a reinforced concrete wall structure.

The lumped mass system is used for the dynamic analytical model for the AB structure. (Fig. 2) The model consists of six mass points and a rigid base mat with swaying and rocking springs which represent the interaction effects between the building and subsoil. The dimensions of the lumped mass model are shown in Table-I. The stiffness of the super structural members are estimated by the equivalent shear method.

Total of 18 elasto-plastic models are calculated for combinations of two input motions (Input Motion - A, B), three input motion levels (500, 750 and 1000 gals), and three hysteresis curves (Origin-oriented, Degrading tri-linear and Slip type).

Nonlinear dynamic responses of the building structure to the input ground motions are computed using the step direct integration method (Newmark's β method).

The elastic and inelastic floor response spectra are produced from the calculated acceleration time history of the AB using a one-degree of freedom system. The damping ratio of the mechanical equipment is fixed at 1%.

3. Input Motion

Two artificial earthquakes (Input Motion - A, B) were used for input ground motion. (Fig. 3) These earthquakes were simulated from the statistic response spectra for firm ground. This spectra is chiefly classified by magnitude (M) and epicentral distance (Δ).

The artificial earthquakes are generated with respect to the amplitude of the estimated design spectrum and the phase of the actual earthquake to fit the actual site conditions. Parameters of two artificial earthquakes are presented in Table-IV.

The maximum acceleration of input motion is normalized to 500, 750 and 1000 gals.

4. Hysteresis Curves of Structural Members

The results of the dynamic responses are influenced by the hysteresis characteristics of the structural members. The hysteresis curves should be determined based on from the structural model tests. However, several hysteresis curves are proposed for the reinforced concrete and steel members.

In this paper, the following three basic hysteresis curves are adopted for the RC structural members from these proposed data. (Fig. 4)

The first is the Origin-oriented type, in which the loop of shear forces and deformations always progress towards the point of origin. This type simulates well the RC structural members which are deformable by shear.

The second is the Degrading tri-linear type, in which the structural rigidity (K_1, K_2) decreases as the deformation increases in the K_3 range. This type is reported as matching the RC frame structure.

The third is Slip type, in which if the first loop area is closed, it loses the loop area until the displacement crosses the former maximum displacement. This type, like the first type, is suitable to the shear wall structures.

The upper braced steel frame is presented as an idealized bi-linear type. The swaying spring of soil is linear but rocking spring is geometrically nonlinear.

5. Results of Inelastic Responses of Building Structure

Fig. 5 shows the maximum response accelerations. These results show that the differences among the accelerations calculated from the three hysteresis types are very small at 500 gals. The accelerations of the roof are nearly equal at all three input motion levels. In cases of 750 and 1000 gals, the maximum response accelerations do not increase proportionally to the input ground motion level, but the increases in response are observed at the middle floors.

Fig. 6 shows the ductility factor (μ); this parameter presents the deformability of the structural members. At 500 gals, the ductility factor is less than one except for the member No. 5, so the responses of the AB are regarded as within the elastic range. The plastic deformation of the member No. 5 increases and its ductility factor (μ) attain 3~8, at magnitudes of 750 and 1000 gals.

The response of the Degrading tri-linear type is minimal; on the other hand the Origin-oriented and the Slip type are larger than the tri-linear type and the responses of two types being nearly equal.

The differences in the responses are caused mainly by the hysteresis loop areas of three types.

6. Results of Inelastic Floor Response Spectra (IFRS)

The inelastic floor response spectra are calculated at three nodal points, that is, at 2, 4 and 6. In this paper, the figures of the IFRS at nodal point 4 are presented.

Fig. 7 shows the results compared with three hysteresis types and input ground motion levels. In general, the amplification factors of the response spectra increase in proportion to the input motion level in the high frequency range, but the Zero Period Acceleration (ZPA) of the IFRS increases slightly at the three input levels selected.

Meanwhile, in the low frequency range (1~3.5 hz), the amplification factor increases in proportion to the input levels, because the first mode frequency of the AB is out-of-range and is directly affected by the ground motion.

The shape and predominant frequency of the IFRS peak is not changed by the Degrading tri-linear type, but is shifted to low frequency range by both the Origin-oriented and the Slip types.

Corresponding to the second or third mode frequencies of the AB, the peaks of the IFRS increase, because the fourth and fifth members of the AB response are mostly in the inelastic range.

Fig. 8 shows the results compared with the elastic and inelastic floor response spectra to 500 gals. There is no difference between them, because the responses of the AB remain in the elastic range at 500 gals.

7. Conclusions

The results of this study are summarized as follows,

(1) It is very difficult to make an accurate elasto-plastic model which considers the local deformation and stresses of all the structural elements in the actual aseismic design. Therefore, the lumped mass model is very useful at present time for the elasto-plastic analysis, if the dynamic characteristics of the hysteresis curves are properly simulated.

(2) This AB is designed for 300 gals, but the responses calculated from the three hysteresis curves nearly equal at 500 gals. Comparing the ultimate strength and the largest deformation with the response value, it is concluded that the safety of the AB are satisfactorily assured.

(3) The Inelastic Floor Response Spectra (IFRS) computed from the Origin-oriented type by which shear deformable structures like the AB, is well simulated, and are nearly equal to the elastic spectra at 500 gals, except that the peak shifts slightly at low frequency.

(4) In designing an equipment machine to simulate the severe earthquakes, it should be remembered that the first mode frequency of the AB shifts to the low range and the second or the third mode is predominant, due to inelastic response.

Acknowledgement

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References:

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3) Mahendra P. Singh & Yi-Kwei Wen, "NONSTATIONARY SEISMIC RESPONSE OF LIGHT EQUIPMENT", Vol. 103, No. EM6, December, 1977.

4) H. SATO, M. KOMAZAKI & M. OHORI, "AN EXTENSIVE STUDY OF A SIMPLE METHOD FOR ESTIMATING THE RESPONSE SPECTRUM BASED ON A SIMULATED SPECTRUM", Nuclear Engineering and Design 50 (1978) p.p 399-410.

TABLE - I
ELASTIC PROPERTIES OF MATERIALS

MATERIAL	E (KG/CM²)	ν	h (%)
CONCRETE	2.1×10^5	0.17	5
STEEL	2.1×10^6	0.3	2
ROCK	1.0×10^5	0.3	5

CONCRETE C − 250
STEEL SM − 41

E : Young's Modulus
ν : Poisson's Ratio
h : Damping Ratio

TABLE - II
MODEL PROPERTIES

NP	MASS m_i (TS²/CM)	EN	STIFNESS k_i (T/CM)
1	0.42	1	2450
2	1.84	2	6330
3	18.49	3	411680
4	32.59	4	541250
5	35.01	5	555340
6	31.49	6	808560
7	49.80		

$K_H = 7.0746 \times 10^5$ (T/CM)
$K_R = 1.2898 \times 10^{13}$ (TCM/RAD)

TABLE - III
FREQUENCIES AND MODAL DAMPING RATIO

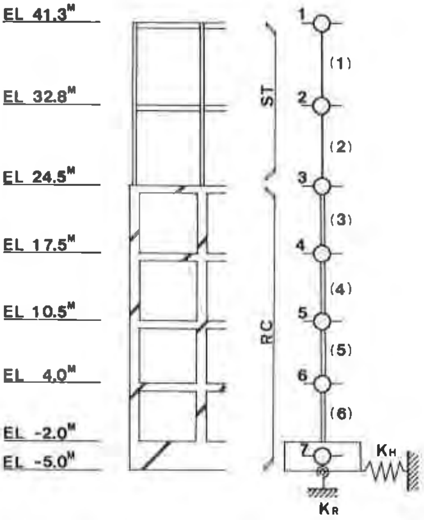
FIXED-BASE MODEL

	f_i	h_i
1	7.402	0.0280
2	9.009	0.0418
3	14.347	0.0202
4	22.936	0.0499
5	33.003	0.0500
6	38.911	0.0500

SOIL - INTERACTION MODEL

	f_i	h_i
1	6.435	0.0436
2	8.203	0.0265
3	14.327	0.0203
4	17.699	0.0497
5	26.667	0.0500
6	33.784	0.0499
7	39.900	0.0500
8	41.494	0.0500

f_i : Natural Frequencies (HZ)
h_i : Modal Damping Ratio



RC : Reinforced Concrete
ST : Steel
K_H : Swaying Stiffness
K_R : Rocking Stiffness

Fig. 2. DYNAMIC ANALYSIS MODEL

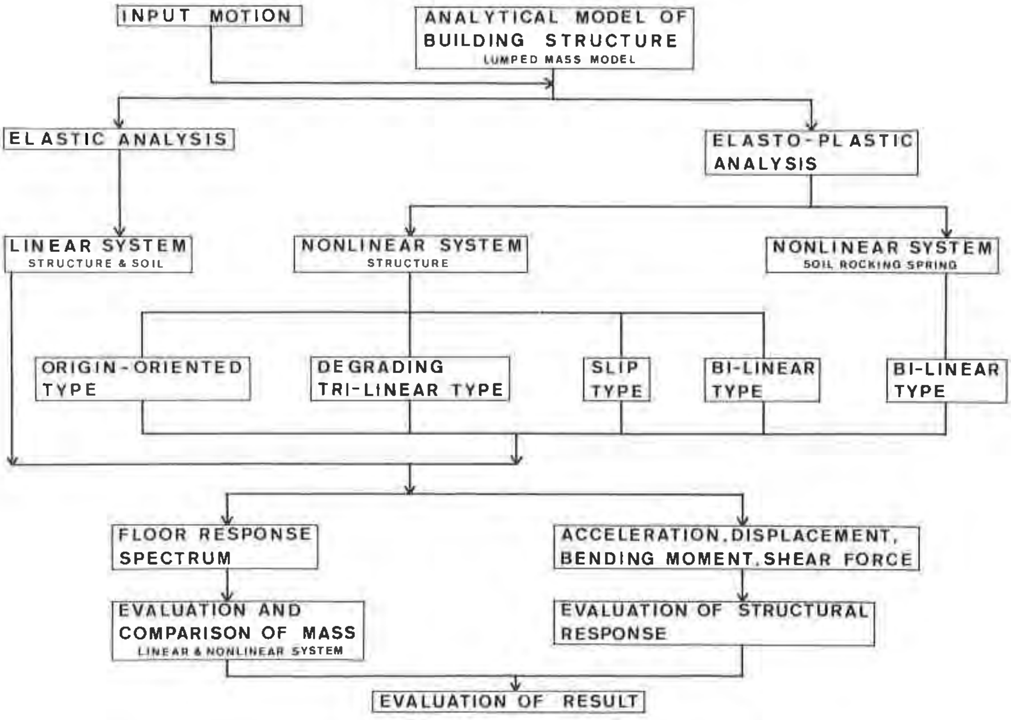


Fig. 1. FLOW CHART OF THIS STUDY

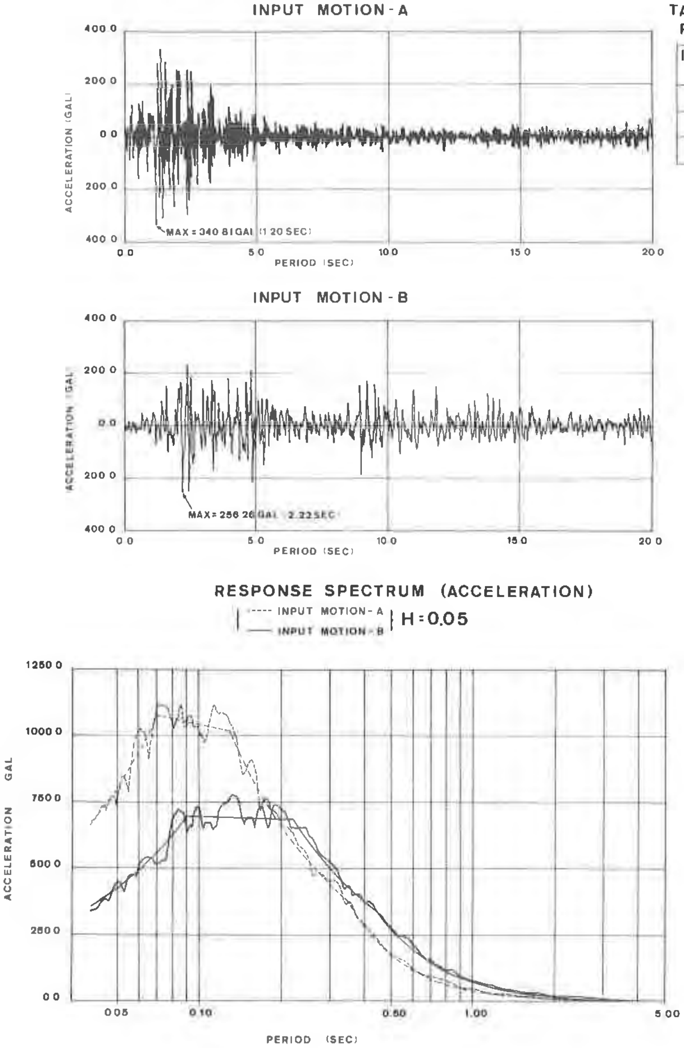


Fig. 3. INPUT GROUND MOTIONS

TABLE - IV
PARAMETERS OF INPUT MOTIONS

INPUT MOTION			ACTUAL EARTHQUAKE USED FOR PHASE			
No	M	Δ	M	Δ	α_{MAX}	EQ NAME
A	6	0	5.3	13.0	102.8	GOLDEN GATE E.W.
B	7	10	7.1	6.4	341.7	EL CENTRO N.S.

M ; MAGNITUDE

Δ ; EPICENTRAL DISTANCE (KM)

α_{MAX}; MAXIMUM ACCELERATION (GAL) (ORIGINAL)

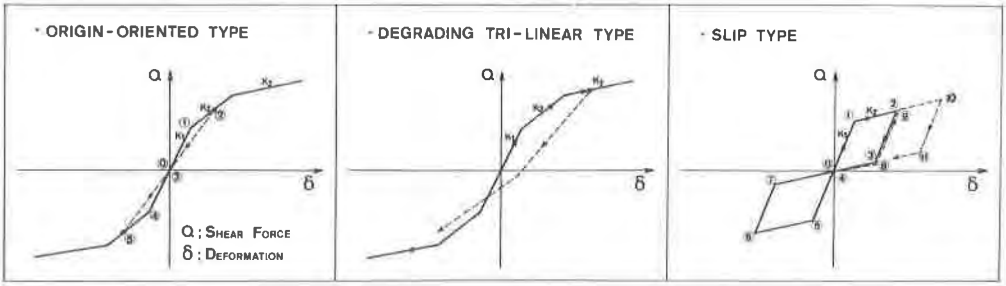


Fig. 4. HYSTERESIS CURVES FOR RC MEMBERS

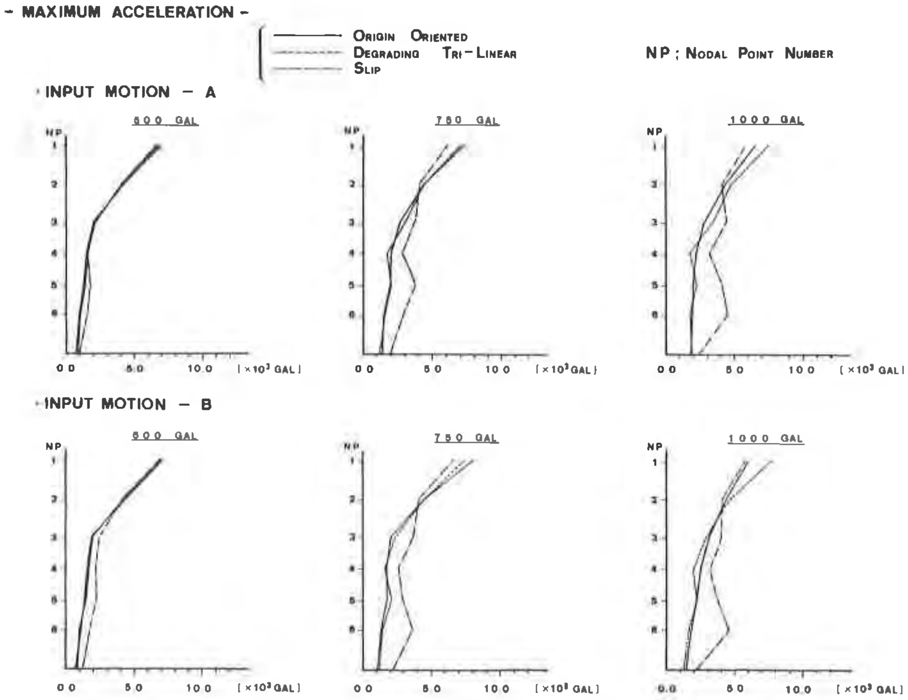


Fig. 5. MAXIMUM ACCELERATION OF BUILDING

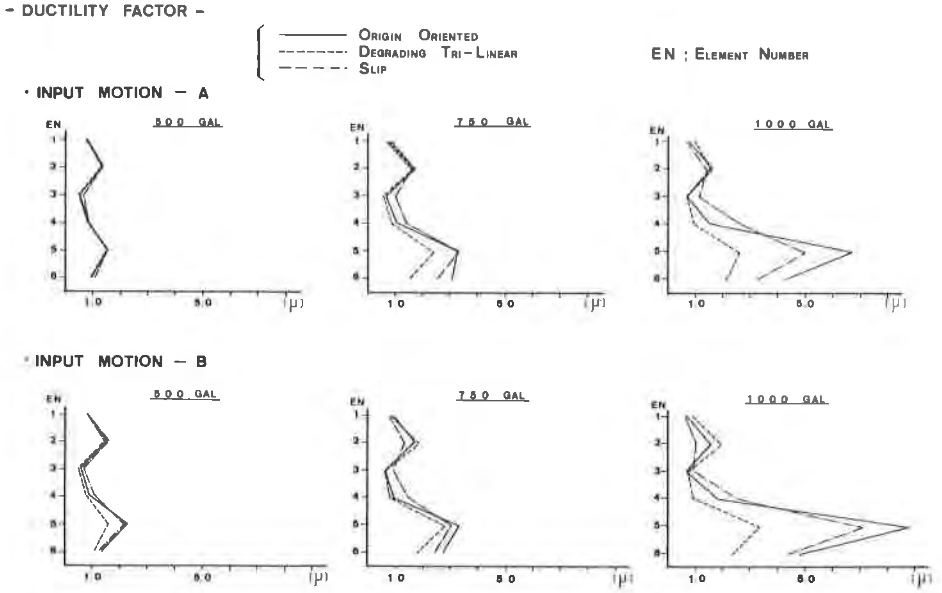


Fig. 6. DUCTILITY FACTOR(μ) OF BUILDING

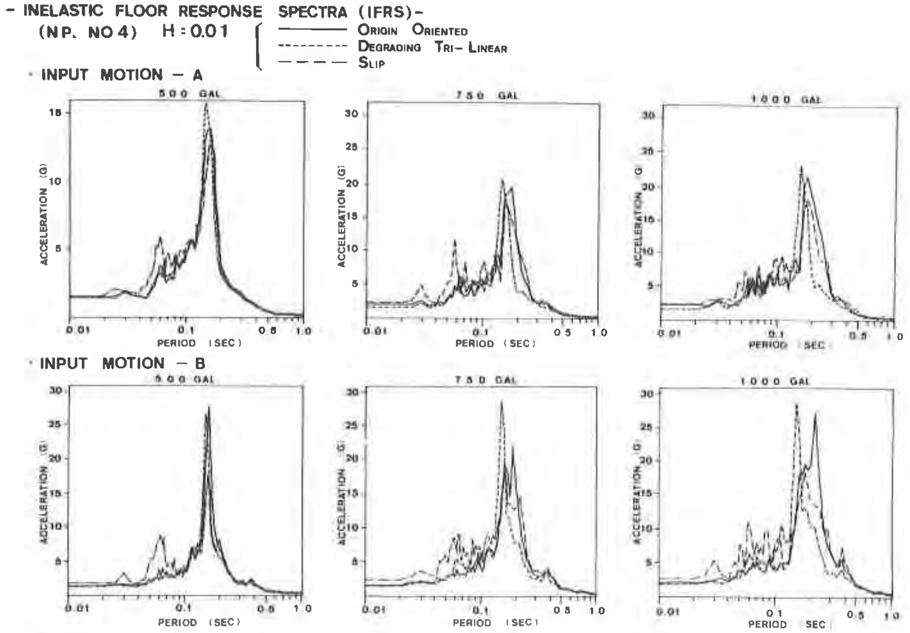


Fig. 7. INELASTIC FLOOR RESPONSE SPECTRA(IFRS)

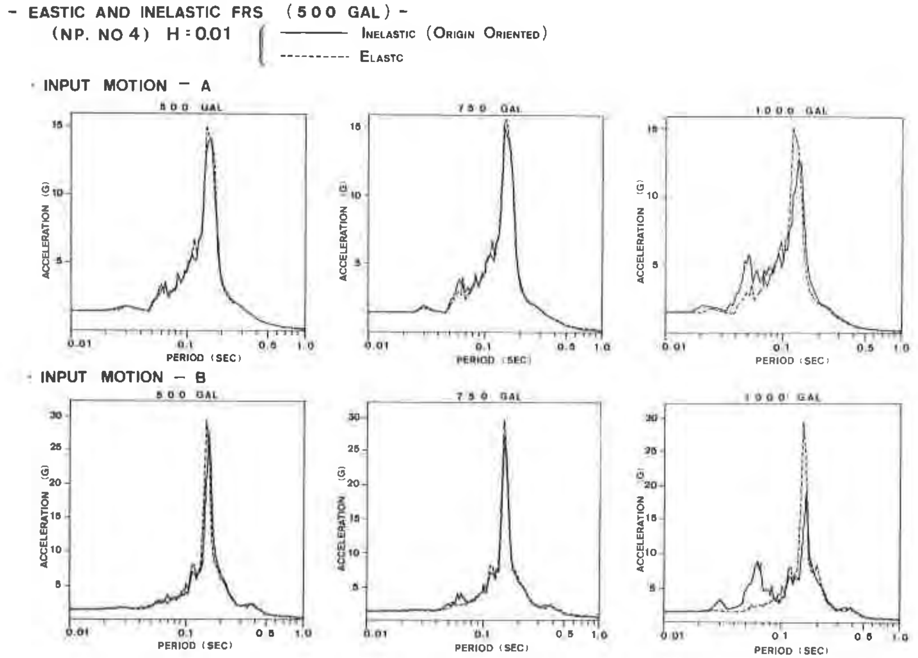


Fig. 8. COMPARISON OF ELASTIC AND INELASTIC FRS
(500 gals)