# Development of Elastic Design Spectrum for Indian Context and Its Comparison with Other Codes

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# Development of Elastic Design Spectrum for Indian Context and Its Comparison with Other Codes

**Major Project**

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**Master of Technology in Civil Engineering**
**(Computer Aided Structural Analysis & Design)**

By

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**AHMEDABAD-382481**
**May 2014**

# Declaration

This is to certify that

a. The dissertation comprises my original work towards the Degree of Master of Technology in Civil Engineering (Computer Aided Structural Analysis and Design) at Nirma University and has not been submitted elsewhere for a degree.

b. Due acknowledgement has been made in the text to all other material used.

**Payal V. Mehta**

# Certificate

This is to certify that the Major Project entitled **"Development of Elastic Design Spectrum for Indian Context and Its Comparison with Other Codes"** submitted by **Ms. Payal V. Mehta (11MCLC51)**, towards the partial fulfillment of the requirements for the degree of Master of Technology in Civil Engineering (Computer Aided Structural Analysis and Design) of Nirma University, Ahmedabad, is the record of work carried out by her under my supervision and guidance. In my opinion, the submitted work has reached a level required for being accepted for examination. The results embodied in this major project, to the best of my knowledge, haven't been submitted to any other university or institution for award of any degree or diploma.

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# Abstract

Earthquake is one of the most destructive natural hazards that claims human lives and cause damages to almost all manmade structures. It is important to estimate seismic demand pose by an earthquake on structures in order to present damages. Seismic code of various countries provide Design Spectrum or Response Spectrum to estimate seismic demand on structures. However, for critical facilities, site specific response spectrum should be developed to estimate seismic demand more accurately. For Indian subcontinent, seismic demand is estimated as per design spectrum given in IS:1893(Part I)-2002, whose basis are unknown.

In the present study, site specific response spectrum is developed using past records of earthquakes of Indian subcontinent. Earthquakes are classified to strong ground excitation based on Peak Ground Acceleration (PGA), Root Mean Square, Amplitude and Duration. A response spectrum is generated by classifying strong motion excitations to four zones, namely, North, East, West and South-East regions as per their locations. The mean and mean plus one standard deviation response spectrum for each regions are developed for acceleration, velocity and displacement quantities.

A design spectrum for each region is developed from response spectrum. Appropriate amplification factors are determined from first principle. Comparison among developed design spectrum for East and North region and design spectrum specified in IS:1893 (Part-I) - 2002 is carried out through numerical example. Comparison shows that mean response spectrum yields base shear value lower than the IS based design spectrum for highest seismic zone V. However, the IS based design spectrum yields lower base shear value when compared with mean plus one standard deviation design spectrum. Comparison among developed mean response spectrum for West and South-East region shows the later yields lower base shear value as compared to IS based design spectrum while former yields higher base shear value.

Apart, important provisions of seismic code of countries like Mexico, United States of America, Chile, Philippines and China are studied and compared. It is observed that United States of America and Philippines Code is based on Uniform Building Code (UBC).

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**- Payal V. Mehta**
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# Abbreviation Notation and Nomenclature

SDOF ........ Single Degree of Freedom
EQ ........ Earthquake
PGA ........ Peak Ground Acceleration
PGV ........ Peak Ground Velocity
PGD ........ Peak Ground Displacement
RMS ........ Root Mean Square
m ........ Mass of Building
$k$ ........ Stiffness of Building
$c$ ........ Damping of Building
$\sigma$ ........ Standard deviation
$\zeta$ ........ Damping Ratio
$\omega_n$ ........ Natural Frequency (Hz)
$u_g$ ........ Ground Displacements
D ........ Relative displacement
V ........ Pseudo-velocity
A ........ Pseudo-acceleration
Sa ........ Spectral acceleration
Tn ........ Natural time period
SRSS ........ Square root of sum of square
CQC ........ Complete quadratic combination
$f_{ck}$ ........ Characteristic Strength of Concrete
$f_y$ ........ Characteristic Strength of Steel

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# Chapter 1

# Introduction

## 1.1 General

Earthquakes are perhaps the most unpredictable and devastating of all natural disasters. They not only cause great destruction in terms of human casualties, but also have a tremendous economic impact on the affected area. An earthquake disaster, from the engineering point of view, is a situation in which the intensity of ground shaking produces stresses and strains that exceed the strength of structures. For design of a project in a seismic region, the specification of the earthquake resistance is a key element to prevent failure or excessive damage in the event of an earthquake. Codes and recommendations, postulated by the relevant authorities, study of the behaviour of structures in past earthquakes, and understanding the physics of earthquakes are some of the factors that help in the designing of an earthquake-resistant structure.

## 1.2 Concept of Response Spectra

Response Spectrum is an important tool for seismic analysis and design of structures. It provides a very handy tool for engineers to quantify the demands of earthquake ground motion on the capacity of buildings to resist earthquakes. It provides a practical approach to apply the knowledge of structural dynamics to the seismic design of

structure. Response spectrum is a central and widely accepted concept in earthquake engineering to estimate lateral force on the structure. It is an envelope of maximum response of various Single Degree of Freedom (SDOF) systems to a specified earthquake ground excitation. The response spectrum can't be used uniformly to design any structure since it is very much ground motion dependent. Apart, it is very much jagged in nature and required to be smoothen out. A plot of the peak value of a response quantity as a function of the natural vibration period Tn of the system is called the response spectrum for that quantity. Each such plot is for SDOF systems having a fixed damping ratio $\zeta$, and several such plots for different values of $\zeta$ are included to cover the range of damping values encountered in actual structures.
Factors Influencing Response Spectra:

- Magnitude
- Source mechanism and characteristics
- Distance from the source of energy release
- Wave travel path
- Rupture directivity
- Local geology and site conditions

## 1.3 Design Spectra

It is the smooth spectra developed from the response spectra by removing the jaggedness of the response spectra. The design spectrum is based on statistical analysis of the response spectra for the ensemble of ground motions. The amplification factors are developed from the cut off time periods from sensitive regions like acceleration sensitive region, velocity sensitive region and displacement sensitive regions. These amplification factors are used to develop elastic design spectra from peak ground acceleration, velocity and displacement values for different time period.

## 1.4 Need of Study

The design spectrum is intended for the design of new structures, the safety evaluation of existing structures and to resist future earthquakes. The design spectrum represents severity of ground motions recorded at the site during past earthquakes. Design spectrum plays vital role for estimation of seismic demand of any structure. It is important to develop design spectrum from recorded ground motion to design important facilities. Apart, it is important to study various parameters that influence design spectrum among various countries code, so as deficiencies, if any found can be surfaced out.

## 1.5 Objectives of Study

For the present study, following objectives are outlined:

- To develop response spectrum base on recorded ground motions of past earthquakes of Indian Subcontinent.
- To develop design spectrum from response spectrum for Indian Subcontinent.
- Compare seismic demand on structure by design spectrum developed for Indian Subcontinent with the ones obtained from design spectrum specified in IS:1893(Part- I)-2002.
- Study seismic code provisions of various countries to evaluate strength and weakness of IS:1893(Part- I)-2002.

## 1.6 Scope of the Work

To achieve above mentioned objectives, following scope of work is proposed.

- Compile ground motion records of past earthquake.
- Verification of ground motions collected for its correctness.

- Classify ground motions to strong ground motion with respect to parameters like Peak Ground Acceleration (PGA), Duration and Frequency Content. Development of Strong Ground Motion records region wise like North, South-East, East and West.
- Develop displacement, velocity and acceleration response spectrum region wise.
- Carry out statistical analysis to derive mean and mean plus one standard deviation response spectrum.
- Develop Tripartite plot of response spectrum for each regions.
- Determine amplification factor for ensembles of strong ground motion from first principal.
- Develop design spectrum from response spectrum for each region.
- Compare seismic demand on a building structure through Numerical example using site specific and IS:1893(Part- I)-2002 base design spectrum.
- Study various provisions of seismic codes of different countries like Mexico, USA, Chile, Philippines and China.
- Line out comparison among seismic codes to establish efficiency and deficiency.

## 1.7 Organization of Report

The Major Project Part - I is divided into seven chapters. They are as follows:

Chapter 2 comprises of literature review covering various research papers, report etc. It focuses on various studies carried out to define strong ground motion parameters and their characteristics. It also includes papers discussing concept of response spectrum, related to elastic spectrum, compilation of various countries code.

Chapter 3 highlights concepts of response spectrum. It includes equation of motion for earthquake excitation and its solution by Newmark-Beta method. It deals with the generation of response spectrum for SDOF system under El Centro (1940) earthquake excitation using MATLAB code. Chapter covers verification of ground motion data for Indian context and response spectrum of verified data for Champawat (Uttarakhand) is developed. Tripartite plot for all four regions is developed for mean and mean plus one standard deviation.

Chapter 4 provides concepts of design spectrum. It covers information amplification factors cut off time periods for sensitive regions. It also includes steps to generate elastic design spectrum from response spectrum. Design spectrum is developed for mean values.

Chapter 5 covers estimation of seismic demand of G+3 storey building using design spectrum developed as well as IS specified. Critical observations are brought out and same are out lined.

Chapter 6 comprises of study related to five country codes Mexico, USA, Chile, Philippines and China are compared. Various parameters are considered for comparison of seismic analysis in these codes. Design spectrum is also compared through various parameters.

Chapter 7 comprises of summary of work carried out in major project, conclusion and future scope of work.

# Chapter 2

# Literature Review

## 2.1 Introduction

Design spectrum is an important part to evaluate the seismic demand of the structures. Various factors are to be considered to smooth the spectrum from available time histories. Various authors and researchers have considered different procedures and factors to construct the design spectrum. This chapter includes various papers and documents which covers the ideas and concepts to generate the design spectrum from response spectrum. It also includes the comparison of various codes covering different parameters to evaluate the seismic demand of the structures. Literature survey is divided into following subparts:
1)Response spectrum
2)Elastic design spectrum
3)Seismic code comparison of various countries

## 2.2 Response Spectrum

Various papers have been studied for development of response spectra. Some of the important and relevant literatures are summarized below.
**Malhotra[3]** has given an improved method of constructing a smooth response spectrum from peak values of ground acceleration, velocity and displacement (PGA, PGV

and PGD). He has drawn tripartite response spectra of 5% damping for horizontal ground motion recorded at a station in the 90 (East) direction, during the 1994 Northridge, California earthquake. "Central" period of the ground motion is calculated by

$$T_{cg} = 2\pi\sqrt{\frac{PGD}{PGA}} \tag{2.1}$$

$T_{cg}$ makes boundary between high and low frequencies regions of the response spectrum. The period along the horizontal axis is normalized with respect to $T_{cg}$. He has also proposed the acceleration, velocity and displacement amplification factors for median horizontal and vertical spectrum of different damping ratios. Functional forms of Amplification Factors for Horizontal and Vertical Spectra is given by following equation.

$$\alpha(\zeta) = a + b\ln\zeta + c(\ln\zeta)^2 \tag{2.2}$$

where,$\alpha$=$\alpha_A$, $\alpha_V$, $\alpha_D$ and $\zeta$ is percentage of critical damping. The coefficients a, b, and c in equation are determined through least-squares fitting of the data points.

Comparison is made for the horizontal amplification factors obtained in this study with those reported by Mohraz (1976) and Newmark and Hall (1982). The Mohraz values are the average of those for various soil conditions. The $\alpha_A$ values obtained in this study are up to about 10% higher than Newmark-Hall and about 10% lower than Mohraz. These differences are considered to be negligible. The $\alpha_V$ values obtained in this study are up to about 10% lower than Newmark-Hall and about 20% higher than Mohraz. The differences from the Mohraz values are somewhat significant. The $\alpha_D$ values obtained in this study are up to about 30% higher than Newmark-Hall and about 10% lower than Mohraz. The differences from the Newmark-Hall values are significant. The possible causes of differences are (1) a priori assumption of cutoff periods in previous studies and (2) asymptotically incorrect behaviour of response spectra used in those studies.

Procedure to construct smooth spectrum is suggested. The smooth spectra of numerous horizontal ground motions were computed by this method. The actual spectra of these ground motions were calculated by method suggested by Malhotra and by this way validation of proposed procedure is done.

**Ghasemi, Zare and Sinaeian**[4] has developed the smooth spectra of horizontal and vertical ground motions for Iran. The main concern of the present study is to propose a practical procedure for constructing smooth response spectra from the peak values of ground motion. The dynamic amplification factors are calculated for horizontal and vertical components. Functional forms of Amplification Factors for Horizontal and Vertical Spectra is given by following equation.

$$\alpha(\zeta) = a + b \ln \zeta \tag{2.3}$$

where,$\alpha$=$\alpha_A$, $\alpha_V$, $\alpha_D$ and $\zeta$ is percentage of critical damping.
The coefficients a, b, and c in equation are determined through least-squares fitting of the data points. Comparison is made for the horizontal amplification factors obtained in this study with those reported by Mohraz (1976) and Newmark and Hall (1982) and Malhotra (2006). The $\alpha_A$ values obtained in this study are up to about 10% higher in comparison with those reported by Mohraz (1976), 13% higher as compared to those given by Newmark and Hall (1982), and 3% higher than the values reported by Malhotra (2006). Similarly, the $\alpha_V$ values are about 10% higher than the values reported by Mohraz (1976), 28% lower than those reported by Newmark and Hall (1982), and 18% lower than those given by Malhotra (2006). Further, the $\alpha_D$ values are up to about 4% higher than those given by Mohraz (1976), 23% higher than those reported by Newmark and Hall (1982), and 4% lower than those given by Malhotra (2006). The present results for $\alpha_A$ and $\alpha_D$ factors are mostly consistent with those obtained by Malhotra (2006), and for $\alpha_V$ values with those of Mohraz (1976). Numerical example on constructing smooth response spectra is also solved. The cut off periods for each region are slightly lower than the values reported in Mohraz (1976)

and Malhotra (2006), indicating that those can change from one set of ground motions to another.

**Hudson[5]** discussed several types of response spectrum of use in earthquake engineering and the relationships between these spectra and other basic quantities such as energy inputs and seismic coefficients were given. The use of the response spectrum to reveal significant characteristics of ground motion was discussed, and the role of the response spectrum in establishing seismic coefficients for structural behavior was illustrated by experimental data. It was noticed that there were many irregular peaks and an amount of damping effectively removes most of the peaks.

An evaluation of seismic coefficients or lateral force coefficients could not be obtained without the use of the response spectrum. The maximum accelerations expected in a structure were not those which were recorded by the ground motion accelerometer, since dynamic amplification effects occur which made the structural accelerations considerably larger than the ground accelerations. From the response spectrum, the maximum value of the total shear force was directly obtained.

## 2.3 Elastic Design Spectrum

**Jain and Pal[6]** has carried out the analysis using the analytical probability distribution rather than statistical analysis. Earthquake E1 simulates a shallow ground motion of magnitude 4.5-5.5 and the earthquake E2 simulates a motion of magnitude 7 close to fault. Earthquake E1 was of 5 sec duration and peak ground accelerations varied between 0.15 g and 0.3 g. Earthquake E2 was of 30 sec duration and peak ground accelerations varied between 0.25 g and 0.4 g. These records were used to determine the maximum displacement response of different single degree of freedom systems having 5% viscous damping.

Trapezoidal lines have been fitted to the elastic spectra of artificial records and amplification factors fa, fv and fd for acceleration, velocity and displacement region of spectra are obtained. The amplification factors of the present study are compared with those obtained by Newmark and Hall (1969), Newmark and Riddell (1980) and

Riddell and Newmark (1979).
This paper presents probabilistic analysis of amplification factors used for generating elastic response spectra for a single degree of freedom system. The probabilistic amplification factors for two different artificial earthquakes are different. It is recommended that analytical probabilistic amplification factors should be obtained for a site for important structures.

**Eduardo[7]** has given the brief summary on previously studies of linear elastic response spectra (LERS) and inelastic response spectra (IRS) by various authors for different ground motions. This study is based on 124 earthquake ground motions recorded on rock, alluvium and soft soil sites. Method of analysis is given to compute the displacement ductility ratio. Various plots are derived based on effects of site conditions on Elastic response spectra and on inelastic response spectra.
The shape of inelastic response spectra differs significantly from the shape of elastic response spectra. The difference between the shape of LERS and IRS increases with increase in ductility. This difference depends on the level of inelastic deformation, the local site conditions, the period of vibration.

**Newmark[16],** have developed vertical and horizontal response spectra for a series of 14 strong motion earthquake records, including four San Fernando records for the various frequencies range and for the 0.5, 2, 5 and 10 percent of critical damping.

The errors in the earthquake records have been discussed by illustrated example and the procedure is explained to correct this errors. The errors are due to a) instrument errors, including effects associated with mounting and instrument housing; and b) the processing of the record where the initial conditions and the zero acceleration line are not known. The procedures to correct this error are a) Parabolic baseline adjustment and b) Segmental adjustment.

The non dimensional ratio $ad/v^2$, is in part a function of the focal distance of the

earthquake and the attenuation of motion in the ground. The ratio increases as the focal distance decreases. This ratio provides some bound on the relative magnitude of ground motion and it is important in selection of ground motions for use in constructing the design spectra. Various ranges of this ratio and method to average it are discussed. $v/a$ ratio and $a_v/a_h$ ratio are discussed for various site condition like rock site, alluvial site and various ranges for these sites are also discussed.
Amplification factors for given ground motions in different frequencies ranges and for various probability percentile are concluded. Based on all these values, design spectrum is generated for horizontal and vertical motions.

**Freeman[10]** traces the development of building code provisions and the relationship to response spectra. The author has developed response spectra for the ground motion recorded at the ground level of the Holiday Inn hotel structure during the Northridge earthquake of January 1994 in California, U.S.A. Response spectra used for design tend to be smooth curves, whereas response spectra obtained from ground motion recordings are generally very ragged with sharp spikes and valleys. The effects of these differences are discussed along with recommendations on how to graphically smooth out the curves.

When earthquake ground motion data is available, the use of response spectra can be very useful in understanding how buildings perform and to identify deficiencies and damage potential. For single-degree-of-freedom systems responding in a linearly elastic manner, response spectra give good credible results, assuming that the data is credible. For multi-modal systems, the combination of modes is generally done by SRSS (square root of the sum of the squares) or CQC (complete quadratic combination) rule. Although these rules are based on probability approximations, the results are generally reasonable. The more technical time-history method is generally considered more exact.

## 2.4 Seismic Code Comparison of Various Countries

Five countries codes are considered to compare various parameters and design spectrum to evaluate the lateral force for the structures. Some papers are considered to compare different parameters in various codes. The codes are listed as below:

1) Mexico
2) U.S.A.
3) Chile
4) Philippines
5) China

**Benito, Bernal, Torres and Hermanns[12]** has presented comparative analysis between the elastic response spectra for different European codes like: Spanish building code NSCE-02, Eurocode 8 (EC-8), Italian building code NTC-08 and National Annex to EC-8 for Portugal and France. Comparison of the response spectra given by the Spanish code NCSE-02 with the other ones anchored with similar acceleration on rock site. Comparison of the response spectra close to the Portugal-Spain and France-Spain boundaries using all the parameters defined by the respective codes is made.
None of the analyzed European codes, Portugal National Annex to EC-08 (PNA-EC8), French National Annex to EC-08 (FNA-EC8) and Italian Building Code (NTC08) adopt the parameters proposed by default in EC-8 for the construction of the elastic response spectra, changing soil factors in the case of PNA-EC8, FNA-EC8 and introducing a complete change of philosophy in the Italian Building Code NTC-08. The amplification factor defined in NCSE-02 as in the response spectra is used by almost all the analyzed normative.

**Edoardo, Masayoshi, Khalid [23]** have compared EuroCode 8 (EC8) and the Japanese seismic design code (BCJ) for steel moment frames and braced frames. Soil classification, magnitude and shape of unreduced elastic response spectra, distribution of seismic shear along the height, member ductility requirements, and behavior factor are compared. It was found that the two codes are relatively similar except for the seismic force stipulated for the serviceability limit state. EC8 gives an approximately 2.5 times larger force for this limit state. Although the behavior factor is less conservative in EC8, the net strength required by EC8 is significantly greater than the corresponding BCJ strength for steel moment frames, and it occurs because of the significantly larger design force stipulated for serviceability in EC8.

The unreduced spectra corresponding to the strong ground motions stipulated in EC8 and BCJ are comparable.With reference to the moderate earthquakes, design spectra provided by EC8 are significantly larger. For systems having time period less than 1.0 s, EC8 spectra may be up to three times its BCJ counterpart. Because of the large design seismic forces stipulated for the serviceability limit state, the story drift requirement in EC8 appears significantly more stringent than that required in BCJ. Seismic design of moment-resisting frames is generally controlled by the serviceability requirements. Because of the large seismic forces corresponding to moderate ground motions stipulated in EC8, European frames hold a larger lateral story strength, by up to 70% for soft soil and systems having time period less than 0.8 s. For frames with diagonal braces, the lateral story strength required by BCJ is about twice that required by EC8. The lateral story strength of European chevron frames is significantly larger than its Japanese counterpart when slender braces are used. It is about 70% larger in the considered case. This difference occurs primarily because the brace strength estimated by EC8 is significantly more conservative than that estimated by BCJ.

**Noor, Ansary and Seraj [24]** have reviewed and compared Uniform Building Code (UBC) 1994 edition, The Criteria for Earthquake Resistant Design Standard Institutes (IS) 1984 editions, the National Building Code of Canada (NBC) 1995 editions, the Building Standard Law of Japan (BSLJ) 1987 editions. Different parameters like zone factor, importance factor, structural system factor, site geology and soil char-

acteristics, time period etc. which calculates the base shear has been compared and evaluated. Moment resisting concrete and steel buildings have been considered for analysis purpose. STRAND6 software has been used to compare code listed time period. It has been observed that for calculating base shear in the equivalent static methods almost all codes of practices adopt similar definitions for the numerical coefficient of the base shear formula.
A direct comparison of seismic forces is not possible because there are large differences in the seismic intensity from country to country, leading to differences in the design value of zone factor Z. Observations of structural systems responding in the inelastic range indicate that as the structure yields, the period, damping and other dynamic properties change. The effect of these changes in dynamic properties is that, while the force level actually experienced by the structure are greater than those used in design, they are less than those that would occur in a fully elastic response. It is expected that in future seismic conditions will be described in terms of a system of maps with different return periods and construction verification criteria of structures along with the importance of the structures.

**Santos, Lima and Arai[11]** has compared general evaluation of the South American seismic codes with the American Standard ASCE/SEI 7/10 and with the European Standard Eurocode 8.

This study is focused in some critical topics like definitions of the recurrence periods for establishing the seismic input,seismic zonation and design ground motion values, the shape of the design response spectra. It also considered the study of soil amplification, soil liquefaction and soil-structure interaction, classification of the structures in different importance levels, the seismic force resisting systems and respective response modification coefficients, consideration of structural irregularities and the allowable procedures for the seismic analysis.

The comparison of above criteria is analyzed through numerical example. In figure

2.1, comparison is made for elastic response spectra according the several standards. This graph is between spectral acceleration-time period. ASCE-2010 American standards shows the maximum spectral acceleration as compared to other standards.

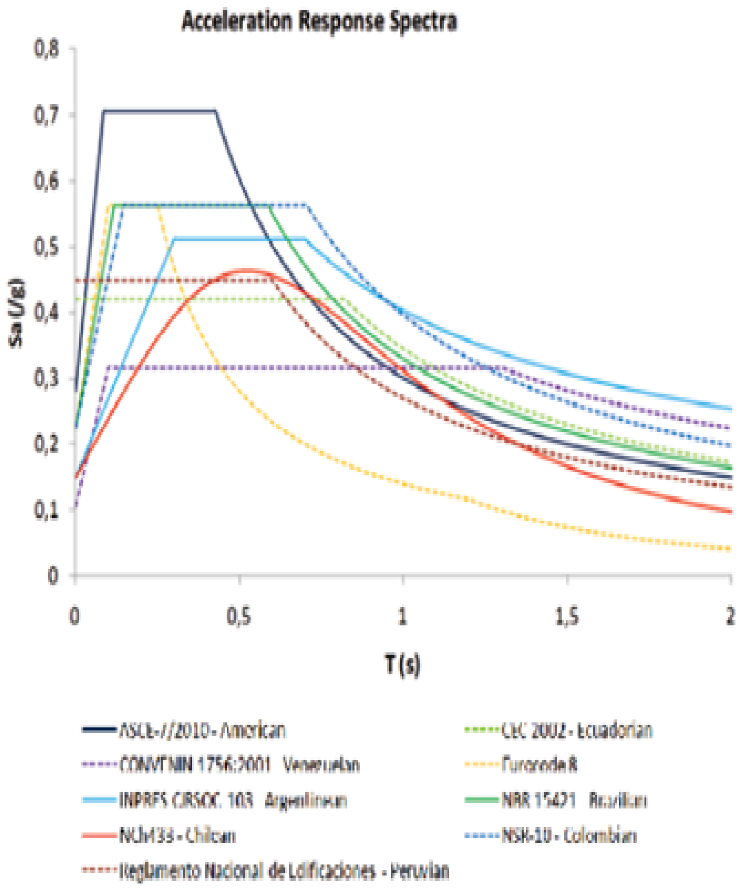


Figure 2.1: Elastic response spectra according the several standards

## 2.5 Summary

In this chapter, review of some important and relevant literatures is summarized. The review of literature includes various methodology adopted by various researchers to develop design spectrum, various factors considered to construct design spectrum and comparison of different codes considering some critical topics.

# Chapter 3

# Development of Response Spectrum

## 3.1 Introduction

The response of structures to ground shaking caused by an earthquake is the one of the most important applications of the theory of structural dynamics. The earthquake response of single degree of freedom systems to earthquake motions is discussed in this chapter. Analytical solution of the equation of motion for a single degree of freedom system is not possible if ground acceleration varies with time. Problems related to structures come under the ground excitation are falls in this category. Such problems can be tackled by numerical time-stepping methods for integration of differential equations. Equation of motion for SDOF system subjected to ground excitation is solved by using Newmark-Beta method through MATLAB. All available ground motion data for Indian context are verified through numerical integration method. Tripartite plot of four regions is developed on four way logarithmic plot.

## 3.2 Characteristics of Ground Motion

Ground motion parameters are essential for describing the important characteristics of strong ground motion. Many parameters are proposed to characterize the strong ground motions. Amplitude, Frequency content and Duration of strong ground motion are the important characteristics for which the parameters are defined.

1) **Amplitude parameters**
   - Peak ground acceleration (PGA)
   - Peak ground velocity (PGV)
   - Peak ground displacement (PGD)
2) **Frequency content parameters**
   - Fourier spectra
   - Response spectra
3) **Duration of strong ground motion**
4) **Other parameters**
   - Root mean square acceleration (RMSa)
   - Arias intensity

The above parameters are briefly described as below :

1) **Amplitude parameters** Time history is the most common way to describe a ground motion. The ground motion parameters are acceleration, velocity and displacement. Out of the three amplitude parameters, only one of these is recorded directly and the others are computed from it by integration/differentiation. The acceleration time history displays more high frequency content (relatively), the velocity time history displays more intermediate frequency content (relatively), and the displacement displays more low frequency content (relatively). The peak acceleration provides a good indication of the high-frequency component of a ground motion. The peak velocity and peak displacement describe the amplitudes of the intermediate and low frequency components respectively.

2) **Frequency content** It is generally described through the use of different types of spectra. Fourier spectra and power spectra directly illustrate the frequency content of the motion itself. Response spectra reflect the influence of the ground motion on structures of different natural periods. Since the frequency content of an earthquake motion will strongly influence the effects of that motion, characterization of the motion cannot be completed without consideration of its frequency content.

3) **Duration of motion** The duration of strong ground motion have a strong influence on earthquake damage. An earthquake accelerogram generally contains all accelerations from the time the earthquake begins until the time the motion has returned to the level of background noise. For engineering purposes, only the strong motion portion of an accelerogram is of interest. Different approaches have been taken to evaluate the duration of strong motion in an accelerogram. Since the total duration of an accelerogram depends on the pre and post-event intervals, for digital records, it is not possible to define the duration of strong shaking as simply the time between the start and finish of an accelerogram. Many definitions of strong-motion duration have been proposed to isolate a certain portion of the accelerogram during which the strongest motion occurs. It is found that all of these definitions can be classified into one of three generic categories.

   **Bracketed duration**

   It is defined as the total time elapsed between the first and last excursions of a specified threshold acceleration.

   **Uniform duration**

   It is defined as the sum of the time interval during which the acceleration is greater than a given threshold.

   **Significant duration**

   It is defined as the time interval over which a portion of the total energy integral is accumulated. It is calculated as the integral of the square of the ground acceleration, velocity or displacement. If the integral of the ground acceleration is performed then the quantity is related to the Arias intensity, AI. It is defined as

$$AI = \frac{\Pi}{2g}\int_0^t a^2(t)dt \tag{3.1}$$

where a(t) is the acceleration time history, t is the total duration of the accelerogram and g is acceleration due to gravity.

## 3.3 Equation of Motion for Earthquake Excitation

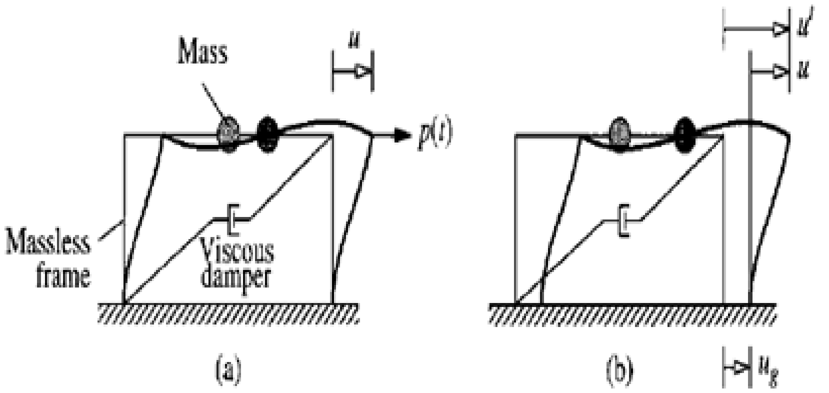


Figure 3.1: Single Degree of Freedom System: (a) Applied Force p(t); (b) Earthquake Induced Ground Motion[1]

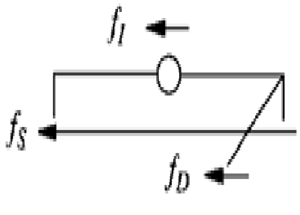


Figure 3.2: Freebody Diagram of Forces[1]

The system considered as a single storey structure consists of a mass ’m’ concentrated at the roof level, a massless frame that provides stiffness to the system and a viscous damper that dissipates the energy. This system is constrained to move only in the direction of the excitation - lateral displacement, so it is called single degree of freedom system.

In this system the displacement of the ground is denoted by $u_g$, the total displacement of the mass by $u^t$ and the relative displacement between the mass and ground by u. At each instant of time these displacements are related by

$$u^t(t) = u(t) + u_g(t) \tag{3.2}$$

Considering dynamic equilibrium, $f_I$ denotes the inertia force, $f_S$ the spring force and $f_D$ denotes the damping force the equation is,

$$f_I + f_D + f_S = 0 \tag{3.3}$$

As the structure is linearly elastic, therefore elastic resisting force is,

$$f_S = ku \tag{3.4}$$

The viscous damping force $f_D$ is assumed to vary linearly with relative velocity $c\dot{u}$, so for a linear system the damping force is,

$$f_D = c\dot{u} \tag{3.5}$$

The inertia force is equal to the product of mass times its acceleration and acts opposite to the direction of acceleration. It is related to the total acceleration $\ddot{u}^t$ at the mass by,

$$f_I = m\ddot{u}^t \tag{3.6}$$

Substituting equation 3.3, 3.4 and 3.5 in equation 3.2

$$m\ddot{u}^t + c\dot{u} + k(u) = 0 \tag{3.7}$$

$$m\ddot{u}(t) + c\dot{u}(t) + ku(t) = -m\ddot{u}_g(t) \tag{3.8}$$

## 3.4 Solution of Equation of Motion

Following equations of time-stepping methods is developed by N. M. Newmark:

$$\dot{u}_{i+1} = \dot{u}_i + [(1-\gamma)\Delta t]\ddot{u}_i + (\gamma\Delta t)\ddot{u}_{i+1} \tag{3.9}$$

$$u_{i+1} = u_i + (\Delta t)\dot{u}_i + [(0.5-\beta)(\Delta t)^2]\ddot{u}_i + [\beta(\Delta t)^2]\ddot{u}_{i+1} \tag{3.10}$$

In above equations $\beta$ and $\gamma$ parameters provides the variations of acceleration over a time step. These parameters also determine the stability and accuracy characteristics of the method. At the end of time step, the equilibrium equation is combined with these two equations to provide the basis for computing $u_{i+1}$, $\dot{u}_{i+1}$ and $\ddot{u}_{i+1}$ at time i+1 from the known $u_i$, $\dot{u}_i$ and $\ddot{u}_i$ at time i. Two special cases of Newmark's method are as follows:

1) Average acceleration method ($\gamma$ =1/2, $\beta$ =1/4)

2) Linear Acceleration method ($\gamma$ =1/2, $\beta$ = 1/6 )

The complete algorithm using the Newmark Beta integration method is given in Table 3.1.

Table 3.1: Algorithm of Newmark Beta Method[1]

**1)Initial calculation**

**(1.1)** Form stiffness matrix [k], mass matrix [m] and damping matrix [c]

**(1.2)** Specify integration parameter $\gamma$ and $\beta$

**(1.3)** Specify initial conditions $u_0$, $\dot{u}_0$, $\ddot{u}_0$

**(1.4)** $\ddot{u}_0 = \frac{p_0 - c\dot{u}_0 - ku_0}{m}$

**(1.5)** Select $\Delta$t time interval

**(1.6)** Calculate modified stiffness, $\widehat{k}$ = k + $\frac{\gamma}{\beta \Delta t}$c + $\frac{1}{\beta (\Delta t)^2}$m

**(1.7)** Calculate constants, a = $\frac{1}{\beta \Delta t}$m + $\frac{\gamma}{\beta}$c; and b = $\frac{1}{2\beta}$m + $\Delta$t($\frac{\gamma}{2\beta}$-1)c.

**2) Calculation for each time step, *i***

**(2.1)** $\Delta\ \widehat{p_i} = \Delta p_i$ + a$\dot{u}_i$ + b$\ddot{u}_i$

**(2.2)** $\Delta u_i = \frac{\Delta \widehat{p}_i}{\widehat{k}}$

**(2.3)** $\Delta\ \dot{u}_i = \frac{\gamma}{\beta \Delta t}\Delta u_i$ - $\frac{\gamma}{\beta}\ \dot{u}_i$ + $\Delta$t(1-$\frac{\gamma}{2\beta}$)$\ddot{u}_i$.

**(2.4)** $\Delta\ \ddot{u}_i = \frac{1}{\beta(\Delta t)^2}\Delta u_i$ - $\frac{1}{\beta \Delta t}\ \dot{u}_i$ - $\frac{1}{2\beta}\ddot{u}_i$

**(2.5)** $u_{i+1} = u_i + \Delta u_i$, $\dot{u}_{i+1} = \dot{u}_i + \Delta \dot{u}_i$ and $\ddot{u}_{i+1} = \ddot{u}_i + \Delta \ddot{u}_i$

**3) Repetition for the next time step. Replace *i* by *i* + 1 and implement steps 2.1 to 2.5 for the next time step.**

As per the algorithm of Newmark Beta method, parameters like $\beta$ and $\gamma$ is to be specified as per the case consideration discussed above. Initial conditions of ground displacement ($u_0$), ground velocity ($\dot{u}_0$) and ground acceleration ($\ddot{u}_0$) are to be specified. Time interval is to be selected. $\widehat{k}$ and $\Delta\ \widehat{p_i}$ can be found from system properties mass, stiffness and damping and incremental displacement $\Delta u_i$ can be computed. Once $\Delta u_i$ is known, incremental velocity $\Delta\ \dot{u}_i$ and incremental acceleration $\Delta\ \ddot{u}_i$ can be computed from the equations given in the algorithm. These all steps are to be repeated for the next time step i+1.

## 3.5 Compilation of Ground Motions for Indian Sub-continent

A set of 184 Indian time histories (23 earthquake events) has been collected from different regions of the country for the detailed study. Table 3.2 shows various earthquake events at various recording stations in different regions of the country recorded by the instruments installed under the strong motion instrumentation programme. This programme was started in the mid-sixties by the Department of Earthquake Engineering, Indian Institute of Technology, Roorkee. Table 3.3 shows various earthquake ground motion records after 2005 of the country which are made available through web portal. Primarily the recorded time histories are grouped according to four zones North, East, South and West of the country which are shown in Table 3.2. It is seen from the Table 3.2 that large number of records are available for East region and North region. It is noted that records of strong earthquake ground motions are limited in number for West region followed by South region.

Table 3.2: Events Recorded by Indian Strong Motion Instrument Network[13]

| **Events** | **Recording** Station | **Magnitude** | **PGA** ($g$) | **Recorded time** ($sec$) |
|---|---|---|---|---|
| Dharmsala | Bandlakhas | 5.5 | 0.145 | 10.8 |
| | Baroh | | 0.059 | 13.78 |
| | Bhawarna | | 0.037 | 11.98 |
| | Dharmsala | | 0.175 | 16.18 |
| | Jawali | | 0.015 | 17.96 |
| | Kangra | | 0.148 | 20.66 |
| | Nagrotabagwan | | 0.149 | 20.3 |
| | Shahpur | | 0.204 | 20.1 |
| | Sihunta | | 0.051 | 17.62 |
| North-East India | Baithalongso | 5.2 | 0.045 | 12.56 |
| | Dauki | | 0.089 | 17.9 |
| | Khliehriat | | 0.031 | 13.4 |
| | Nongkhlaw | | 0.055 | 29.64 |
| | Nongpoh | | 0.054 | 14.08 |
| | Nongstoin | | 0.019 | 8.54 |
| | Panimur | | 0.039 | 11.02 |
| | Pynursla | | 0.093 | 18.58 |
| | Saitsama | | 0.113 | 20.66 |
| | Ummulong | | 0.113 | 16.94 |
| | Umrongso | | 0.027 | 11.76 |
| | Umsning | | 0.101 | 20.06 |
| India-Burma border 1987 | Baithalongso | 5.7 | 0.034 | 22.34 |
| | Bamungao | | 0.019 | 29.48 |
| | Berlongfer | | 0.072 | 42.76 |
| | Bokajan | | 0.029 | 26.00 |
| | Diphu | | 0.086 | 39.10 |
| | Gunjung | | 0.042 | 16.04 |
| | Haflong | | 0.055 | 13.54 |
| | Hajadisa | | 0.078 | 16.56 |
| | Hatikhali | | 0.031 | 36.22 |
| | Laisong | | 0.042 | 16.78 |
| | Nongpoh | | 0.017 | 20.48 |
| | Panimur | | 0.04 | 10.96 |
| | Saitsama | | 0.037 | 27.52 |
| | Umrongso | | 0.02 | 12.24 |
| India-Bangladesh border 1988 | Baigao | 5.8 | 0.022 | 12.92 |
| | Baithalongso | | 0.03 | 11.72 |
| | Bamungao | | 0.016 | 8.86 |
| | Dauki | | 0.027 | 9.52 |
| | Gunjung | | 0.036 | 13.02 |

Table: 3.2 Events Recorded by Indian Strong Motion Instrument Network[13](Continued...)

| **Events** | **Recording** Station | **Magnitude** | **PGA** ($g$) | **Recorded time** ($sec$) |
|---|---|---|---|---|
| | Haflong | | 0.035 | 10.12 |
| | Hatikhali | | 0.024 | 11.80 |
| | Katakhal | | 0.009 | 10.38 |
| | Khliehriat | | 0.079 | 15.08 |
| | Mawphlang | | 0.081 | 28.16 |
| | Nongkhlaw | | 0.107 | 45.28 |
| | Nongpoh | | 0.027 | 17.72 |
| | Pynursla | | 0.049 | 34.60 |
| | Saitsama | | 0.066 | 15.76 |
| | Shillong | | 0.048 | 11.74 |
| | Ummulong | | 0.056 | 24.52 |
| | Umrongso | | 0.046 | 14.86 |
| | Umsning | | 0.039 | 23.86 |
| India-Burma border 1988 | Baigao | 6.8 | 0.0221 | 54.82 |
| | Baithalongso | | 0.154 | 78.08 |
| | Bamungao | | 0.093 | 38.58 |
| | Berlongfer | | 0.301 | 119.70 |
| | Bokajan | | 0.151 | 57.78 |
| | Cherrapunji | | 0.052 | 21.28 |
| | Dauki | | 0.108 | 34.84 |
| | Diphu | | 0.282 | 81.74 |
| | Doloo | | 0.064 | 38.26 |
| | Gunjung | | 0.094 | 63.90 |
| | Hajadisa | | 0.092 | 64.20 |
| | Harengajao | | 0.065 | 30.50 |
| | Hojai | | 0.108 | 63.78 |
| | Jellalpur | | 0.029 | 15.86 |
| | Jhirighat | | 0.107 | 42.34 |
| | Kalain | | 0.057 | 29.70 |
| | Katakhal | | 0.063 | 35.18 |
| | Khliehriat | | 0.07 | 61.5 |
| | Koomber | | 0.049 | 25.46 |
| | Loharghat | | 0.058 | 38.36 |
| | Mawkyrwat | | 0.046 | 22.68 |
| | Mawphlang | | 0.119 | 52.14 |
| | Mawsynram | | 0.085 | 23.70 |
| | Nongkhlaw | | 0.142 | 70.98 |
| | Nongstoin | | 0.052 | 52.96 |
| | Panimur | | 0.168 | 72.06 |
| | Pynursla | | 0.054 | 47.54 |

Table: 3.2 Events Recorded by Indian Strong Motion Instrument Network[13](Continued...)

| **Events** | **Recording** Station | **Magnitude** | **PGA** ($g$) | **Recorded time** ($sec$) |
|---|---|---|---|---|
| | Saitsama | | 0.211 | 81.10 |
| | Shillong | | 0.075 | 34.78 |
| | Silchar | | 0.064 | 46.80 |
| | Ummulong | | 0.09 | 66.14 |
| | Umrongso | | 0.076 | 64.74 |
| | Umsning | | 0.122 | 70.60 |
| India-Burma border 1990 | Baigao | 6.1 | 0.056 | 9.92 |
| | Baithalongso | | 0.061 | 22.00 |
| | Bamungao | | 0.029 | 14.62 |
| | Berlongfer | | 0.145 | 62.84 |
| | Diphu | | 0.092 | 32.24 |
| | Gunjung | | 0.051 | 13.96 |
| | Hajadisa | | 0.054 | 18.94 |
| | Hojai | | 0.041 | 13.04 |
| | Laisong | | 0.062 | 9.04 |
| | Maibang | | 0.064 | 16.44 |
| | Panimur | | 0.077 | 15.68 |
| | Saitsama | | 0.062 | 26.52 |
| | Ummulong | | 0.046 | 11.86 |
| | Umrongso | | 0.036 | 15.22 |
| Uttarkashi 1991* | Almora | 6.5 | 0.018 | 21.34 |
| | Barkot | | 0.095 | 31.74 |
| | Bhatwari | | 0.253 | 36.16 |
| | Ghansiali | | 0.118 | 42.34 |
| | Karnprayag | | 0.062 | 22.26 |
| | Kosani | | 0.029 | 13.36 |
| | Koteshwar | | 0.101 | 33.70 |
| | Koti | | 0.021 | 15.96 |
| | Purola | | 0.075 | 35.70 |
| | Rudraprayag | | 0.053 | 39.70 |
| | Srinagar | | 0.067 | 41.10 |
| | Tehri | | 0.073 | 31.96 |
| | Uttarkashi | | 0.242 | 39.92 |
| Chamba | Chamba | 4.9 | 0.146 | 18.24 |
| | Rakh | | 0.029 | 9.18 |
| India-Burma border 1995 | Baigao | 6.4 | 0.057 | 12.18 |
| | Bamungao | | 0.016 | 12.60 |
| | Berlongfer | | 0.072 | 81.72 |
| | Diphu | | 0.081 | 28.58 |
| | Haflong | | 0.031 | 12.94 |

Table: 3.2 Events Recorded by Indian Strong Motion Instrument Network[13](Continued...)

| **Events** | **Recording** Station | **Magnitude** | **PGA** ($g$) | **Recorded time** ($sec$) |
|---|---|---|---|---|
| | Hatikhali | | 0.044 | 18.84 |
| | Hojai | | 0.022 | 16.50 |
| | Khliehriat | | 0.022 | 13.32 |
| | Umrongso | | 0.023 | 15.96 |
| Xizang-India border | Ukhimath | 4.8 | 0.038 | 15.20 |
| India-Bangladesh border 1997 | Doloo | 5.7 | 0.077 | 27.42 |
| | Jellalpur | | 0.117 | 25.60 |
| | Jowai | | 0.084 | 27.36 |
| | Katakhal | | 0.107 | 26.58 |
| | Nongpoh | | 0.048 | 47.38 |
| | Nongstoin | | 0.048 | 39.02 |
| | Pynursla | | 0.028 | 28.62 |
| | Shillong | | 0.072 | 25.06 |
| | Silchar | | 0.095 | 26.92 |
| | Ummulong | | 0.155 | 28.66 |
| | Umsning | | 0.077 | 27.34 |
| Chamoli 1999* | Almora | 6.4 | 0.027 | 9.04 |
| | Barkot | | 0.017 | 14.98 |
| | Chinaylisaur | | 0.052 | 25.68 |
| | Ghansiali | | 0.073 | 26.32 |
| | Gopeshwar | | 0.199 | 25.42 |
| | Joshimath | | 0.071 | 25.06 |
| | Lansdowne | | 0.005 | 7.12 |
| | Roorkee | | 0.056 | 43.525 |
| | Tehri | | 0.054 | 23.76 |
| | Ukhimath | | 0.091 | 24.78 |
| | Uttarkashi | | 0.054 | 14.76 |
| Kachchh | Ahmedabad | 7.0 | 0.106 | 133.525 |

Table 3.3: Ground Motion Data After 2005 Available Through Web Portal[13]

| **Events** | **Recording** Station | **Magnitude** | **PGA** ($g$) | **Recorded time** ($sec$) |
|---|---|---|---|---|
| Chamoli 2005* | Bageshwar | 5.2 | 0.05425 | 29.995 |
| | Chamoli | | 0.4113 | 44.61 |
| | Champawat | | 0.0311 | 36.93 |
| | Pauri | | 0.105 | 33.745 |
| | Roorkee | | 0.02341 | 66.215 |
| | Rudraprayag | | 0.21455 | 36.965 |
| | Tehri | | 0.05708 | 31.435 |
| | Uttarkashi | | 0.10588 | 39.095 |
| Uttarkashi 2007* | Nathpa | 5.0 | 0.04903 | 40.70 |
| | Roorkee | | 0.01914 | 63.58 |
| Andaman Islands 2008* | Port blair | 6.7 | 0.22505 | 63.41 |
| Nagaland | Tinsukia | 5.1 | 0.02263 | 66.10 |
| Uttarakhand | Champawat | 5.1 | 0.01678 | 70.10 |
| | Dharchula | | 0.04355 | 65.005 |
| | Ghansiali | | 0.0185 | 65.015 |
| | Joshimath | | 0.04852 | 68.51 |
| | Kapkot | | 0.04722 | 67.435 |
| | Munsiari | | 0.09464 | 70.085 |
| | Pithoragarh | | 0.03444 | 76.56 |
| Andaman Islands 2010* | Port blair | 7.8 | 0.04073 | 181.435 |
| India-Myanmar border (Manipur) | Coochbihar | 6.4 | 0.03903 | 80.005 |
| | Guwahati | | 0.18383 | 164.795 |
| | Jorhat | | 0.03932 | 95.10 |
| | Jowai | | 0.14172 | 93.05 |
| | Khokhrajhat | | 0.06996 | 100.72 |
| | Naogaon | | 0.32113 | 135.445 |
| | Sibsagar | | 0.03212 | 67.795 |
| Assam | Golaghat | 5.4 | 0.08996 | 66.69 |
| | Jorhat | | 0.04763 | 81.48 |
| | Khokhrajhar | | 0.05925 | 110.995 |
| Phek (Nagaland) | Golaghat | 5.8 | 0.14703 | 76.555 |
| | Jorhat | | 0.10267 | 97.29 |
| | Tinsukia | | 0.04046 | 65.00 |
| Kohima (Nagaland) | Golaghat | 5.5 | 0.16254 | 79.475 |
| | Jorhat | | 0.0901 | 128.87 |
| | Naogaon | | 0.05932 | 84.595 |

* Two different records at the same location are included in the study. Table 3.3 shows the ground motion records which took place after 2005. In order to describe accurately the highly irregular variation of acceleration, the time variation was choosen to be 0.005second and 0.02 second for the records shown in Table 3.2 and 3.3. Listing of the earthquakes in each region of the country are presented in Table 3.4.

Table 3.4: Classification of Earthquake Records into Four Regions[13]

| **Region** | **Events** | **Recording Station** |
|---|---|---|
| East | North-East India | 12 |
| | India-Burma border 1987 | 14 |
| | India-Bangladesh border 1987 | 18 |
| | India-Burma border 1988 | 33 |
| | India-Burma border 1990 | 14 |
| | India-Burma border 1995 | 9 |
| | India-Bangladesh border 1997 | 11 |
| | Nagaland | 1 |
| | India-Myanmar border (Manipur) | 7 |
| | Assam | 3 |
| | Phek | 3 |
| | Kohima | 3 |
| North | Dharmsala | 9 |
| | Uttarkashi 1991 | 13 |
| | Chamba | 2 |
| | Xizang-India border | 1 |
| | Chamoli 1999 | 11 |
| | Chamoli 2005 | 8 |
| | Uttarkashi | 7 |
| | Uttarakhand | 7 |
| South-East | Andaman Island 2008 | 1 |
| | Andaman Island 2010 | 1 |
| West | Kachchh | 1 |

In the present study, there are total 184 ground motion records from past 23 earthquake events of India, out of which 67 are classified as strong ground motions based on the peak ground acceleration values and strong motion duration which is calculated by selecting r.m.s. acceleration and a threshold value. Table 3.5 shows all the 67 classified strong ground motions from 23 earthquake events for different regions of our country.

Table 3.5: Available Indian Strong Ground Motion Earthquake Records[13]

| **Region** | **Recording Station** | **PGA** ($m/sec^2$) | **Recorded Time (s)** | **R.M.S. value** ($m/sec^2$) | **Strong Motion Duration (s)** |
|---|---|---|---|---|---|
| Dharmsala | Bhawarna | 0.365 | 11.98 | 0.06042 | 11.26 |
| | Jawali | 0.149 | 17.96 | 0.03455 | 17.90 |
| | Shahpur | 2.00 | 20.10 | 0.19083 | 4.22 |
| North-East India | Nongkhlaw | 0.539 | 29.64 | 0.0878 | 20.98 |
| | Pynursla | 0.91 | 18.58 | 0.11357 | 12.96 |
| | Saitsama | 1.11 | 20.66 | 0.12153 | 9.84 |
| | Ummulong | 1.11 | 16.94 | 0.12409 | 10.54 |
| India-Burma border 1987 | Bamungao | 0.194 | 29.48 | 0.04464 | 29.16 |
| | Berlongfer | 0.706 | 42.76 | 0.12665 | 35.70 |
| | Diphu | 0.843 | 39.10 | 0.13374 | 36.16 |
| | Hatikhali | 0.305 | 36.22 | 0.06453 | 35.56 |
| | Saitsama | 0.364 | 27.52 | 0.084 | 25.36 |
| India-Bangladesh border 1988 | Mawphlang | 0.796 | 28.16 | 0.166 | 24.76 |
| | Nongkhlaw | 1.05 | 45.28 | 0.1084 | 35.22 |
| | Pynursla | 0.487 | 34.60 | 0.0689 | 29.86 |
| | Ummulong | 0.553 | 24.52 | 0.08593 | 23.84 |
| | Umsning | 0.39 | 23.86 | 0.0735 | 23.82 |
| India-Burma border 1988 | Baithalongso | 1.51 | 78.08 | 0.23523 | 66.36 |
| | Berlongfer | 2.95 | 119.70 | 0.2949 | 44.86 |
| | Hajadisa | 0.902 | 64.20 | 0.15697 | 51.10 |
| | Khliehriat | 0.688 | 61.50 | 0.11547 | 57.06 |
| | Panimur | 1.65 | 72.06 | 0.2455 | 62.36 |
| | Saitsama | 2.07 | 81.10 | 0.28524 | 58.10 |
| | Ummulong | 0.886 | 66.14 | 0.1717 | 53.56 |
| | Umrongso | 0.748 | 64.74 | 0.14623 | 55.26 |
| | Umsning | 1.20 | 70.60 | 0.18582 | 56.72 |
| India-Burma border 1990 | Baithalongso | 0.603 | 22.00 | 0.13487 | 21.54 |
| | Berlongfer | 1.42 | 62.84 | 0.15972 | 21.82 |
| | Diphu | 0.898 | 32.24 | 0.16487 | 20.12 |
| | Saitsama | 0.61 | 26.52 | 0.12 | 22.96 |
| Uttarkashi | Bhatwari | 2.48 | 36.16 | 0.35314 | 11.04 |
| | Rudraprayag | 0.523 | 39.70 | 0.13157 | 32.22 |
| | Srinagar | 0.654 | 41.10 | 0.11265 | 37.24 |
| | Uttarkashi | 2.37 | 39.92 | 0.34458 | 10.72 |
| Chamba | Chamba | 1.43 | 18.24 | 0.1635 | 5.40 |
| | Rakh | 0.29 | 9.18 | 0.0541 | 5.90 |
| India-Burma border 1995 | Berlongfer | 0.707 | 81.72 | 0.08521 | 60.46 |
| | Diphu | 0.790 | 28.58 | 0.16141 | 21.60 |
| | Hatikhali | 0.437 | 18.84 | 0.09236 | 17.04 |

Table 3.5: Available Indian Strong Ground Motion Earthquake Records[13] (Continued...)

| | | | | | |
|---|---|---|---|---|---|
| Xizang-India border | Ukhimath | 0.371 | 15.20 | 0.06097 | 4.76 |
| India-Bangladesh border 1997 | Katakhal | 1.05 | 26.58 | 0.20927 | 19.22 |
| | Nongpoh | 0.476 | 47.38 | 0.05278 | 40.30 |
| | Nongstoin | 0.469 | 39.02 | 0.07386 | 31.12 |
| | Pynursla | 0.279 | 28.62 | 0.05826 | 25.20 |
| Chamoli 1999 | Ghansiali | 0.714 | 26.32 | 0.1619 | 26.22 |
| | Gopeshwar | 1.95 | 25.42 | 0.267 | 15.78 |
| | Roorkee | 0.554 | 43.525 | 0.07948 | 37.95 |
| | Ukhimath | 0.891 | 24.78 | 0.14311 | 21.20 |
| Kachchh | Ahmedabad | 1.04 | 133.525 | 0.11335 | 54.765 |
| Chamoli 2005 | Chamoli | 0.411 | 44.61 | 0.05032 | 17.173 |
| | Roorkee | 0.023 | 66.215 | 0.00347 | 54.666 |
| Uttarkashi 2007 | Nathpa | 0.049 | 40.70 | 0.00907 | 34.955 |
| | Roorkee | 0.019 | 63.58 | 0.0036 | 56.095 |
| Andaman Islands 2008 | Port blair | 0.225 | 63.41 | 0.0384 | 35.972 |
| Nagaland | Tinsukia | 0.023 | 66.10 | 0.00314 | 45.066 |
| Uttarakhand | Champawat | 0.017 | 70.10 | 0.00164 | 42.127 |
| | Munsiari | 0.095 | 70.085 | 0.0083 | 20.628 |
| | Pithoragarh | 0.034 | 76.56 | 0.00354 | 41.757 |
| Andaman Islands 2010 | Port blair | 0.041 | 181.435 | 0.00496 | 127.566 |
| India-Myanmar (Manipur) border | Guwahati | 0.184 | 164.795 | 0.01416 | 85.557 |
| | Jorhat | 0.039 | 95.10 | 0.00826 | 94.285 |
| | Naogaon | 0.321 | 135.445 | 0.026 | 75.712 |
| Assam | Golaghat | 0.09 | 66.69 | 0.0179 | 42.262 |
| | Khokhrajhar | 0.059 | 110.995 | 0.00722 | 77.99 |
| Phek (Nagaland) | Golaghat | 0.147 | 76.555 | 0.0146 | 58.0812 |
| Kohima (Nagaland) | Golaghat | 0.162 | 79.475 | 0.0139 | 66.826 |
| | Jorhat | 0.09 | 128.87 | 0.01 | 94.62 |

## 3.6 Verifications of Ground motions for Indian Subcontinent

Since the digitized records from the instruments are in terms of acceleration time-histories, the corresponding velocity and displacement are obtained by integration. The errors in earthquake records may arise from any number of sources such as (i) the instrument errors, including effects associated with mounting and instrument housing; and (ii) the processing of the record where the initial conditions (some motion is required to trigger the mechanism) and the zero acceleration line are not known. The errors in the velocity and displacement time-histories arising from integration of the accelerogram are largely associated with the latter category. To verify the available ground motion data, it is required to apply numerical integration method and study the plot of acceleration, velocity and displacement versus time period. In order to minimize the record processing errors, the initial conditions are taken as zero, and a baseline correction is to be applied to the accelerogram record. Among various baseline adjustment procedures, one which minimizes the square of the error in the velocity is most commonly used. This procedure assumes a polynomial, usually a second degree, for the correct acceleration baseline. Segmental adjustment is also another method for the acceleration baseline adjustment.

All acceleration ground motion data for 23 earthquake events and 67 stations are available, which is integrated through numerical integration method to find velocity-time period plot and double integration is done to find displacement-time period plot. MATLAB code is developed for numerical integration method. Figure 3.3 and Figure3.4 shows original acceleration record followed by velocity and displacement response derived through numerical integration for Champawat (Chamoli) and Nicobar (Portblair) station respectively. It is evident from Figure 3.3 and Figure3.4 that time history is already adjusted and no adjustment is required for these records. Same procedure is followed for all 67 strong ground motion time histories and all are found adjusted.

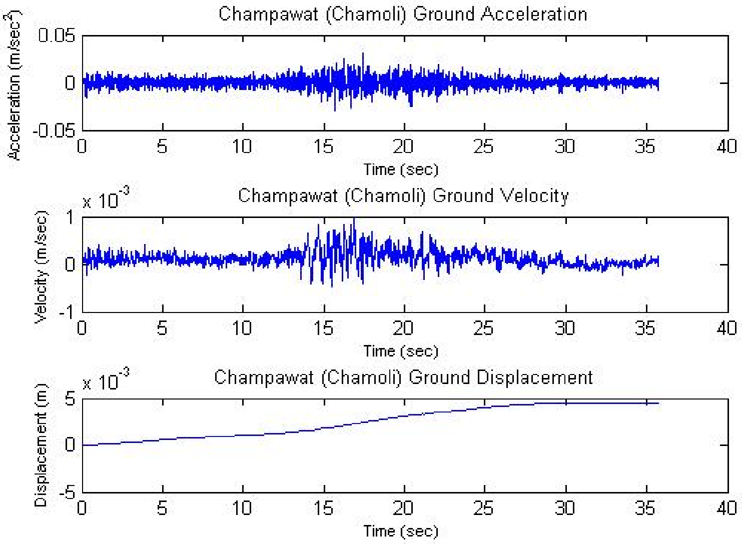


Figure 3.3: Champawat (Chamoli) Ground Acceleration, Ground Velocity, Ground Displacement

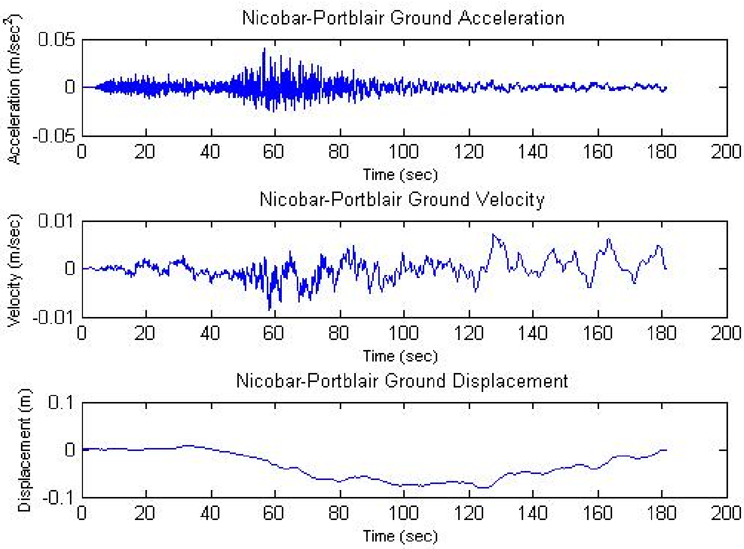


Figure 3.4: Nicobar (Portblair) Ground Acceleration, Ground Velocity, Ground Displacement

## 3.7 Development of Response Spectrum

In this section, method to construct Response Spectrum by obtaining response quantities is shown under El Centro earthquake excitation. In order to obtain response quantity, equation of motion is solved using Newmark-Beta method through MATLAB. The response spectrum for El Centro ground motion component $\ddot{u}_i(t)$ is developed by implementing following steps :

1. Collect the ground motion data of an El Centro earthquake. Define the ground acceleration $\ddot{u}_g(t)$ numerically. This ground motion ordinates are defined at time interval of 0.02 second.

2. Select the natural vibration period $T_n$ and damping ratio $\zeta$ of a SDOF system.

3. Compute the deformation response u(t) of this SDOF system due to the ground Motion $\ddot{u}_g(t)$ by any of numerical methods such as Newmark-Beta method, Runge-Kutta method etc.

4. Determine maximum deformation ($u_o$) which is the peak value of relative deformation u(t).

5. Determine the spectral ordinates using relation $V = \omega_n D$ and $A = \omega_n^2 D$.

6. Repeat steps 2 to 5 for a different range of $T_n$ and $\zeta$ values which covers all possible systems of engineering interest.

7. Present the results of steps 2 to 6 graphically to produce three separate spectra.

In order to validate solution technique adopted to determine response spectrum, N-S Component of El Centro ground motion available in Chopra is considered for 3000 SDOF systems. The response spectrum is generated by MATLAB code and is compared with the results given in book of Chopra.

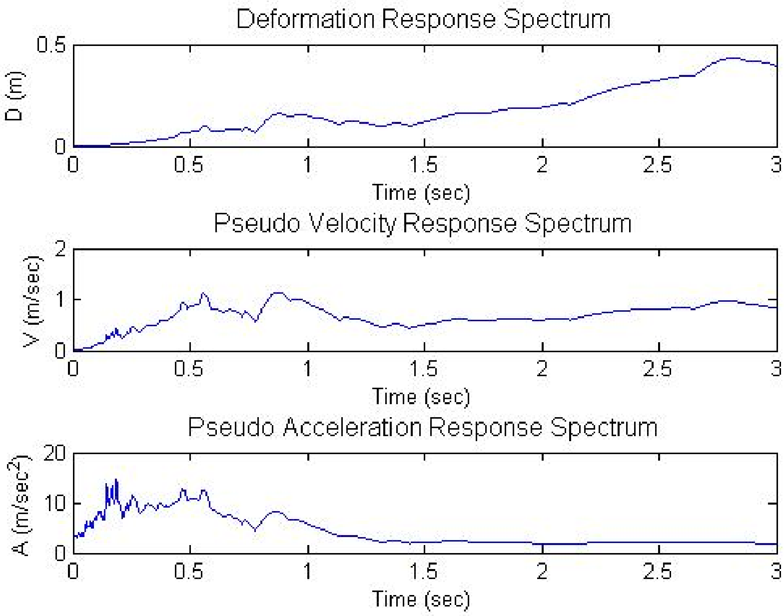


Figure 3.5: Elcentro Deformation, Pseudo-Velocity, Pseudo-Acceleration Response Spectrum

After the development of El-centro response spectrum, this MATLAB code is used to develop the response spectrum for available time histories in Indian context. Figure 3.6 shows Champawat (Chamoli) response spectrum for deformation, pseudo velocity and pseudo acceleration.

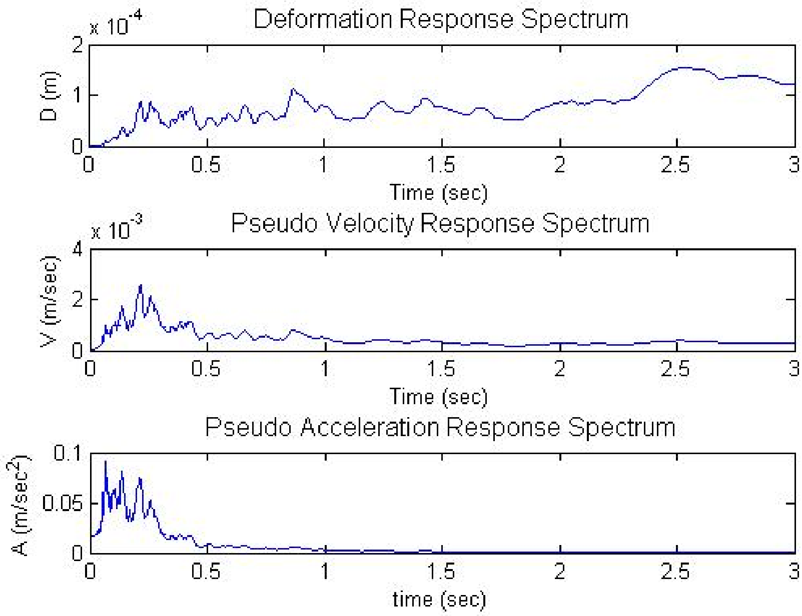


Figure 3.6: Champawat (Chamoli) Ground Acceleration, Ground Velocity Ground Displacement

## 3.8 Tripartite Response Spectrum

Each of the deformation, pseudo-velocity and pseudo-acceleration response spectra for a given ground motion contains the same information, only the way of presenting them is different. If any one of the spectra is known, the other two are easily obtained. Each spectrum directly provides a physically meaningful quantity i.e. the deformation spectrum provides the peak deformation of a system, the pseudo-velocity spectrum is related directly to the peak strain energy stored in the system during the earthquake and the pseudo-acceleration spectrum is related directly to the peak value of the equivalent static force and base shear. So it is especially useful to show all of the three spectral quantities in a combined plot known as the tripartite plot. All spectral quantities, like displacement, velocity and acceleration are displayed in a single graph (on log-log scale), known as the tripartite graph. The computed response spectrum shows correct behavior at both short and long periods, that is, the pseudo-acceleration (A) approaches PGA at short periods and the relative deformation (D) approaches

PGD at long periods. The pseudo-velocity (V) is read along the vertical axis, the pseudo-acceleration (A) is read along the -45 axis, and the relative deformation is read along the +45 axis, with respect to the natural period T along the horizontal axis. Relationship between pseudo-acceleration, pseudo-velocity and displacement is

$$A/\omega_n = V = \omega_n D \tag{3.11}$$

In terms of natural time period $T_n$,

$$T_n * A/2\pi = V = 2\pi * D/T_n \tag{3.12}$$

Considering

$$V = T_n * A/2\pi \tag{3.13}$$

Taking logarithm,

$$logV = logT_n + logA - log2\pi \tag{3.14}$$

$$logV = logT_n + logC \tag{3.15}$$

Considering

$$V = 2\pi * D/T_n \tag{3.16}$$

Taking logarithm,

$$logV = logD + log2\pi - logT_n \tag{3.17}$$

$$logV = -logT_n + logC \tag{3.18}$$

From these two equations slope of deformation at +45 and slope of pseudo acceleration at -45 can be obtained on four way logarithmic graph paper.

In order to validate solution technique adopted to develop the tripartite plot on four way logarithmic plot, N-S Component of El Centro ground motion available in Chopra is considered. The tripartite plot is generated through MATLAB code and the results of deformation, pseudo velocity and pseudo acceleration as shown in Table 3.6 for different time period are compared with the results given in Chopra. Figure

3.7 shows El-centro tripartite plot.

Table 3.6: Response Quantity under El Centro earthquake

| $T_n$ | **Damping** $\zeta$ % | D (m) | V (m/sec) | A (m/$sec^2$) |
|---|---|---|---|---|
| 0.5 | 2 | 0.0682 | 0.85549 | 10.75 |
| 1 | 2 | 0.15 | 0.9464 | 5.934 |
| 2 | 2 | 0.1899 | 0.5959 | 1.832 |

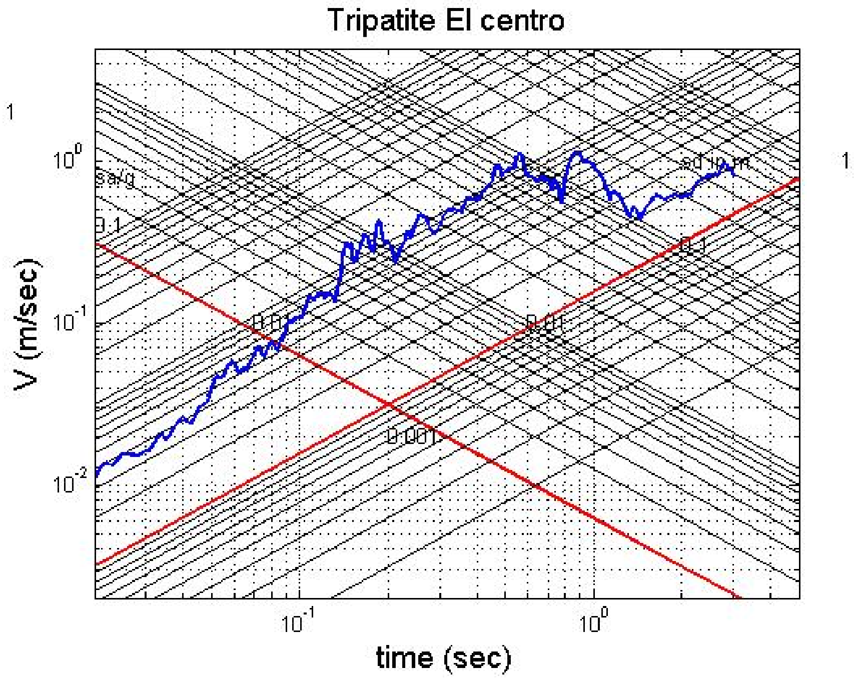


Figure 3.7: El-centro Tripartite Plot

### 3.8.1 Mean Response Spectrum

Statistical analysis of strong ground motion is carried out for the spectral ordinate (deformation, pseudo velocity, pseudo acceleration) which provide its mean value and its standard deviation value at each period $T_n$. For mean response spectrum, considering 43 stations in east region, 1 station in west, 21 stations in north region and 2 stations in South-East region are considered.

For example, mean values of pseudo velocity for east region for 3000 SDOF systems and time period upto 3 sec,

$$Mean = (V1 + V2 + . + V43)/43 \tag{3.19}$$

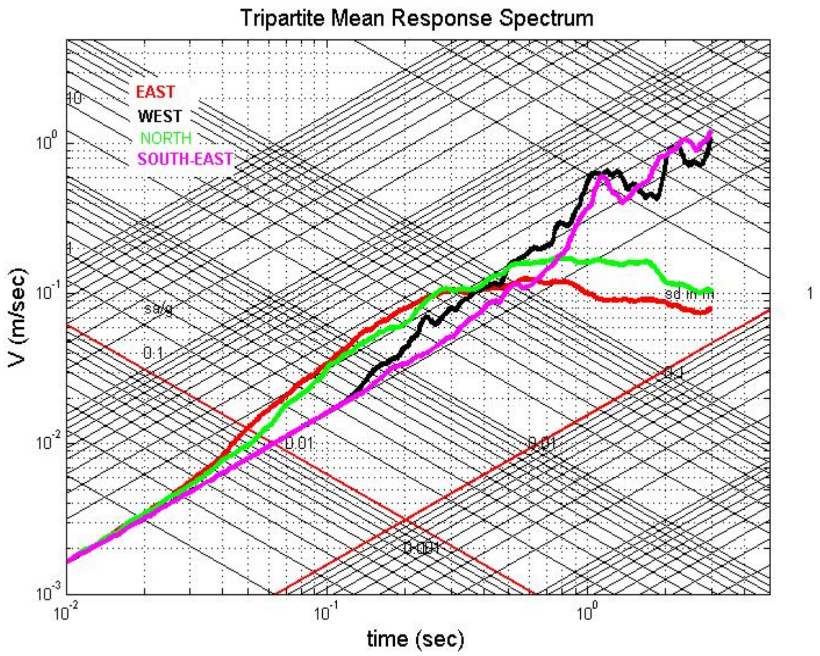


Figure 3.8: Tripartite Plot - Mean Response Spectrum for Four Regions

From Figure 3.8 it is observed that, for time period, between 0.001 sec to 0.03 sec all four regions are having same seismic demand. After 0.03 sec upto 3 sec, seismic demand offered by North and East response spectrum is similar while same observation is valid for West and South-East response spectrum.

### 3.8.2 Mean plus One Standard Deviation Response Spectrum

Mean plus one standard deviation ($\sigma$) values for 3000 SDOF systems and time period upto 3 sec,

$$\sigma = \sqrt{\frac{\Sigma(x - \dot{x})^2)}{(I - 1)}} \tag{3.20}$$

where, $\dot{x}$ = mean value of all stations at a particular time period x = spectral ordinate for a station at same time period I = No. of stations

By connecting all mean plus 1 standard deviation values for each $T_n$, it will give mean plus 1 standard deviation response spectrum. From Figure 3.9, it is observed that

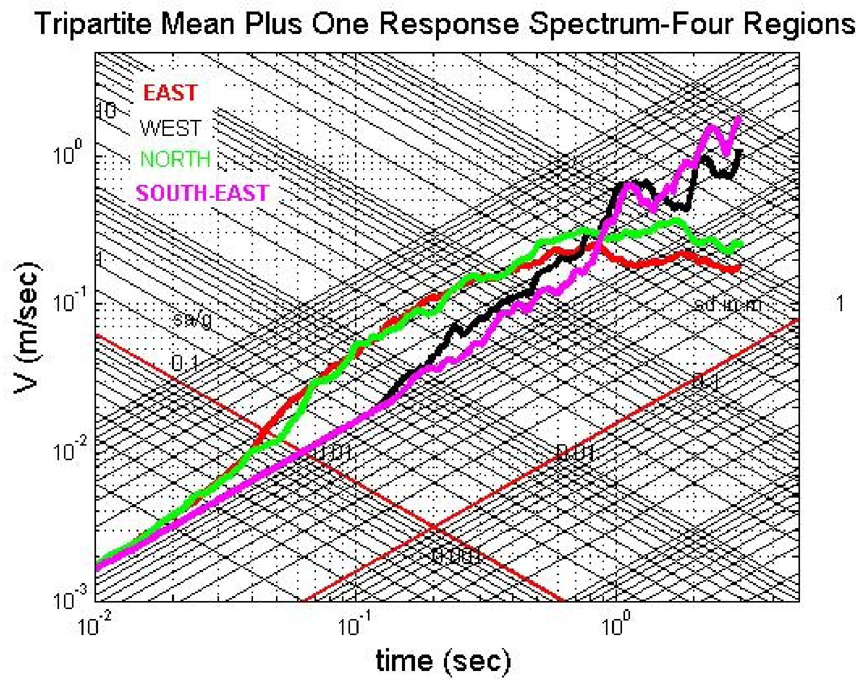


Figure 3.9: Tripartite plot - Mean Plus One Standard Deviation Response Spectrum for Four Regions

seismic demand for mean plus one standard deviation response spectrum is increased as compared to mean response spectrum between time period 0.3 sec to 3 sec for all four regions. Both mean and mean plus one standard deviation response spectrum is very much similar for period less than 0.1 sec.

## 3.9 Summary

The chapter deals with the verification of time histories for Indian context. MATLAB code is developed to generate response spectrum. Mean and mean plus one standard deviation response spectrum (tripartite plot) is developed on four way logarithmic plot. Some critical observations are made from this tripartite plot.

# Chapter 4

# Development of Design Spectrum

## 4.1 General

A set of design spectra consists of smooth curves or a series of straight line segments, with one curve for each damping level. The design spectrum is a specification of the level of seismic design force, or displacement, as a function of natural time period and damping level. The design spectrum should satisfy certain requirements because it is intended for the design of new structures, the seismic safety evaluation of existing structures, to resist future earthquakes.

## 4.2 Amplification Factors

Amplification factor is the ratio of the computed response to the maximum ground motion - for displacement, velocity and acceleration at each frequency for the range of interest. The amplification factors can be used to develop design spectra. The amplification factors for two different nonexceedance probabilities, 50% and 84.1% suggested by Newmark and Hall for the El-centro ground excitations are given below for different values of damping. The 50% nonexceedance probability represents the median value of the spectral ordinates and the 84.1% approximates the mean plus one standard deviation value for Newmark and Hall amplification factors as given in Table 4.1.

Table 4.1: Newmark and Hall Amplification Factors

| Damping % | Mean | | | Mean+1$\sigma$ | | |
|---|---|---|---|---|---|---|
| | $\alpha_A$ | $\alpha_V$ | $\alpha_D$ | $\alpha_A$ | $\alpha_V$ | $\alpha_D$ |
| 1 | 3.21 | 2.31 | 1.82 | 4.38 | 3.38 | 2.73 |
| 2 | 2.74 | 2.03 | 1.63 | 3.66 | 2.92 | 2.42 |
| 5 | 2.12 | 1.65 | 1.59 | 2.71 | 2.3 | 2.01 |
| 10 | 1.64 | 1.37 | 1.2 | 1.99 | 1.84 | 1.69 |
| 20 | 1.17 | 1.08 | 1.01 | 1.26 | 1.37 | 1.38 |

## 4.3 Design Spectrum

The design spectrum is the representative of ground motions recorded at the site during past earthquakes. If the data are not available, then the design spectrum should be based on ground motions recorded at other sites under similar conditions. The factors in the selection are the magnitude of the earthquake, the distance of the site from the earthquake fault, the fault mechanism, the geology of the travel path of seismic waves from the source to the site and the local soil conditions at the site.

The design spectrum is based on statistical analysis of the response for the ensemble of ground motions. Suppose that the response spectrum for each ground motion is computed and at a particular natural period, the ordinates of the response spectrum for the ith ground motion in the ensemble are $D_i/u^i_{go}$, $V_i/\dot{u}^i_{go}$, and $A_i/\ddot{u}^i_{go}$ where $D_i$, $V_i$ and $A_i$ are the deformation, pseudo-velocity and pseudo-acceleration spectral ordinates and $u_{go}$, $\dot{u}^i_{go}$ and $\ddot{u}^i_{go}$ are the peak displacement, velocity and acceleration of the ground motion. Thus at each natural period there are as many spectral values as the number I of ground motion records in the ensemble. Following steps are to be followed for the development of elastic design spectra.

Steps to develop elastic design spectra

Following steps are covered to construct the elastic design spectrum as shown in Figure 4.1.

- Draw the tripartite plot of ground motion data
- Normalized these plots to get same peak values of all these ground motion data.
- This normalization can be done by taking mean values or mean plus one standard deviation values of all the peak values of ground motion data.
- Connecting all mean values give the mean response spectrum and connecting all the mean plus one standard deviation values give the mean plus one standard deviation spectrum.
- Smooth this response spectrum by series of straight lines by any curve fitting techniques, which replace the actual spectrum by an idealized spectrum of a selected shape.
- Select the values of amplification factors ($\alpha_A$, $\alpha_V$, $\alpha_D$) for selected damping ratio $\zeta$ for acceleration, velocity and displacement regions.
- Multiply $\ddot{u}_{go}$ by amplification factor $\alpha_A$ to obtain straight line b-c representing a constant value of pseudo acceleration A.
- Multiply $\dot{u}_{go}$ by amplification factor $\alpha_V$ to obtain the straight line c-d representing a constant value of pseudo velocity V.
- Multiply $u_{go}$ by amplification factor $\alpha_D$ to obtain the straight line d-e representing a constant value of deformation D.
- Draw the line $A = \ddot{u}_{go}$ for periods shorter than $T_a$ and the line $D = u_{go}$ for periods longer $T_f$.
- Join the lines a-b and e-f to complete the spectrum.

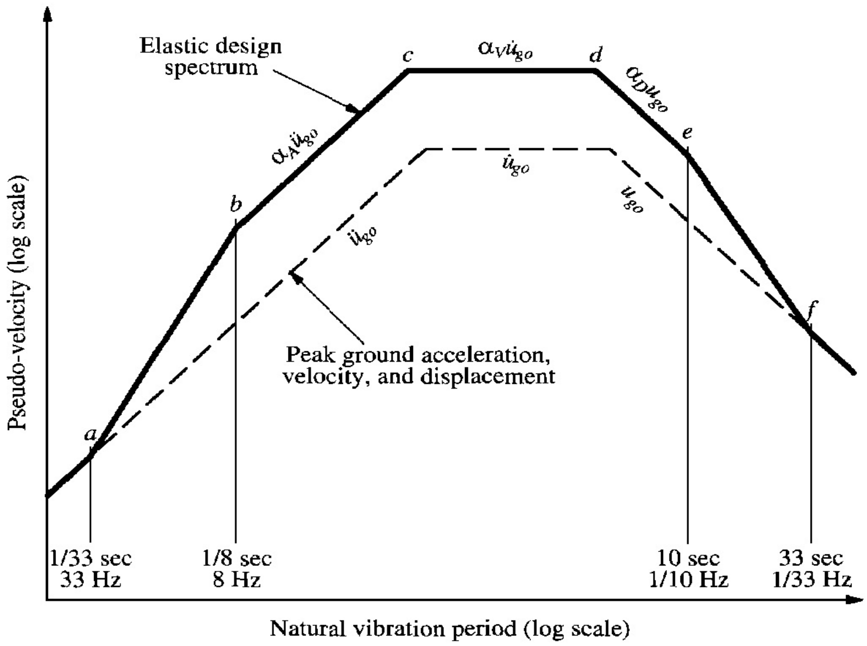


Figure 4.1: Construction of Elastic Design Spectrum[1]

For the El-centro ground motion data, excel sheets have been prepared considering 2%, 5%, 10% and 20% damping ratio at 0.001 sec time interval upto 50 sec time period for 50000 SDOF systems to find out cut off time periods for various sensitive regions like acceleration sensitive region, velocity sensitive region and displacement sensitive region. Amplification factors are also derived considering ratio of spectral values to peak ground values for acceleration, velocity and displacement sensitive regions which is given in Table 4.2.

Table 4.2: Cut off Time Periods and Amplification Factors for El-centro Ground Excitations

| **Damping ratio in percentage** | **Acceleration sensitive region Time period in sec** | **Velocity sensitive region Time period in sec** | **Displacement sensitive region Time period in sec** | $\alpha_A$ | $\alpha_V$ | $\alpha_D$ |
|---|---|---|---|---|---|---|
| 2 | 0.035-0.238 | 0.239-2.144 | 2.145-13.884 | 2.65 | 2.03 | 1.56 |
| 5 | 0.036-0.24 | 0.25-2.24 | 2.25-13.262 | 2.11 | 1.58 | 1.35 |
| 10 | 0.038-0.371 | 0.372-2.452 | 2.453-12.611 | 1.83 | 1.29 | 1.14 |
| 20 | 0.037-0.451 | 0.451-2.96 | 2.97-8.58 | 1.42 | 0.97 | 0.88 |

## 4.4 Design Spectrum for Indian Context

The procedure given in above section, same is followed to construct the design spectrum for four regions of Indian Context. 15000 SDOF systems at the interval of 0.001 sec for the time period upto 15 sec and 5% damping ratio are considered. 43 stations for east region, 21 stations for north region, 2 stations for south-east region and 1 station for west region are considered to generate mean and mean plus one response spectrum through MATLAB code. Excel sheets have been prepared to decide cut off time periods of sensitive regions. Amplification factors are derived for acceleration, velocity and displacement regions for mean and mean plus one standard deviation as given in Table 4.3.

Table 4.3: Cut off Time Periods and Amplification Factors for East and North Regions

| | $T_n$ in sec | | | Mean | | | Mean $+1\sigma$ | | |
|---|---|---|---|---|---|---|---|---|---|
| | Acceleration sensitive region | Velocity sensitive region | Displacement sensitive region | $\alpha_A$ | $\alpha_V$ | $\alpha_D$ | $\alpha_A$ | $\alpha_V$ | $\alpha_D$ |
| East | 0.033-0.126 | 0.127-1.66 | 1.67-11.4 | 1.73 | 2.28 | 2.45 | 3.72 | 3.83 | 4.19 |
| North | 0.044-0.158 | 0.159-2.404 | 2.405-9.878 | 1.5 | 2.08 | 2.54 | 4.28 | 4.36 | 9.56 |

For very short time period system is extremely stiff and undergo very less deformation. This fixed mass move rigidly with the ground, so its pseudo acceleration (A) is nearly equal to peak ground acceleration $\ddot{u}_0$. For very long time period system is extremely flexible and pseudo acceleration (A) is very small while deformation value is nearly equal to peak ground displacement $u_0$. In this case, mass would be remain stationary and the ground below moves.

To evaluate amplification factors, ratio of computed response to peak ground motion values is taken into consideration. Time period upto which the system is amplified for acceleration sensitive region is decided. The average ratio of pseudo acceleration (A) to peak ground acceleration ($\ddot{u}_0$) is derived for acceleration sensitive region to evaluate amplification factor for acceleration ($\alpha_A$). For intermediate period of time, system is amplified for velocity sensitive region and the average ratio of pseudo velocity (V) to peak ground velocity ($\dot{u}_0$) is derived for velocity sensitive region to evaluate amplification factor for velocity ($\alpha_V$). Same is followed to decide amplification factor for displacement ($\alpha_D$).

Design spectrum for mean values for East region is shown in Figure 4.2. Cut off

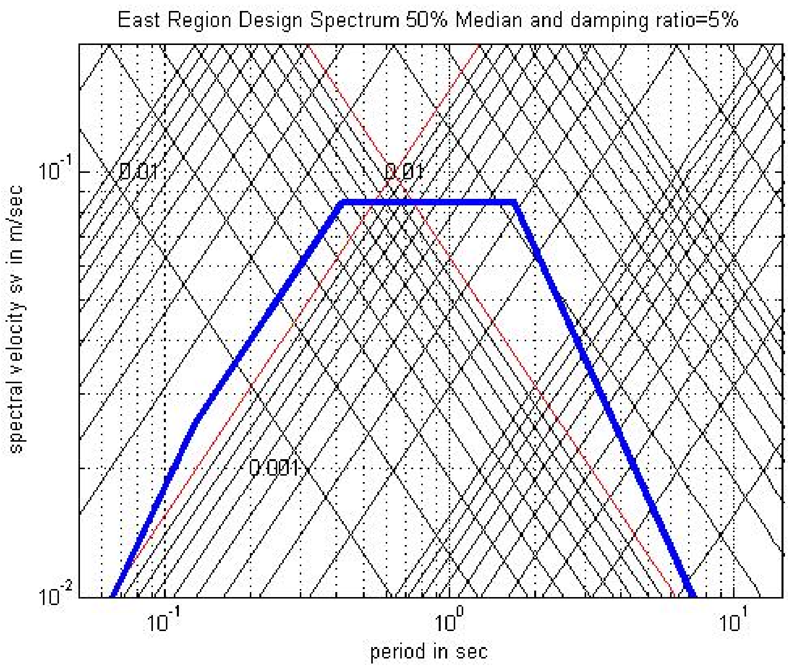


Figure 4.2: Design Spectrum for East Region for Mean Values

time periods for sensitive regions and amplification factors are considered from Table

4.3 in MATLAB code. From Figure 4.2 it is observed that, time period upto 0.033 sec pseudo acceleration is nearly equal to peak ground acceleration, while system is amplified upto 0.126 sec in acceleration sensitive region. For intermediate period of time, system is amplified upto 1.66 sec in velocity sensitive region and for long period of time system is amplified upto 11.4 sec in displacement sensitive region. After this time period, deformation of system is nearly equal to peak ground displacement.

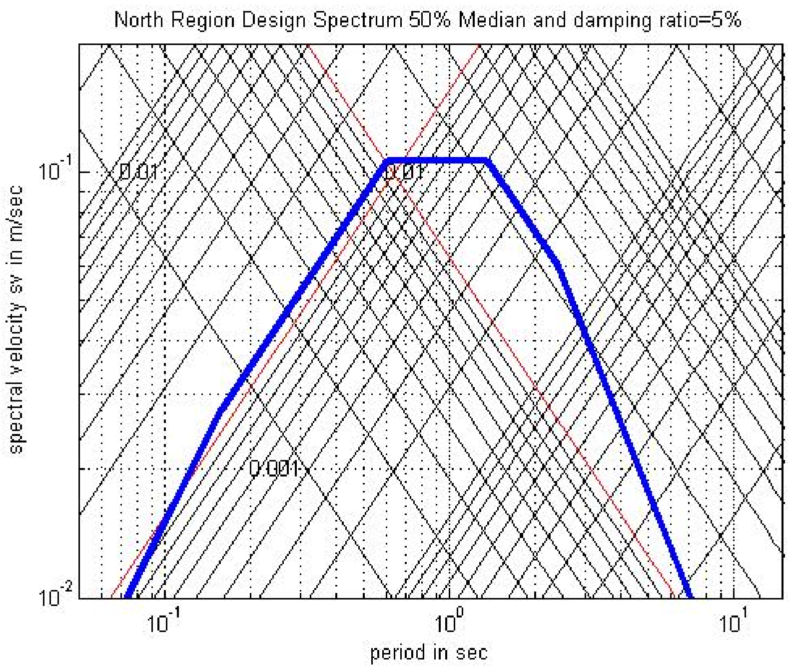


Figure 4.3: Design Spectrum for North Region for Mean Values

Design spectrum for mean values for North region is shown in Figure 4.3. Observations are made from Figure 4.3 that system is amplified upto 0.158 sec in acceleration sensitive region while it is amplified upto 2.404 sec in velocity and upto 9.878 sec in displacement sensitive region.

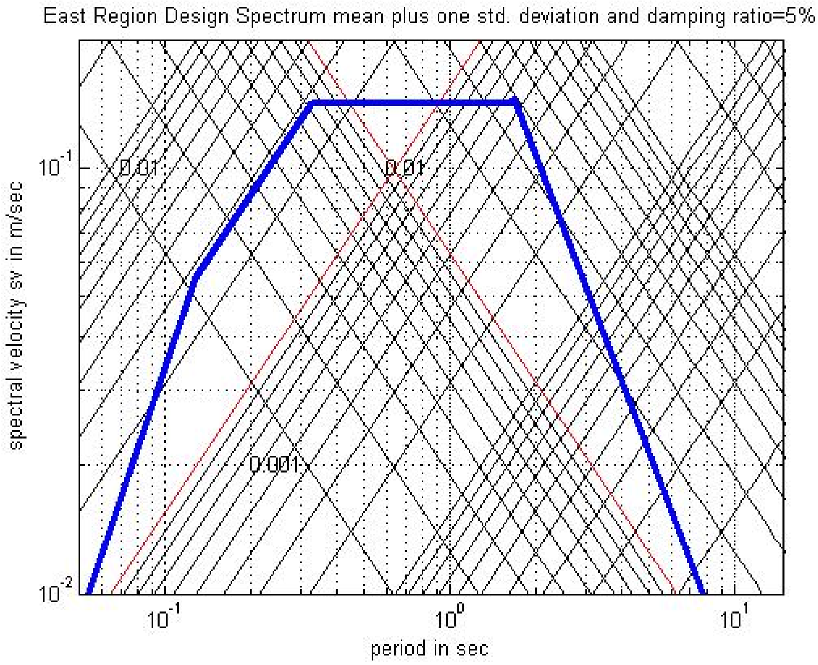


Figure 4.4: Design Spectrum for East Region for Mean plus One Standard Deviation Values

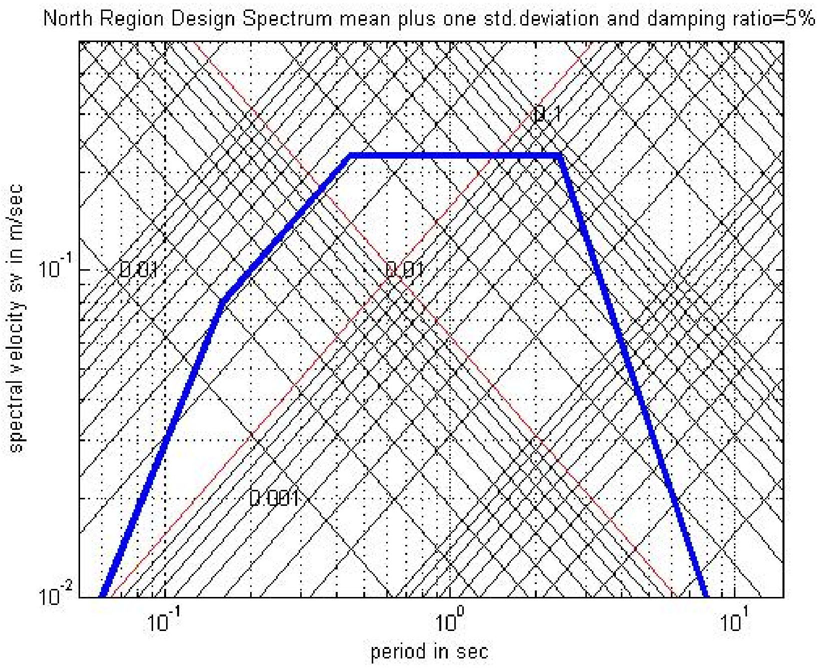


Figure 4.5: Design Spectrum for North Region for Mean plus One Standard Deviation Values

Similarly, Design spectrum for mean plus one standard deviation values for East and North regions are shown in Figure 4.4 and Figure 4.5 respectively. Cut off time periods for sensitive regions and amplification factors are considered from table 4.3 in MATLAB code. The system is amplified more in each region for mean plus one standard deviation values as compared to mean values. In north region, mean plus one standard deviation values are increased from mean values more as compared to east region.

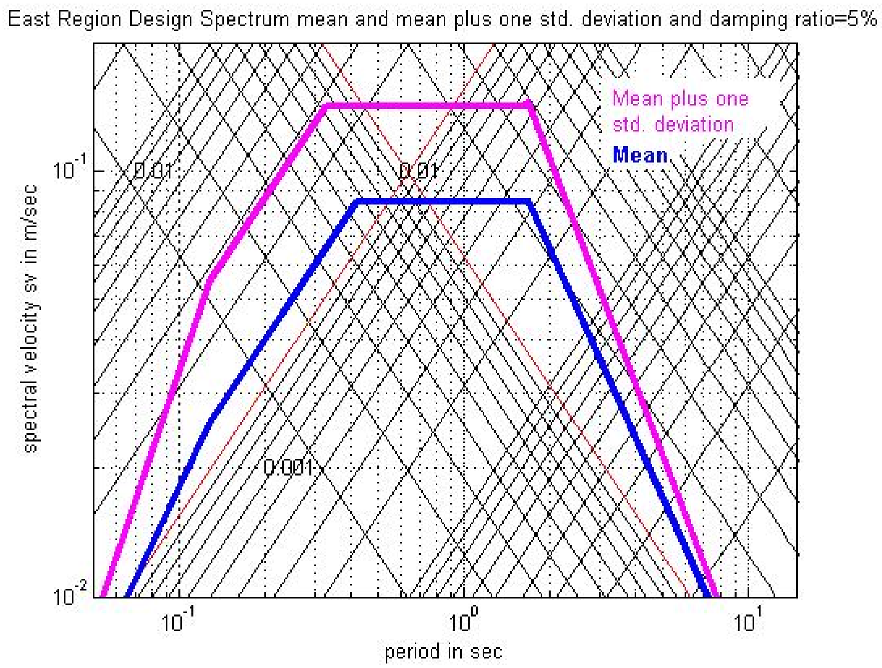


Figure 4.6: Design Spectrum - East Region for Mean and Mean + $1\sigma$

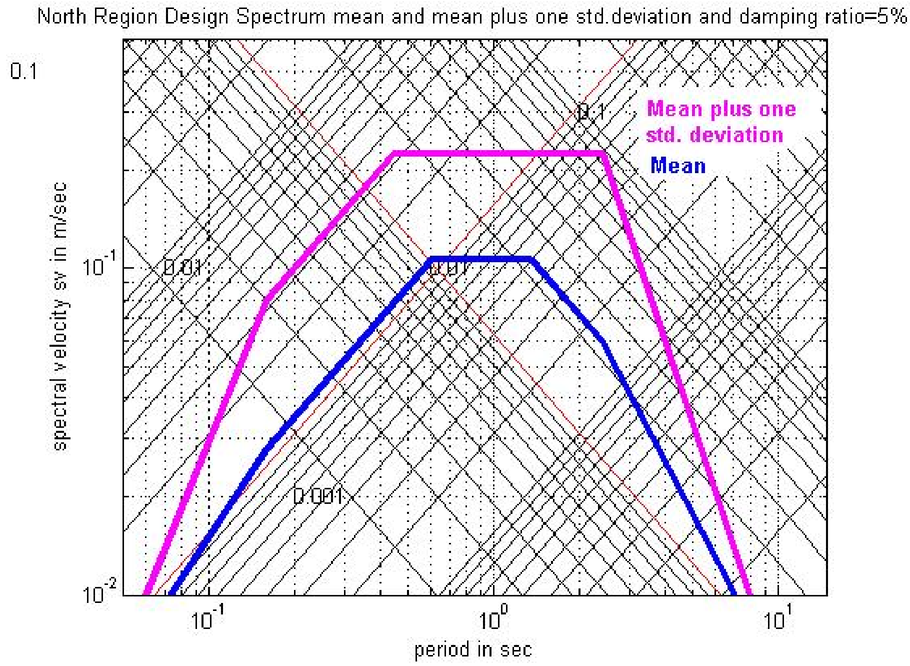


Figure 4.7: Design Spectrum - North Region for Mean and Mean + $1\sigma$

Combined plots of mean and mean + $1\sigma$ values for East and North region are shown in Figure 4.6 and Figure 4.7 respectively. Seismic demand for mean + $1\sigma$ is more as compared to mean plot as shown in figure. As there are only two stations in South-East region and one station in West region, response spectrum is to be taken into consideration for seismic analysis of any structure in these regions.

## 4.5 Summary

Amplification factors and time period for sensitive regions are important parameters for the construction of design spectrum. Seismic demand is increased for mean plus one standard deviation values as compared to mean values of design spectrum. Due to less number of stations in South-East and West regions, response spectrum is sufficient to carry out the seismic demand of structures.

# Chapter 5

# Case Study of G+3 storey building

## 5.1 Introduction

The main aim of earthquake resistant design of any structure is to estimate the lateral load under the action of earthquake ground motions. The chapter deals with the static analysis of 4 - storey RC framed building. For the building as shown in Figure 5.1, the properties like natural time period and base shear are obtained. In subsequent section, estimated lateral load using design response spectrum of IS:1893(Part-I)-2002 for various zone is compared with lateral load obtained from proposed mean and mean plus one standard deviation design and response spectrum for four regions of the country for this building.

## 5.2 Geometry of G+3 storey building

A G+3 storey reinforced concrete building is considered to estimate seismic demand.

- No. of Storey = G+3 Storey
- Story Height = 3 m
- Slab Thickness. = 120 mm
- No. of Bays in X-Direction = 3

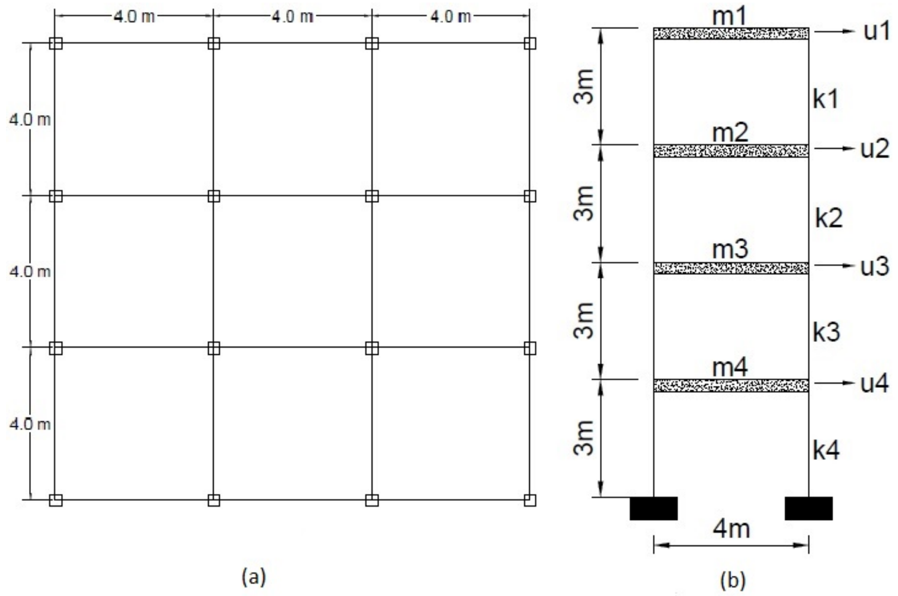


Figure 5.1: (a) Geometrical Plan, (b) Lumped Mass Model of G+3 Storey building

- No. of Bays in Y-Direction = 3
- Bay Width in X-Direction = 4 m
- Bay Width in Y-Direction = 4 m
- Column Size = 0.3 m × 0.3 m
- Beam Size = 0.23 m × 0.3 m
- $f_{ck}$= 25 $N/mm^2$ ( M 25 grade of concrete)
- $f_y$ = 415 $N/mm^2$ ( Fe 415 grade of steel)
- Live Load on Typical Storey = 3 $kN/m^2$

## 5.3 Seismic Demand as per Indian Code

Consider a four-storey reinforced concrete building as shown in Figure 5.1 located in seismic zone V having soil condition of medium soil site. The R.C. frames are ordinary moment resistant frames.

**Step-I:** Mass of the building

Self weight of slab = 0.12 x 12 x 12 x 25 = 432 kN

Self weight of beams = 24 x 4 x 0.23 x (0.3-0.12) x 25 = 99.36 kN

Self weight of columns = 16 x 0.3 x 0.3 x (3-0.3) x 25 = 97.2 kN

Total dead load at each floor = 432 + 99.36 + (97.2/2) = 579.96 kN

Live load at each floor = 0.5 x 3 x 12 x 12 = 216 kN

Total load at each floor = 795.96 kN

Total seismic weight of building = 3 x 795.96 + 579.96 = 2967.84 kN

Total mass of building = 302532.11 kg

**Step-II:** Stiffness of building

Considering top and bottom both are fixed.

$$K = 16 \times \frac{12EI}{l^3} \tag{5.1}$$

where E = Modulus of elasticity of concrete = $5000\sqrt{f_{ck}}$
I = Moment of inertia of column = $bd^3/12$

$$K = 120000kN/m \tag{5.2}$$

**Step-III:** Natural frequency of the building

$$\omega_n = \sqrt{\frac{K}{m}} \tag{5.3}$$

$$\omega_n = 19.92rad/sec \tag{5.4}$$

$$T_n = \frac{2\pi}{\omega_n} = 0.315sec \tag{5.5}$$

As per IS:1893-2002, for medium soil site $S_a/g$ = 2.5 for zone V, Z = 0.36 and for OMRF, R = 3

$$A_h = \frac{Z}{2} \times \frac{I}{R} \times \frac{S_a}{g} \tag{5.6}$$

$$A_h = 0.1 \tag{5.7}$$

**Step-IV:** Base Shear

$$V_B = A_h \times W = 445.17kN \tag{5.8}$$

Lateral load distribution throughout the height as per IS:1893-2002 is given in Table 5.1.

Table 5.1: Lateral Load Distribution as per IS:1893-2002

| Storey | $W_i$ | $h_i$ | $W_i h_i^2$ | Q = $\frac{W_i h_i^2}{\Sigma W_i h_i^2}$ |
|---|---|---|---|---|
| Roof | 579.96 | 12 | 83514.24 | 140.26 |
| 3 | 795.96 | 9 | 64472.76 | 108.25 |
| 2 | 795.96 | 6 | 28654.56 | 48.11 |
| 1 | 795.96 | 3 | 71.64 | 0.12 |
| Total | 2967.84 | | 176713.2 | |

## 5.4 Seismic Demand as per Elastic Design Spectrum

For mean design spectrum of east region, value of pseudo acceleration (A) is 1.308 $m/sec^2$.

$$V_B = mA = 396kN \tag{5.9}$$

For mean design spectrum of north region, value of pseudo acceleration (A) is 1.094 $m/sec^2$.

$$V_B = mA = 330.88kN \tag{5.10}$$

For mean response spectrum of south-east region, value of pseudo acceleration (A) is 1.193 $m/sec^2$.

$$V_B = mA = 360.96kN \tag{5.11}$$

For west region value of pseudo acceleration (A) is 1.591 $m/sec^2$.

$$V_B = mA = 381.28kN \tag{5.12}$$

Similar calculations are done for mean plus one standard deviation values of elastic design spectrum as shown in Table 5.2.

Table 5.2: Lateral Load Distribution as per Design Spectrum

| Storey | $W_i$ | $h_i$ | $W_i h_i^2$ | Q = $\frac{W_i h_i^2}{\Sigma W_i h_i^2}$ | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | East | | North | | South-East | West |
| | | | | Mean | Mean+1$\sigma$ | Mean | Mean+1$\sigma$ | | |
| Roof | 579.96 | 12 | 83514.24 | 181.15 | 426.48 | 156.37 | 483.34 | 170.59 | 227.45 |
| 3 | 795.96 | 9 | 64472.76 | 144.48 | 329.23 | 120.72 | 373.14 | 131.69 | 175.59 |
| 2 | 795.96 | 6 | 28654.56 | 64.21 | 146.32 | 53.65 | 164.84 | 58.53 | 78.04 |
| 1 | 795.96 | 3 | 71.64 | 0.16 | 0.37 | 0.13 | 0.41 | 0.15 | 0.20 |
| Total | 2967.84 | | 176713.2 | | | | | | |

## 5.5 Results & Discussions

In east and south-east region of India earthquake zone V exists while in north region earthquake zone II,III,IV,V exists and in west region of India earthquake zone III,IV,V exists. Table 5.1 shows base shear calculation as per IS:1893-2002 for all earthquake zones. It also shows base shear calculation for mean and mean+1$\sigma$ developed design and response spectrum for all four regions of India. For east, north and south-east

Table 5.3: Base Shear Calculations

| | | Base shear (in kN) Zone wise | | | |
|---|---|---|---|---|---|
| | | II | III | IV | V |
| IS:1893-2002 | | 123.66 | 197.85 | 296.78 | 445.17 |
| East (only zone V) | Mean | 396 | | | |
| | Mean + 1$\sigma$ | 902.41 | | | |
| North (zone II/III/IV/V) | Mean | 330.88 | | | |
| | Mean + 1$\sigma$ | 1022.73 | | | |
| South-East (only zone V) | Mean | 360.96 | | | |
| | Mean + 1$\sigma$ | 360.96 | | | |
| West (zone III/IV/V) | | 481.28 | | | |

regions IS is conservative for zone V mean values while for west region IS is deficient for zone V mean values. In north and west regions IS is deficient for zone III and IV mean values. IS is deficient for mean + $1\sigma$ values of east and north regions while IS is conservative mean + $1\sigma$ values of south-east region.

## 5.6 Summary

In this chapter, estimation of base shear is done by using IS:1893-2002. This base shear is compared with mean and mean + $1\sigma$ design and response spectrum for all four regions of India. The results are compared zone wise for all regions. Mean and mean + $1\sigma$ response spectrum for south-east region gives same base shear for this building.

# Chapter 6

# Seismic Codes Comparison Study

## 6.1 Introduction

For design of earthquake resistant structure, design spectrum is the prime focus. Estimation of lateral force is one of the important factor in earthquake resistant design. In seismic codes of various countries have considered different parameters for seismic evaluation of any structures. In this chapter, five seismic codes - Mexico, United States of America, Chile, Philippines and China are considered for comparison.

## 6.2 Need of Codal Comparison Study

To develop design spectrum many parameters like sensitive regions, amplification factors, site conditions are considered. Various countries seismic codes have considered different factors in design spectrum as well as lateral force estimation. To study and understand of these factors, this study has been carried out. In all seismic codes, various methods are considered for seismic analysis.

## 6.3 Provisions of Various Seismic Codes

### 6.3.1 Mexico

In Mexico official national code for seismic design is not available. However, national code is contained in the manual for design of civil works published by a federal commission.

In the static method of estimation of lateral force $F_i$, it is assumed that the design lateral seismic forces act at the various levels of the building where the masses of the structure are supposed to be concentrated.

$$F_i = \frac{W_i h_i}{\sum_{i=1}^{N} W_i h_i} V_0 \tag{6.1}$$

where,

$$V_0 = \frac{c}{Q'} W_0 \tag{6.2}$$

where, $W_i$ = weight of $i^{th}$ level

$h_i$ = height of $i^{th}$ level

$W_0$ = total weight of structure

c = seismic coefficient

$Q'$ = reduction factor

$Q'$ = Q, for $T \geq T_a$

$Q'$ = 1+$\frac{T}{T_a}$(Q-1), for $T < T_a$

Q is a factor that depends on the type and characteristics of the structure. $T_a$ is selected from the table given in code which depends on seismic zone and soil type. The code allows the reduction in the lateral force determined from above equations.

Figure 6.1 shows the Mexico code design spectrum between spectral acceleration versus time period. This spectrum is defined by following coordinates.

a = $(1 + 3T/T_a)$c/4, for $T \leq T_a$

a = c, for $T_a < T \leq T_b$

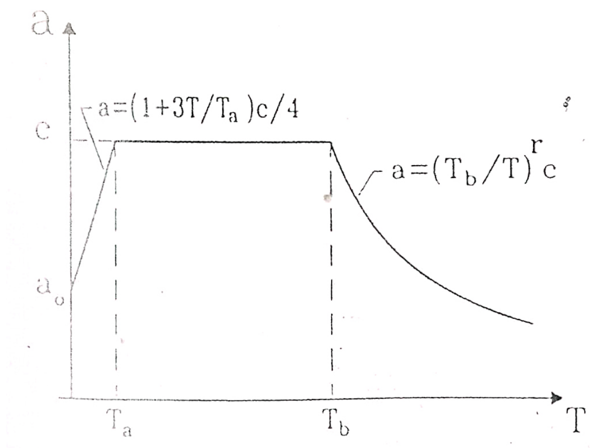


Figure 6.1: Mexico Code Design Spectrum[18]

a = $(T_b/T)^r$c, for $T > T_b$

Values of $T_a$, $T_b$ and r is given for four seismic zone and three types of soil.

### 6.3.2 United States of America

Several building codes are currently in use in different regions of USA. The Uniform Building Code (UBC) published by the International Conference of Building Officials (1991) is the building code most extensively used.

In addition to UBC, three other major building codes are used.

1) The BOCA (Building Officials and Code Administrators International - 1990)

2) The National Building Code, published by the American Insurance Association (1996)

3) The Standard Building Code of the Southern Building Code Congress International (1991)

In static lateral load method, base shear force (V) is estimated by following equation.

$$V = \frac{ZIC}{R_w}W \tag{6.3}$$

$$C = \frac{1.25S}{T^{2/3}} \leq 2.75 \quad (6.4)$$

where, Z = Seismic zone factor

(for zone 1 - 0.075, zone 2A - 0.15, zone 2B - 0.2, zone 3 - 0.3, zone 4 - 0.4, zone 0 - not required to be designed for earthquake)

S = Site coefficient depending on the characteristic of the soil at the site

I = Occupancy importance factor related to the anticipated use of the structure (I=1.25 for essential and hazardous facilities and I=1 for all other structures)

$R_w$ = The structural factor ranging from 4 to 12

(It is a measure of the capacity of the structural system to absorb energy in the inelastic range through ductility and redundancy)

W = Seismic weight

T = Fundamental period of the building

T can be determined by any of following two methods.

**Method A (Approximate Method)**

$$T = C_t({h_N}^{3/4}) \quad (6.5)$$

where, $h_N$ = total height of the building in feet

$C_t$ = 0.035 for steel moment resisting frames

= 0.030 for reinforced concrete moment resisting frames and eccentrically braced frames

= 0.020 for all other buildings

**Method B (Appropriated Dynamic Analysis or Rayleigh's Formula)**

$$T = 2\pi\sqrt{\frac{\Sigma_{i=1}^{N} W_i {\delta_i}^2}{g\Sigma_{i=1}^{N} f_i \delta_i}} \quad (6.6)$$

where, $f_i$ = any lateral force distribution applied at various levels of the building

$W_i$ = seismic weight at level i

$\delta_i$ = elastic lateral displacements produced by the lateral forces $f_i$

**Distribution of lateral forces:** The base shear force V is distributed at various levels of the building by,

$$F_x = \frac{(V - F_t)W_x h_x}{\Sigma_{i=1}^{N} W_i h_i} \tag{6.7}$$

In which $F_t$ = 0.07TV $\leq$ 0.25V, for T $>$ 0.7sec

$F_t$ = 0, for T $\leq$ 0.7sec

N = Total numbers of stories

$F_x$, $F_i$, $F_N$ = lateral force applied at level x, i or N

$F_t$ = portion of the base force V at the top of the structure in addition to $F_N$

$h_x$, $h_i$ = height of level x or i above the base

$W_x$, $W_i$ = seismic weight of $x^{th}$ or $i^{th}$ level

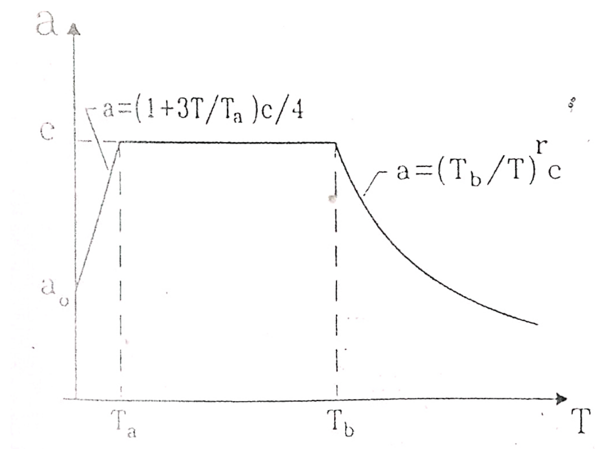


Figure 6.2: United States of America Code - Normalized Response Spectra[19]

Figure 6.2 shows normalized response spectra between $\frac{Spectral Acceleration}{Effective Peak Ground Acceleration}$ versus time period (sec). This normalized response spectra is reproduced from Uniform Building Code, 1991 with permission of the publisher, the International Conference of Building Officials. This spectral is for three types of soil.

1) Soft to medium sand and clays

2) Deep cohesionless or stiff clay soils

3) Rock and stiff soils

This spectra is used for dynamic method to find spectral acceleration ($S_a$). This spectral acceleration is used to determine modal base shear.

### 6.3.3 Chile

In Chile, official Chilean code is NCH433.0f96. Base shear (Q) is calculated by static analysis method.

$$Q = CIP \tag{6.8}$$

where C = Seismic coefficient

$$C = \frac{2.75A_0}{gR}(\frac{T^{'}}{\dot{T}})^n \tag{6.9}$$

where n, $T^{'}$ = parameters relative to foundation soil type

$A_0$ = maximum effective acceleration based on seismic zone

R = Reduction factor based on structural system and structural material

$\dot{T}$ = period of mode with highest translational equivalent mass in the direction of analysis

I = coefficient value related to building category

P = Total weight of the building

Design Spectrum that determines the seismic resistance of the structure is defined by:

$$S_a = \frac{IA_0\alpha}{\dot{R}} \tag{6.10}$$

I and $A_0$ are as above.

$$\alpha = \frac{1 + 45(\frac{T_n}{T_0})^P}{1 + (\frac{T_n}{T_0})^3} \tag{6.11}$$

where $T_n$ = vibration period of mode n

$T_0$, P = parameters relative to foundation soil type for which table is given in code

$$\dot{R} = 1 + \frac{\dot{T}}{0.1T_n + \frac{\dot{T}}{R_0}} \tag{6.12}$$

where $\dot{T}$ = period of mode with highest translational equivalent mass in the direction of analysis

$R_0$ = value for the structure based on structural system and structural material for which table is given in code

### 6.3.4 Philippines

Seismic code of Philippines is National Structural Code of Philippines (NSCP) volume 1, fourth edition 1992. In static lateral load method, base shear force (V) is estimated by following equation.

$$V = \frac{ZIC}{R_w} W \tag{6.13}$$

where, Z = Seismic zone factor

(for zone 2 - 0.2, zone 3 - 0.3, zone 4 - 0.4)

I = Occupancy importance factor related to the anticipated use of the structure for which table is given in code

$R_w$ = Numerical coefficient based on basic structural system and lateral load resisting system for which table is given in code

W = Total Seismic load

C = Numerical coefficient

C = $\frac{1.25S}{T^{2/3}}$ S = Site coefficient based on soil characteristic for which table is given in code

T = Fundamental period of vibration in sec

T can be determined by any of following two methods.

**Method A (Approximate Method)**

$$T = C_t ({h_N}^{3/4}) \tag{6.14}$$

where, $h_N$ = total height of the building in meter

$C_t$ = 0.085 for steel moment resisting frames

= 0.075 for reinforced concrete moment resisting frames and eccentrically braced frames

= 0.050 for all other buildings

**Method B (Appropriated Dynamic Analysis or Rayleigh's Formula)**

$$T = 2\pi\sqrt{\frac{\Sigma_{i=1}^{N} W_i {\delta_i}^2}{g\Sigma_{i=1}^{N} f_i \delta_i}} \tag{6.15}$$

where, $f_i$ = any lateral force distribution applied at various levels of the building

$W_i$ = seismic weight at level i

$\delta_i$ = elastic lateral displacements produced by the lateral forces $f_i$

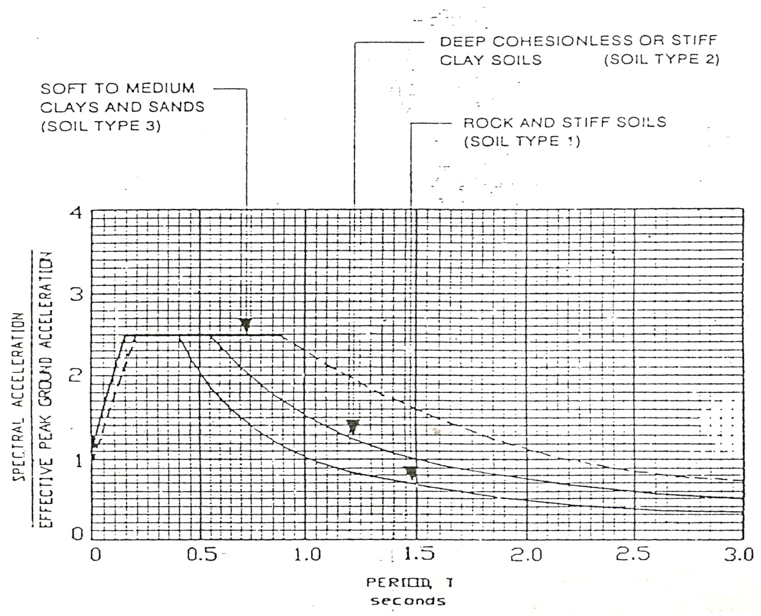


Figure 6.3: Philippines Code - Normal Response Spectra[21]

Figure 6.3 shows normal response spectra between $\frac{Spectral Acceleration}{Effective Peak Ground Acceleration}$ versus time period (sec).This spectrum is used to determine spectral acceleration ($S_a$). This spectral is for three types of soil.

1) Soft to medium sands and clays (soil type 3)

2) Deep cohesionless or stiff clay soils (soil type 2)

3) Rock and stiff soils (soil type 1)

### 6.3.5 China

Before 1964, there was no seismic resistant design code for buildings or other structures in China. Seismic Design Code for buildings and structures, GBJ 11-89 was published in 1989 and put into effect in January 1991.
As per this code, base shear force can be determined by equivalent lateral force method. Total horizontal seismic action $F_{EK}$ is given by,

$$F_{EK} = \alpha W_{eq} \tag{6.16}$$

$$W_{eq} = \Sigma_{i=1}^{N} W_i \tag{6.17}$$

where, $W_{eq}$ = total equivalent seismic weight of a building or a structure
$\alpha$ = seismic coefficient
$\alpha = (5.5T_1{+}0.45)\alpha_{max}$, for $T_1 \leq 0.1$ sec
$\alpha = \alpha_{max}$, for $0.1 < T_1 \leq T_g$
$\alpha = (T_g/T_1)^{0.9}\alpha_{max}$, for $T_g < T_1 < 3.0$ sec

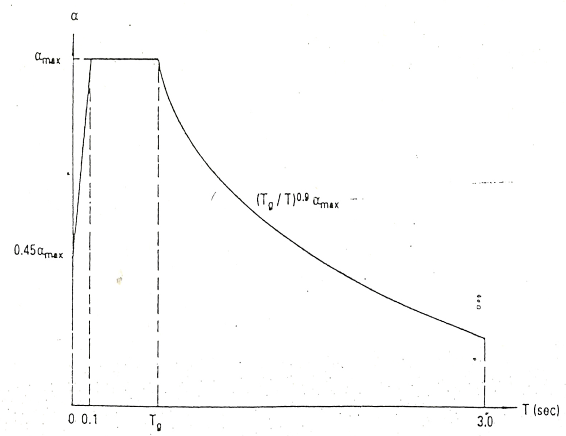


Figure 6.4: China Code - Seismic Coefficient[22]

Figure 6.4 shows the plot between seismic coefficient and time period. From this plot, seismic coefficient can be determined which is used to evaluate base shear force.The maximum value of seismic coefficient is based on intensity of earthquake for which table is given in the code.

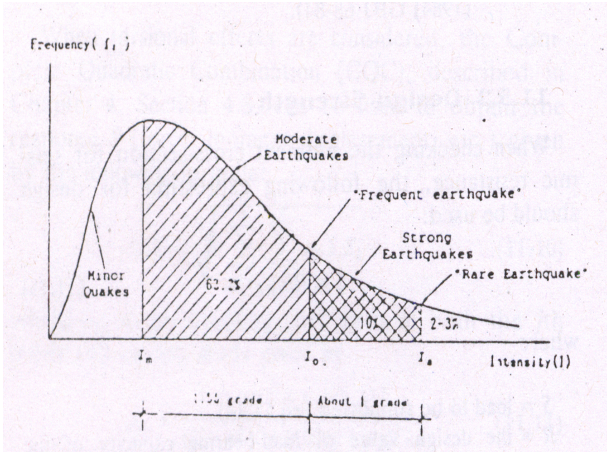


Figure 6.5: Frequency Distribution of Earthquake as Function of Intensity[22]

The code established that there should be "no damage during a frequent moderate earthquake and no collapse during a rare strong earthquake". A probability plot of earthquake frequency, within a period of 50 years versus intensity is given in Figure 6.5. In this plot, earthquake of intensity less than IV were omitted. The design intensity for a "rare (strong) earthquake" $I_s$ is defined as the intensity value that is exceeded by only 2-3% of all the earthquake. The design intensity for a "frequent (moderate) earthquake" $I_0$ as the intensity with a probability of exceedance of 10-13% as indicated in Figure 6.5. This figure also indicates the mode intensity $I_m$ defining the "minor (weak) earthquake".

## 6.4 Discussion

Table 6.1: Codal Comparison

| Seismic Parameters | Mexico | United States of America | Chile | Philippines | China |
|---|---|---|---|---|---|
| Zone | 4 zones (A.B,C,D) | 6 zones (1,2A,2B,3,4,0) | 3 zones (1,2,3) | 3 zones (2,3,4) | - |
| Soil type | I,II,III | S1,S2,S3,S4 | I,II,III,IV | S1,S2,S3,S4 | I,II,III,IV |
| Building type or category (Importance factor) | - | I=1<br>I=1.25 | A.B,C,D | I,II,III,IV | - |
| Based on structural system and material | - | Ranging from 4 to 12 | Ranging from 2 to 7 | Ranging from 4 to 12 | - |
| Design Spectrum | Spectral acceleration -Time period | Spectral acceleration/ Effective PGA -Time period | - | Spectral acceleration/ Effective PGA -Time period | Seismic Coefficient -Time period |

Table 6.1 shows the comparison of various seismic parameters. Different seismic codes cover various methods to determine lateral force, spectral acceleration and time period. Mexico code has considered four zones and three soil types. Importance factor and structural system factor are not considered in Mexico code. United States of America seismic code has considered six seismic zones and four types of soil. Importance factor is considered as 1 for regular building while 1.5 for very important structures. Structural system factor range is between four to twelve based on system as well as material used in structure. Chile seismic code has considered three seismic zones, four types of soil and four category of building type for importance factor. It is having structural systems ranging from two to seven. Philippines seismic code is very much similar to United States of America code as both codes are derived from Uniform Building Code (UBC). In Philippines code, three seismic zones four type of building category are considered. China seismic code is based on soil type and seismic coefficient value. Other factors like seismic zone, importance factor and structural

system factors are not considered in China code.

## 6.5 Summary

This chapter focuses on comparison of various seismic parameters of five countries' seismic code. United States of America and Philippines Code is based on Uniform Building Code (UBC). Various methods of seismic evaluation have been compared among different seismic codes.

# Chapter 7

# Summary and Conclusions

## 7.1 Summary

This dissertation is an attempt to understand the concept of Response Spectrum and Design Spectrum. Various factors required to generate the Design spectrum are also the prime focus of the study. The main objective of the work is to generate tripartite response spectrum for four regions of Indian subcontinent and convert it into smooth elastic design spectrum. Numerical algorithm of Newmark Beta method is used to solve equation of motion of SDOF system and response quantities such as displacement, velocity and acceleration are obtained. A MATLAB Code is generated for development of response spectrum and tripartite response spectrum as well as elastic design spectrum.

Across the country, 184 earthquake ground motions from 23 recording stations of India are collected from various source. Out of 184 ground motions, 67 earthquake ground motions are considered as strong ground motion based on duration, RMS acceleration and PGA parameters. All strong ground motions i.e 67, are verified for its correctness by MATLAB Code of Numerical integration method. 67 strong ground motions are divided into four regions of the country - East, North, South-East and West. Tripartite Response Spectrum for mean and mean plus one standard deviation values is developed for all four regions of India for 3000 SDOF systems having damping ratio 5%. Cut off time periods for acceleration sensitive region, velocity sensitive region and displacement sensitive region are identified for 15000 SDOF systems for all 67 strong ground motions. Amplification factors are developed from these cut off time periods for acceleration, velocity and displacement sensitive regions. Statistical approach is carried out to generate smooth elastic design spectrum. MATLAB Code is developed to generate mean and mean plus one standard deviation design spectrum. These developed design spectrum are compared with code based design spectrum for all four regions of the country.

Seismic demand of four storey RC framed structure is determined using design spectrum developed. Response quantities such as spectral acceleration and lateral force is estimated for this building from proposed design spectrum for four regions of the country through static analysis. These response quantities are compared with design response spectrum of IS:1893-2002 (Part-I). Five seismic codes of various countries like Mexico, United States of America, Chile, Philippine and China are considered for comparison of seismic parameters. Methods of lateral load estimation and design spectrum of all these five seismic codes are compared.

## 7.2 Conclusions

This section covers important conclusions derived through current study.
Based on the Design spectrum generated for Indian subcontinent, following points are concluded.

- Mean response spectrum yields base shear value lower than the IS based design spectrum for highest seismic zone V for all regions.

- The IS based design spectrum yields lower base shear value when compared with mean plus one standard deviation design spectrum.

- Comparison among developed mean response spectrum for West and South-

East region shows the later yields lower base shear value as compared to IS based design spectrum while former yields higher base shear value.

- Very less strong motion values are available for West and South-East regions.
- Cut off time periods for sensitive regions and amplification factors are site dependent parameters and very much important to develop design spectrum.

Based on the seismic code comparison for seismic analysis, following points are concluded.

- United States of America and Philippines seismic codes are based on Uniform Building Code.
- In China, seismic action is evaluated considering only soil type and seismic coefficient which is based on natural time period.
- In Chile, base shear is calculated considering seismic parameters like soil type, zone, building category and structural system. Design spectrum is not available in this code.
- In Mexico, soil type, seismic zone and design spectrum is considered for lateral load estimation.

## 7.3 Future Scope of the Work

The present work can be extended as follows.

- More exhaustive data of ground motion can be collected to develop design spectrum. In this regards institutes like Indian Seismological Research Center (ISR), Indina Meteorological Department (IMD) can be connected.
- Inelastic Design Spectrum for Indian subcontinent can be developed.
- Rigorous study of seismic codes of various countries can be done.

# Appendix A

# MATLAB Code

**A) MATLAB Code for verification of ground motion data using Numerical Integration Method**

```
% Verification of Champawat ground motion data
clear,clc
close all
fid=fopen('.txt file of strong ground motion data after 2005 of champawat (chamoli)');
acc=fscanf(fid,'%g');
X=0.005:0.005:35.765; % increment in time
Y=0.01*acc; % acceleration
Z=cumtrapz(X,Y); % velocity
max(abs(Z));
subplot(3,1,1)
plot(X,Y)
xlabel('time (sec)','Fontsize',12)
ylabel('$Acceleration(m/sec^2)$','Fontsize',12)
title('champawat (chamoli) gound acceleration','Fontsize',12)
subplot(3,1,2)
plot(X,Z)
xlabel('time (sec)','Fontsize',12)
```

```
ylabel('velocity (m/sec)','Fontsize',12)
title('champawat (chamoli) ground velocity','Fontsize',12)
D=cumtrapz(X,Z); % displacement
max(abs(D));
subplot(3,1,3)
plot(X,D)
xlabel('time (sec)','Fontsize',12)
ylabel('Displacement (m)','Fontsize',12)
title('champawat (chamoli) ground displacement','Fontsize',12)
```

**B) MATLAB Code for Response spectrum construction using Newmark-Beta Method**

```
% Development of Response Spectrum for El Centro earthquake excitation using
Newmark-Beta method clear,clc
m=10000;
% mass of SDOF system
zeta=0.02;
% damping ratio
fid=fopen('.txt file of el centro');
acc=fscanf(fid,'%g');
acc=[0;acc]; acc=acc.*9.81;
pga=max(abs(acc))
p0=-m*acc;
% integration parameter for constant acceleration method
beta=1/4;
gamma=1/2;
dt=0.02;
% increment in time
u0=0;
```

% initial displacement

v0=0;

% initial velocity

i=1;

for Tn=0:0.001:3 % 3000 possible SDOF systems

k(i)=$m * (2 * pi/Tn)^2$; % stiffness of system

c(i)=zeta*4*m*pi/Tn; % damping of system

a0(i)=(p0(1,:)-c(i)*v0-k(i)*u0)/m;

k1(i)=k(i)+((gamma/(beta*dt))*c(i))+((1/(beta*dt*dt))*m);

aa(i)=((1/(beta*dt))*m)+(gamma/beta)*c(i);

bb(i)=((1/(2*beta))*m)+dt*((gamma/(2*beta))-1)*c(i);

u(1,:)=u0;

v(1,:)=v0;

a(1,:)=a0(i);

for j=2:1560

% number of data points

dp(j-1,:)=p0(j,:)-p0(j-1,:)+aa(i)*v(j-1,:)+bb(i)*a(j-1,:);

du(j-1,:)=dp(j-1,:)/k1(i);

dv(j-1,:)=(gamma/(beta*dt)*du(j-1,:))-(gamma/beta)*v(j-1,:)+dt*(1-(gamma/(2*beta)))*a(j-1,:);

da(j-1,:)=(1/(beta*dt*dt))*du(j-1,:)-(1/(beta*dt))*v(j-1,:)-(1/(2*beta))*a(j-1,:);

u(j,:)=u(j-1,:)+du(j-1,:);

v(j,:)=v(j-1,:)+dv(j-1,:);

a(j,:)=a(j-1,:)+da(j-1,:);

end

u1(i)=max(abs(u)); % relative displacement

v1(i)=max(abs(v)); % relative velocity

a1(i)=max(abs(a)); % relative acceleration

V(i)=((2*pi)/Tn)*u1(i); % pseudo-velocity

$A(i) = (((2 * pi)/Tn)^2) * u1(i)$; % pseudo-acceleration

```
i=i+1;
end
u1
v1
a1
V
A
Tn=0:0.001:3;
subplot(3,1,1)
plot(Tn,u1)
xlabel('time (sec)','Fontsize',14)
ylabel('D (m)','Fontsize',14)
title('Deformation response spectrum','Fontsize',14)
subplot(3,1,2)
plot(Tn,V)
xlabel('time (sec)','Fontsize',14)
ylabel('Pseudo velocidty (m/sec)','Fontsize',14)
title('Pseudo Velocity response spectrum','Fontsize',14)
subplot(3,1,3)
plot(Tn,A)
xlabel('time (sec)','Fontsize',14)
ylabel('Pseudoacceleration(m/sec^2)','Fontsize',14)
title('Pseudo Acceleration response spectrum','Fontsize',14)
```

**C) MATLAB Code for Tripartite Response spectrum**

```
% Development of Tripartite Response Spectrum for Indian Context
clear,clc
for k=.00001:.00001:.0001
x=0.01:1:100
```

```
t=log((2*pi)*k)-log(x)
y=exp(t)
loglog(x,y,'k'),grid on
hold on
t=log(k*9.81/(2*pi))+log(x)
y=exp(t)
loglog(x,y,'k')
hold on
end
for k=.0001:.0001:.001
x=0.01:1:100
t=log((2*pi)*k)-log(x)
y=exp(t)
loglog(x,y,'k'),grid on
hold on
t=log(k*9.81/(2*pi))+log(x)
y=exp(t)
loglog(x,y,'k')
hold on
end
for k=.001:.001:.01
x=0.01:1:100
t=log((2*pi)*k)-log(x)
y=exp(t)
loglog(x,y,'k'),grid on
hold on
t=log(k*9.81/(2*pi))+log(x)
y=exp(t)
loglog(x,y,'k')
hold on
```

```
end
xlabel('period in sec')
ylabel('spectral velocity sv in m/sec')
for k=.01:.01:.1
x=0.01:1:100
t=log((2*pi)*k)-log(x)
y=exp(t)
loglog(x,y,'k'),grid on
hold on
t=log(k*9.81/(2*pi))+log(x)
y=exp(t)
loglog(x,y,'r','linewidth',2)
hold on
end
for k=.1:.1:1
x=0.01:1:100
t=log((2*pi)*k)-log(x)
y=exp(t)
loglog(x,y,'k'),grid on
hold on
t=log(k*9.81/(2*pi))+log(x)
y=exp(t)
loglog(x,y,'r','linewidth',2)
hold on
end
for k=1:1:10
x=0.01:1:100
t=log((2*pi)*k)-log(x)
y=exp(t)
loglog(x,y,'k'),grid on
```

```
hold on
t=log(k*9.81/(2*pi))+log(x)
y=exp(t)
loglog(x,y,'k')
hold on
end
for k=10:10:100
x=0.01:1:100
t=log((2*pi)*k)-log(x)
y=exp(t)
loglog(x,y,'k'),grid on
hold on
t=log(k*9.81/(2*pi))+log(x)
y=exp(t)
loglog(x,y,'k')
hold on
end
for k=100:100:1000
x=0.01:1:100
t=log((2*pi)*k)-log(x)
y=exp(t)
loglog(x,y,'k'),grid on
hold on
t=log(k*9.81/(2*pi))+log(x)
y=exp(t)
loglog(x,y,'k')
hold on
end
for k=1000:1000:10000
x=0.01:1:100
```

```
t=log((2*pi)*k)-log(x)
y=exp(t)
loglog(x,y,'k'),grid on
hold on
t=log(k*9.81/(2*pi))+log(x)
y=exp(t)
loglog(x,y,'k')
hold on
end
axis([0.01 5 0.001 5])
text(0.2,0.002,'0.001');
text(0.6,0.01,'0.01');
text(2,0.03,'0.1');
text(7,0.1,'1');
text(20,0.3,'10');
text(80,1,'100')
text(2,0.1,'sd in m')
text(0.01,20,'100')
text(0.01,2,'10')
text(0.01,0.2,'1')
text(0.02,0.04,'0.1')
text(0.07,0.01,'0.01')
text(.02,0.08,'sa/g')
m=10000;
% mass of SDOF system
zeta=0.05;
fid=fopen('.txt file of East mean plus one norm sgm.xls');
mean plus one east=fscanf(fid,'%g');
fid=fopen('.txt file of West mean plus one norm sgm.xls');
mean plus one west=fscanf(fid,'%g');
```

```
fid=fopen('.txt file of North mean plus one norm sgmf.xls');
mean plus one north=fscanf(fid,'%g');
fid=fopen('.txt file of South-East mean plus one norm sgm.xls');
mean plus one southeast=fscanf(fid,'%g');
Tn=0:0.001:3;
plot(Tn,mean plus one east,'r','linewidth',3)
hold on
plot(Tn,mean plus one west,'k','linewidth',3)
hold on
plot(Tn,mean plus one north,'g','linewidth',3)
hold on
plot(Tn,mean plus one southeast,'m','linewidth',3)
hold off
xlabel('time (sec)','Fontsize',14)
ylabel('V (m/sec)','Fontsize',14)
title('Tripartite Mean Plus One Response Spectrum-Four Regions','Fontsize',14)
```

**D) MATLAB Code for Elastic Design spectrum**

```
% Development of Elastic Design Spectrum for Indian Context
pga=0.73;
pgv=0.037;
pgd=0.00927;
ca=1.73;
cv=2.28;
cd=2.45;
for k=.00001:.00001:.0001
x=0.01:1:100
t=log((2*pi)*k)-log(x)
y=exp(t)
```

```
loglog(x,y,'k'),grid on
hold on
t=log(k*9.81/(2*pi))+log(x)
y=exp(t)
loglog(x,y,'k')
hold on
end
for k=.0001:.0001:.001
x=0.01:1:100
t=log((2*pi)*k)-log(x)
y=exp(t)
loglog(x,y,'k'),grid on
hold on
t=log(k*9.81/(2*pi))+log(x)
y=exp(t)
loglog(x,y,'k')
hold on
end
for k=.001:.001:.01
x=0.01:1:100
t=log((2*pi)*k)-log(x)
y=exp(t)
loglog(x,y,'k'),grid on
hold on
t=log(k*9.81/(2*pi))+log(x)
y=exp(t)
loglog(x,y,'k')
hold on
end
xlabel('period in sec')
```

```
ylabel('spectral velocity sv in m/sec')
for k=.01:.01:.1
x=0.01:1:100
t=log((2*pi)*k)-log(x)
y=exp(t)
loglog(x,y,'k'),grid on
hold on
t=log(k*9.81/(2*pi))+log(x)
y=exp(t)
loglog(x,y,'r','linewidth',2)
hold on
end
for k=.1:.1:1
x=0.01:1:100
t=log((2*pi)*k)-log(x)
y=exp(t)
loglog(x,y,'k'),grid on
hold on
t=log(k*9.81/(2*pi))+log(x)
y=exp(t)
loglog(x,y,'r','linewidth',2)
hold on
end
for k=1:1:10
x=0.01:1:100
t=log((2*pi)*k)-log(x)
y=exp(t)
loglog(x,y,'k'),grid on
hold on
t=log(k*9.81/(2*pi))+log(x)
```

```
y=exp(t)
loglog(x,y,'k')
hold on
end
for k=10:10:100
x=0.01:1:100
t=log((2*pi)*k)-log(x)
y=exp(t)
loglog(x,y,'k'),grid on
hold on
t=log(k*9.81/(2*pi))+log(x)
y=exp(t)
loglog(x,y,'k')
hold on
end
for k=100:100:1000
x=0.01:1:100
t=log((2*pi)*k)-log(x)
y=exp(t)
loglog(x,y,'k'),grid on
hold on
t=log(k*9.81/(2*pi))+log(x)
y=exp(t)
loglog(x,y,'k')
hold on
end
for k=1000:1000:10000
x=0.01:1:100
t=log((2*pi)*k)-log(x)
y=exp(t)
```

```
loglog(x,y,'k'),grid on
hold on
t=log(k*9.81/(2*pi))+log(x)
y=exp(t)
loglog(x,y,'k')
hold on
end
axis([0.05 15 0.01 2])
text(0.2,0.002,'0.001');
text(0.6,0.01,'0.01');
text(2,0.03,'0.1');
text(7,0.1,'1');
text(20,0.3,'10');
text(80,1,'100')
text(2,0.1,'sd in m')
text(0.01,20,'100')
text(0.01,2,'10')
text(0.01,0.2,'1')
text(0.02,0.04,'0.1')
text(0.07,0.01,'0.01')
text(.02,0.08,'sa/g')
xc(1)=0.05;
xc(2)=0.033;
xc(3)=0.127;
xc(4)=cv*pgv*2*pi/(ca*pga);
xc(5)=cd*pgd*2*pi/(cv*pgv);
xc(6)=1.67;
xc(7)=11.4;
xc(8)=15.0;
yc(1)=pga*0.05/(2.0*pi);
```

```
yc(2)=pga*0.033/(2*pi);
yc(3)=ca*pga*0.127/(2*pi);
yc(4)=cv*pgv;
yc(5)=cv*pgv;
yc(6)=cd*pgd*2*pi/1.67;
yc(7)=pgd*2*pi/11.4;
yc(8)=pgd*2*pi/15;
line(xc,yc,'color','b','LineWidth', 3.0)
title('East Region Design Spectrum 50% Median and damping ratio=5%')
```

# Appendix B

# List of paper presented

- Mehta Payal and Purohit Sharadkumar, "Development of Elastic Spectrum for Indian Context", International Civil Engineering Symposium, Vellore Institute of Technology, Tamil Nadu, March 2014

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