GOVERNMENT OF INDIA
CENTRAL WATER COMMISSION

GUIDELINES FOR PREPARATION AND SUBMISSION
OF
SITE SPECIFIC SEISMIC STUDY REPORT OF WATER RESOURCE PROJECT
TO
NATIONAL COMMITTEE ON SEISMIC DESIGN PARAMETERS

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FE&SA Directorate, 8th Floor (N), Sewa Bhawan, R.K. Puram
New Delhi 110066
(October 2011)

Second Revision: June 2024

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FOREWORD

The Ministry of Water Resources constituted a high-level inter-disciplinary official body, the "National Committee on Seismic Design Parameters (NCSDP) for River Valley Projects" in 1991 (formerly known as Standing Committee) to recommend the site-specific design seismic parameters for the design of dams and other appurtenant structures of the water resource projects. The site-specific reports for the determination of seismic parameters involve the estimation of seismic parameters either using the deterministic seismic hazard analysis (DSHA) method or the probabilistic seismic hazard analysis (PSHA) method. Both approaches involve using various assumptions in the modelling, and the reliability of the results depends upon the correctness of the assumptions made based on scientific judgment and experience.

Currently, the probabilistic approach is more accepted worldwide. A review of past results on Seismic Design Parameters (SDP) adopted for various water resource projects shows that the results from the Deterministic approach are too conservative to be adopted in the design.

A need was felt to update India's approach to estimating SDP per international standards and revise the NCSDP Guidelines focusing on the Probabilistic approach. The guidelines aim to minimise the subjectivity in the Probabilistic approach and variation in the results by providing all the modelling details, including the procedure, modelling of source zones and various assumptions made in the process. Henceforth, the site-specific seismic design parameters evaluated using the probabilistic approach will be considered for approval by the NCSDP committee. The deterministic approach will only be used to evaluate the deviation of SDP for the MCE condition and determine the reasons for that. I am confident that these revised guidelines will significantly reduce the subjectivity in analysing seismic design parameters evaluation and provide credible results.

I sincerely thank all the present and Ex-Members of NCSDP and officers from CWPRS, Pune, IIT, Roorkee and CWC for their invaluable contribution and cooperation in helping CWC prepare these guidelines.

For this meticulous work, I express my heartfelt gratitude for the sincere and untiring efforts made by Dr I D Gupta, Ex-Director, CWPRS, Pune, Prof M L Sharma, IIT-R, Prof Manish Shrikhande, IIT-R, Shri Rakesh Kashyap, Chief Engineer (DSO), CWC, Shri Samir Kumar Shukla, Director, CWC & Member Secretary NCSDP and Shri Satyam Aggarwal, Deputy Director, CWC. I am also pleased to acknowledge the support and cooperation of officers and staff of the FE&SA Directorate of Dam Safety Organization, Central Water Commission, in preparation of this document.

I hope these guidelines will help estimate seismic design parameters for various water resource projects in the country per international standards.

New Delhi
June 2024

(S.K. Sibal)
Chairman, NCSDP & Member(D&R)

Contents

ABBREVIATIONS

DBE	Design Basis Earthquake
DSHA	Deterministic Seismic Hazard Analysis
ICOLD	International Committee on Large Dams
IS	Indian Standard
LET	Local Earthquake Tomography
MCE	Maximum Credible Earthquake
MCM	Million Cubic Meters
MPa	Mega Pascal
MT	Magnetotellurics
NCSDP	National Committee on Seismic Design Parameters
NGA	Next Generation Attenuation
OBE	Operating Basis Earthquake
PGA	Peak Ground Acceleration
PSHA	Probabilistic Seismic Hazard Analysis
Sa	Spectral acceleration
SEE	Safety Evaluation Earthquake
SGM	Strong Ground Motion
SSZ	Seismic Source Zones

GUIDELINES FOR PREPARATION AND SUBMISSION OF SITE-SPECIFIC SEISMIC STUDY REPORT OF WATER RESOURCE PROJECTS TO NATIONAL COMMITTEE ON SEISMIC DESIGN PARAMETERS

1.0 SCOPE

1.1 These guidelines provide the methodologies and procedures for preparing a site-specific seismic study report for a river valley project site and its submission to the National Committee on Seismic Design Parameters (NCSDP) for necessary approval. The guidelines will help estimate the site-specific ground motion parameters required for seismic design by dynamic response analysis and safety evaluation of new or existing dams and their appurtenant structures. The guidelines are expected to bring uniformity in site-specific seismic studies being carried out by different investigators vis-à-vis the widely used international practice.

1.2 The site-specific seismic studies need to be carried out and submitted for the approval of NCSDP in respect of dams (irrespective of the seismic zone in which the dam lies) falling under the category Intermediate and Large (as classified in clause 3.1.2 of IS 11223: Guidelines for Fixing Spillway Capacity)

1.3 Concerning projects wherein a dam/water storage structure already exists, the project is to be considered as a whole along with its components, i.e., old structure, new structure, and appurtenant structure. Hence, site-specific seismic studies need to be carried out and submitted for the approval of NCSDP for all such structures, irrespective of whether they are old or new.

1.4 The site-specific seismic studies need to be carried out and submitted for the approval of NCSDP in respect of all existing dams where–

(i) any extreme seismic event is observed which has the potential to affect or damage structure or an event with a magnitude of Peak Ground Acceleration greater than the values specified in paragraph 6.4.2 (Table 3) of IS: 1893-2016 (Part 1) relating to Criteria for Earthquake Resistant Design of Structures developed by the Bureau of Indian standards;

(ii) dam re-sectioning is proposed or carried out to the original structure, or there are changes in design criteria;

(iii) Major geological activity is reported by the Geological Survey of India for the region, such as the identification of new faults or movement in existing faults:

Provided that the site-specific seismic studies shall be carried out only for those existing specified dams where risk assessment study warrants.

1.5 The guidelines' provisions also apply to river valley projects and their appurtenant structures, as well as the powerhouse and other structures located near the dam whose failure can result in an uncontrolled release of water from the reservoir. However, the guidelines' provisions need not be applied to project canals and canal structures and also not to temporary structures such as coffer dams.

1.6 The site-specific seismic studies that are not mandated per the above conditions need not be referred to NCSDP unless directed otherwise by a government or judicial authority. In all such exempt cases, the selection of seismic design parameters will continue to be governed as per the values given in Section 13 of this guideline.

1.7 The terms used in these guidelines have standard meanings that apply generally to all seismic studies. The glossary, given as Annexure A, further elucidates some of the key terms.

2.0 BACKGROUND AND INTRODUCTION

2.1 The design of dams to resist damage due to earthquakes is of increasing relevance to dam designers. The present guidelines were first published in October 2011 and revised in June 2014, mainly by adding two annexures for a glossary of terminologies and the list of the seismic design parameters for 177 projects approved by NCSDP since 1991. The revision includes recent developments in hazard analysis methodologies and ground motion prediction equations (GMPEs), traditionally termed attenuation relationships. The revised guidelines more explicitly and elaborately present the various aspects related to the 'Determination of Seismic Input Parameters' required for the seismic analysis. This document aims to enable a fair amount of consistency in earthquake design aspects to international practices, evaluate the performance of dams in existence, and ensure compliance so as to fulfil requirements of dam safety by all concerned. However, the use of recent developments in the subject matter from time to time shall be acceptable as long as there are no fundamental deviations from these guidelines.

2.2 Dams have been traditionally designed using the pseudo-static analysis method (IS: 6512 – 1984; IS: 7894 – 1975), in which the earthquake effects are represented by static forces defined by multiplication of the horizontal and vertical seismic coefficients with the structure's weight. Highly reduced values of the seismic coefficients are generally used compared to the maximum ground acceleration that a dam may experience during real earthquakes. Though the dams designed by this method are, in most cases, expected to perform satisfactorily under actual site-specific earthquake excitation, this method is unable to establish explicitly the safety of gravity dams against damage caused by excessive stresses and the safety of earth and rock-fill dams against permanent crest settlement and liquefaction. The seismic safety of dams can be ascertained explicitly only by detailed dynamic response analysis using site-specific design ground motion defined in terms of the acceleration time histories (termed as design accelerograms) of both horizontal and vertical motion components and the corresponding design response spectra with different damping values.

2.3 The initial design of a dam arrived at by seismic coefficient method must be tested by simplified first-mode response spectrum method and finalised by dynamic response analysis using rigorous linear time history analysis with finite element modelling under the design basis earthquake (DBE) level of site-specific ground motion. The DBE represents the level of ground motion for which there should be no or easily repairable insignificant damage to the dam and appurtenant structures. However, the dam's safety must be assessed under the maximum credible earthquake (MCE) level of site-specific ground motion. The MCE represents a much higher level of site-specific ground motion for which significant damage to the dam body is acceptable, provided no uncontrolled release of water occurs from the reservoir.

2.4 The DBE level of ground motion is intended to occur with reasonably high probability during the life of a dam. Hence, it is to be defined for a return period of 475 years (10% probability in 50 years) using the probabilistic seismic hazard analysis (PSHA) method, which has become the state-of-the-art methodology for estimating the design ground motion for all important structures. On the other hand, the MCE level of ground motion is intended to be a much rarer event during the life of a dam. It is, therefore, required to be defined by the PSHA method for a suitably selected long return period between 2475 and 9975 years, as defined in Table 1 of this guideline. The MCE level of ground motion is proposed to be estimated using the deterministic seismic hazard analysis (DSHA) method, and the final estimate will be arrived at from a critical comparison of the estimates from both methods.

2.5 Using suitably selected GMPEs for the spectral amplitudes at different natural periods, the DBE and MCE levels of site-specific design ground motions are obtained directly in terms of horizontal and vertical response spectra with a damping ratio of 5%, which are termed as the target response spectra (TRS). The pairs of TRS of horizontal and vertical motion components for both DBE and MCE conditions are used to generate 3–7 uncorrelated pairs of compatible design accelerograms for use in detailed dynamic response analysis for design and safety evaluation purposes. If required for any analysis, the TRS with a damping ratio of 5% can be used to obtain the response spectra with other damping ratios using the period-dependent scaling factors given in IS: 1893 (Part 1).

2.6 These guidelines provide details and recommendations on the various aspects of the DSHA and PSHA methods for estimating MCE and DBE levels of horizontal and vertical TRS and generating the design accelerograms. However, the preliminary design and sizing of a dam may be arrived at using pseudo-static methods of analysis as per IS: 6512 and IS: 7894 for gravity and earth dams, respectively, with the minimum values of the **pseudo-static horizontal and vertical seismic coefficients for different seismic zones** as prescribed in section 13.0 of this guideline may be used.

3.0 USEFUL CONCEPTS AND DEFINITIONS

The generation of earthquake ground motion at a site involves a complex process of displacement over a fault surface deep inside the earth as the source of the earthquake, propagation of the seismic waves from the source to the site, and amplification of the ground motion due to local geology and soil condition at the site. The site-specific nature of the ground motion stems from the dependences on the characteristics of the earthquake source, wave propagation path, as well as local site conditions, all of which have to be modelled realistically to arrive at a realistic estimate of the design ground motion parameters at a river valley project site. Some useful concepts and definitions related to the site-specific studies are given below:

3.1 ***Seismic Source Zones*:** Site-specific evaluation of design ground motion requires identifying all probable sources of earthquakes which may affect a project site of interest. Ideally, all seismic sources should be individual active faults (line or dipping surface). Still, the area sources of diffused seismicity are commonly used in real applications due to a lack of exact knowledge about active faults and their seismic potential. Each seismic source is characterised by distinctly different seismic potential (occurrence rates and/ or maximum magnitude) from adjacent sources. Area sources are first identified grossly based on differences in physiography, geology, and tectonic setup and then subdivided into smaller units based on the differences in the seismicity characterised by available data on past earthquakes supplemented by data on paleoseismicity and GPS-based or geologically determined strain or slip rates.

3.2 ***Fault Rupture Parameters:*** The source of each earthquake in even an area source has to be modelled by a rectangular rupture plane of specified length and width depending upon the earthquake magnitude and predominant style of faulting (Wells and Coppersmith, 1994). The direction of the strike and the dip angle must also be specified to define the position of the rupture plane inside the earth completely. Two important parameters governing the kinematics of the fault rupture process are the average stress drop and the seismic moment, which may significantly influence the ground motion characteristics. However, the effects of these parameters are generally not accounted for explicitly in practical engineering applications.

3.3 ***Earthquake Distance Parameters:*** Earthquake events are traditionally characterised by their magnitudes, epicentral locations, and focal depths. The focal depth and the distances to the epicentre and the hypocenter of an earthquake are thus used as simple and convenient distance parameters in the older attenuation relationships. However, several different distance parameters are used to account for the effects of the finite size of the fault rupture plane in the modern ground motion prediction equations (Abrahamson and Shedlock, 1997), which includes the closest distance to the fault rupture plane (R_{rup}), the closest distance to the surface projection of the rupture plane (R_{jb}), perpendicular distance to the surface projection of the upper edge of the rupture plane (R_x), and the depth to the top of the fault rupture plane (Z_{tor}).

3.4 ***Site Soil and Geological Conditions:*** The earthquake ground motion at a site depends strongly and differently on the shallow soil deposits and the geological strata up to significant depths. In earthquake engineering applications, the geological soil conditions used to be defined qualitatively till recent times by a limited number of broad categories. However, more comprehensive and quantitative characterisations are being used at present, among which is the time-averaged shear wave velocity in m/s, denoted by Vs_{30}, which is the most widely used parameter. The NEHRP site classes A, B, C, D and E, representing sites falling within different broad intervals of Vs_{30} (BSSC, 2003), are also used in some cases. The geological condition is presently characterised commonly by depth in km to the strata with shear wave velocity of 1.0 km/s or 2.5 km/s, denoted commonly by $z_{1.0}$ or $z_{2.5}$, respectively.

3.5 ***Ground Acceleration Time Histories***: When the seismic waves from an earthquake source reach a site, they set the ground particles into motion, which is termed as ground motion. For engineering applications, the most comprehensive description of ground motion is provided by the two orthogonal horizontal and one vertical components of ground acceleration, known as strong motion accelerograms (SMA). The SMA records are characterised by strong motion portions of almost uniformly intense ground motion between a very short building-up portion in the beginning and a slowly decaying long portion at the end. Along with the peak ground acceleration (PGA), the duration of the strong motion portion as well as the total duration constitutes important characteristic to be built in appropriately in the site-specific design accelerograms.

3.6 ***Response Spectra of Accelerograms****:* The response spectrum of an accelerogram represents the maximum response (absolute acceleration, relative velocity or relative displacement) of a set of single-degree-of-freedom (SDOF) oscillators with different natural periods and a specified damping ratio when excited by that accelerogram. The absolute acceleration response spectrum in engineering applications is commonly approximated by the pseudo-spectral acceleration amplitudes, $PSA(T)$, defined from the exact spectral displacement amplitudes, $SD(T)$, as $PSA(T) = (2\pi / T)^2 SD(T)$. The response spectrum of the horizontal ground motion is defined in several different ways considering both the horizontal components. The rotation-dependent non-geometric mean median spectrum (RotD50) is currently the most widely used horizontal spectrum (Boore, 2010). However, the geometric mean of two recorded components of motion and some other definitions of the horizontal spectrum being used in the past are still being used in some studies (Beyer and Bommer, 2006).

3.7 ***Ground Motion Prediction Equations (GMPEs):*** Ground motion prediction equations (GMPE) are simple mathematical models developed empirically from recorded strong motion data. Equations are commonly developed to predict the median ground motion parameters (e.g., PGA and spectral amplitudes) in terms of a limited number of predicting variables defining the source, path, and site characteristics. The inherent random nature of the ground motion and the effects of not including the dependence on many of the governing parameters which cannot be defined accurately are modeled by developing suitable probability distributions for the residuals between the recorded ground motion data and the median predictions. To define a GMPE completely, the values or the predictive relations for the statistical parameters involved in the distributions for the residuals have to be provided along with the median prediction equation. Such prediction equations are also termed as ground motion models (GMMs), ground motion attenuation relations, or ground motion scaling relations. The median prediction equations along with statistical distribution of residuals can be used to predict the ground motion parameters with any desired probability of not exceeding (confidence level) due to a given set of the predicting variables.

3.8 ***Seismic Hazard Analysis Methods:*** The PSHA and DSHA are the two methods, that can be used to arrive at the site-specific estimates of the MCE and DBE levels of horizontal and vertical TRS at a selected project site. In the PSHA method,the seismicity is characterized by the occurrence rates of earthquakes between a minimum magnitude of engineering significance and the maximum possible magnitude at all possible locations in the region around the project site, which are used along the probability of exceeding specified values of the ground motion parameter obtained from the selected GMPEs to estimate the TRS for a given probability of exceeding during a specified life period (or equivalently a given return period). The DSHA method on the other hand attempts to arrive at the maximum possible estimate of the TRS by considering a fixed earthquake scenario of the maximum magnitude at the closest possible distance without any regard to the likelihood of its occurrence.

3.9 ***DBE Level of Ground Motion*****:** Dams and appurtenant structures are designed to be safe for a level of ground motion that can be expected to occur within the service life of a dam with a reasonably high probability. This has been termed as the design basis earthquake (DBE) ground motion and is proposed to be estimated using PSHA method for a return period of 475 years, which is equivalent to 10% probability of exceeding in 50 years. In the ICOLD Bulletin 148 (2016), this has been termed as Operating Basis Earthquake (OBE) ground motion and is defined for a much lower return period of 145 years, which represents 50% probability of exceeding in 100 years. Taking the life period of the dams as 100 years, this means that the estimated DBE ground motion may be exceeded by some amount in 50% of the cases, which is quite excessive. Thus, to ensure the safety of dams adequately, a return period of 475 years can be considered more reliable, which has only 19% probability of exceeding in 100 years.

3.10 ***MCE Level of Ground Motion (MCE):*** This is the level of ground motion under which considerable structural damage and deformations are accepted as long as the dam is able to store the water in the reservoir safely and the water level in the reservoir can be controlled after the earthquake. This level of earthquake is thus also termed as the safety evaluation earthquake (SEE) in the ICOLD Bulletin 148 (2016). The MCE level of TRS is required to be defined by the PSHA method for a sufficiently long return period representing very low probability of exceeding during the life of a dam. Alternatively, this can also be defined by the DSHA method at 84th percentile (mean plus one SD) for an earthquake scenario leading to the most critical ground motion for a dam at the site of interest. These guidelines propose to estimate the MCE level of ground motion by both PSHA and DSHA method and arrive at the final estimate from a critical comparison of the estimates from the two independent methods.

3.11 ***Performance Requirements:*** The dams and appurtenant structures are actually proposed to be designed for the DBE level of ground motion with no or easily repairable insignificant damage. The dam, appurtenant structures and equipment should remain functional after the occurrence of an earthquake shaking not exceeding the DBE. Under MCE level of ground motion, it is necessary that no catastrophic failure, resulting in uncontrolled release of water from the reservoir, takes place. However, considerable damage and economic losses are permitted, provided the water retaining and safe evacuation capabilities of the dam are not jeopardized. Thus, the safety critical elements like bottom outlets, spillway, and control units are required to be designed for the MCE level of ground motion.

4.0 REGIONAL TECTONIC AND GEOLOGIC SETTINGS

Detailed information on the geological setup and the tectonic features in a large region surrounding a dam site of interest forms an important and essential database for seismic hazard analysis by both PSHA and DSHA methods. This along with data on past seismicity is utilized to define the sources of earthquakes that could affect the dam site under consideration. Defining and understanding the seismic sources is a very crucial part of the seismic hazard analysis and has to be established in a realistic way.

The tectonic features refer to the geological structures developed in the Earth's lithosphere due to the geodynamic and plate tectonic processes, which may be the sources of expected future seismicity in a region. Knowledge of tectonic features forms an important input to seismic hazard assessment. Various tectonic features of significance in seismic hazard studies may be listed as: faults, folds, shear zones, rift-basins, and major lineaments. The earthquakes can be caused only by active faults, but other tectonic features may also be the locales of earthquakes, because such structures may be an indirect manifestation of the active faults. The site-specific study report should provide a detailed account on all the regional tectonic features vis-à-vis their geological and geophysical manifestations. This may be based on a combination of comprehensive literature survey and investigations carried out for the project under study. The regional tectonic and geological data reviewed shall include:

(i) Physiographic and tectonic province within which the project is located,

(ii) Geologic history of the project area,

(iii) Description of geologic formations, rock types and soil deposits,

(iv) Major geological structural features including folds, fracture pattern, sedimentary basins, rift valleys, etc.,

(v) Major tectonic features including faults, thrusts, shear zones, and major lineaments and their capability to generate earthquakes,

(vi) Interpretation of the regional tectonic mechanism and associated style of faulting, A regional tectonic map covering an area of not less than 6°× 6° in latitudes and longitudes around the dam site should be prepared on the basis of the above review and to be included in the study report. The area of this map may be enlarged suitably to avoid any excessive truncation of an important tectonic domain. The tectonic map for the areas within the Indian Territory should conform to the 'Seismotectonic Atlas of India and its Environ' published by Geological Survey of India (Dasgupta et al., 2000) and available also at the Bhukosh site of GSI (http://bhukosh.gsi.gov.in). Tectonic features for the areas falling outside the Indian Territory should also be included in the tectonic map from the other authentic sources. Additional tectonic features for the areas within the Indian Territory may also be added from the authentic published sources. The study report should also include a detailed description on the regional tectonic map included in the report.

5.0 LOCAL GEOLOGY AND SITE SOIL CONDITION

Site-specific geologic information is necessary to ascertain some of the characteristics of the ground motion expected at the dam site and to assess the needs for any treatments required in the foundation level rock. The study report should summarize the local geological mapping at the sites of all important components of the project on 1:2000 or larger scale along with topographic contours. The report should also include geological sections along and across dam axis and other important structures. The geological sections should be derived through drilling and other geo-physical probing, and they should show depth to overburden, faults, shear zones etc. The local geological data should include the following:

(i) Definition of type, extent, thickness, mode of deposition/formation, and stability characteristics of rock units and soil deposits.

(ii) Location and chronology of local faulting, including amount and type of displacements estimated from stratigraphic data, time of last rupture, rates of activity, strain rates, slip rates, etc., to the extent possible.

(iii) Interpretation of the structural geology including orientation and spacing of joint systems, bedding planes, dip and strike of geologic units, folds and intrusive or extrusive bodies.

(iv) Determination of the permeability characteristics of the formations encountered.

(v) Determination of foundation and abutment conditions and their physical properties.

The site-specific characteristics of the design ground motion at a river valley project site depend strongly on both the local geological and the site soil conditions. The local geology refers to the earth strata up to large depth, whereas the site soil condition refers to shallow formations within a few tens of meters above the actual or engineering bedrock. The effects of the local geological and site soil conditions are accounted by modeling the dependence of the ground motion parameters on the min the GMPEs. The older GMPEs (Douglas, 2021) generally include the dependence on either the geologic condition (defined qualitatively as bedrock, deep sediments and intermediate sediments) or the soil condition (defined qualitatively as rock sites, stiff soil sites and soft soil sites). However, the recent GMPEs (Douglas, 2021) include the effects of the site soil condition defined in terms of the time-averaged shear wave velocity (V_{S30}) and the local geological condition characterized by the depth to the stratum where shear wave velocity becomes 1.0 km/s ($Z_{1.0}$) or where it becomes 2.5 km/s ($Z_{2.5}$).

For a realistic site-specific estimation of the ground motion for a new project site it is necessary to estimate the V_{S30} values by site experiments at the locations of all the major components of the project using methods like Multichannel Analysis of Surface Waves (MASW), electrical resistivity survey, seismic refraction method, Cross-Hole Seismic Tomography or Seismic Cone Penetration Testing (SCPT).

The Vs_{30} shall be determined as the 30m average from the foundation level of dam. However if the foundation is to be laid on hard rock the Vs_{30} may be approximated by shear wave velocity at the foundation level/hard rock level.

The site experiments for the existing projects may be carried out adjacent to the various structures or V_{S30} may be defined approximately using correlations with in situ SPT or CPT value or undrained shear strength estimates (Wair et al., 2012), if available from the older studies carried out before the construction. The site-specific study report should indicate the locations on the project layout plan of all the sites at which the experiments were carried out to estimate the V_{S30} values. The V_{S30} values obtained at all the sites should be tabulated in the report by indicating the representative value adopted for the hazard computation and basis for its selection.

The site experiments carried out for estimation of V_{S30} will generally be useful to get the estimate of $Z_{1.0}$ also. The $Z_{2.5}$ on the other hand may be estimated from the published regional velocity models derived from teleseismic receiver function analysis (e.g., Borah et al., 2015; Bora et al., 2014; Srinivas et al., 2013; etc.) or from earthquake travel time inversion analysis. Lacking the site-specific estimates, the $Z_{1.0}$ and $Z_{2.5}$ parameters may be estimated using empirical relationships in terms of the average shear wave velocity V_{S30} at the site as given in Kaklamanos et al. (2011).

6.0 EARTHQUAKE CATALOG AND ANALYSIS OF PAST SEISMICITY

The data on past earthquakes has the strongest bearing on the hazard estimation for a dam site, because the seismic activity rates as well as the maximum earthquake magnitudes for various seismic sources are arrived at largely from the analysis of the available data on past seismicity. Compilation of a reliable and comprehensive earthquake catalog prepared by unifying the data from all possible sources including both historical and instrumental periods for the region of study assumes great importance in having realistic and reliable seismic hazard evaluation at a project site.

6.1 Compilation of the Earthquake Catalogue

The earthquake catalog adopted from a single source cannot be considered adequate for the purpose of seismic hazard analysis. The main source of earthquake data in India is a catalog made available online by National Centre for Seismology (NCS), New Delhi at which is https://riseq.seismo.gov.in/riseq/earthquake/archive, which is known popularly as the IMD Catalog. However, the Indian National Seismological Network has grown at a very slow pace with a mere number of 21 observatories for the vast area of country by end of 1988, which increased marginally to 35 by the end of 2002 and has grown slowly to 54 during 2007–2018 (Bansal et al., 2021). Thus, this catalog is not complete even for the most recent period and is increasingly incomplete as one goes back in time. The completeness of this catalog is still poorer for the trans-Himalayan area adjacent to the Indian Territory. Also, the type of magnitude is not specified in this catalog for the period up to 31 May 1998. The use of this catalog alone in a seismic hazard analysis application is not expected to provide accurate and reliable ground motion estimates.

In view of the above, it is essential that a starting catalog is prepared by combining the data from the NCS catalog and the reviewed bulletin of International Seismological Center (ISC) (www.isc.ac.uk) by adopting the types of magnitude from the ISC bulletin for the maximum number of events possible. To the extent possible, the initial catalog should next be enhanced by including data from the local seismological networks operated by different organizations (e.g., NGRI, CWPRS, MERI, GERI, IITR, WIHG, NEIST, ISR, etc.) in different parts of the country from time to time. The compiled catalogue should be checked critically to eliminate the duplicate events and should include for each event the date (year, month, day), origin time (hour, minute), epicentral location (latitude and longitude), focal depth, and the magnitude with type viz. M_W (Moment Magnitude), M_S (Surface wave Magnitude), m_b (Body wave Magnitude) and M_L (Ritcher's local Magnitude).

The ISC bulletin integrates reports from over 130 seismological agencies worldwide operating at global and/or local/regional scales. It is thus necessary to follow a suitable hierarchy for the preferred agencies for adopting the magnitudes of the earthquakes. It is proposed that the preferred agencies for M_S be used as ISC, NEIC, MOS, and IDC; that for m_b as ISC, NEIC, MOS, IDC, DJA, NDI, and DMN; that for M_W as GCMT, NEIC, and NDI; and that for M_L as NDI, DMN, BJI, BKK, and DJA in the indicated orders of preference.

6.2 Homogenization and Declustering of the Catalog

For use in the seismic hazard analysis, it is necessary that the magnitudes of all the events in the catalog are converted to moment magnitude, M_W, using empirical conversion relations suitable for India. The process is commonly known as homogenization of the catalog. The homogenized catalog should be produced as an Appendix to the report. If the total numbers of events are very large, events above a selected threshold magnitude only may be presented in the report.

The PSHA formulation is based on the assumption that the earthquake events follow a Poisson distribution, which is commonly considered to have been met by removing the dependent events (foreshocks and aftershocks) from the homogenized catalog.

This process of eliminating the dependent events from the catalog is termed as declustering. However, several different algorithms are available for identification of the aftershocks (van Stiphout et al., 2012), which results in widely differing results. It is necessary that the algorithms resulting in very severe declustering are avoided (e.g., Gardner and Knopoff, 1974), because it would result in significant underestimation of the hazard (Marzocchi and Taroni, 2014; Teng and Baker, 2019; Mizrahi et al., 2021). To avoid excessive removal of aftershocks, the cluster identification method due to Reasenberg (1985) with standard parameters $(\tau_{\min} = 1, \tau_{\max} = 10, \text{ and } r_{fact} = 10)$ is proposed to be used for declustering in the site-specific studies.

6.3 Analysis of Past Seismicity Data

To get a quick idea about the important characteristics of the past seismicity in the region under study, it is necessary that the study report presents with the help of histograms or tables the following analyses:

(i) Temporal, magnitude wise and distance wise distributions of the available data in the compiled catalog. The evolution of data from the historic period of up to 1899, early instrumental period of1900-1963, and the modern instrumental period since 1964 should be identified and discussed in the analysis.

(ii) To analyze the correlation between the past seismicity and the tectonic features in the region, a seismotectonic map should be prepared by superimposing the epicenters of the available past data on the regional tectonic map. As the correlation of past seismicity provides direct evidence for the active status of a fault, association of the epicenters of past earthquakes with major faults and other tectonic features should be analyzed critically by taking into account the dipping nature of faults and possible errors in the epicentral locations.

(iii) At least one regional seismotectonic section through the dam site and across the major tectonic trend of the region should be presented and discussed in the report. The section covering a minimum of 50 km reach on either side of the section line should clearly show (if necessary, by vertical exaggeration) the subsurface disposition of the major faults and earthquake hypocenters.

7.0 DELINEATION AND PARAMETERIZATION OF SEISMIC SOURCE ZONES

Identification of the various seismic source zones and defining the expected occurrence rates of different magnitudes of earthquakes between a minimum and possible maximum earthquake magnitude at all possible locations in each source zone forms the most crucial input to the PSHA method. It is also necessary to define the predominant focal mechanism parameters (angles of strike and dip and style of faulting) and the probable focal depth for the earthquakes at various locations in each source zone. The results of a PSHA study depend very strongly on the occurrence rates as well as the focal mechanism parameters, both of which are associated with significant uncertainties and are defined with widely varying assumptions and approximations. This section outlines the guidelines to perform the aforementioned tasks in the most realistic manner possible with the available data on past seismicity and the information on the tectonic features and geologic setup of the region of study.

7.1 Delineation of Seismic Source Zones

As the earthquakes in a region are generated essentially by active faults, seismic sources should ideally be specific faults only. Though a near vertical fault can be idealized by a line source on the ground surface, a dipping fault has to be modeled by an inclined surface inside the earth. However, all the active faults in a region are generally not known and also the past seismicity is generally not seen to correlate closely with the known faults. Area types of seismic sources are therefore used more commonly in practical hazard analysis applications without or in combination with fault sources. If the epicenters can be associated with a system of closely related faults or with a regional geological structure (e.g., fold belt, rift valley, etc.), the source zone may be modeled by an elongated area source. A very small size of an area source at long distance from the site of interest can also be idealized as a point source. Thus, in general, the hazard analysis has to be carried out using a combination of the point, line, dipping surface and large size area types of seismic sources. To estimate the occurrence rates of earthquakes at various locations covering a vast region around a project site it is necessary that the all-possible seismic source zones are delineated in the region in a realistic way following set scientific principles with minimum arbitrariness.

Fault specific line and dipping surface types of sources can be defined in a straight forward way when the past seismicity is associated with a known fault with its geometry known accurately. The area sources on the other hand are generally defined when the past seismicity is related only approximately with some of the known faults and also diffused widely over intervening areas. The area types of seismic sources are required to be as small as possible in size, such that each source is characterized by distinctly different seismicity defined by the frequency of earthquakes and/ or maximum magnitudes compared to the adjacent source zones.

Area types of seismic sources within a region of about 6° latitudes × 6° longitudes around a project site should be delineated by keeping in mind the physiographic divisions, geotectonic characteristics, tectonic features, and the expected future seismicity over a much larger area, and not in an isolation. The general principles and step-by-step procedure to be followed for delineation of area sources within the region around a project site can be enunciated as below:

(i) One may start with by segregating the areas of different physiographic divisions in the region. The main physiographic divisions of Indian sub-continent include the Himalayan Mountain Belt, Northern Plains, Peninsular Plateau, and the Offshore Areas.

(ii) The physiographic divisions should next be subdivided based on the geotectonic setup of the Indian subcontinent as depicted schematically in Figure 1. The major geotectonic units include the rigid cratonic blocks of Precambrian age, Proterozoic Mobile Belts and Sedimentary Basins, Gondwana Basins, Volcanic Province, and the Plate Boundary Zones.

(iii) Area of each geotectonic unit can next be divided into smaller areas on the basis of the similarity of the tectonic features and the geodynamic deformation rates. The closely related systems of faults, folds, thrusts, and shear zones, which cannot be modeled as individual tectonic features, are modeled as elongated broad area sources. The tectonic features like fold belts, buried ridges, and rift valleys can also be modeled as elongated area sources. Such area sources can be segmented into smaller sources based on a characteristic change in the trend, intersection by some prominent transverse tectonic feature, or variation in the deformation rate.

(iv) Each of the area sources arrived at as above is confirmed or further divided into smaller areas on the basis of the differences in the seismicity characteristics like maximum magnitude, activity rate, average focal depth, and dominant focal mechanism.

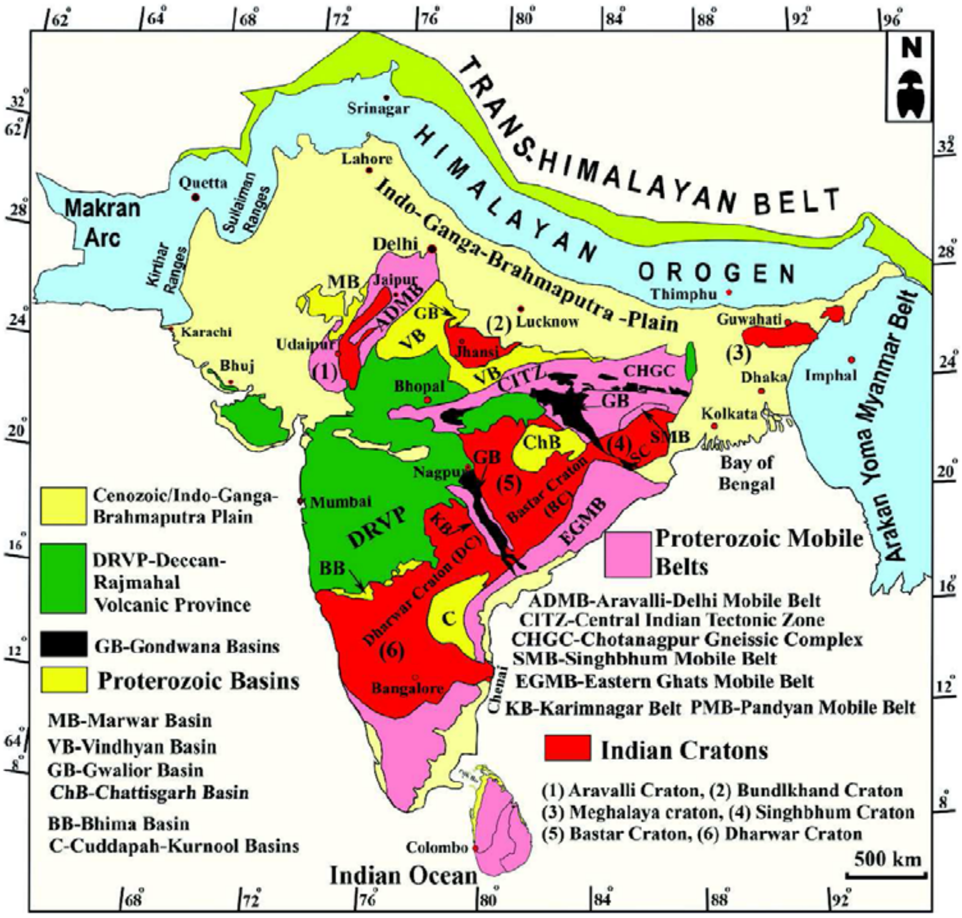

Figure 1A schematic depiction of the major geo-tectonic characteristics of the Indian sub-continent (after Jain and Banerjee, 2020).

The foregoing principles and guidelines, if applied judiciously, shall help in arriving at sufficiently realistic area types of seismic sources in a region without much personal biases. Only the readily available data can be used for this purpose, which includes data and information on physiographic divisions, geotectonic domains, tectonic features, and the available data on past seismicity along with data on paleo-seismicity and the geological and geodetic deformation rates. The study report should provide a comprehensive description on the identification of various seismic sources in the region of study with the major tectonic and geological features in each source zone indicated. To provide an idea about what this description may be, typical examples of delineation of seismic source zones for one project site in the seismically active Himalayan plate boundary region and one in the seismically stable intraplate region of Peninsular India are given in **Annexure B** and **Annexure C**, respectively.

7.2 Earthquake Recurrence Models

Recurrence models define the cumulative occurrence rate as a function of earthquake magnitude, and developing a suitable recurrence model each source zone forms an important part of the PSHA method. Several different forms of recurrence models with upper bound magnitude M_{max} have been proposed by different investigators, which differ mainly in the way the cumulative occurrence rate decays in the vicinity of the M_{max} (Gupta 2009). All these models have been basically derived from the following magnitude-frequency relationship proposed by Gutenberg and Richter (1944) without any upper bound magnitude

$$\log_{10} N(M) = a - bM \tag{7.1}$$

This is commonly termed as the G-R relationship with $N(M)$ as the cumulative occurrence rate of earthquakes with magnitude M or above and a and b are the constants specific to each source zone.

Two most commonly used models with upper bound magnitude given in Eq. (7.2) and (7.3) are the (i) truncated model defined simply by truncating the original G-R relationship at M_{max} (e.g., Bath, 1978; Anderson, 1979) and (ii) the exponentially decaying model in which the cumulative occurrence rate decays asymptotically to zero at M_{max} (e.g., Page, 1968; Cornell and Vanmarcke, 1969).

$$N(M) = \begin{cases} 10^{a-bM}; M \le M_{max} \\ 0; \text{Otherwise} \end{cases} \tag{7.2}$$

$$N(M) = N_{min} \frac{\exp(-\beta M) - \exp(-\beta M_{max})}{\exp(-\beta M_{min}) - \exp(-\beta M_{max})}; M \le M_{max} \tag{7.3}$$

The N_{min} in Eq. (7.3) is the cumulative occurrence rate above a selected threshold magnitude M_{min} and parameter $\beta = b \ln 10$. The threshold magnitude M_{min} is not necessarily equal to the minimum magnitude used in the hazard estimation. The model of Eq. (7.3) is found to underestimate significantly the occurrence rates in the vicinity of the maximum magnitude $M_{\max}$ leading to significant underestimation of the hazard. The truncated G-R model of Eq. (7.2) may in general be considered more realistic in most cases, unless the exponential form of Eq. (7.3) is shown to be appropriate by the trend of the observed data in a source zone. In some cases, the observed data may indicate the need for using a bilinear truncated model defined by two different *b*-values for magnitudes below and above a certain intermediate magnitude.

In view of the above, the form of the recurrence model for each source zone should necessarily be decided on the basis of the observed behavior of the available data on past earthquake in the source zone, rather than fixing it a priori. Further, the parameters a and b, and the maximum magnitude $M_{\max}$ required to define the recurrence model should be estimated from a judicious analysis of the available past earthquake data as described in the next two sections.

7.3 Estimation of Parameters *a* and *b*

The parameters a and b for a source zone are estimated by fitting the G-R relationship of Eq. (7.1) to the available past earthquake data in the source zone. As the available earthquake data is generally not complete for all the magnitudes for the entire period of the catalog, it becomes necessary to identify the periods of completeness for different cut-off magnitudes in a realistic manner. The various methods available for the completeness analysis fall into two broad categories, viz. the methods based on the linearity of G-R relationship (Woessner and Wiemer, 2005) and the methods based on the stability of the occurrence rate as a function of time (Stepp, 1973; Tinti and Mulargia, 1985; Herak et al., 2009).

The first category of methods defines a single magnitude of completeness above which the data are considered to be complete for the entire period of the catalog. However, this cannot be realistic for a catalog compiled from several different sources and covering a very long period of time. These methods are thus not recommended for use in seismic hazard analysis as they may underestimate the occurrence rates of smaller magnitudes of earthquakes significantly. The second category of methods predict increasing periods of completeness with increase in the cut-off magnitude in a physically realistic way and are thus more appropriate in the hazard analysis applications.

Among second category of methods, the most commonly used method is due to Stepp (1973) and a somewhat less commonly used method is the slope method due to Tinti and Mulargia (1985). However, a not so commonly used method due to Herak et al. (2009) can be considered to provide very robust estimates of the periods of completeness with minimal personal judgment. Further, the period of completeness for the largest magnitudes in the catalog may generally be larger than even the complete period of the catalog, and those should be assigned, so that the occurrence rates of the largest earthquakes do not fall out of the trend for the lower magnitudes. The study report should include in details of the analysis carried out and the completeness periods arrived at for all the source zones in the region of study.

The occurrence rates for different magnitudes of earthquakes in a source zone should be estimated using the data for only the periods for which the respective magnitudes are estimated to be complete. These should then be used to obtain the cumulative occurrence rates and used for fitting the relationship of Eq. (7.1) to estimate the parameters a and b for each source zone. The fitting of Eq. (7.1) should preferably be carried out using maximum likelihood method due to Weichert (1980), but this method may not converge well when the available database on past earthquakes in the source zone is not sufficiently large. The least-squares fitting may be a more appropriate option in such cases. The study report should tabulate the values of the parameters a and b obtained along with their standard deviations for all the source zones.

7.4 Estimation of the Maximum Magnitudes

To define the recurrence model for a source zone completely, it is necessary that the maximum magnitude, $M_{\max}$, for the source zone is also estimated. However, it is very difficult to arrive at the $M_{\max}$ for a source zone without significant uncertainty, because the various methods available for the purpose (e.g., Bollinger et al, 1992; Gupta, 2002; Wheeler, 2009; 2016) are associated with large inherent uncertainties in their applicability as well as in defining the required input parameters. The $M_{\max}$ estimates from different methods are in general found to vary significantly and the final choice cannot be made without some element of personal judgement. The various methods available for estimation of $M_{\max}$ for a source zone are listed below:

(i) Increasing the largest historical earthquake by suitable magnitude units (Bollinger et al., 1992; Wheeler, 2009).

(ii) Extrapolation of Guttenberg-Richter frequency-magnitude relationship (Bollinger et al., 1992; Wheeler, 2009).

(iii) Statistical method based on the statistics of the available earthquake magnitudes arranged in decreasing order (Dargahi-Noubary, 1999).

(iv) Using mixed data probability distribution (Kijko et al., 2016).

(v) Using cumulative strain energy plot (Makropoulos and Burton, 1983).

(vi) Using region specific fault rupture length (Anbazhagan et al., 2015).

(vii) Using geological slip rate data or the strain rate data based on GPS measurements (Molnar, 1979, Savage and Simpson, 1997).

The illustrative application of all these methods is presented in **Annexure D**. However, due to non-availability of the input parameters, it may not possible to implement all the methods for every source zone. The study report should attempt to use as many of the methods as possible for each source zone and select the final value in a balanced way. The values of the $M_{\max}$ used for all the source zone should also be tabulated along with the values of the parameters a and b. The study report should also present typical examples of the recurrence models based on these parameters along with the observed data with error bars.

7.5 Estimation of Focal Mechanism Parameters

The recurrence model developed for each source zone is used to estimate the total occurrence rates of different magnitudes of earthquakes for the source zone as a whole. To define the input seismicity for PSHA method, these rates are required to be distributed suitably among a grid of sites covering the complete source zone area, with each site postulated to be the epicentral location for the expected future earthquakes. For the computation of the hazard, it is also necessary to define the various distance parameters (e.g., $R_{ij}, R_{rup}, R_x,$ and Z_{tor}) required in the GMPEs from each postulated epicentral location to the project site of interest. This in turn requires associating a fault rupture plane to each postulated epicentral location, which cannot be done accurately because no real fault is associated with every location in an area type of seismic source. In practical hazard analysis applications, virtual fault rupture planes are therefore associated with the various locations in an area source under widely varying assumptions and idealizations (e.g., Kaklamanos et al., 2011; Gupta, 2013; Pagani et al., 2014; Thompson and Worden, 2017; Ordaz and Salgado-Gálvez, 2017; Campbell and Gupta, 2018; etc.).

The focal mechanism parameters (strike, dip and style of faulting) required to specify the virtual rupture planes for all the locations in an area source can be defined only approximately using available data on fault plane solutions of past earthquakes, trends of the major tectonic features, focal depth sections transverse to the major tectonic features, and the directions of principal tectonic stresses in the source zone. If no basis exits to assign the focal mechanism parameters to a source zone even approximately, the style of faulting may be taken as unknown, dip angle as 45°, and strike as uniformly random between 0° and 360° as the last choice. The various distance parameters are very sensitive to the direction of strike, and hence the uncertainty in the strike should be accounted by specifying its possible range. The study report should describe in details the basis for arriving at the focal mechanism parameters for each source zone and tabulate their values for all the source zones in the report. The rupture length and width of the virtual fault can be estimated using an appropriate empirical relationship (e.g.; Wells and Coppersmith, 1994; Leonard, 2014; Strasser, 2010; Thingbaijam et al., 2017; Huang et el., 2024) in terms of earthquake magnitude and the type of faulting

7.6 Estimation of Focal Depths

For estimation of the various distance parameters, the fault rupture plane with specified values of rupture length, rupture width, direction of strike, and dip angle is required to be placed at certain depth inside the earth. This can either be done by fixing the depth to the top of the rupture plane or the focal depth and the position of the hypocenter within the rupture plane. To fix the position of the rupture plane inside the earth, the hypocenter may be taken at the centroid of the rupture plane and fixed at a specified focal depth. However, the focal depth is perhaps the most uncertain parameter among all the parameters of an earthquake because the earthquakes within an area source can occur over a wide range of depths and because the accuracy of the focal depths of even instrumentally recorded earthquakes is generally very poor. This makes it very difficult to assign the focal depths at various locations in an area source accurately and realistically.

Some studies propose to define the focal depth as a function of the earthquake magnitude with larger magnitudes occurring at greater depths (e.g., Kaklamanos et al., 2011). But no definite relation is generally seen to exist between the focal depth and magnitude of earthquakes in a source zone. In reality, all magnitudes of earthquakes are seen to occur over a wide range of focal depths, and assigning deeper focal depths to larger magnitudes would unrealistically underestimate the contributions of the larger magnitudes and overestimate that of the smaller magnitudes. The use of a constant median focal depth for all the magnitudes of earthquakes in a source zone can thus be considered a balanced approach in practical hazard analysis applications. Such an estimate may be arrived at by approximating the observed distribution of the focal depths of past earthquakes in a source zone by a lognormal distribution and may be used with slight conservatism in real applications. However, in case of a dipping fault surface (such as the Himalayan decollement and Burmese subduction zone), the focal depth at each location in the source zone can be taken as the depth to this surface.

8.0 GROUND MOTION PREDICTION EQUATIONS (GMPEs)

The estimation of the site-specific target response spectra with damping ratio of 5% at a project site using PSHA and the DSHA methods requires using ground motion prediction equations (GMPEs) suitable for the region around the project site. The GMPEs are expected to have strong regional dependence and are thus required to be developed using the strong motion acceleration data recorded in the region of application. The GMPEs are also expected to depend significantly on the tectonic environment of the seismic source zone as active crustal region (ACR), stable continental region (SCR) and subduction zone regions (SZR). However, due to highly inadequate recorded strong motion data in India, good quality of region specific GMPEs had not been developed for different parts of the country. Though, several GMPEs have been recently published in reputed journals for certain parts of India (e.g., Raghukanth and Kavitha, 2014; Singh et al., 2016; Gupta and Trifunac, 2018ab; 2019; Bajaj and Anbazhagan, 2019; Chhangte et al., 2021; Raghucharan et al., 2021; Yellapragada et al., 2023), but none of these meets the desired quality requirements for use in the hazard analysis. It is essential that a GMPE included in the hazard analysis satisfy the following general criteria as a minimum (Cotton et al., 2006; Bommer et al., 2010)

- The database used to develop the GMPE should be sufficiently large covering the complete magnitude and distance ranges of interest without any wide gaps.

- The GMPE should be able to account for the magnitude and distance saturation effects in a physically realistic way.
- Site amplification effects should include the dependence on both the thick geological formations as well as the shallow soil deposits with the non-linear soil behavior accounted in a physically realistic way.
- The equation should have been developed using multi-stage or random effects regression analysis with the event-to-event, site-to-site and single-site components of the aleatory variability obtained explicitly.
- The GMPE should be defined at sufficiently large number of natural periods between the lowest period of 0.01 s and the highest period of at least 5.0 s.

The use of a GMPE developed using a large database for another region and meeting the above-mentioned requirements may be considered more appropriate than a region-specific equation not satisfying these requirements (Douglas, 2007).

Based on the data-driven scores (Delavaud et al., 2009; Kale and Akkar, 2012) from the limited strong motion data available, the following two GMPEs from the NGA-West2 models for the horizontal response spectrum amplitudes are found appropriate for both the Himalaya and the northeast India regions:

(i) Abrahamson NA, Silva WJ and Kamai R (2014). Summary of the ASK14 ground motion relation for active crustal regions, Earthquake Spectra, 30(3), 1025–1055.

(ii) Boore DM, Stewart JP, Seyhan E and Atkinson GM (2014). NGA-West2 equations for predicting PGA, PGV, and 5% damped PSA for shallow crustal earthquakes, Earthquake Spectra, 30(3), 1057–1085.

The corresponding GMPEs are available for the response spectra of vertical motion as follows:

(i) Gülerce Z, Kamai R, Abrahamson NA and Silva WJ (2017). Ground motion prediction equations for the vertical ground motion component based on the NGA-W2 database, Earthquake Spectra, 33(2), 499–528.

(ii) Stewart JP, Boore DM, Seyhan E and Atkinson GM (2016).NGA-West2 equations for predicting vertical-component PGA, PGV, and 5%-damped PSA from Shallow crustal earthquakes, Earthquake Spectra, 32(2), 1005–1031.

These equations should preferably be used to estimate directly the target response spectra of the vertical component of motion by both DSHA and PSHA methods. Alternatively, the TRS of vertical motion may also be obtained from the TRS of horizontal motion using the period dependent multiplication factors due to Rezaeian et al. (2014), which with a lower limit of 2/3rds can be approximated as follows:

$$V/H = \begin{cases} 0.66667; T \le 0.03\text{s} \;\text{ or }\; T > 0.1\text{s} \\ -2.05 - 4.57\log T - 1.84(\log T)^2;\, 0.03s < T \le 0.1\text{s} \end{cases} \tag{8.1}$$

Based on a study by Scaria et al. (2021) and a critical analysis of the suitability of the

GMPEs for the Central and Eastern North America (CENA) have indicated that the above GMPEs are suitable for the Peninsular India also. Thus, these GMPEs only are proposed to be used for all other parts of India, except for the deep focus intraslab earthquakes in the Burmese Subduction Zone.

Based on the physical considerations and the data-driven scores estimated from the available strong motion data, the following two GMPEs are found appropriate for the Burmese and the Andaman Subduction Zone earthquakes:

(i) Abrahamson NA and Gulerce Z (2022). Summary of the Abrahamson and Gulerce NGA-SUB ground-motion model for subduction earthquakes, Earthquake Spectra, 38(4), 2638–2681.

(ii) Si H, Midorikawa S, and Kishida T (2022). Development of NGA-Sub ground-motion prediction equation of 5%-damped pseudo-spectral acceleration based on database of subduction earthquakes in Japan, Earthquake Spectra, 38(4), 2682–2706.

The above ground motion models may be replaced by their updated versions or by acceptable quality of region-specific models, when becomes available in future. Use of any other GMPE may also be acceptable by establishing its suitability on physical grounds and by data-driven scores based on recorded strong motion data in the region of study.

9.0 TARGET RESPONSE SPECTRA BY PSHA METHOD

The probabilistic seismic hazard analysis (PSHA) method has currently become the state-of-the-art approach for estimation of site-specific design ground motion for important projects like dams, power houses, and other infrastructure facilities. The PSHA method can be used to obtain directly the design basis earthquake (DBE) and maximum credible earthquake (MCE) levels of ground motions in terms of the response spectra of horizontal and vertical components of motions with damping ratio of 5%, which are termed commonly as the target response spectra (TRSs). The PSHA method accounts for the random nature of the earthquakes and the resulting ground motion at a project site and is able to consider the effects of all the expected earthquakes simultaneously and in a balanced way to estimate the TRSs. The various elements of the PSHA method are described in the following sections.

9.1 Mathematical Formulation

The PSHA method is primarily based on computing the occurrence rate, $\upsilon[SA(T)]$, of exceeding a specified value of spectral amplitude $SA(T)$ at natural period T at a project site of interest due to all magnitudes of earthquakes expected to occur at all possible locations in the various source zones in the region around the site. Based on the formulations due to Cornell (1968) and McGuire (1977), the mathematical expression for $\upsilon[SA(T)]$ is commonly presented in a complex triple integral form (Gupta, 2009). However, by discretizing the earthquake magnitude and epicentral locations, the following simplified expression in terms of summations only is used in the actual computation (Anderson and Trifunac, 1978; Gupta, 2002; 2009)

$$\upsilon[SA(T)] = \sum_{k=1}^{K}\sum_{j=1}^{J_k}\sum_{i=1}^{I_k} q_k[SA(T) \mid M_j, \Re_{ij}]\lambda_k(M_j, E_i) \tag{9.1}$$

The quantity $\lambda_k(M_j, E_i)$ in this expression represents the annual occurrence rate of earthquakes within a small magnitude interval around the central magnitude M_j at the *i*th epicentral location E_i in the *k*th seismic source zone, and the quantity $q_k[SA(T) \mid M_j, \Re ij]$ represents the probability of exceeding the spectral amplitude *SA*(*T*) due to the magnitude M_j at *i*th epicentral location in the *k*th seismic source with $\Re_{ij}$ representing the set of the associated distance parameters needed in the GMPEs (e.g., R_{rup}, R_{jb}, R_x & Z_{tor}). The summations in Eq. (9.1) are taken over *K* number of seismic source zones, J_k number of discretized magnitude intervals used, and I_k number of discretized epicentral locations used for the occurrence of earthquakes in the *k*-th source zone.

If the earthquake events are assumed to follow a Poisson distribution, the occurrence rates $\upsilon[SA(T)]$ can also be shown to follow a Poisson distribution. Thus, the probability of exceeding a specified spectral amplitude *SA*(*T*) during an exposure period of *Y* years can be defined by

$$P[SA(T)] = 1 - \exp\{-\upsilon[SA(T)] \cdot Y\} \tag{9.2}$$

This probability distribution is commonly used to compute the spectral amplitudes at all the natural periods with a specified probability of exceeding during a given life period of Y years, which corresponds equivalently to a return period of $T_{RP}[SA(T)]$ years given by

$$T_{RP}[SA(T)] = \frac{1}{\upsilon[SA(T)]} = \frac{-Y}{\ln(1 - P[SA(T)])} \tag{9.3}$$

As the $T_{RP}[SA(T)]$ can also be defined directly as the reciprocal of occurrence rate $\upsilon[SA(T)]$, it is not essential to make the Poisson assumption for estimating the spectral amplitudes for a specified return period, which justifies the recommendation made in section 6.2 that a severe declustering of the catalog should be avoided.

The plots of $P[SA(T)]$ or $T_{RP}[SA(T)]$ versus $SA(T)$ are termed as the hazard curves, which are interpolated to get the spectral amplitudes at all the natural periods with a specified probability of exceeding during a specified life period or equivalently a specified return period. The response spectra thus obtained by the PSHA method are termed as the uniform hazed target response spectra. The PSHA method for computing the target response spectra for a project site can essentially be considered to comprise mainly the estimation of the two input quantities, viz. the occurrence rates

$\lambda_{k,i}(M_j)$ and the probabilities $q_k[SA(T) | M_j, \Re ij]$, involved in the expression of Eq. (9.1).

9.2 Estimation of Earthquake Occurrence Rates $\lambda_k(M_j, E_i)$

To obtain an estimate of the occurrence rates $\lambda_k(M_j, E_i)$ for the *k*th source zone, the recurrence model with upper bound magnitude developed for the source zone as described in sections 7.2 to 7.4is used to estimate the occurrence rates $n(M_j)$ for the source zone as a whole for several small sizes of magnitude intervals, $(M_j - \delta M_j, M_j + \delta M_j)$, covering the complete magnitude range between a selected minimum magnitude, $M_{\min}$, and the maximum magnitude, $M_{\max}$, for the source zone as

$$n(M_j) = N(M_j - \delta M_j) - M(M_j + \delta M_j) \tag{9.4}$$

The desired occurrence rates $\lambda_k(M_j, E_i)$ are then obtained by distributing the rates $n(M_j)$ suitably over the complete extent of the source zone. In case of a line source (vertical fault plane), the fault rupture length for different magnitudes is floated along the fault trace in small steps (say, 1 km apart) till the entire fault trace length has been covered. The $\lambda_k(M_j, E_i)$ for each position of the rupture length is obtained by distributing $n(M_j)$ equally among all the possible positions of the rupture length with the epicentral location taken at the middle of the rupture length. Similarly, for a dipping fault surface, the fault rupture area for different magnitudes is floated along the fault length and width in small steps (say, 1 km apart in both directions) till the entire fault surface area has been covered. The $\lambda_k(M_j, E_i)$ for each position of the rupture area is obtained by distributing $n(M_j)$ equally among all the possible positions of the rupture area with the hypocentral location taken at the centroid of the rupture area and the epicentral location as its projection on the earth's surface. However, in the case of the most commonly used area types of source zones, the source zone area is divided into a grid of small size square elements (say, 0.1° in both latitudes and longitudes) and the center of each grid element is considered to be the expected epicentral location. The $\lambda_k(M_j, E_i)$ for each epicentral location is obtained by distributing $n(M_j)$ among all the grid points uniformly or non-uniformly.

The traditional uniform distribution of seismicity over an area source can be achieved simply by distributed the rate $n(M_j)$ equally among all the epicentral locations defined by the centroids of the grid cells. However, a spatially uniform distribution of seismicity cannot be considered realistic on physical grounds. Epicenters of past earthquakes in an area source is in reality seen to be distributed quite heterogeneously and thus a non-uniform spatial distribution of the rates $n(M_j)$ based on spatially smoothed epicentral locations of available past earthquake data can be considered more realistic. The spatial smoothing based on a circular Gaussian kernel (Frankel,

1995) may be used if the epicenters of past earthquakes show no preferred direction of alignment. When the epicenters show a dominant trend, it will be more realistic to use an elliptical Gaussian kernel (Lapanje et al., 2003) with the major principal direction of the ellipse coinciding with predominant direction of the epicenters. The non-uniform spatial distribution is based on the assumption that the future seismicity is more likely to occur around the locations of the past earthquakes. This will thus result in lower hazard estimate at if no past seismicity is known to have occurred in the vicinity of the project site. In view of the limited period of the earthquake catalog and the large uncertainty associated with the locations of the past earthquakes, it is proposed that higher of the hazard estimates based on the non-uniform and the uniform spatial distributions of the expected seismicity be used in real applications.

9.3 Estimation of Probabilities $q_k[SA(T)\,|\,M_j, \Re_{ij})$

The probability, $q_k[SA(T)\,|\,M_j, \Re_{ij})$,represents the probability of exceeding a spectral amplitude $SA(T)$ due to magnitude M_j of earthquakes at *i*th epicentral location in the *k*th source zone with occurrence rate $\lambda_{k,i}(M_j)$ as defined in the previous section. These probabilities are commonly computed using a Gaussian distribution for $\ln[SA(T)]$ with the mean and standard deviation obtained from the selected GMPEs, which requires estimating the various distance parameters (R_{rup}, R_{jb}, R_x and Z_{tor}) denoted collectively by $\Re_{ij}$.

Estimation of the various distance parameters for various locations in an area type of source zone requires associating a virtual fault rupture plane to each location, which cannot be done in a unique and exact manner as discussed already in section 7.5. To have uniformity in defining the required rupture parameters (rupture geometry and size, angles of strike and dip and style of faulting, and position of the rupture plane inside the earth) for associating the virtual fault rupture plane for various locations in an area source, the following guidelines are proposed to be used:

(i) *Rupture Geometry and Size:* The fault rupture plane of real earthquakes may not have any regular shape, but it is commonly approximated by circular or rectangular shape, where circular rupture cannot be considered realistic for magnitudes greater than about 5.5. The option of using the circular rupture in the widely used R-CRISIS software (Ordaz and Salgado-Gálvez, 2017) should thus be avoided. The rupture length and width for a rectangular fault shall be approximated by the median estimates obtained from suitable empirical scaling relations in terms of the magnitude M_j and style of faulting (e.g., Wells and Coppersmith, 1994).

(ii) *Strike, Dip and Style of Faulting*: As discussed in section 7.5, the angle of strike and style of faulting for an area source as a whole may be approximated by their predominant values, but the angle of strike should be taken to be uniformly distributed over a limited or complete range (Gupta, 2013; Campbell and Gupta, 2018). These parameters can be arrived at most reliably by examining the correlation between tectonic features and the fault plane solutions of the past earthquakes if sufficiently large number of those is available for a source zone. In other cases, dominant direction of strike can be inferred from the trends of major tectonic features and the distribution of the epicenters of past earthquakes, dominant dip angle can be decided from the focal depth sections across major faults, and the dominant style of faulting may be inferred from the directions of principal tectonic stresses. However, when no basis exists to arrive at the source zone specific values of any of the parameters, the strike may be taken uniformly random between 0° and 360°, dip angle may be taken as 45°, and style of faulting as unknown (all types).

(iii) *Positioning of the Rupture Plane inside the Earth*: To specify the position of the rectangular rupture plane inside the earth, the centroid of the rupture plane may be taken as the hypocenter and the rupture plane oriented as per the specified angles of strike and dip may then be placed such that hypocenter lies vertically below the epicenter at a specified focal depth. The focal depth for this purpose may be arrive at following the guidelines given in section 7.6.

Having defined the details and position of the fault rupture plane inside the earth for each magnitude M_j at each *i*th location in a source zone, all the associated distance parameters can be estimated in a straight forward manner. However, to take the uncertainty in the angle of strike into account, values of each distance parameter shall be estimated for all the expected angles of strike at small intervals and the average value shall be taken as the final estimate (Gupta, 2013; Campbell and Gupta, 2018). The Openquake software (Pagani et al., 2014) provides several different options to model the uncertainty in the angle of strike, whereas the commonly used R-CRISIS software has no provisions to model this uncertainty.

For the simple case of a vertical fault and the epicentre at the middle of the fault rupture length, Appendix C in Petersen et al. (2014) by S.C. Harmsen presents the analytical expressions for the mean value of R_{jb} for a given magnitude of earthquake in terms of the epicentral distance by considering the strike to be uniformly random between 0 and 2π. Thompson and Worden (2017) have generalized it to a dipping fault plane and proposed an expression for the mean R_{jb} in a quintuple integral form with the dip angle to be random between 0 and $\pi/2$, taking the position of hypocenter to be uniformly random along both the rupture length and the rupture width, and accounting for the uncertainties in the rupture length and the rupture width by considering the rupture area to follow a lognormal distribution. However, these studies do not indicate that how the other distance parameters have to be estimated. The use of the relations given in Kaklamanos et al. (2011) for estimating the other distances (R_x and R_{rup}) from R_{jb} will need specifying a fixed direction of strike of the fault, whereas it has been taken as completely random in estimating the mean R_{jb}.

In view of the widely varying assumptions and approximations proposed to be used for estimation of the various distance parameters for area type of source zones, it is necessary that the study report describes clearly the assumptions made and the values of the focal mechanism parameters used to estimate the distance parameters. The distance parameters obtained along with the V_{S30} value at the project site can be used to compute the mean and standard deviation of the logarithm of spectral amplitude, $\ln[SA(T)]$, using the selected GMPE. These can be then used to estimate the desired probability $q_k[SA(T)\,|\,M_j, \Re_{ij})$ based on the Gaussian probability distribution, as mentioned before.

9.4 Estimation of Target Response Spectra

The design basis earthquake (DBE) level of target response spectra represents the level of ground motion for which a dam and the appurtenant structures (intake, penstocks, power house, etc.) are actually designed to be safe with none or insignificant damage. This is intended to be the maximum level of ground motion that can well be expected to occur during the life time of a dam. The ICOLD (2016) guidelines have termed it as the operating basis earthquake (OBE) level of ground motion and proposes to estimate it by PSHA method for a return period of 145 years, which has 50% probability of exceeding in 100 years. The 50% probability of exceeding may be considered quite high to ensure the safety of the dam design adequately. For actual design of all the dams (specified as well as others), these guidelines therefore propose to estimate the DBE level of ground motion by the PSHA method for a return period of 475 years, which has 10% probability of exceeding in 50 years or 19% probability of exceeding in 100 years. To have equally reliable dam designs in all parts of the country, the return period of 475 years is proposed to be used for the dam sites in all the seismic zones

The safety of the design of a dam arrived at using DBE level of ground motion is also required to be evaluated for a much stronger ground motion, termed as the maximum credible earthquake (MCE) or the safety evaluation earthquake (SEE) level of ground motion. Significant damage to the dam is permitted under this level of ground motion, provided that no uncontrolled release of the water impounded in the reservoir takes place due to sudden collapse of the dam. Also, the safety related elements like bottom outlets, spillway gates, control units, and power supply are required to functional after this level of earthquake, so that reservoir can be evacuated in a controlled manner.

Thus, in principle, the MCE level of ground motion is intended to be the largest possible ground motion that can be expected to occur at a dam site. However, as it may be acceptable to use somewhat lower level of safety evaluation level of ground motion for dams with lower consequences of failure, the ICOLD (2016) guidelines recommend to estimate this ground motion by PSHA method for return periods of about 10,000, 3000, and 1000 years for dams with high, moderate, and low consequences of failure, respectively. Further, due to much longer recurrence period for the largest possible earthquakes in the Peninsular India compared to that in Himalaya, the MCE level of ground motion in the Peninsular India is expected to occur with much longer return periods than in the Himalaya. Thus, to arrive at equally severe ground motion in all parts of the country, these guidelines also propose to use different return periods for estimation of the MCE level of ground motion by PSHA method in different parts of the country, in addition to that for the dams with different consequences of failure.

As no guidelines exists to categorize the dams on the basis of the consequences of failure in place in India, till such time the return periods used for estimation of the MCE level of ground motion by PSHA method for the three size categories of dams i.e. Large, Intermediate and small (as classified in clause 3.1.2 of IS: 11223: Guidelines for Fixing Spillway Capacity) are given in Table 1along with the equivalent probability of exceeding in 50 years given in parentheses.

Table 1: Return periods with equivalent probabilities of exceeding in 50 years given in parentheses for estimation of MCE level of TRS by PSHA method for three different categories of dams located in different seismic zones of India.

Seismic Zones	Return Period for MCE level of ground motion for dam in Category		
	Small	Intermediate	Large
IV and above	1225 Years (4% in 50 Years)	2475 Years (2% in 50 Years	4975 Years (1% in 50 Years
II & III	2475 Years (2% in 50 Years)	4975 Years (1% in 50 Years)	9975 Years (0.5% in 50 Years)

10.0 MCE LEVEL OF TARGET RESPONSE SPECTRA BY DSHA METHOD

The MCE level of ground motion, which is intended to be the maximum possible ground motion at a dam site, is conceptually the ground motion corresponding to a fixed earthquake scenario of maximum possible magnitude at the minimum possible distance from the dam site. The deterministic seismic hazard analysis (DSHA)method is used to arrive at such an earthquake scenario by (i) considering all capable faults in the vicinity of the dam sites, (ii) estimating the maximum credible earthquake (MCE) magnitude for each fault, (iii)estimating the various distance parameters required in the GMPEs by assuming the MCE magnitude on each fault at the nearest possible location to the dam site, and finally (iv) identifying the MCE scenario that is expected to generate the most critical ground motion at the dam site. The earthquake scenario thus obtained is known as the controlling MCE scenario. The MCE level of deterministic target response spectra (TRSs) is computed from the selected GMPEs at a fixed percentile level (number of standard deviations above the mean) using the magnitude and the distance parameters of the controlling MCE.The ICOLD (2016) guidelines proposes to estimate the MCE level of deterministic spectra at 84th, between 50th and 84th, and 50th percentile levels for dams with high, moderate, and low consequences of failure, respectively. These guidelines propose to estimate the MCE level of deterministic TRSs at 84th percentile level (mean plus one standard deviation) for Intermediate and Large categories of dams and at 50th percentile level for small category of dams, respectively.

Though, the DSHA method described as above appears to be very simple conceptually, its use in practical applications is not free from large uncertainties to specify the various inputs in deterministic way without strong personal biases. All the faults in the vicinity of a dam site are generally not known and the seismic status of the known faults is generally not known precisely, particularly for the intraplate region of the Peninsular India. Whereas, in the Himalaya, the faults like MCT, MBT, and MFT are not the sources of the largest possible earthquake magnitude, and the decollement surface with which the largest earthquakes are associated is characterized by a width of more than 150 km from north of MCT to MFT, which makes it difficult to fix the position of the rupture width of the MCE magnitude between MCT and MFT for the deterministic method. Further, the available geological and seismological data and information are seldom adequate to estimate the MCE magnitudes for various faults in a scientifically defendable way. Also, the precise knowledge about the focal mechanism parameters required for estimation of distance parameters for each fault considered are generally not known accurately. Lacking the required information about the active faults and their MCE magnitudes, the DSHA method is also practiced using area types of seismic sources by assuming the MCE magnitude for a source zone to occur at a location closest to the project site. This will unrealistically put the MCE magnitude right below the dam site for the source zone within which the project site is located.

The above-mentioned uncertainties in the DSHA method are generally overcome by assuming the largest possible magnitude to occur at the closest distance on the nearest known fault without any scientific basis, which results in highly exaggerated estimates of the design ground motion. On the other hand, the PSHA method accounts for the various uncertainties in the earthquake events and the ground motion prediction by suitable probability distributions with comparatively much less subjectivity. To arrive at a more realistic final estimate of the design ground motion, it is proposed that the DSHA estimates are reviewed critically vis-à-vis the corresponding PSHA estimates, and both or either of the estimates are rationalized in case of unacceptably large differences.

11.0 FINALIZATION OF TARGET RESPONSE SPECTRA

The general guidelines to be followed for arriving at MCE and DBE levels of the final TRS from a comparison of the MCE level of TRSs estimated by PSHA and DSHA methods are given below:

(i) If the MCE level of TRS by the DSHA method is lower than the corresponding PSHA estimate or not higher by more than 25% of the PSHA estimate over the natural period range of 0.2 s to 1.0 s, both the DBE and MCE levels of the target spectra by the PSHA method shall be used as the final target response spectra.

(ii) In case the MCE level of TRS by the DSHA method is higher by more than 25% of the corresponding PSHA estimate, and if the controlling MCE scenario is largely subjective and does not have very wide acceptability, the choice of the controlling MCE scenario should be rationalized based on disaggregation of the MCE level of TRS amplitudes by PSHA method at suitably selected natural period (say, natural period of the dam). The method for carrying out the disaggregation of the probabilistic estimates is described in **Annexure E**. However, no change is proposed in the DBE and MCE levels of the target spectra by the PSHA method, and those are proposed to be used as the final target response spectra in such cases also.

(iii) Finally, if the MCE level of TRS by the DSHA method is higher by more than 25% of the corresponding PSHA estimate, and if sufficiently high confidence can be imposed on the occurrence of the controlling MCE magnitude, M_{max}, on a specific fault, it is proposed to consider that fault as a separate line or dipping surface type of seismic source zone (refer section 7.1) in the PSHA method also. The occurrence rates of different magnitudes of earthquakes within a small magnitude range near M_{max} (say, $M_{max} - 0.5$ to M_{max}) are proposed to be distributed over this fault specific source zone only, and to distribute the occurrence rates of the lower magnitudes of earthquakes over the complete area source within which the said fault is located. With this combination of a fault and the area sources, the DBE and MCE levels of ground motion by PSHA method are proposed to estimated again and to be considered the final target spectra.

12.0 DESIGN ACCELEROGRAMS AND RESPONSE SPECTRA

For dynamic response analysis of dams and appurtenant structures, the site-specific ground motion is required to be defined in terms of the design accelerograms and the design response spectra for several damping ratios of covering all the structures of interest. The finalized four TRS corresponding to the horizontal and vertical components of motion for DBE and MCE conditions can be used to generate the uncorrelated pairs of horizontal and vertical design accelerograms compatible with the corresponding pairs of the target response spectra. Only a single set of accelerograms is considered sufficient for use in the linear elastic dynamic response analysis under both DBE and MCE levels of excitations. For use in simplified dynamic response analysis, the smoothed design response spectra for other damping ratios of interest can be computed from the design accelerograms or obtained directly from the target spectra using the period-dependent scaling factors given in IS: 1893. However, for use in the nonlinear response analysis to predict the failure modes under MCE level of ground motion, the analyst will be required to use a suitably selected and scaled set of at least seven real accelerograms matching closely the MCE level of target spectra in the vicinity of the natural period of the dam. The guidelines given in the American Standards ASCE/SEI 41-13 and ASCE/SEI 7-22 may be adopted for the purpose of selection and scaling of the acceleration time-histories for nonlinear analysis.

12.1 Generation of Design Accelerograms for Linear Elastic Response Analysis

The accelerograms compatible with a given TRS can be generated by modifying iteratively a suitably selected real accelerogram or a synthetic accelerogram. Several studies have suggested the methods for generation of synthetic accelerograms and for spectrum matching (e.g., Gupta and Joshi, 1993; Giaralis and Spanos, 2009; Rezaeian and Der Kiureghian, 2011; etc.). Other investigators (e.g., Mukherjee and Gupta, 2002; Al Atik and Abrahamson, 2010; Alexander et al., 2014; Yang et al., 2019; etc.) have proposed the spectrum matching techniques for real accelerograms, which may also be applied to artificially generated initial accelerograms.

The horizontal and vertical components of the real accelerograms are already uncorrelated, but the artificially generated horizontal and vertical accelerograms are required to be transformed along the principal directions (Penzien and Watabe, 1975) to get a pair of uncorrelated accelerograms. Any of the available methods can be then used to generate the pair of uncorrelated accelerograms compatible with the pair of the final TRS. The spectrum compatible accelerograms should finally be subjected to the baseline correction in the same way as the recorded accelerograms (Boore and Bommer, 2005; Gupta, 2018), so that physically realistic velocity and displacement records can be obtained by double integration of the accelerograms.

The selected real or the synthetic accelerograms are also required to be characterized by realistic strong motion duration, which is commonly defined as the duration between building up of 5% and 95% of the Arias intensity (Trifunac and Brady, 1975). Several empirical prediction equations are available for this strong motion duration in the published literature (e.g., Novikova and Trifunac, 1994; Bommer et al., 2009; Kempton and Srewart, 2006; Afshari and Stewart, 2016; Du and Wang, 2017, etc.). Any of the mean prediction equations that accounts for the dependence on earthquake magnitude, source-to-site distance, and the site soil condition can be used to estimate the strong-motion duration to be realized in the design accelerograms. As the strong motion duration plays crucial role in attaining the steady state condition in the structural response, a minimum of 5.0 s of the strong motion duration shall be used in generating the design accelerograms. However, the total duration of the design accelerograms does not play that crucial role and hence a total duration of four times the strong motion duration can be considered an optimum choice, because longer durations will take longer time in response analysis.

The study report shall describe briefly the method used for generation of design accelerograms indicating the duration of strong motion used and the basis for its estimation. At least one typical plot shall be given to illustrate the compatibility between the TRS and the time-history computed response spectrum. The study report shall also present the plots of all the four design accelerograms obtained (horizontal and vertical accelerograms for DBE and MCE conditions) along with the digital values of their amplitudes in soft form at equally spaced time interval of not greater than 0.01 s.

12.2 Design Response Spectra for Different Damping Ratios

For use in the estimation of the maximum dynamic response of dams and appurtenant structures using simpler method of linear-elastic mode superposition analysis, the smoothed response spectra may be computed for damping ratios of 1%, 2%, 3%, 5%, 10% and 15% from the four design accelerograms generated from the TRS with damping ratio of 5%. The design response spectra should be computed at sufficiently large number of natural periods between 0.01 s and 5.0 s, so that no excessive interpolation is required for use in practical applications. To preserve the site-specific nature of the design ground motion, the design response spectra should not be normalized by PGA or approximated in terms of the amplitudes at a few natural periods. The study report shall present the plots for all the four sets of design response spectra along with the digital values of their actual amplitudes for all the six damping ratios in soft form at sufficiently large number of natural periods.

13.0 DESIGN SEISMIC COEFFICIENTS

The site-specific design accelerograms and response spectra are meant for design of new dams and safety evaluation of existing dams using methods based on the detailed dynamic response analyses. However, preliminary design of dams can be evolved using pseudo-static methods of analyses given in Indian Standards IS: 6512 and IS: 7894 for gravity and earth dams, respectively.

Horizontal seismic coefficient: The horizontal seismic coefficient values (αh) for all types of dams shall be computed using effective peak ground acceleration (EPGA) criteria as per the DBE level of design response spectrum of horizontal motion with damping ratio of 5%. and return period of 475 years. The EPGA is determined by dividing the spectral acceleration value of the DBE level of design response spectrum with a damping ratio of 5% at natural period of 0.2 s by 2.5. (USACE EM 1110-2-6053). The horizontal seismic co-efficient is then arrived at by taking 2/3rd of the EPGA value.
The horizontal seismic co-efficient (αh) thus obtained shall be compared with the values arrived as per the decision taken in the 35th meeting of NCSDP for seismic zones II, III, IV, and V of India as 0.08, 0.12, 0.18, and 0.27, respectively and the higher of the two values shall be adopted.

Vertical seismic coefficient: Vertical seismic co-efficient (αv) shall be taken as 2/3rd of the horizontal seismic co-efficient.

14.0 PREPARATION OF THE STUDY REPORT

To facilitate the reviewing of a site-specific study report by the National Committee on Seismic Design Parameters (NCSDP), it is necessary that the report includes all the necessary details in an explicit and transparent manner. For the purpose of uniformity, a template for preparation of the reports is given in **Annexure F**.

The full study report should be compiled in a single dossier along with the proforma given in **Annexure G** duly filled up and signed. This proforma reflecting the status of compliances (along with reasons for non-compliances, if any) for different items of the study should be furnished as a check-list in the beginning of the study report. The list of projects with seismic design parameters approved by National Committee on Seismic Design Parameters (NCSDP) from1991 onwards is given in **Annexure I** for ready reference.

Fifteen (15) bound volumes and one soft copy of the study report should be submitted to the NCSDP Secretariat (Foundation Engineering & Special Analysis Directorate, Central Water Commission, 8th Floor (N), Sewa Bhawan, R.K. Puram, New Delhi). In order to ensure consideration of study report in a particular meeting of the NCSDP, the study report should reach the secretariat at least two months ahead of that meeting. Only such study reports, which are found satisfactory (in terms of compliances of the guidelines) on preliminary inspection by the Secretariat, will be put up to the NCSDP for consideration and approval.

15.0 PRESENTATION OF STUDY REPORT BEFORE NCSDP

The date on which study report of a particular project will come up before NCSDP will be intimated by the Secretariat to the project authorities. It will be the responsibility of the project authorities to ensure presence of experts/ consultants connected with the study on the stipulated date and time. The project authorities will make a PowerPoint presentation of the study report before NCSDP, and answer to the queries of the members of the Committee.

The presentation should cover: (i) details of the project; (ii) regional geological & seismotectonic setting; (iii) seismic history; (iv) local geological setting; (v) study methodology and deviation, if any, from the recommended approach; (vi) evaluated parameters of the site-specific seismic study; and (vii) recommendations on design approach.

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