EARTHQUAKE PARAMETERS AND STRUCTURAL RESPONSE

A Dissertation
submitted in partial fulfilment
of the requirements for the degree
of
MASTER OF ENGINEERING
in
EARTHQUAKE ENGINEERING
WITH SPECIALIZATION IN STRUCTURAL DYNAMICS

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November, 1971

C E R T I F I C A T E

Certified that the thesis entitled "EARTHQUAKE PARAMETERS AND STRUCTURAL RESPONSE" which is being submitted by Sri Sahadeo in partial fulfilment for the award of the degree of Master of Engineering in 'STRUCTURAL DYNAMICS', Earthquake Engineering of the University of Roorkee, Roorkee is a record of student's own work carried out by him under our supervision and guidance. The matter embodied in this thesis has not been submitted for the award of any other degree or diploma.

This is further to certify that he has worked for a period of 9 months from Feb.1971 to Nov. 1971 for preparing this thesis for Master of Engineering degree at the University.

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ACKNOWLEDGEMENT

The author wishes to express his deep sense of gratitude towords Dr. A.S.Arya, Professor and Head and Sri S.K. Thakkar, Lecturer in Structural Dynamics, Department of Earthquake Engineering, University of Roorkee, Roorkee, for their invaluable guidance and help rendered to him during the preparation of this thesis.

Thanks are also due to staff members of Computer centre, S.E.R.C., Roorkee and Delhi, School of Economics, Delhi University for the help sought by the author during computational work on IBM 1620 and I.B.M. 360/44 systems.

SYNOPSIS

The purpose of this thesis is to study the elastic and inelastic response of single degree of freedom systems for Koyna accelerograms as recorded as well as for modified.

For elastic analysis the accelerogram is derived in any arbitrary direction from the recorded accelerograms in mutually perpendicular directions. The elastic response of structures is studied for the modified accelerograms. The effect of orientation of this direction with respect to recorded accelerogram on the elastic response is also studied.

For the inelastic analysis the earthquake record is modified by altering its time base by a factor of 1.5. The effect of this modification is studied on the inelastic response of the structures.

C O N T E N T S

CHAPTER - 1

INTRODUCTION

1.1 Introduction

The nature of the earthquake motion differs from place to place and also in different directions at the same place. Strong motion records are available only for very few earthquakes. The informations are limited due to the fact that the whole seismic region can not be covered by the recording instruments as they are very costly. Therefore the aim is to utilise the available information for the design purpose. Since earthquake motion differs from place to place therefore the motion recorded at one place need to be modified to use at other place. The effect of accelerogram modification has already been studied for linear systems by various investigators and some important relations have been obtained. In the present thesis two types of accelerogram modification studies are carried out as stated below.

(1) As the earthquake records are generally available in three perpendicular directions and therefore the response canbe obtained only in these directions. But some times we need to calculate the response in any general direction. Here the modified accelerogram is obtained for any general horizontal direction and the effect of the direction is studied on the elastic response of the structure.

(2) In case of inelastic studies the effect of modifying the time base without altering the ordinates is studied on the inelastic displacement response of the structure. The elastic response for such modifications has been studied previously(14).

1.2 Objectives of the Study

The objects of the thesis may specifically be stated as follows :

1. To investigate the effect of the orientation of a structure with respect to two recorded accelerograms in mutually perpendicular directions on the elastic response of the structure.

2. To study the effect of the time base modification on the inelastic response of the structures.

To achive the above objectives the following work has been carried out. Koyna accelerograms recorded in longitudinal and transverse directions of the Koyna Dam are taken as the basis for all computations in the present study.

(i) The modified accelerogram is obtained for any direction ' Θ ' by vectorial addition of the ordinates of the two accelerograms where ' Θ ' is the angle from longitudinal component.

(ii) Acceleration, velocity and displacement response spectra and spectral intensity are computed for the recorded and the modified accelerogram and comparision is made between them.

(iii) In-elastic response of single degree systems having various yield acceleration values have been computed for the Koyna longitudinal component with the origional time base as well for the elongated time base by a factor 1.5

(iv) The variation of ductility ratio with natural period and yield level has been studied for the origional and modified accelerograms.

(v) The reduction factor have been worked out for a structure of given period and different ductility ratios.

(vi) The elastic and inelastic displacement response values have been compared with referance to ductility ratio and damping values.

$$\log_e a = \frac{1}{3} I - 0.5 \quad \ldots \quad (2.1)$$

Hershberger (19) studied 108 strong motion records of 60 earthquakes as united states during 1947 – 1954 and gave a relationship.

$$\log e \; a = \frac{3}{7} I - 0.9 \quad \ldots \quad (2.2)$$

All the above studies show that variation in ground accelerations for the same intansity is so great that such values are hardly of significance.

It was considered more appropriate to use 'magnitude' which is an instrumental measurement of the shock for relating with the ground acceleration.

Guttenberg and Richter(18) assume that intensity of ground motion is proportional to the cube root of the energy release. This energy is calculated from the relationship.

$$\log_{10} E = 9.4 + 2.14M - 0.054M^2 \quad .. \quad (2.3)$$

This above equation is now modified as

$$\log_{10} E = 11.4 + 1.5M \quad \ldots \quad (2.4)$$

Also it is assumed that ground motion intensity is inversely proportional to the square of the distance from epicentre. The ground motion distance relationship has been borne out from the results of blast recorded by Carder and Cloud (9) The relationship is as below

$$a = c(E)^{1/3} \frac{h}{D^2 + h^2} \quad \ldots \quad (2.4)$$

Review of Literature

2.1 General

Earthquake resistant design becomes essential in highly seismic areas espacially in case of tall and important structures. For computation of structural response in seismic regions, the maximum anticipated accelerations and the form of an accelerogram are required. As very small number of past earthquake records are available therefore it is necessary to take advantage of the data already collected and establish, relationships expressing accelerations as a function of magnitude, focal depth of anticipated earthqu-ke and distance of the site from the epicentre.

2.2 Intensity-Acceleration and Magnitude Acceleration Relationships

Two approaches are generally used for determining design coefficients for engineering structures in seismic zones. One is based on the 'Intensity' concept and the other on the energy criterion. The magnitude (Richter) of anearthquake is related with the energy released at the focus therefore in the latter the peak acceleration is derived from the magnitude of the shock.

Attempt has been made to relate ground accelerations, with the intensity asigned on the basis of personal feeling and judgement (17, 18, 19, 35) Guttenberg and Richter (18) are proposed a loggithmic relationship between maximum ground acceleration 'a' and intensity 'I' as follows:

where a = ground acceleration

E = energy released obtained from equation (2.3)

D = epicentral distance

h = focal depth

c = constt absorbing the effect of ground conditions.

Equation (2.4) would give exceedingly large accelerations for earthquakes of magnitude greater than 7, specially near the epicentre. Housner (20) believes that there seems to be an upper limit to the ground acceleration during earthquake however big the shock may be. The bigger is the magnitude of an earthquake the greater is the area with high intensity of motion and therefore highest intensity of ground motion near the epicentre does not greatly differ from that during moderate shocks. A value of 0.5 g has been suggested as an upper limit to the acceleration by Housner. This value is only rough estimate of expected acceleration.

During Koyna earthquake 1967 (Magnitude 6.7) the maximum acceleration recorded was 0.63g. Also in Assam shock of 1897 (Magnitude 8.5) throughing up of boulders from mountain slopes was an indication of acceleration to be of the order of 0.6 to 0.65 g. It is significant that maximum ground acceleration was same in both shocks but the extent of areas that suffered damage was widely different in the two cases.

Assuming 0.65 g as an upper limit to the epicentral acceleration Jai Krishna and Brijesh Chandra (31) have given the relationships for calculating the epicentral acceleration and acceleration at any other point, far distant from the epicentre.

Using the acceleration-magnitude relationship (30) the following relation is obtained

$$\frac{ao}{g} = \frac{2.925 \; \frac{10^{(M-5)}}{h}}{1 + 4.5 \; \frac{10^{(M-5)}}{h}} \not> 6.5 \quad \ldots \quad (2.5)$$

Regarding attenuation of acceleration it is postulated that shallow focus shocks die out faster where as the attenuation is much slower in deep focus shock. It is assumed that the attenuation is an exponential function of $(D/h)^{3/2}$. Expressing acceleration 'a' at any distance D,

$$a = ao \; e^{-\alpha (D/h)^{3/2}} \quad \ldots \quad (2.6)$$

where α = arbitrary constt. Parkfield earthquake of 1966 has offered acceleration values for more than one location, and therefore provides useful data for evaluating according to this α = 0.26 therefore

$$\frac{a}{g} = \frac{2.925 \; \frac{10^{(M-5)}}{h}}{1 + 4.5 \; \frac{10^{(M.5)}}{h}} \; e^{-0.26 \, (D/h)^{3/2}} \quad .. \quad (2.7)$$

Equation 2.7 expresses maximum ground accelerations at a distance 'D' from the epicentre with magnitude M.and focal depth h

The equation (2.7) is also available in the form of curves. The values of the attenuation factor α as determined by sliding and overturning of objects for Koyna and Broach area s are 0.1 and 0.4 respectively.

2.3 Effect of Various Parameters of Accelerogram on the Response of Structures

The important parameters of accelerogram which affects the response of the structure are

1. Peak acceleration
2. Frequency or period of wave.
3. Effective duration and total duration of record.

To study the affect of above parameters on the response of structure, a comparative study of Koyna and El-centro earthquakes was carried out by Jaikrishna and S.S. Saini (32).

	Koyna 1967	Elcentro 1940
Peak acceleration	0.63 g	0.33 g
Total duration	10 Sec	30 Sec
Magnitude	6.5	7.1
Epicentral distance-with in 2 milo		30 miles.

For the two earthquakes the velocity spectra were drawn and it was concluded that for very short period the response due to Koyna earthquake was more than that due to Elecntro but for longer periods the response due to Elcentro earthqu-ke was more than due to Koyna earthquake. The response spectra for the Koyna shock is depressed in the longer period range and thus exhibits a different pattern than obtained for Elcentro shock. Higher frequency components are present in the Koyna record than in Elcentro record.

The peak ground acceleration of Koyna earthquake is approximately twice that of Elcentro earthquake. Had the waveform of the two been of the same pattern, the response due to Koyna shock would have been twice that of due to Elcentro. However, the response due to Koyna is much lesser over a wide range of longer periods. Therefore peak acceleration alone does not represent the exciting potential of an earthquake shock. The frequencies associated with the acceleration pulses are as important as the peak acceleration. In fact the response is an integrated effect over the effective duration of strong ground motion.

Effective Duration

An Earthquake results in the highest spectral response during the few seconds of the record having highest peaks. The rest of record before and after these peaks does not effect the maximum response. The duration of this part of the record is thus termed as effective duration.

Effect of Epicentral Distance on the Response

The higher frequency components are attenuated very quickly. Therefore as the epicentral distance increases only the lower frequency components remains, the structures having larger period will be affected much more than the structures of low periods.

2.4 Elastic Response of Structures

(The elastic response of the structures can be very well obtained with the help of the spectum curves. For the design purpose Housner's average spectra may be used by multiplying a suitable multiplying factor.

2.5 Average Spectra (24)

For the purpose of obtaining response parameter Sv a standard spectra must be defined in such a way that the excitation potential 'Q' of an earthquake may be used to obtain the multiplying factor. Also the standard spectra must take care of the fact that in different shocks the peaks will have random distribution with respect to period parameter Housner's average spectra satisfy these requirements. These are obtained by averaging the spectrum values of the 8 components of the four strong ground motion records (Elcentro 1934, Elcentro 1940, Olympia 1949 and Thaft 1952) and turnout is a neat smooth shapes. Multiplying factors for these shocks have been asigned as 1.9, 2.7, 1.9 and 1.6 respectively.

2.6 Determination of Multiplying Factor (13)

A method to workout this factor was developed by Jaikrishna (30) using the magnitude, distance-acceleration relationships. Multiplying factor could then be calculated in proportion to the peak acceleration at that site. The response of the structures is not only affected by the peak acceleration but also affected by the frequency of wave form. Therefore question of multiplying factor should be viewed with respect to response spectrum rather than the peak acceleration alone. In fact the excitation potential of an earthquake shock at a site would be better represented by the quantity spectral intensity(24) which gives a qualitative idea regarding the structural response of structures having periods varying from 0.1 sec to 0.25 sec.

Mathematically

$$S.I. = \int_{0.1}^{0.25} S_v\,(T,\xi)\,dT$$

For the purpose of comparing the potential of various shocks it is desirable that only undamped spectral intensities should be workout.

Problem of determination of multiplying factor is divided in to the following steeps

1. Determination of undamped spectral intensity of an earthquake with peak ground acceleration as unity. This will be referred to as normalised spectral intensity $(SIo)_n$ and epicentral distance D is sought.

2. Determination of peak ground acceleration 'a' expected at sight.

3. Exciting potential of an earthquake 'Q' could then be workout at any place from the following equation

$$'Q' = a\,(SI_o)_n$$

4. 'Q' thus calculated may be interpreted as a multiplying factor for the standard spectra.

$$\text{Multiplying factor} \quad F = \frac{'Q' \times 2.7}{8.35}$$

For calculating the quantity 'Q', a and $(SI_o)_n$ are required. These may approximately be computed as follow

a) $(SI_o)_n = 0.425D + 5.73$ .. (2.8)

b) $$a/g = \frac{2.925 \dfrac{10^{(M-5)}}{h}}{1+4.5 \times \dfrac{10^{(M-5)}}{h}} e^{-0.26(D/h)^{3/2}} \quad ..(2.9)$$

By the above procedure, the effective structural response spectra in the elastic range can be worked out without actually having the recorded accelerogram. The parameters to be assumed are the magnitude M, the depth of focus h and the epicentral distance D. For determining these a statistical approach based on past earthquake history of the area, location of active faults and short term micro-tremor study has to be used and above all, trained judgement based on study of past earthquakes and their corelation with seismo tectonics will be most essential.

2.7 Concept of Reduction Factor (21)

For very high seismic force the elastic design of the structures becomes uneconomical and plastic deformations are

permitted to a cirtain extent. The plastic design becomes very much economical from the fact that for inelastic range the hysterisis loop enclose a larger area and therefore the energy dissipation is better in this case. Ultimately our aim is to dissipate the energy fed into the structure due to earthquake and therefore plastic design is recommended. Though the plastic design is desired but at the same time it is very cumbersome and time consuming to design the structure for plastic range. There. fore the structure is designed elastically but for a cirtain reduced seismic force and this factor by which we reduce our seismic force for design is known as the reduction factor
The reduction factor depends upon the ductility ratio i.e. upto which extent we want to go in plastic range. The ductility is the ratio of maximum deflection to the yield deflection.

2.8 Reserve Energy Technique (5,6)

An alternative approach to the determination of effective seismic coefficient is to consider the energy absorption during deformations for balancing the dynamic energy input to the structure. Such an energy balance may be assumed as a necessary requirement for stability of the structure at the instant of time when the structure has the maximum velocity spectrum value Sv and W the weight of the structure, the maximum energy in put will be = $\frac{WS_v^2}{2g}$. The structure must be capable of balancing this energy by partly storing as elasti strain energy, partly dissipating it by damping and partly absorbing by plastic deformations at that instant of time. Whe the energy absorbed by the structure equals the energy input for a perticular deflection Δm then the reconciliation of energy takes place. This approach is more suitable for multi-storeyed buildings than the more sophisticated approach of inelastic analysis because of many secondary elements existing on the buildings the effect of which can not be included in the sophisticated analysis but could easily be considered in the energy approach.

2.9 Significant Results of Previous Studies

1. Use of average spectra can be made use for the elastic design of structure, which can take care of frequently occurring earthquakes in the life time of the structure.

2. For larger shocks the strength so provided will be adequate if the structure has ductile deformation capacity without decrease in strength.

CHAPTER - 3

Elastic Response for Recorded & Modified Ground Motions

3.1 General

As it is not necessary that all the structures may be located in the direction of the recorded accelerogram, in order to analyse the structures which are situated in any general direction the nacessity of modifying the accelerograms in that direction is felt. Here an attempt is made to know the response spectra in any general direction. The Koyna earthquake accelerograms are used for this purpose.

With the help of the two recorded accelerogram in the two mutually perpendicular directions, accelerogram in any general direction 'θ' is obtained by the vector addition, where 'θ' is the angle with the koyna longitudinal component. For this purpose the two accelerograms were scanned simultaneously. Every peak of each accelerogram was considered one after the other. For each peak of one, the corresponding acceleration value of the other was determined by linear interpolation and the two were then vectorially combined to gives the peak in the accelerogram at angle 'θ'. Thus number of peaks in the accelerograms of intermediate angles is very much increased. A computer program for accelerogram modification was prepared and is given in Apendix II. Modified accelerograms are obtained here for $\theta = \pi/6$, $\theta = \pi/4$ and $\theta = \pi/3$ and are shown in Figure 4.1 c, d and e.

Elastic response spectra are obtained for recorded and modified Koyna accelerograms. For comparision the spectral intensities for various dampings are calculated for all recorded and modified Koyna accelerograms using Simpson's Rule. The computed spectral intensities are compared in Table 3.1.

3.2 Elastic Response of Single Degree Freedom System

Equation of Motion

Considering a single degree freedom system consisting of a single concentrated mass 'm' a linear spring constant 'k' and a viscously damped dashpot having a damping force proportional to the relative velocity, the equation of motion is given by

$$m\ddot{x} + 2p\xi\dot{x} + p^2x = -m\ddot{y}(t) \qquad \ldots \qquad (3.1)$$

where x = displacement of mass relative to base

ξ = proportion of critical damping

p = undamped natural frequency of system $=\sqrt{k/m}$

$\ddot{y}(t)$= acceleration of ground, supporting the system.

The elastic response of a system can be obtained by solving equation 3.1. The maximum response of a system such as maximum value of relative displacement, relative velocity and absolute acceleration are also termed as spectral response i.e. displacement response spectra,velocity response spectra=and acceleration response specta. If the ground motion acceleration record is available, the determination of spectral response involves the evaluation of an integral for a series of values of periods and damping. Since the ground motion is very much complicated, no explicit solution is possible Mechanical and Electrical analogs have been used to solve this problem. The use of digital computer for determination of spectral response has become more popular. The response can be obtained by solving the differential equation using numerical techniques such as Rungekutta method (28).

3.3 Parameters of Study

In computing the elastic response spectra for the various angles from zero to $\pi/2$ the following parameters have been used.

Earthquake Motions

Two recorded Koyna longitudinal and transverse components with the duration of 7.15 seconds are used for this study. These accelerograms are shown in Figure 3.1 b and f.

Periods

0.1 sec to 0.3 sec at 0.02 sec intervals

0.3 sec to 1.1 sec at 0.05 sec intervals

1.1 sec to 1.5 sec at 0.1 sec intervals

1.5 sec to 2.5 sec at 0.25 sec intervals

2.5 sec to 3.5 sec at 0.5 sec intervals

Damping Factors

ξ = 0.0, 0.02, 0.05, 0.1, 0.2.

3.4 Response Quantities

The response quanties calculated are the relative displacement, relative velocity, absolute acceleration and spectral intensity. The displacement response spectra, velocity response spectra and acceleration response spectra are plotted for all koyna recorded and modified components. For the sake of the comparision of the damaging potential in various directions, the spectral intensities of koyna modified and recorded components are calculated for ξ = 0.0, 0.02 and 0.05 and are given in Table 3.1.

Spectral Intensity(24)

It is the area under the velocity response curve between the period of 0.1 sec to 2.5 sec for a perticular damping. Mathematically.

$$S.I. = \int_{0.1}^{2.5} S_v \ (T, \xi) \ dT.$$

3.5 Results of Analysis

(a) Displacement Response Spectrum

From displacement spectrum curves, Figure 3.2 to 3.6 it is seen that for a perticular value of damping the displacement response remains almost same for all values of θ

for periods upto 1.5 seconds where as the response greatly differs for periods more than 1.5 seconds. For longer periods the response is maximum for longitudinal component ($\theta = 0$) and is minimum for transverse component ($\theta = \pi/2$) The response for other values of θ varies in between and decreases as the angle 'θ' increases. It is also seen that as the damping increases response decreases.

(b) Velocity Response Spectrum

Velocity spectrum curves from Figures 3.7 to 3.11 for various values of 'θ' show that velocity response decreases as 'θ' increases and is maximum for $\theta =$ 0 and minimum for $\theta = \pi/2$ for wide range of periods.

Spectral intensities are calculated for all values of and for damping factors of $\xi =$ 0.0, 0.02, 0.05 and are plotted against angle θ. Figure 3.12 If is seen that spectral intensity decreases as the angle 'θ' increases. It is maximum for $\theta =$ 0 and minimum for $\theta = \pi/2$. The rate of decrease of spectral intensity increases with 'θ' up to $\theta = \pi/4$ and after that this rate decreases.

(c) Acceleration Response Spectra

From figure 3.13 to 3.17 it is seen that the acceleration response varies very slightly with the variation of For upto periods of 1.5 second the value can be taken almost same, but for periods greater than 1.5 sec. the curves are distinct and response is maximum for $\theta =$ 0 and minimum for $\theta = \pi/2$.

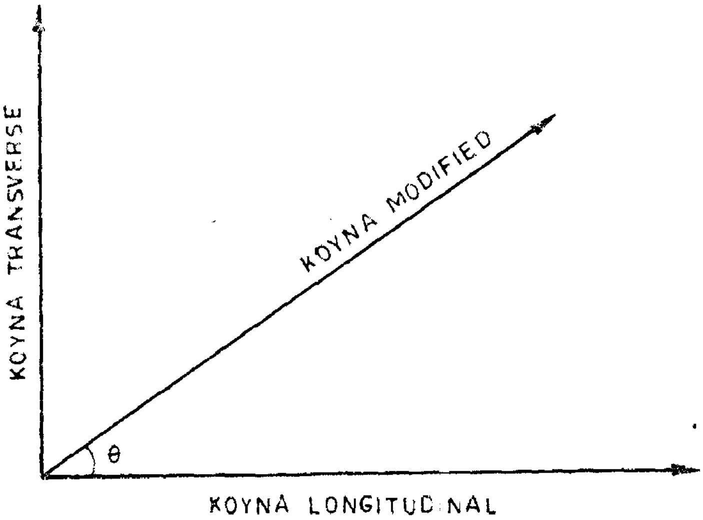
3.6 Conclusion

Response spectral quantities are not much changed for all values of 'θ' for a period range upto 1.5 seconds. But for periods longer than this, the values do differ and are maximum for longitudinal component and minimum for transverse component. For intermediate directions, the response values lie in between. The spectral intensities also decrease from 0 to $\pi/2$.

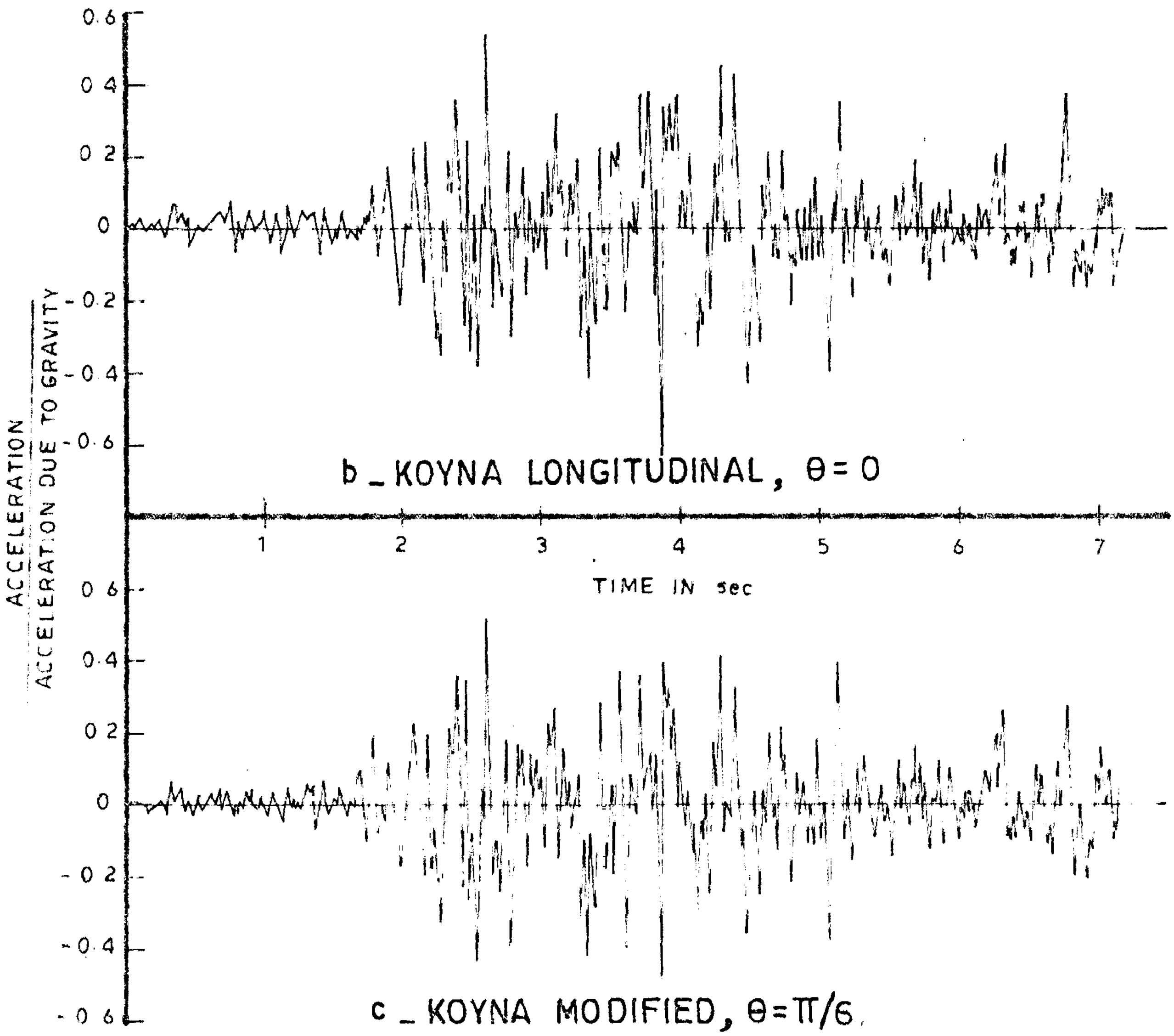
Table 3.1

Spectral Intensities for various modified Koyna Earthquakes

S.No.	Damping factor	Spectral Intensity				
		$\theta = 0$	$\theta=\pi/6$	$\theta=\pi/4$	$\theta=\pi/3$	$\theta=\pi/2$
1.	0.0	1.385726	1.259342	1.131184	1.010053	0.872226
2.	0.02	1.144129	1.013844	0.903480	0.795817	0.718544
3.	0.05	0.981746	0.863506	0.764394	0.689003	0.627893



a _ KOYNA ACCELEROGRAM FOR ANY ANGLE, θ



b _ KOYNA LONGITUDINAL, θ = 0

c _ KOYNA MODIFIED, θ = π/6

FIG. 3.1 _ ACCELEROGRAM FOR KOYNA EARTHQUAKE DEC. 11, 1967 FOR VARIOUS ANGLES, θ

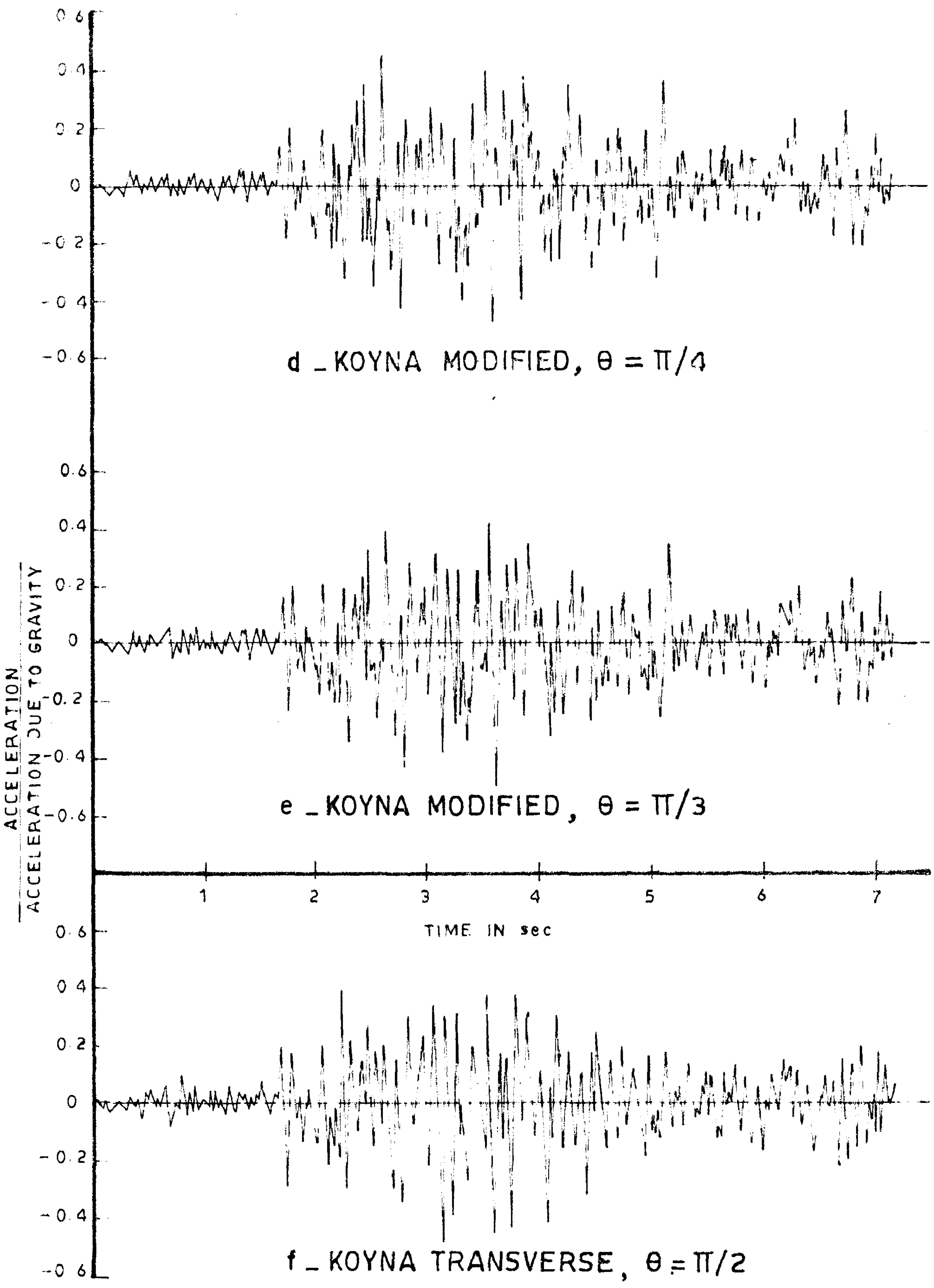


FIG.3.1 _ ACCELEROGRAM FOR KOYNA EARTHQUAKE OF DEC.11,1967 FOR VARIOUS ANGLES, θ

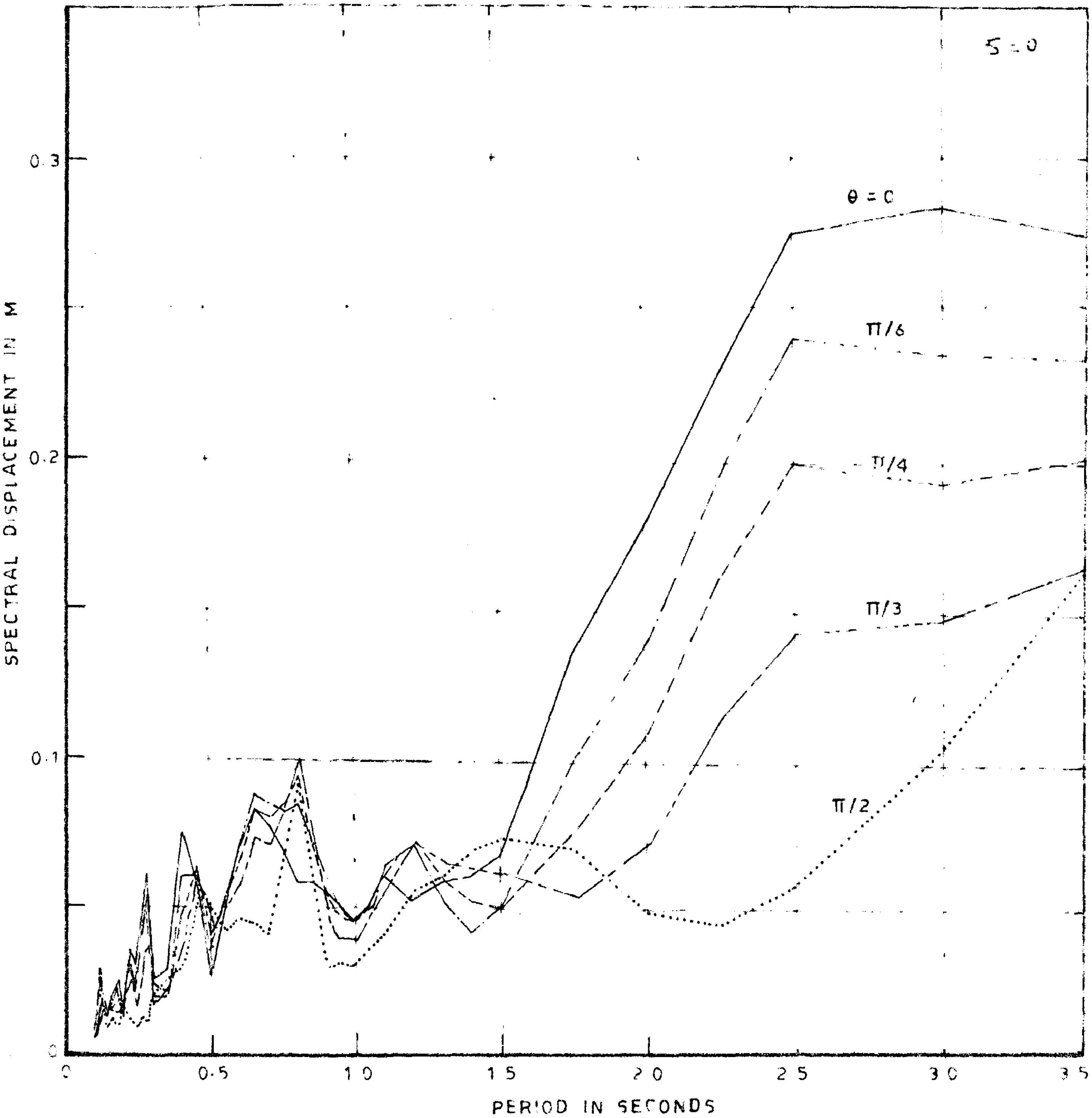


FIG. 3.2 _DISPLACEMENT SPECTRA OF MODIFIED KOYNA EARTHQUAKES

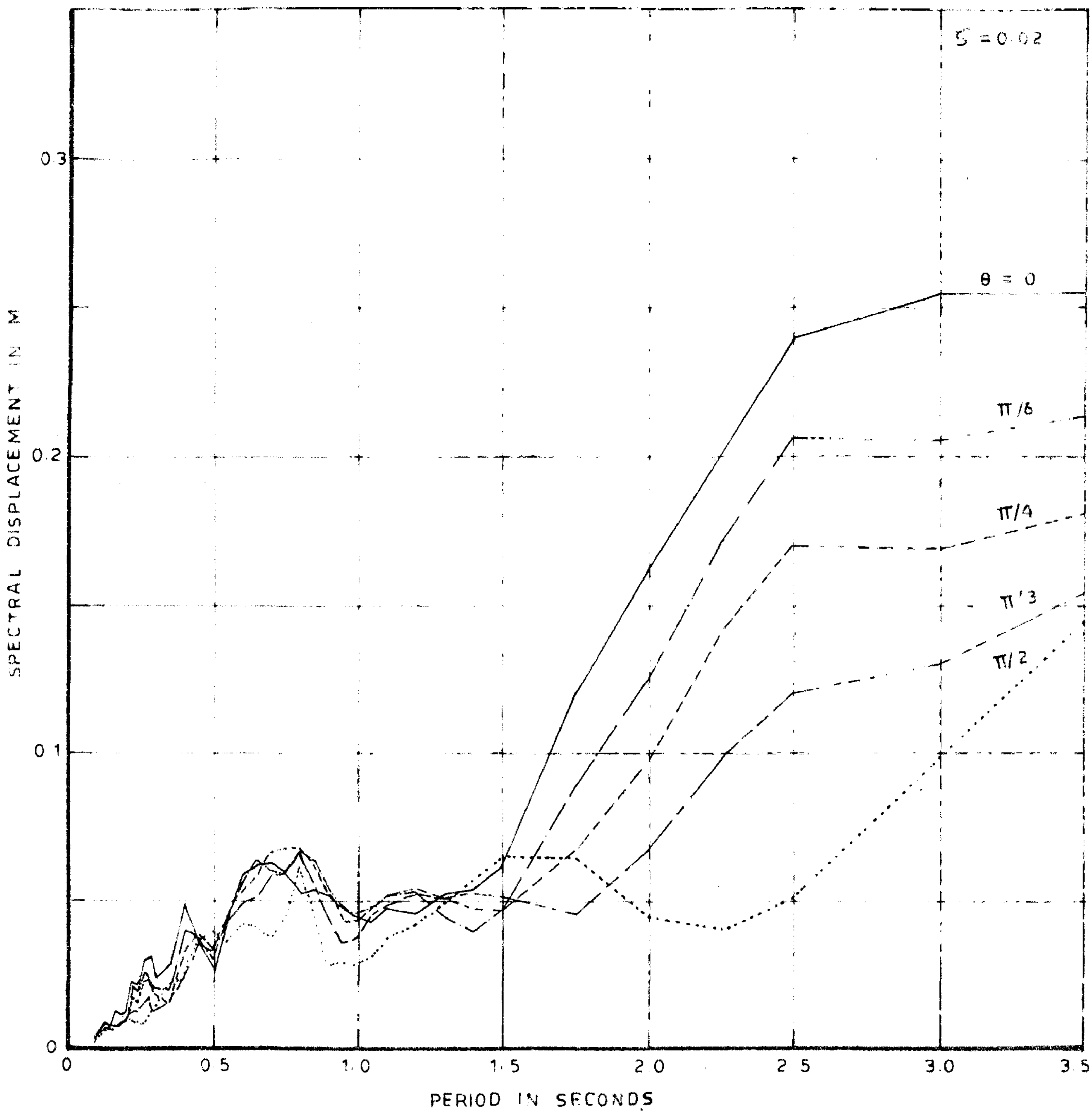


FIG.3.3 _DISPLACEMENT SPECTRA OF MODIFIED KOYNA EARTHQUAKES

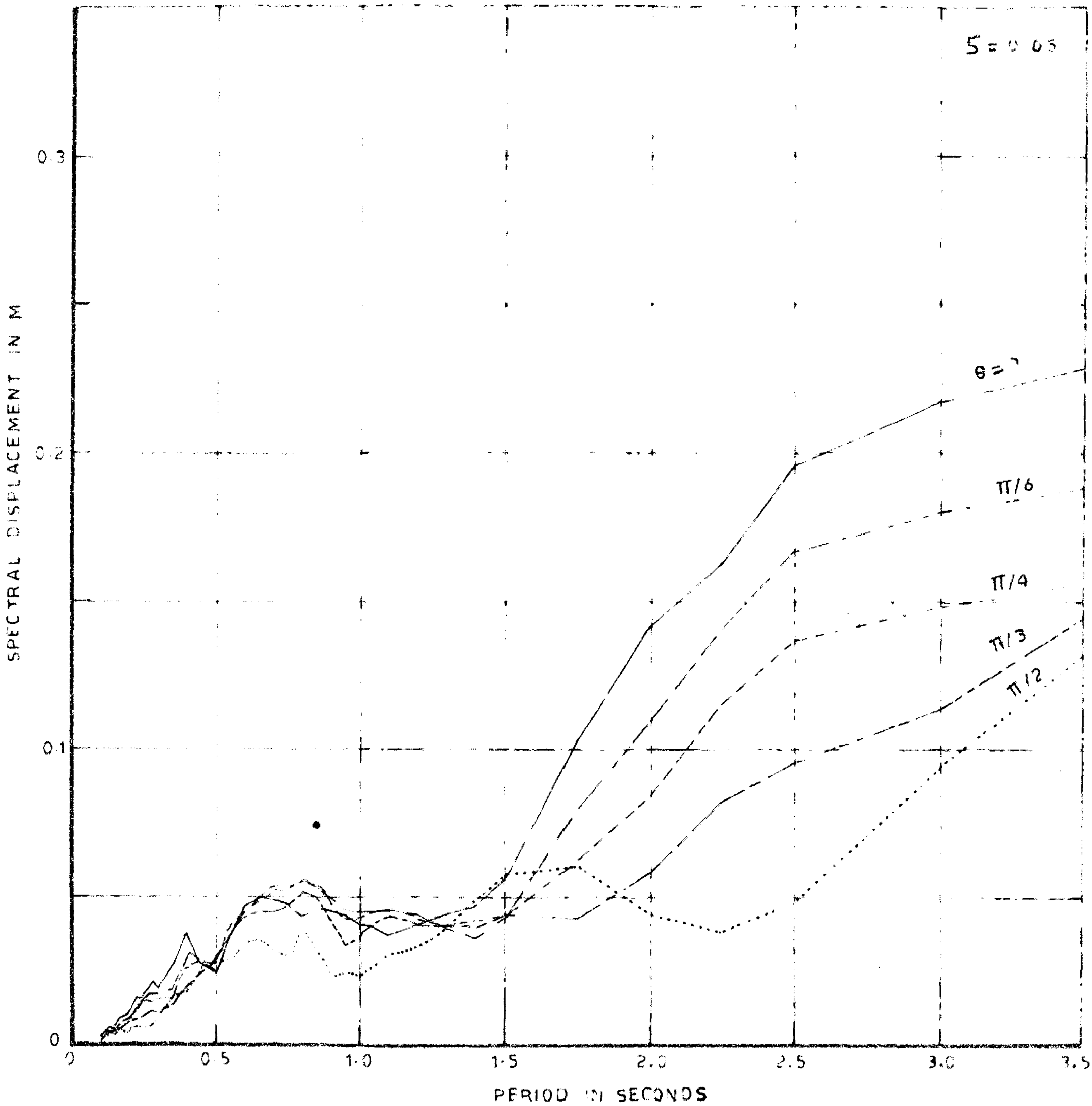


FIG.3.4 _DISPLACEMENT SPECTRA OF MODIFIED KOYNA EARTHQUAKES

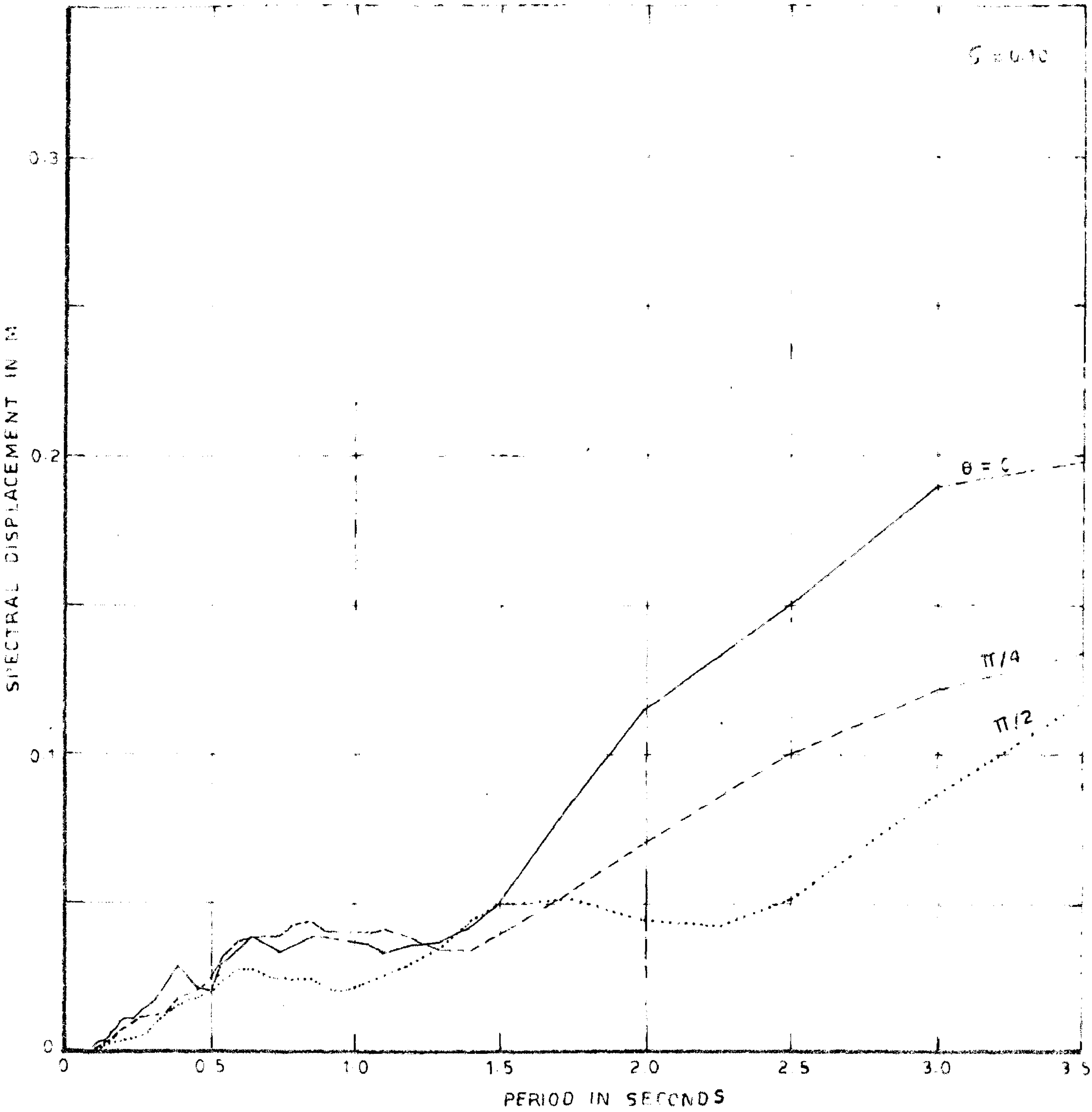


FIG.3.5 _DISPLACEMENT SPECTRA OF MODIFIED KOYNA EARTHQUAKES

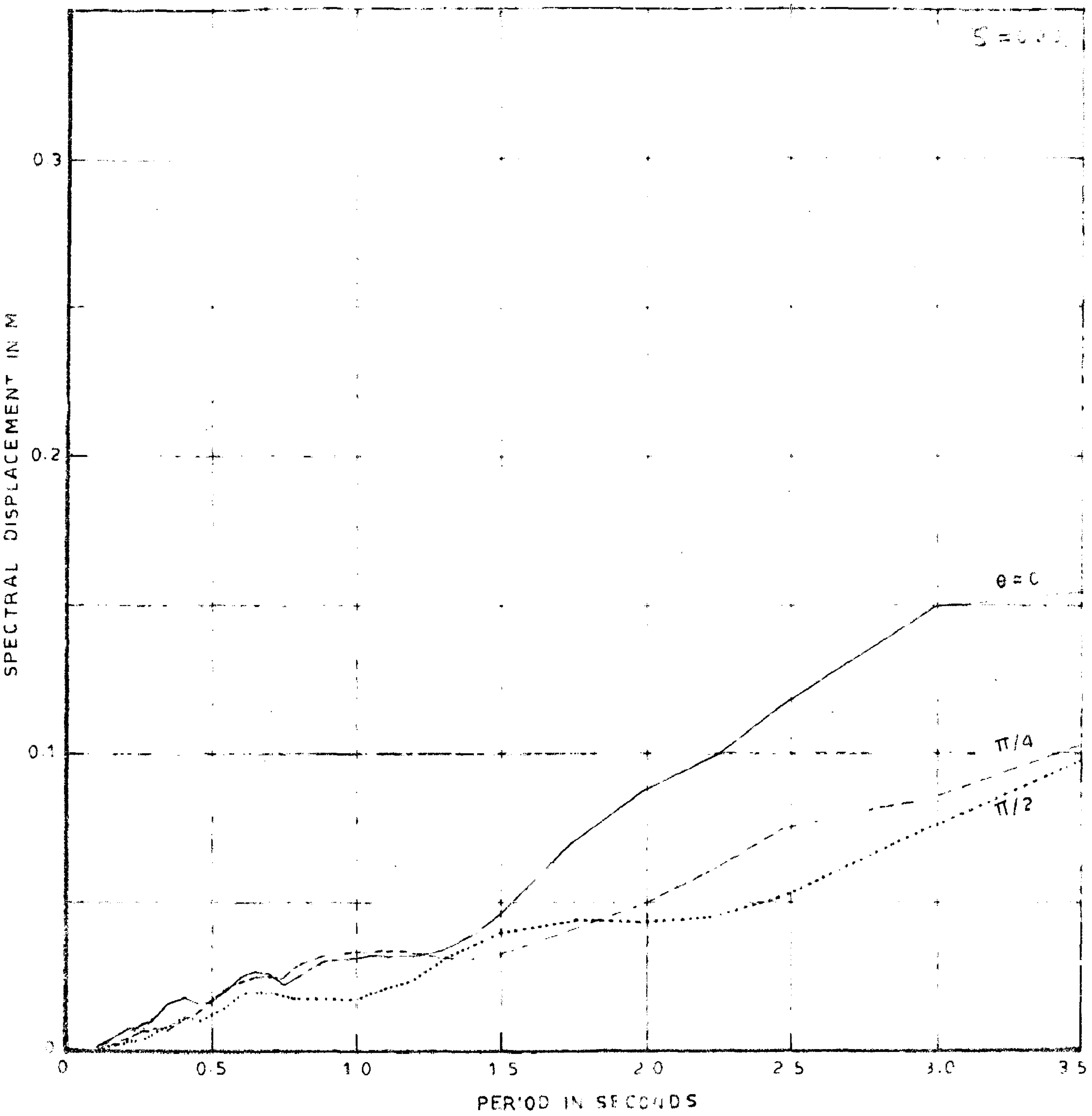


FIG. 3.6 _DISPLACEMENT SPECTRA OF MODIFIED KOYNA EARTHQUAKES

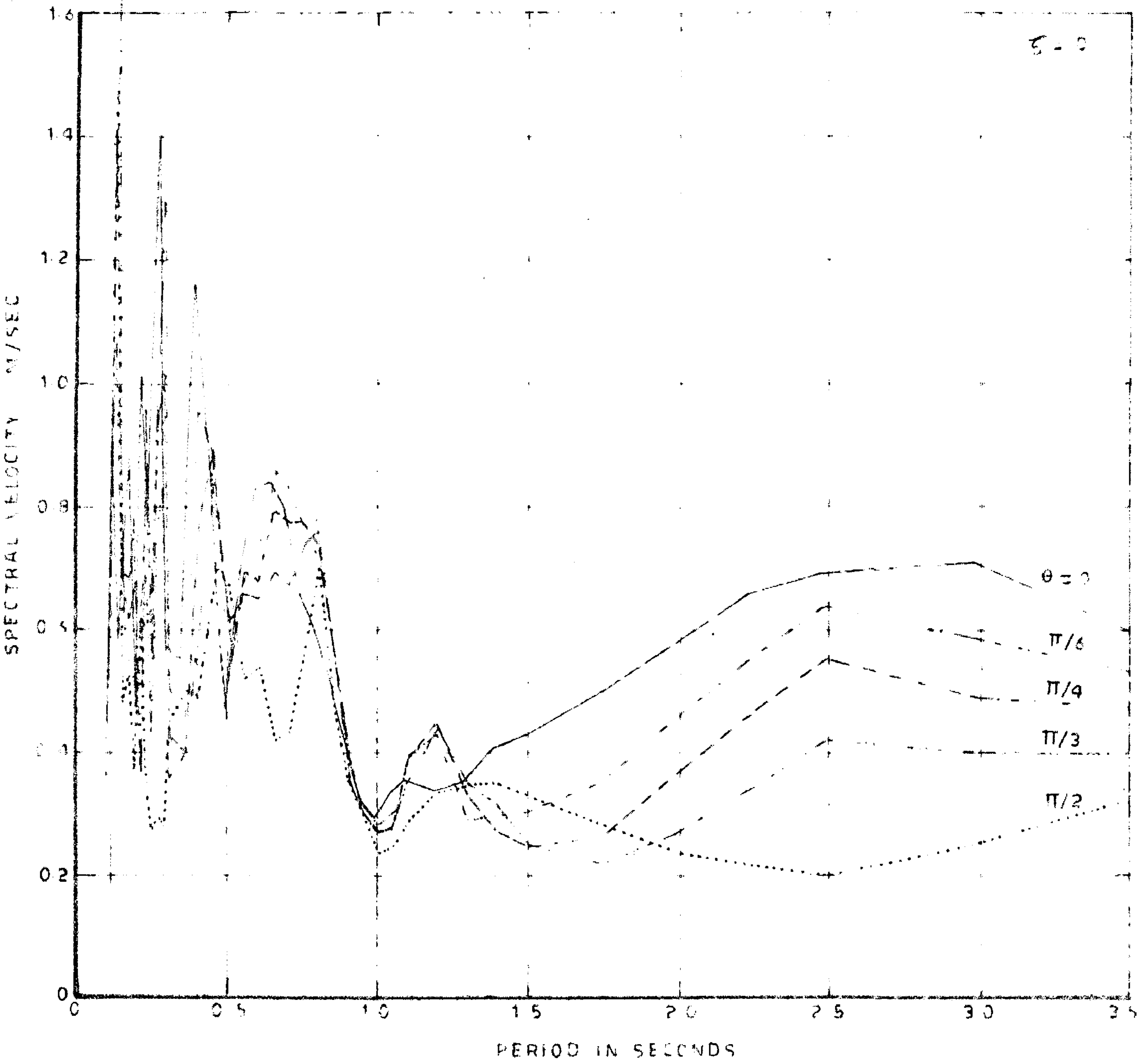


FIG.3.7 _ VELOCITY SPECTRA OF MODIFIED KOYNA EARTHQUAKES

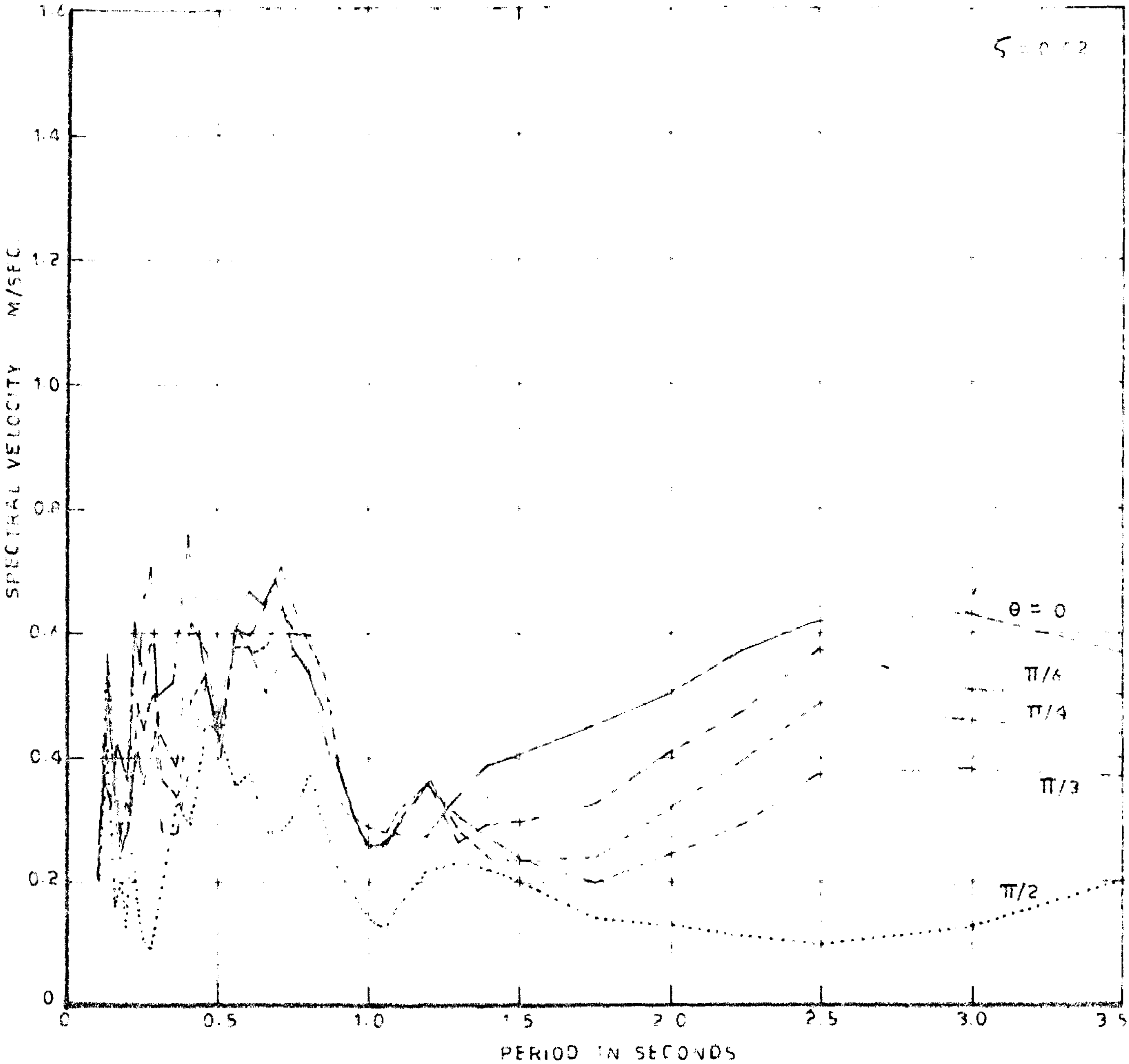


FIG.3.8_VELOCITY SPECTRA OF MODIFIED KOYNA EARTHQUAKES

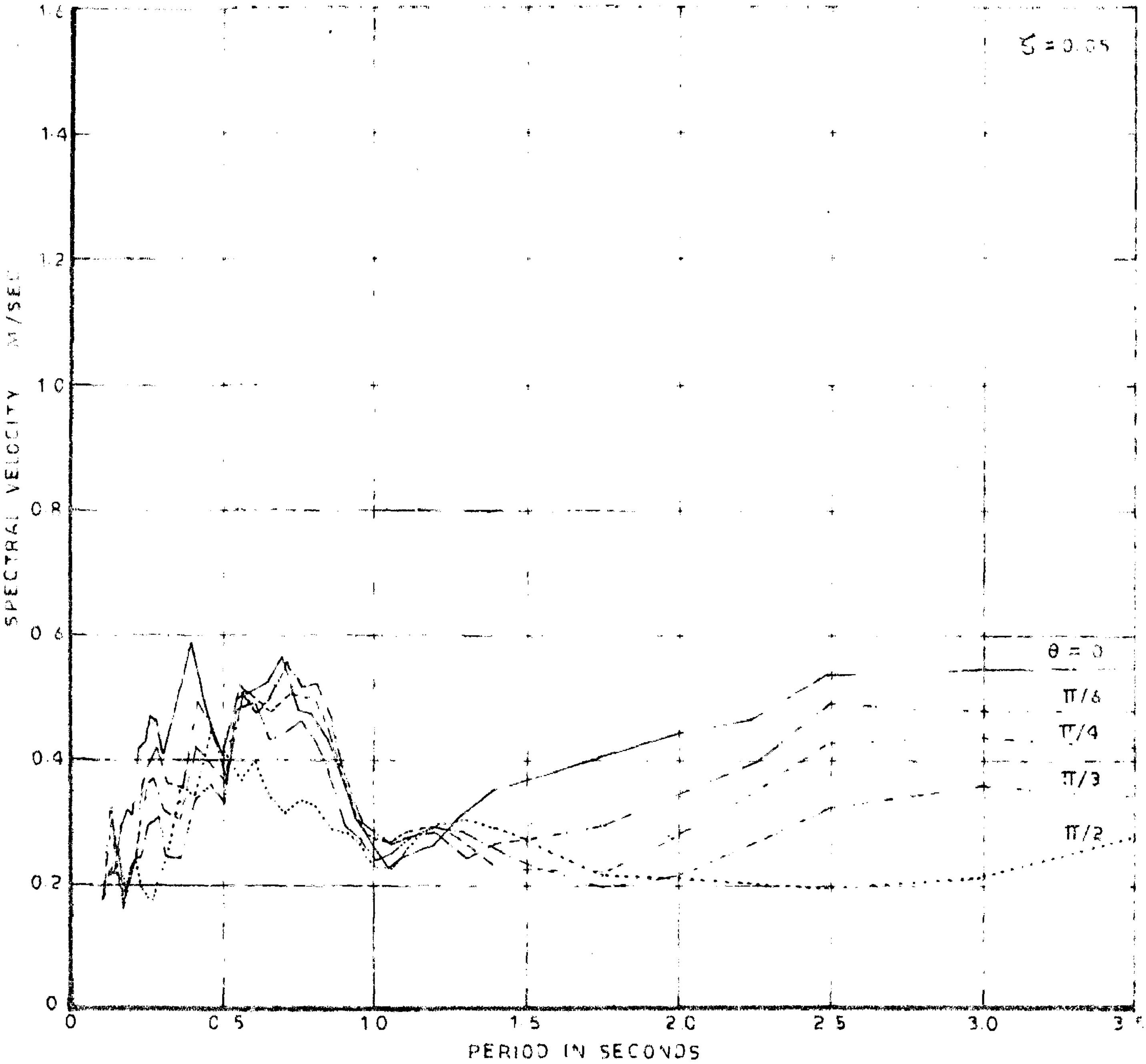


FIG.3.9 _ VELOCITY SPECTRA OF MODIFIED KOYNA EARTHQUAKES

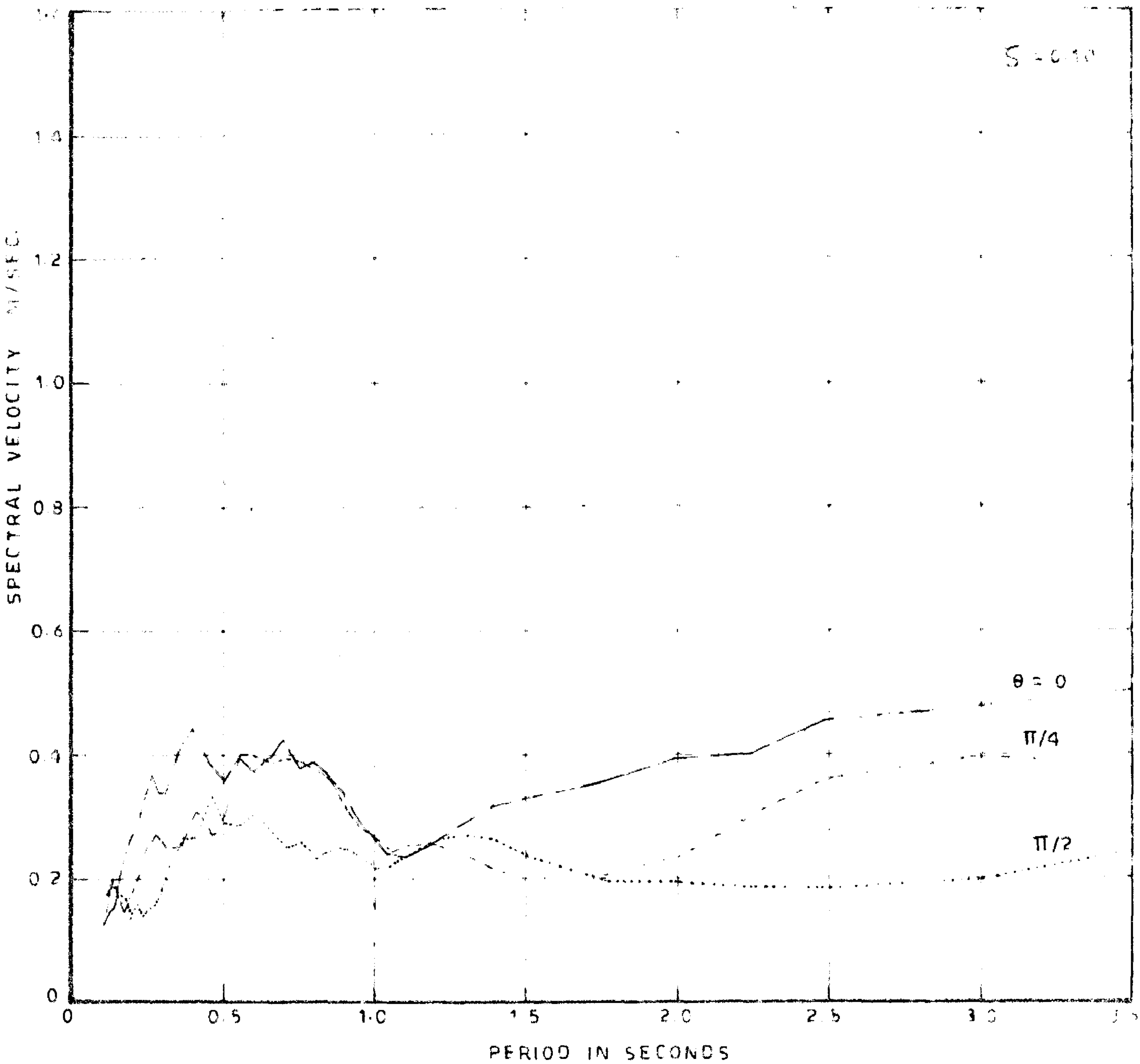


FIG.3.10_VELOCITY SPECTRA OF MODIFIED KOYNA EARTHQUAKES

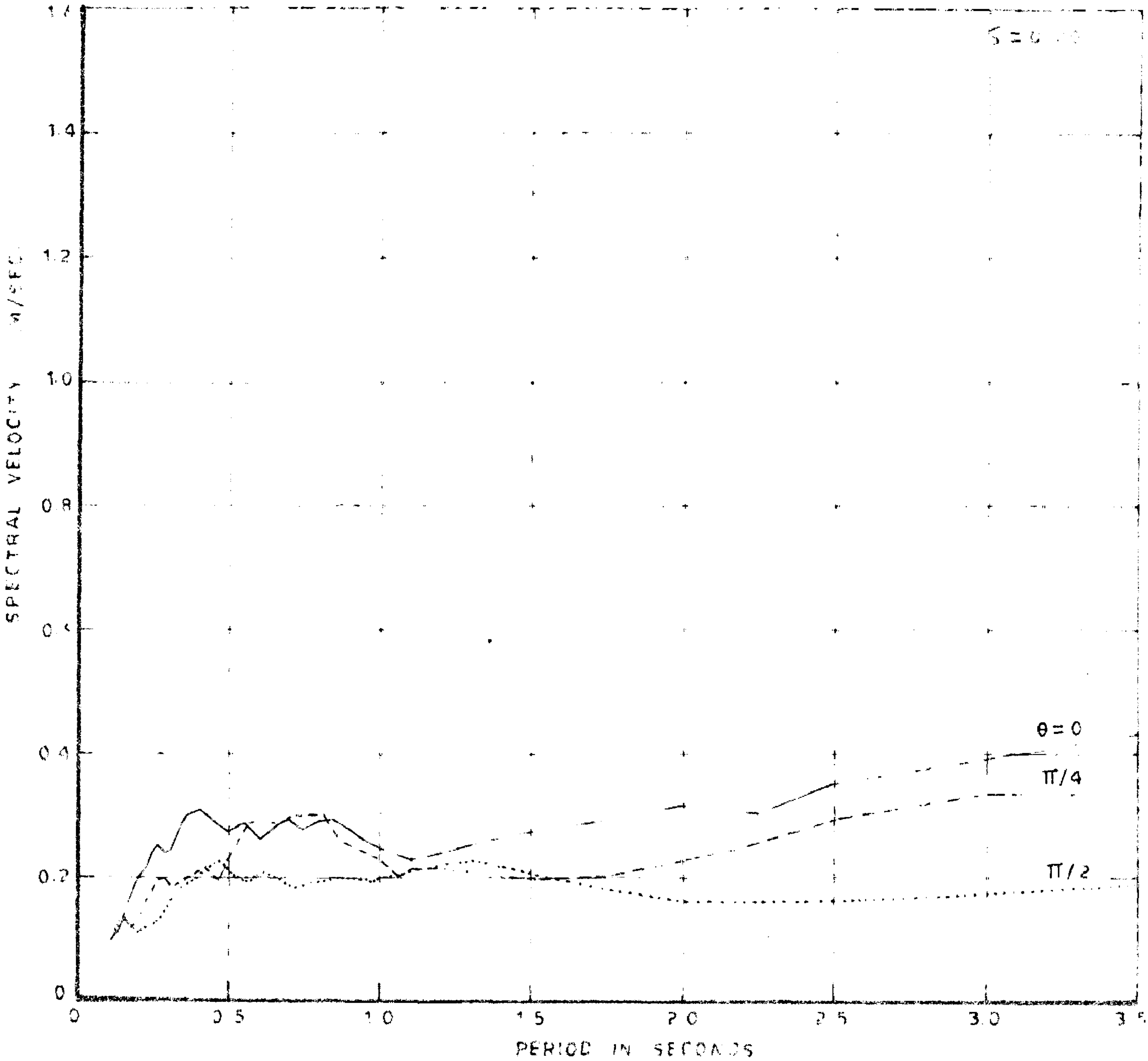


FIG.3.11_VELOCITY SPECTRA OF MODIFIED KOYNA EARTHQUAKES

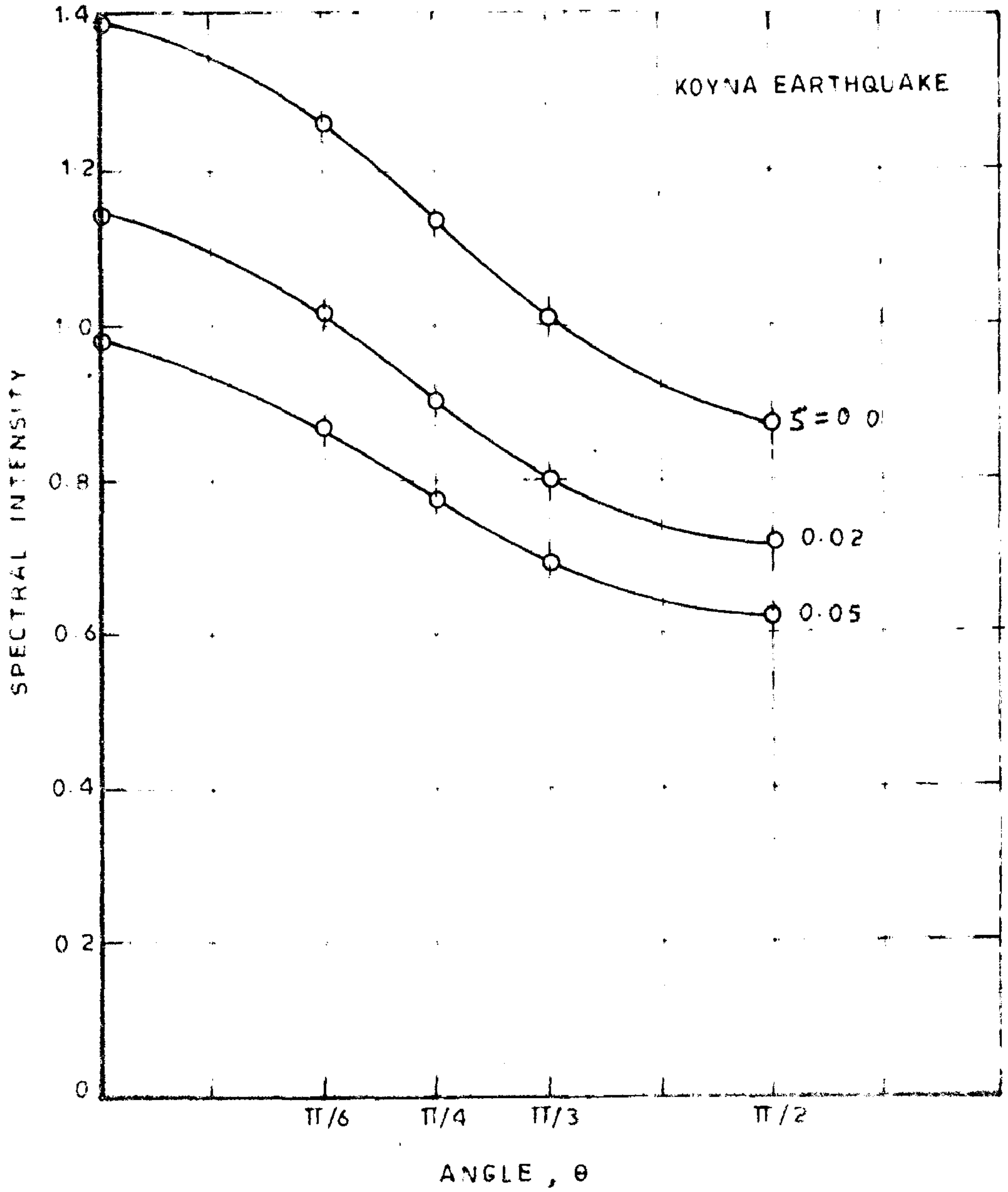


FIG. 3.12 _ SPECTRAL INTENSITY VS ANGLE, θ

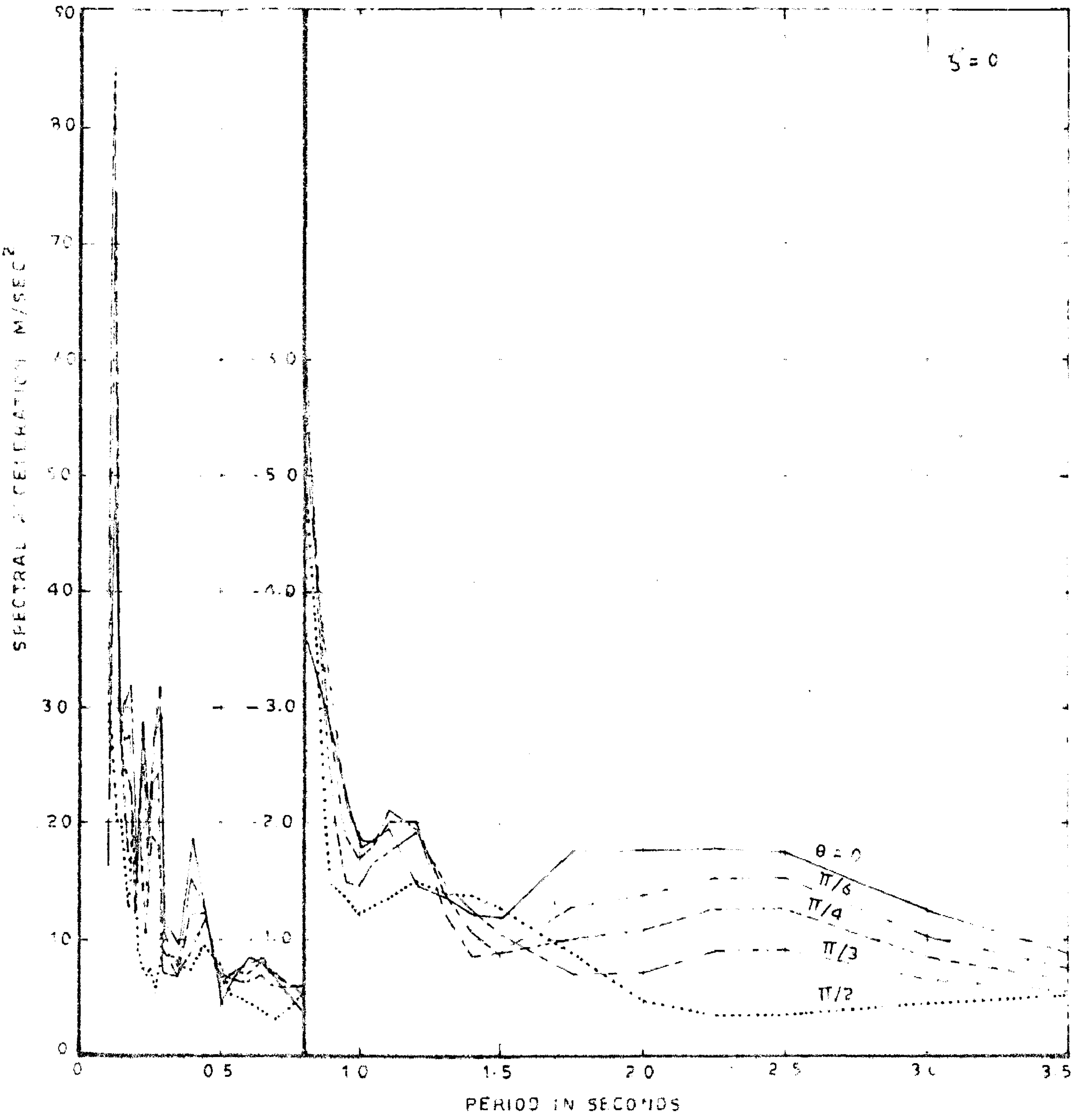


FIG.?13_ ACCELERATION SPECTRA OF MODIFIED KOYNA EARTHQUAKES

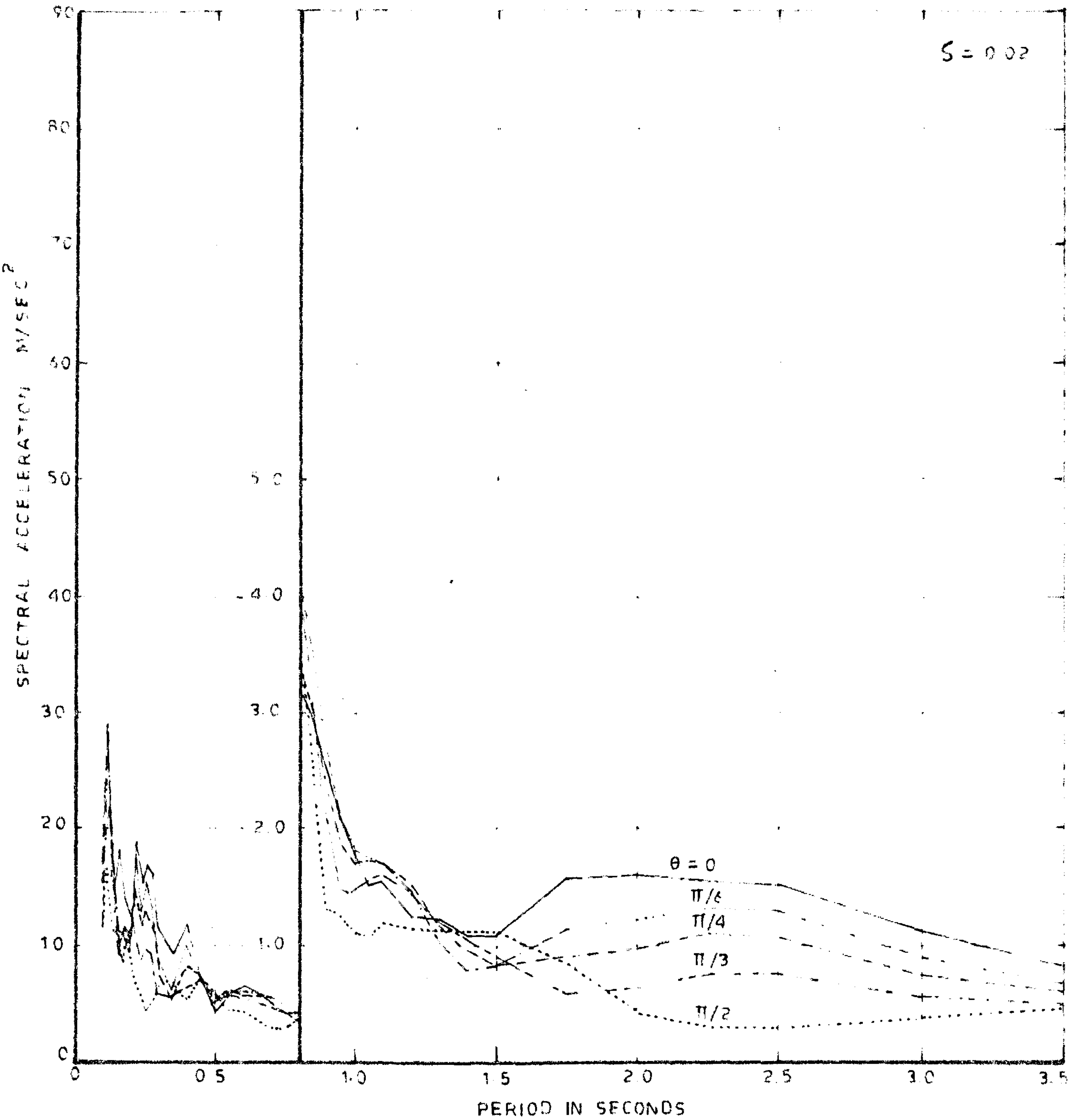


FIG.3.14_ ACCELERATION SPECTRA OF MODIFIED KOYNA EARTHQUAKES

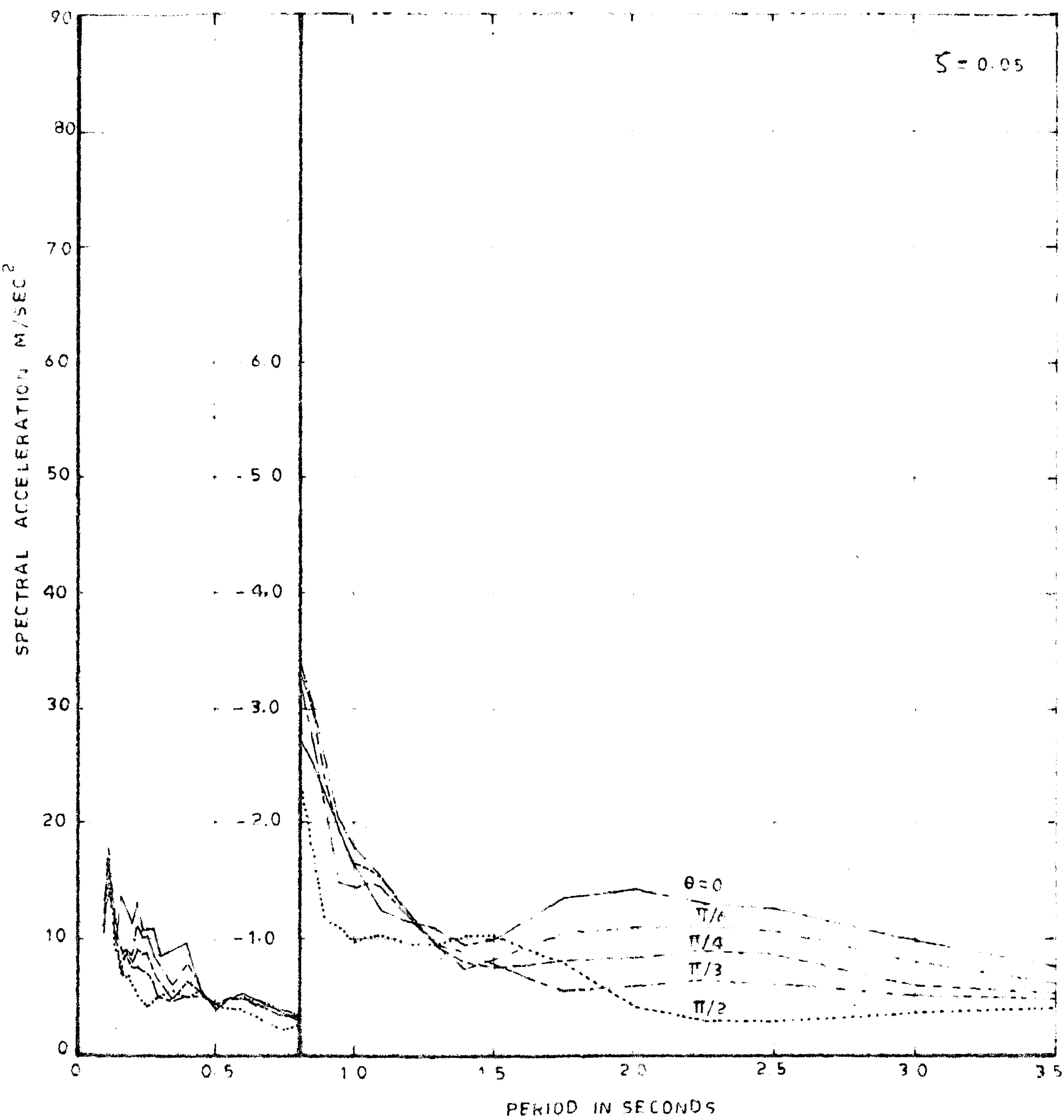


FIG.3.15_ ACCELERATION SPECTRA OF MODIFIED KOYNA EARTHQUAKES

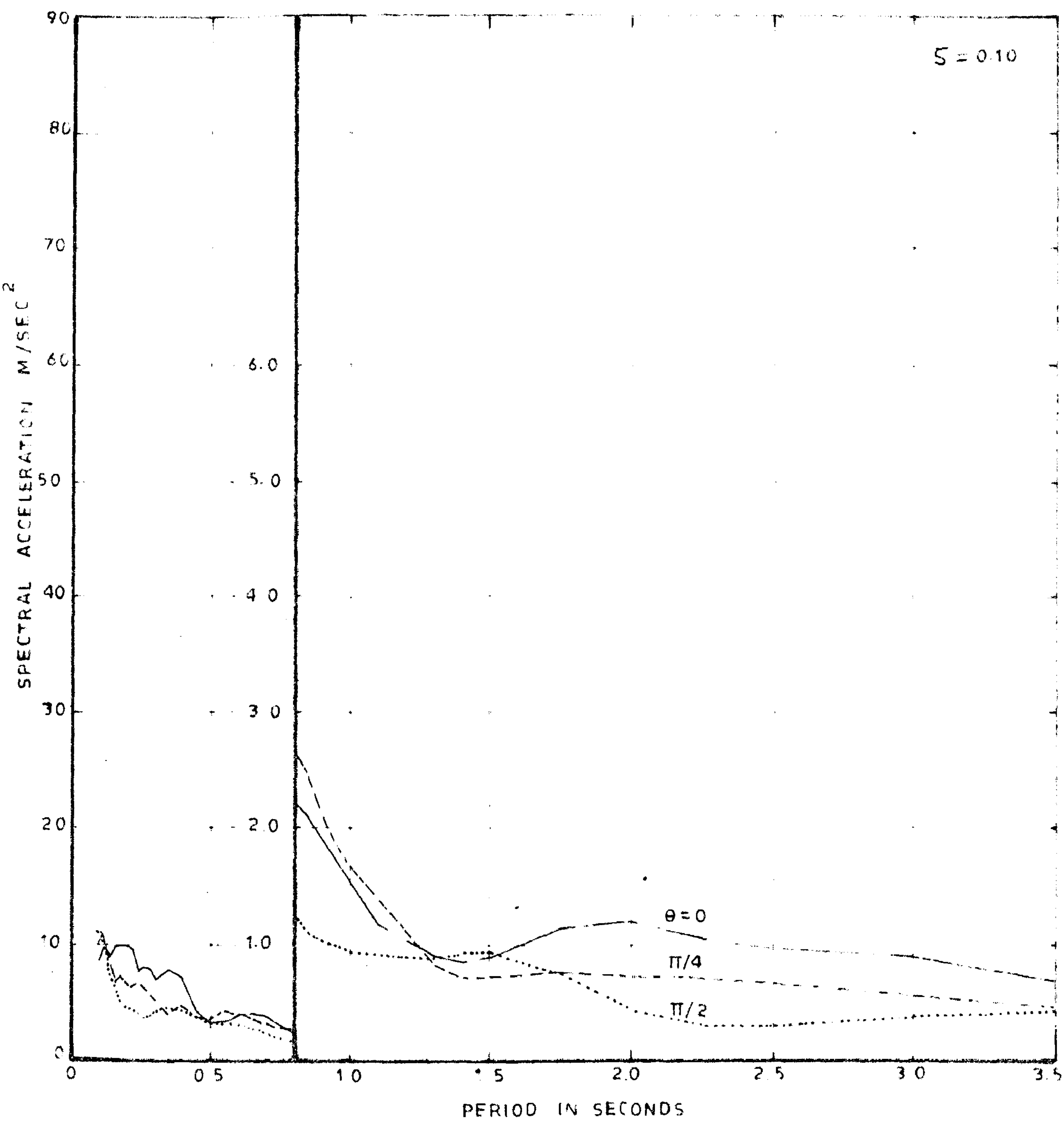


FIG.3.16_ACCELERATION SPECTRA OF MODIFIED KOYNA EARTHQUAKES

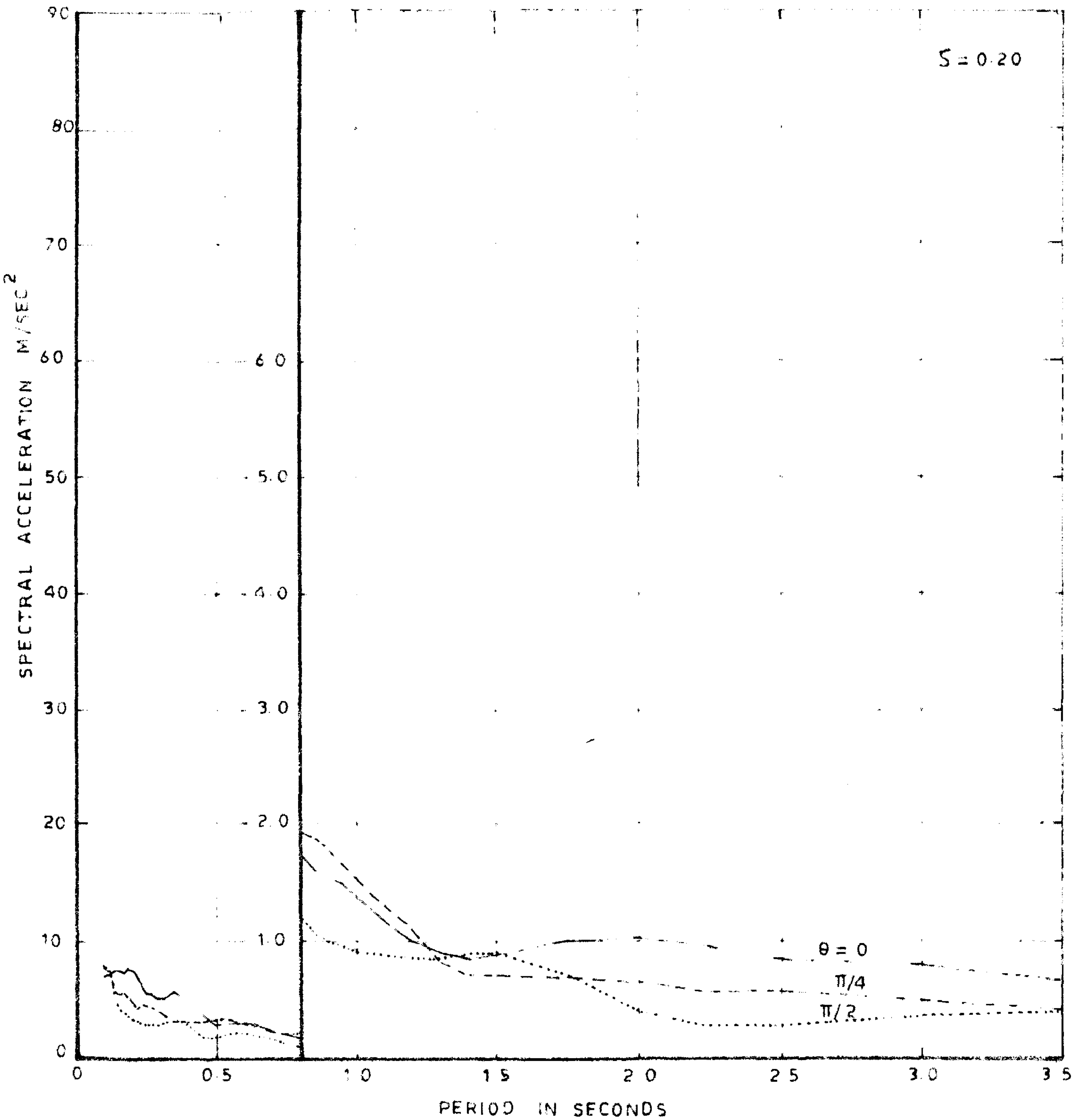


FIG.3.17 ACCELERATION SPECTRA OF MODIFIED KOYNA EARTHQUAKES

Dynamic Response of Inelastic Structures

4.1 General

To achive the economy in design some plastic deformations are permitted during large earthquake shocks. To under stand the behaviour of structures in the post elastic range it is necessary to solve the governing nonlinear defferential equations of motion throughout the history of ground motion. The nonlinearity primarily arises because of non linear force-deflection characteristics of restoring elements of structural system. The general nonlinear force-deflection curve suggested by Jennings (29) explains the actual restoring force characteristics of most of the structures. Elastoplastic force-deflection characteristic is one extremum of general nonlinear curve.

As distance from epicentre increases the higher frequency component of accelerogram dieout and the low frequency components predominate. To study the effect of frequency content of accelerogram on the inelastic response, the time base of the accelerogram is modified. Here for the present study the Koyna longitudinal component is choosen and it is modified by multiplying the time base by a factor $\lambda = 1.5$, which will be treated as modified accelerogram through out the inelastic analysis discussion.

4.2 Effect of Time Base Modification on Elastic Response (14)

The effect of time base modification in the elastic range was studied by Brijesh Chandra and A.R.Chandrasekaran.

Equation of motion for single degree freedom system, elastic response is given as follow :

$$m \frac{d^2x}{dt^2} + c \frac{dx}{dt} + kx = - m \frac{d^2y}{dt^2} \quad .. \quad (4.1)$$

If $\tau = \lambda t$ then equation (4.1) will be modified as

$$m \lambda^2 \frac{d^2x}{d\tau^2} + c\lambda \frac{dx}{d\tau} + kx = - m\lambda^2 \frac{d^2y}{d\tau^2}$$

$$\text{or} \quad m \frac{d^2x}{d\tau^2} + \frac{c}{\lambda} \frac{dx}{d\tau} + \frac{kx}{\lambda^2} = - m \frac{d^2y}{d\tau^2} \quad ... \quad (4.2)$$

Solution of equation (4.2) in terms of spectral quantities of modified time base accelerogram and those of origional can be written as follow :

$$(S_d)_{\lambda T} = (S_d)_T \times \lambda^2$$

$$(S_v)_{\lambda T} = (S\ )_T \times \lambda$$

$$(S_a)_{\lambda T} = (S_a)_T$$

where $(S_d)_{\lambda T}$, $(S_v)_{\lambda T}$ and $(S_a)_{\lambda T}$ are modified values and $(S_d)_T$, $(S_v)_T$ and $(S_a)_T$ are origional values.

Which shows that the spectral displacement is multiplied by λ^2, spectral velocity is multiplied by λ and the spectral acceleration remains same. Spectral intensity is multiplied by λ.

4.3 Equation of motion for nonlinear System (29,40)

The equation of motion of a single degree freedom system subjected to earthquake type of excitation is

$$m\ddot{x} + R(x, \dot{x}, t) = - m\ddot{y}(t) \qquad .... \qquad (4.3)$$

where m = Mass of the structure

R = Resistance force

x = Displacement of mass relative to base

y = Ground motion displacement

t = Time

The superscripted dots defines differentiation with respect to time. The resistance force 'R' is separable into damping force 'D' and restoring force 'Q'.

4.4 Damping Force

Knowledge of damping is necessary in order to explain the observed damage. But complete information is not available about the damping mechanism in actual structures. With the present knowledge of damping characteristics damping is taken into account through a concept of equivalent viscous damping.

4.5 Restoring Force Characteristics

In order to make a rational nonlinear analysis it is necessary to know the appropriate load deflection hysterisis loop. Various type of characteristics are (1) Linear, (2) Bilinear (3) Elastoplastic (4) General nonlinear.

Here for the present analysis elasto-plastic hysterisis loop is chosen.

4.6 Analysis of a Nonlinear System (29,40)

The equation of motion for Single degree freedom nonlinear system is

$$m\ddot{x} + R\,(x, \dot{x}, t) \;=\; - m\ddot{y}(t) \qquad .. \quad (4.3)$$

assuming viscous damping

$$D \;=\; c\dot{x} \qquad .. \quad (4.4)$$

c = coefficient of viscous damping

equation of motion becomes

$$m\ddot{x} + c\dot{x} + Q \;=\; - m\ddot{y}(t) \qquad .. \quad (4.5)$$

dividing both side by $mp^2\,_{xy}$

$$\frac{\ddot{x}}{p^2 x_y} + \frac{c\dot{x}}{mp^2 x_y} + \frac{1}{mp^2 x_y}\,Q \;=\; -\frac{1}{p^2 x_y}\,\ddot{y}(t) \quad (4.6)$$

or $$\frac{\ddot{x}}{p^2 x_y} + 2\xi\frac{\dot{x}}{p x_y} + \frac{Q}{Q_y} \;=\; -\frac{1}{q_y}\,\ddot{y}(t) \qquad .. \quad (4.7)$$

where $Q = f(x)$, $\dfrac{Q}{Q_y} = f\left(\dfrac{x}{x_y}\right)$

$p = \sqrt{\dfrac{Ks}{m}}$ = Undamped natural frequency

$Ks = \dfrac{Q_y}{x_y}$ = slope of load deflection curve at the origin

$$p = \sqrt{\frac{K_s}{m}} = \sqrt{\frac{Q_y}{mx_y}} = \sqrt{\frac{Q_y}{m}}\ \frac{1}{\sqrt{x_y}} = \sqrt{\frac{q_y}{x_y}}$$

$$q_y = \frac{Q_y}{m} = \text{yield level}$$

The yield level q_y is the acceleration of the system that just causes the spring force to attain its yield strength Q_y.

$$\xi = \frac{C}{C_c} = \text{fraction of critical damping}$$

$$C_c = \sqrt{2\ K_s m} = \text{critical damping}$$

Equation (4.7) is of nondimensional form the maximum value of $\frac{x}{x_y}$ that occurs during an earthquake represents the ductility ratio for the system.

Response of the system can be known by solving equation (4.7) which will provide the complete history of deformation of the system as a function of time. The only nonlinear term in the equation is the term corresponding to the restoring force. The restoring force versus deflection curve is assumed elasto-plastic and is shown in Figure (4.1).

The differential equation is solved by fourth order Rungekutta Method (28). A small time intereal is considered desirable to ensure a sufficient accuracy in the numerical solution of nonlinear differenteal equation. A time factor of 40 has been used in the computations. Time factor is defined as a positive constant which determines the desirable time interreal to be used in computations. The desirable time interreal is one which has a duration of T/, Time factor, where T is time period of vibration of the structure.

4.7 Parameters of Study

The following parameters have been used in this study

Accelerogram - koyna longitudinal component

Length of record used = 7.15 seconds

Time base modifications factor, λ = 1.5

Periods : 0.1, 0.2, 0.3, 0.4, 0.5, 0.75, 1.0, 1.25, 1.5, 2.0 and 2.5

Damping factors, ξ = 0.02, 0.05

Yield levels, q_y = 0.05g, 0.1g, 0.15g, 0.2g, 0.25g, 0.3g

Time factor = 40

4.8 Response Quantities Obtained

From the results of inelastic analysis, the significant response quantities are obtained as follows :

i) Displacement response obtained in terms of $\frac{x}{x_y}$

ii) Velocity response obtained in terms of $\frac{\dot{x}}{p x_y}$

iii) Absolute acceleration response obtained interms of $\frac{\ddot{x}}{p^2 x_y}$

Which means that all the response quantities are obtained in nondimensional form.

4.9 Ductility ratio And Reduction Factor

(a) Ductility ratio - It is defined as the ratio of the maximum inelastic displacement to the yield displacement. If maximum inelastic displacement is x_m and yield displacement is x_y then

$\mu = \frac{x_m}{x_y}$ is known as the ductility ratio.

(b) Reduction Factor - A nonlinear system can be related to a corresponding linear system by using the concept of reduction factor. The reduction factor may be defined as follows :

$$R_f = \frac{C}{C_g}$$

where R_f = Reduction factor

C = Seismic lateral load coefficient for the linear system having the same stiffness as a nonlinear system in the elastic range.

$$C_y = \frac{q_y}{g}$$

q_y = Yield level

g = Acceleration due to gravity

4.10 Results of Inelastic Analysis

(a) Ductility Ratio Versus Natural Period of Structures

Figure 4.2 and Figure 4.3 show the variation of ductility ratio with natural periods of structure for different value of yield levels. These graphs are presented for damping factor of 0.05. The general trend of the curves show that for for a perticular yield level the ductility ratio decreases as the period of the structure increases. Also for a perticular structure the ductility ratio decreases as the yield level increases. The structures with period more than 1.0 Sec remains elastic for yield level more than 0.15g in case of Koyna longitudinal. For modified Koyna longitudinal (λ = 1.5) the structures with period more than 1.5 sec remains elastic for yield level more than 0.15g.

The effect of time base modification on ductility ratio versus period is shown in Figure 4.3. All the curves shift towards the longer periods, which means that for a perticular yield level the ductility requirement increases.

(b) Reduction Factor Versus Natural Period

Figure 4.2 was used to determine the reduction factor for a perticular ductility ratio for Koyna longitudinal and for damping factor of 0.05. A plot of reduction factor versus natural period for $\lambda = 1$ and $\lambda = 1.5$ is shown in Figure 4.4. From the curves of different ductility ratio for $\lambda = 1$ it is observed that for a wide range of periods the reduction factor decreases with decrease in ductility ratio. It is also seen that for all values of ductility ratio the reduction factor first increases upto period of 0.4 sec and then decreases. The minimum reduction factor available with ductility ratio of 2, 4, 6 and 8 are 1.6, 2.7, 4.1 and 5.0 respectively. For $\lambda = 1.5$ the reduction factors for all ductility ratios are less than the corresponding reduction factors for $\lambda = 1.0$ Fig. 4.4.

Calculation of reduction factor for various ductility ratios is shown in Table 4.1 and 4.2.

(c) Comparision of Inelastic Displacement Response For Origional and Modified Koyna Longitudinal Component

Ratio of maximum inelastic displacement responce for modified and origional Koyna longitudinal is calculated for various periods and yield levels and is tabulated in Table 4.3. The results are also plotted in the form of curves Figure 4.5. It is seen from the curves that there is no regular relationship between the inelastic response of origional and modified accelerogram and therefore for every time base modification a separate analysis is required.

(d) Comparative Study of Displacement Response of Linear and Nonlinear Systems.

Figure 4.6 shows the comparision of maximum relative displacement of elastoplastic and elastic systems as function of natural period for damping factor of 0.05. The curves are plotted for various values of ductility ratio. It is seen from Figure 4.6 that inelastic displacement response is less than the elastic response upto period range of 0.55 sec and ductility ratio of 4. For longer periods and higher ductility ratios the inelastic response is always greater than the elastic response. Calculation of elastic and inelastic displacement response and their ratio is shown in Table 4.4.

4.11 Conclusions

1. The reduction factor increases with the increase in ductility ratio. For all values of ductility ratio the reduction factor first increases upto a period of 0.4 sec and then decreases. This is the general trend but the time period at which the change occurs varies with the earthquake.

2. There is no regular relationship between inelastic displacement response of origional and modified time base. Therefore for each time base modifications a separate analysis is required.

3. Upto period range of 0.5 sec and ductility ratio 4 the inelastic displacement response is less than the corresponding elastic response. But for periods more than 0.5 sec and ductility ratio more than 4, the inelastic displacement response is greater than the corresponding elastic response.

Table 4.1

=0.05
λ =1.0

Reduction factor for Koyna Earthquake

Ductility Ratios

$\mu = 2$				$\mu = 4$				$\mu = 6$				$\mu = 8$			
T	g_y/g	Elastic accln.	R_f	T	g_y/g	Elastic accln	R_f	T	g_y/g	Elastic accln	R_f	T	g_y/g	Elastic accln	R_f
.38	.3	9.40	3.19	.17	.3	13.26	4.5	.12	.3	14.27	4.85	.08	.3	15.0	5.0
.48	.25	4.58	1.87	.2	.25	11.30	4.62	.14	.25	9.84	4.0	.08	.25	15.0	6.0
.73	.2	3.58	1.82	.38	.2	9.40	4.78	.3	.2	8.66	4.42	.21	.2	12.20	6.25
.87	.15	2.40	1.634	.40	.15	9.65	6.57	.35	.15	9.10	6.2	.31	.15	8.66	5.88
1.0	.1	1.668	1.70	.82	.1	2.68	2.73	.49	.1	4.0	4.1	.4	.1	9.65	9.84
				1.05	.05	1.44	2.94	.93	.05	2.17	4.43	.84	.05	2.54	5.20

Table 4.2

Reduction factor for modified Koyna earthquake

$\xi = 0.05$

$\lambda = 1.5$

$\mu = 2$				$\mu = 4$				$\mu = 6$				$\mu = 8$			
T	q_y/g	Elastic accln	R_f	T	q_y/g	Elastic accln	R_f	T	q_y/g	Elastic accln	R_f	T	q_y/g	Elastic accln	R_f
0.64	0.3	4.80	1.63	0.28	0.3	11.04	3.76	0.24	0.3	10.84	3.7	0.2	0.3	11.30	3.85
0.68	0.25	4.30	1.76	0.3	0.25	8.66	3.54	0.26	0.25	11.05	4.5	0.24	0.25	10.84	4.43
0.98	0.2	1.88	0.96	0.5	0.2	3.88	1.98	0.44	0.2	6.5	3.32	0.4	0.2	9.65	4.93
1.25	0.15	1.105	0.75	0.64	0.15	4.80	3.27	0.52	0.15	4.2	2.86	0.46	0.15	5.25	3.57
1.50	0.1	0.989	1.01	1.15	0.1	1.19	1.22	0.74	0.1	3.5	3.57	0.65	0.1	4.71	4.81
								1.40	0.05	0.95	1.94	1.28	0.05	1.10	2.25

Table 4.3

Comparison of Inelastic Response of Original and Modified Koyna Earthquake

$\xi = 0.05$

T	Ductility Ratio																	
	$q_y = 0.05$			$q_y = 0.10$			$q_y = 0.15$			$q_y = 0.2$			$q_y = 0.25$			$q_y = 0.3$		
	$\lambda=1$	$\lambda=1.5$	μ_2/μ_1	$\lambda=1$	$\lambda=1.5$	μ_2/μ_1	$\lambda=1$	$\lambda=1.5$	μ_2/μ_1	$\lambda=1$	$\lambda=1.5$	μ_2/μ_1	$\lambda=1$	$\lambda=1.5$	μ_1/μ_1	$\lambda=1$	$\lambda=1.5$	μ_2/μ_1
0.10	192.99	325.25	1.69	66.67	114.94	1.71	24.48	35.89	1.46	15.19	18.45	1.21	7.03	17.15	2.44	6.81	13.93	2.05
0.20	72.68	134.09	1.84	31.25	49.68	1.59	12.95	20.65	1.61	8.25	10.99	1.33	3.94	11.15	2.84	3.13	7.71	2.46
0.30	39.55	72.68	1.84	16.66	31.25	1.87	8.73	12.95	1.48	6.13	8.25	1.35	4.83	3.94	0.81	4.32	3.13	0.72
0.40	20.13	48.78	2.43	7.33	19.21	2.62	3.78	10.78	2.85	3.39	8.07	2.38	4.83	6.76	1.40	1.55	5.76	3.70
0.50	13.76	31.08	2.26	5.85	11.47	1.96	2.43	6.38	2.63	4.33	8.00	1.85	1.50	3.42	2.28	1.20	3.10	2.59
0.75	10.41	13.76	1.32	4.84	5.85	1.21	2.88	2.43	0.84	1.83	4.33	2.37	1.29	1.50	1.16	1.07	1.20	1.12
1.0	4.53	11.92	2.63	1.97	4.73	2.40	1.11	2.98	2.68	0.84	1.77	2.11	0.67	1.32	1.97	0.56	1.22	2.18
1.25	2.35	8.55	3.64	1.139	3.54	3.10	0.75	2.05	2.74	0.57	1.40	2.46	0.45	1.07	2.38	0.38	0.89	2.34
1.50	2.48	4.53	1.83	1.00	1.97	1.97	0.66	1.11	1.68	0.56	0.83	1.66	0.40	0.67	1.68	0.33	0.56	1.70
2.0	2.35	2.63	1.12	1.23	1.03	0.84	0.95	0.68	0.72	0.72	0.51	0.71	0.57	0.41	0.72	0.48	0.34	0.71
2.5	2.44	2.12	0.87	1.10	1.21	1.10	0.84	0.84	1.0	0.63	0.63	1.0	0.50	0.50	1.0	0.42	0.42	1.0

Table 4.4

Comparison of Elastic and inelastic Response

$\xi = 0.05$
$\lambda = 1.0$

Ductility Ratio μ	T	q_y/g	q_y	p	p^2	$x_y = \frac{q_y}{p^2}$	$y_{mp} = \mu\ x_y$	y_{me}	$\frac{y_{mp}}{y_{me}}$
2	.38	.3	2.94	16.5	272.5	.01	0.02	.036	0.55
2	.48	.25	2.45	13.1	172.0	0.0145	0.029	.026	1.11
2	.73	.2	1.96	8.6	74.0	0.0271	0.054	.048	1.13
2	.87	.15	1.47	7.23	52.3	0.0287	0.057	.046	1.24
2	1.00	.1	.981	6.28	39.5	0.0253	0.050	.041	1.22
4.0	.17	.3	2.94	37.0	1370	0.00219	0.0088	.009	0.98
4.0	.2	.25	2.45	31.4	990	0.00252	0.010	.01	1.0
4.0	.38	.2	1.96	16.5	272.5	0.00735	0.0294	.036	0.815
4.0	.40	.15	1.47	15.7	247.0	0.00608	0.024	.038	0.63
4.0	.82	.1	0.981	7.66	59.0	0.017	0.068	.0453	1.50
4.0	1.05	.05	0.49	5.98	35.9	0.014	0.056	.0397	1.41
6.0	.12	.3	2.94	52.4	2750	0.00109	0.0066	.0051	1.29
6.0	.14	.25	4.45	44.8	2012	0.00125	0.0075	.0048	1.56
6.0	.3	.2	1.96	20.9	4370	0.00458	0.0275	.0196	1.41
6.0	.35	.15	1.47	18.0	324.0	0.00463	0.0278	.0283	0.98
6.0	.49	.1	0.981	12.83	165.0	0.00606	0.0364	.024	1.52
6.0	.93	.05	0.49	6.28	39.6	0.0126	0.076	.045	1.69

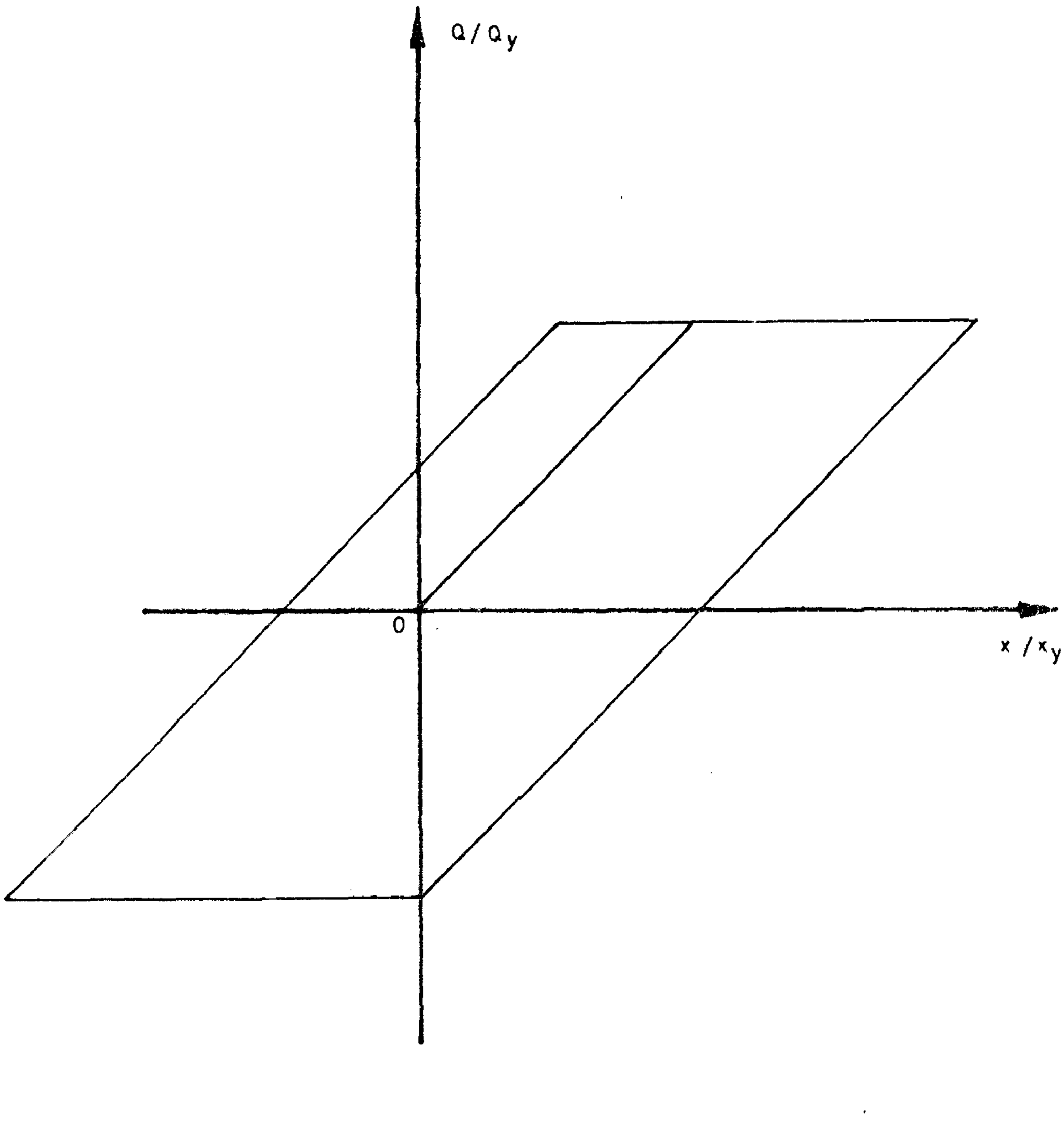


FIG. 4.1 – HYSTERISIS LOOP FOR ELASTOPLASTIC SYSTEM

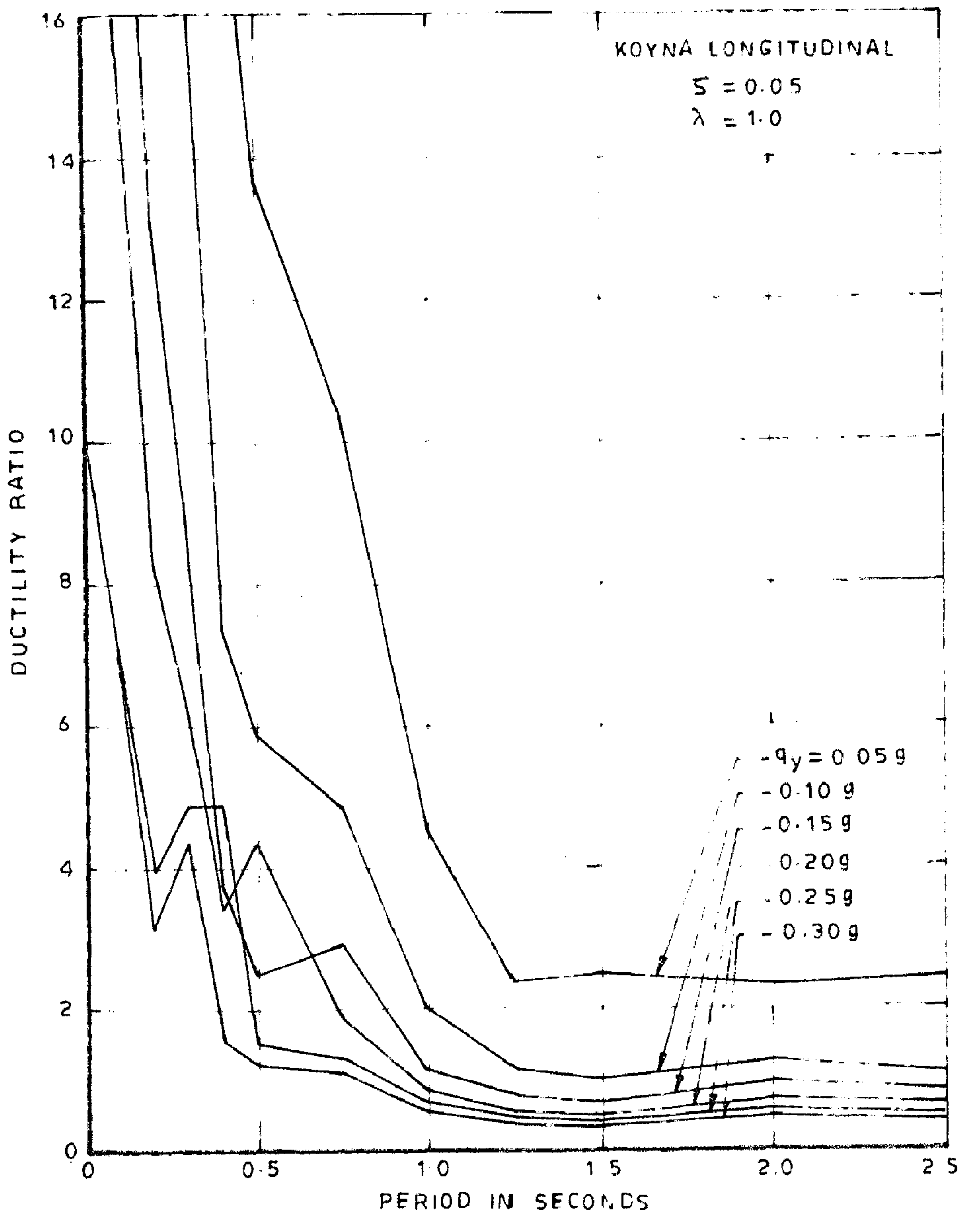


FIG. 4.2 _ DUCTILITY RATIO VS NATURAL PERIOD

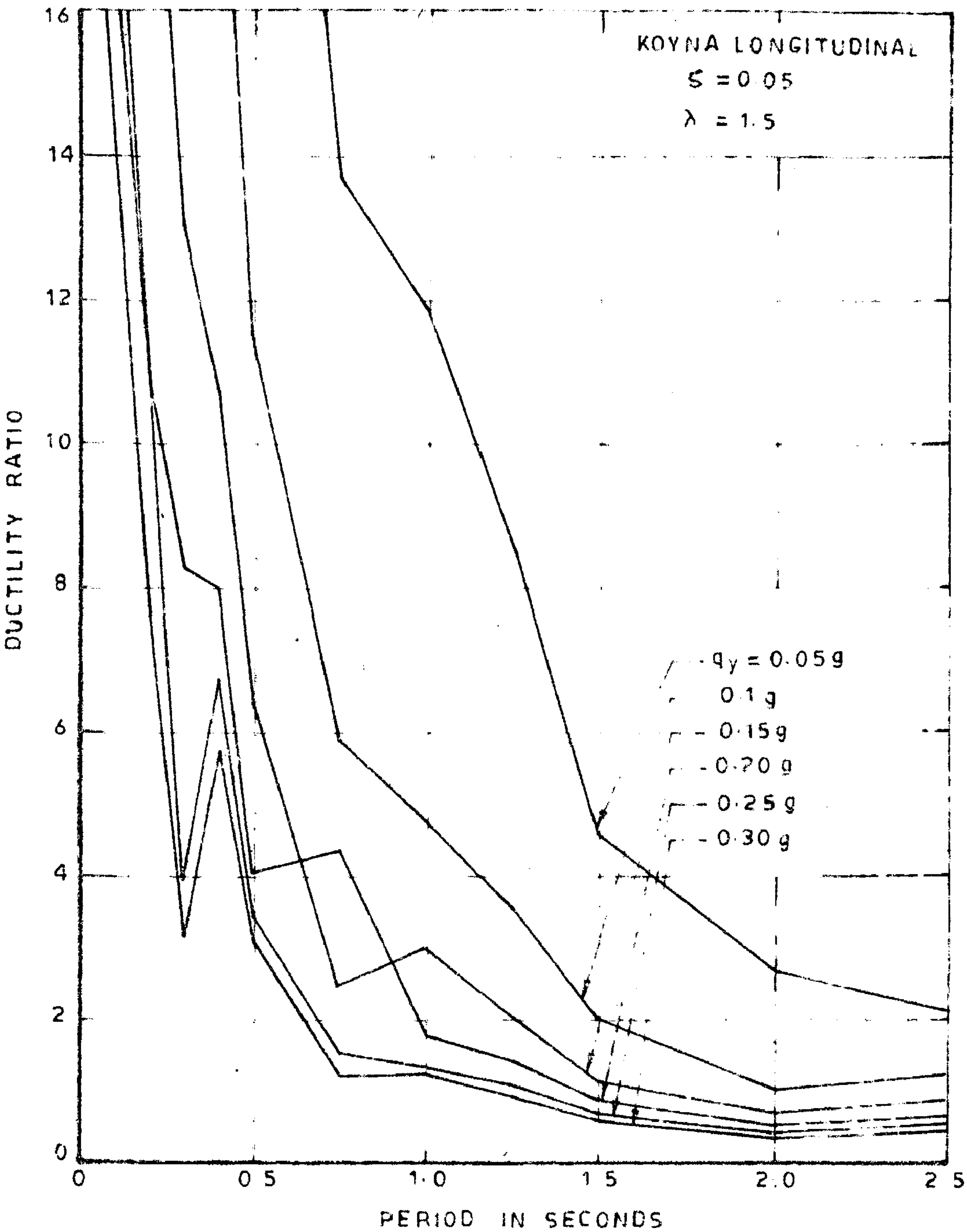


FIG.4.3_ DUCTILITY RATIO VS NATURAL PERIOD

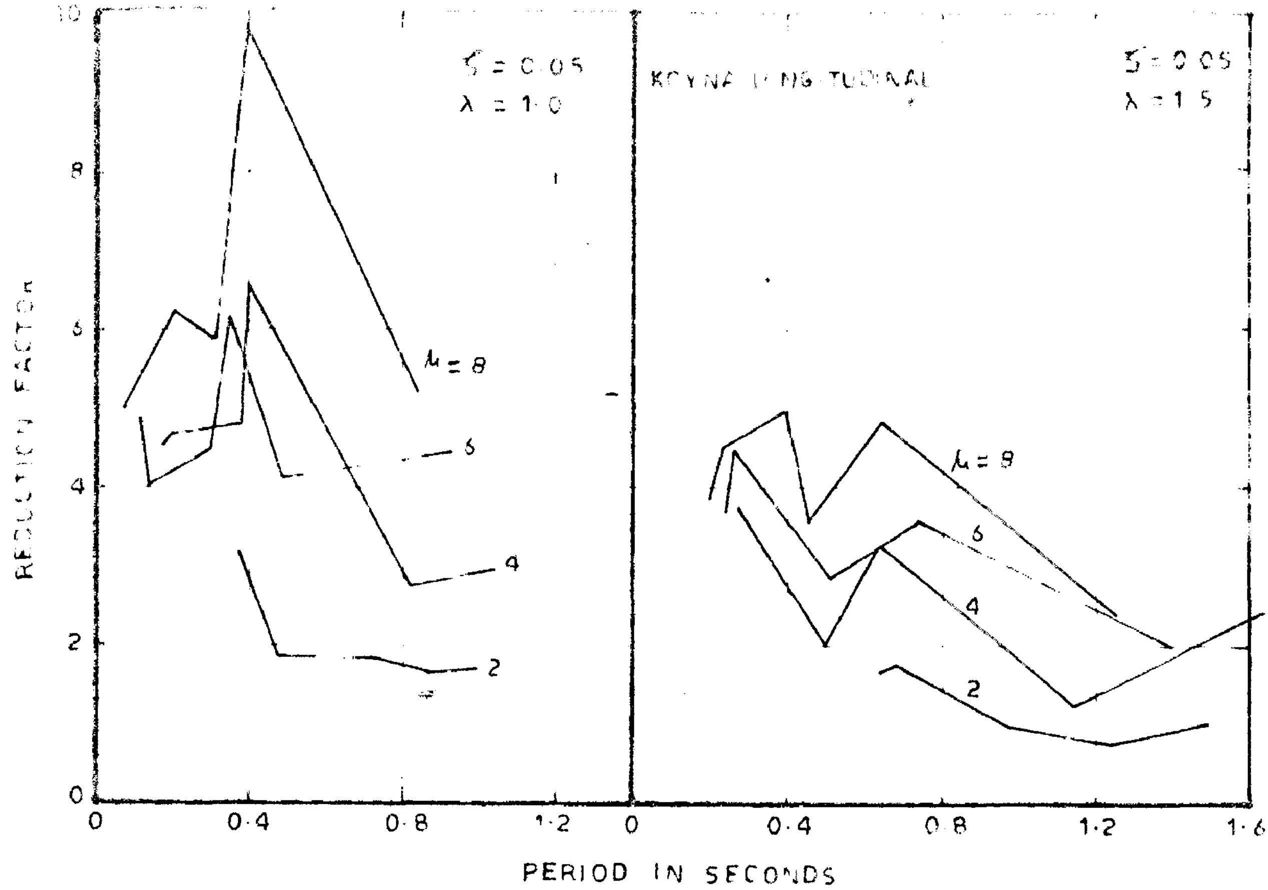


FIG.4·4 _REDUCTION FACTOR VS NATURAL PERIOD

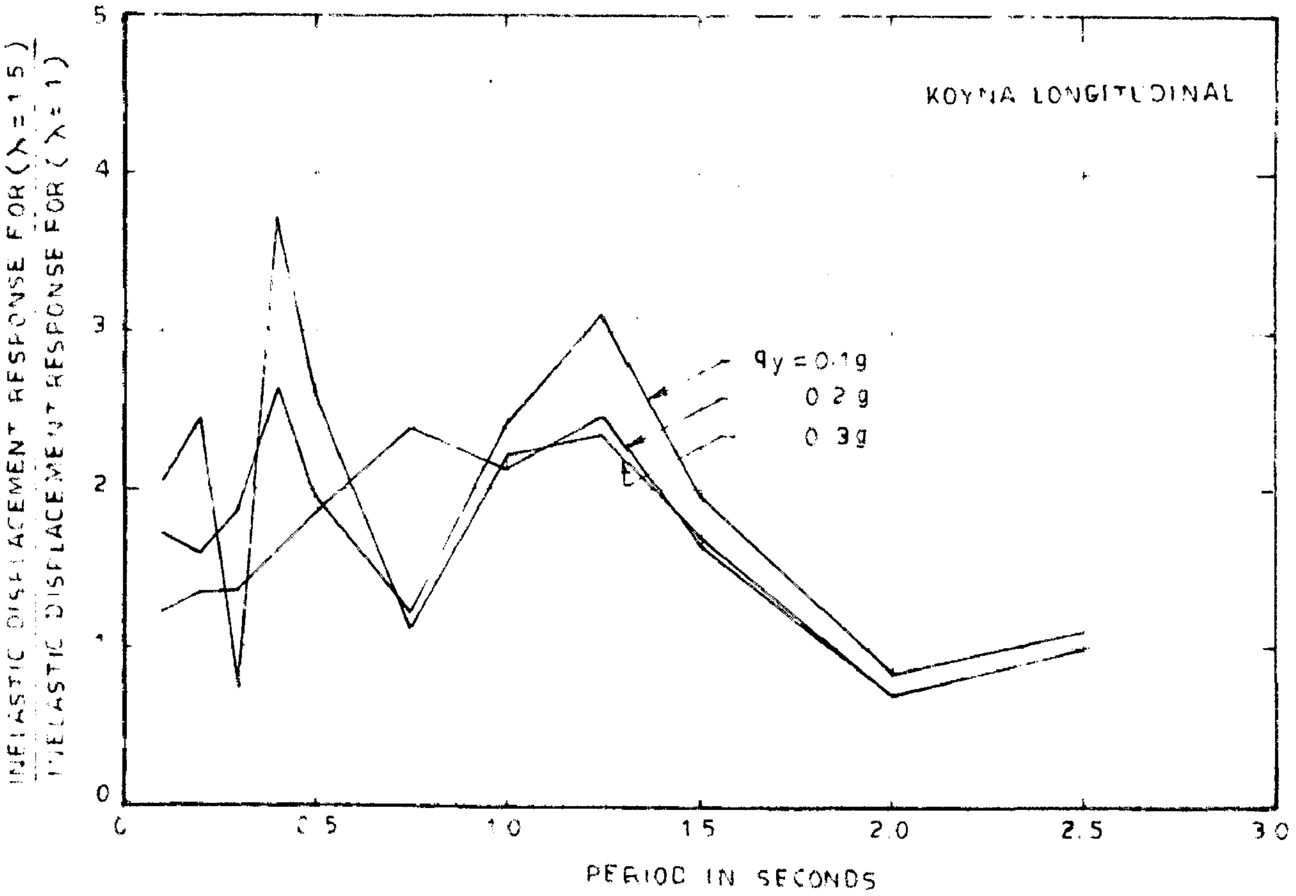


FIG. 4·5 _COMPARISION OF INELASTIC DISPLACEMENT OF ORIGIONAL AND MODIFIED ACCELEROGRAMS

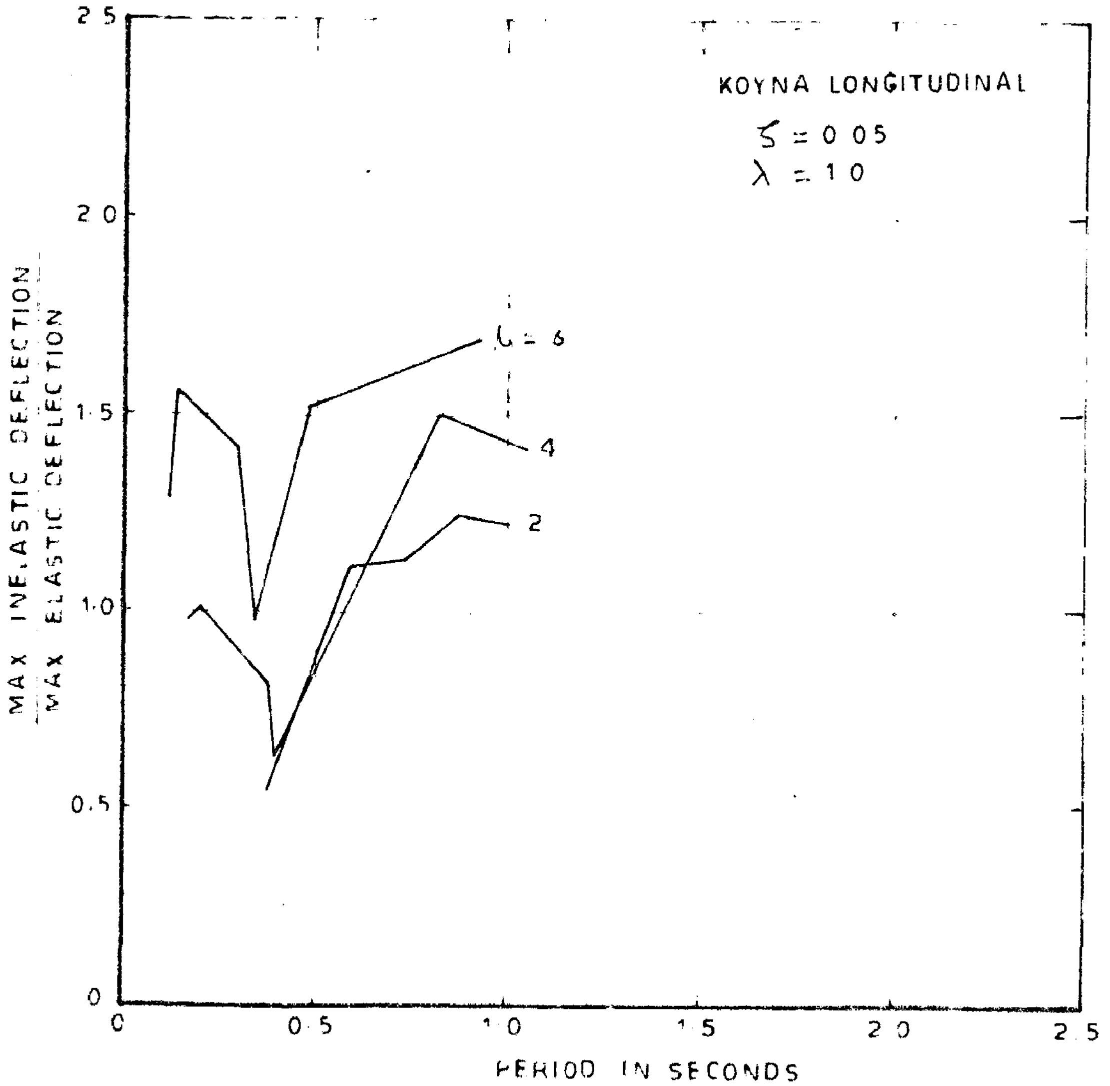


FIG. 4.6 – COMPARISION OF INELASTIC AND ELASTIC DEFLECTION

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NOTATIONS

Notation	Explaination
A_o^o	peak ground acceleration at the epicentre
a	peak ground acceleration at any distance D from epicentre.
c	Coefficient of equivealent damping
C	constant absorbing the effect of ground condition in the energy acceleration relationship
C_c	critical damping
D	epicentral distance
E	energy released at the focus
F	multiplying factor
g	acceleration due to gravity
h	focal depth
I	intensity of earthquake
k	stiffness of the elastic system
K_s	slope of the load deflection curve at the origine
m	mass of the structure
M	Magnitude of earthquake
p	undamped natural frequency = $\sqrt{K_s/m}$
'Q'	exciting potential of an earthquake
Q	restoring force
Q_y	characteristics restoring force
q_y	yield level Q_y/m
R	resistance force
R_f	reduction factor

Notation	Explaination
S.I.	Spectral intensity
$(S.I_o)_n$	normalise spectral intensity
Sa	spectral acceleration
Sd	spectral displacement
Sv	spectral velocity
t	time
T	undamped natural period of structure
W	weight of the structure
x	relative displacement of the system
x_m	maximum displacement
x_y	characteristics displacement
x	relative velocity of the system
x	absolute acceleration of the system
y	ground displacement at any time
y	ground acceleration at any time
α	arbitrary constant in the attenuation curve equation
λ	time base multiplying factor
θ	horizontal angle from Koyna longitudinal component
ξ	damping factor
μ	ductility ratio

COMPUTER PROGRAM

```
C  C   PROGRAM, ACCELOGRAM MODIFICATION, SAHADEO
       DIMENSIONT1(300),T2(300),T(600),A1(300),A2(300),A(600),A11(300)
       READ1,NC1,NC2,IND1,IND2,IND3
    1  FORMAT(2I3,3I5)
   21  FORMAT(I3,4(F8.4,F9.6),I5)
    9  FORMAT(24H INDEX ERROR IN CARD NO=I3)
   10  FORMAT(34H CARDS NOT IN SEQUENCE AT CARD NO=I3)
C      READ LONGITUDINAL ACCELOGRAM DATA
       DO11I=1,NC1
       J2=4*I
       J1=J2-3
       READ21,NC,(T1(K),A1(K),K=J1,J2),IND
       IF(IND1-IND)33,22,33
   22  IF(NC-I)34,11,34
   11  CONTINUE
       GOTO60
   33  PUNCH9,NC
       STOP
   34  PUNCH10,NC
       STOP
C      READ TRANSVERSE ACCELOGRAM DATA
   60  DO110I=1,NC2
       J2=4*I
       J1=J2-3
       READ21,NC,(T2(K),A2(K),K=J1,J2),IND
       IF(IND2-IND)33,220,33
  220  IF(NC-I)34,110,34
  110  CONTINUE
       N=4*NC1
       M=4*NC2
       J1=2
       DO20I=1,N
       DO30J=J1,M
       IF(T1(I)-T2(J))15,16,30
   15  A11(I)=A2(J-1)+(A2(J)-A2(J-1))*(T1(I)-T2(J-1))/(T2(J)-T2(J-1))
       J1=J
       GOTO20
   16  A11(I)=A2(J)
       J1=J
       GOTO20
   30  CONTINUE
   20  CONTINUE
```

```
      K=0
      J1=1
      DO40I=1,M
      IF(I-1)45,70,71
71    IF(T2(I-1)-T1(N))70,70,31
31    K=K+1
      T(K)=T2(I-1)
      A(K)=A2(I-1)
      IF(I-M)40,91,45
91    K=K+1
      T(K)=T2(I)
      A(K)=A2(I)
      GOTO42
70    DO50J=J1,N
      K=K+1
      IF(T2(I)-T1(J))80,81,82
80    T(K)=T2(I)
      A(K)=A2(I)
      J1=J
      GOTO40
81    T(K)=T2(I)
      A(K)=A2(I)
      J1=J+1
      GOTO40
82    T(K)=T1(J)
      A(K)=A11(J)
50    CONTINUE
40    CONTINUE
42    ND=K/4
      DO86NC=1,ND
      J2=4*NC
      J1=J2-3
      PUNCH21,NC,(T(II),A(II),II=J1,J2),IND3
86    CONTINUE
45    STOP
      END
```

```
C  C  HORIZONTAL COMPONENT IN ANY DIRECTION THETA,   SAHADEO
      DIMENSIONT(500),A1(500),A2(500),A(500)
      READ1,NC1,IND1,IND2,IND3,THETA
   1  FORMAT(I3,3I5,F8.6)
   2  FORMAT(I3,4(F8.4,F9.6),I5)
      CS1=COSF(THETA)
      SN1=SINF(THETA)
      DO3I=1,NC1
      J2=4*I
      J1=J2-3
      READ2,NC,(T(K),A1(K),K=J1,J2),IND1
   3  CONTINUE
      DO4I=1,NC1
      J2=4*I
      J1=J2-3
      READ2,NC,(T(K),A2(K),K=J1,J2),IND2
   4  CONTINUE
      N=4*NC1
      DO5I=1,N
      A(I)=A1(I)*CS1+A2(I)*SN1
   5  CONTINUE
      DO6ND=1,NC1
      J2=4*ND
      J1=J2-3
      PUNCH2,ND,(T(I),A(I),I=J1,J2),IND3
   6  CONTINUE
      STOP
      END
```

```
C  C  S.I. BY SIMPSON,S RULE, SAHADEO
      DIMENSIONH(20),Y(100)
C     S.I.=SPECTRAL INTENSITY
C     H=INTERVAL
      READ101,NT
      N=(NT-1)/2
      READ102,(H(I),I=1,N)
   20 READ103,(Y(K),K=1,NT)
  101 FORMAT(I3)
  102 FORMAT(16F5.3)
  103 FORMAT(8F10.6)
  104 FORMAT(5F10.6)
      SUM=0
      DO1I=1,N
      K=2*I
    1 SUM=SUM+H(I)*(Y(K-1)+4.*Y(K)+Y(K+1))
      SI=.3333333*SUM
      PUNCH104,SI
      GOTO20
      STOP
      END
```