GUIDE NO. AERB/SG/NF/S-11 Rev. 1

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GOVERNMENT OF INDIA

AERB SAFETY GUIDE

SEISMIC STUDIES AND DESIGN BASIS GROUND MOTION

FOR

NUCLEAR FACILITY SITES

ATOMIC ENERGY REGULATORY BOARD

AERB SAFETY GUIDE NO. AERB/ NF/SG/S-11, Rev. 1

SEISMIC STUDIES AND DESIGN BASIS GROUND MOTION

FOR

NUCLEAR FACILITY SITES

Atomic Energy Regulatory Board

Mumbai-400094

India

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Orders for this guide should be addressed to:

Chief Administrative Officer
Atomic Energy Regulatory Board
Niyamak Bhavan
Anushaktinagar
Mumbai-400094
India

FOREWORD

Activities concerning establishment and utilization of nuclear facilities and use of radioactive sources are to be carried out in India in accordance with the provisions of the Atomic Energy Act 1962. In pursuance of the objective of ensuring safety of members of the public and occupational workers as well as protection of environment, the Atomic Energy Regulatory Board (AERB) has been entrusted with the responsibility of laying down safety standards and enforcing rules and regulations for such activities. The Board has, therefore, undertaken a programme of developing safety codes, safety standards, and related guides and manuals. While some of the documents cover aspects such as siting, design, construction, operation, quality assurance and decommissioning of nuclear and radiation facilities, the other documents cover regulatory aspects of these facilities.

Safety codes and safety standards are formulated on the basis of nationally and internationally accepted safety criteria for design, construction and operation of specific systems, structures and components of nuclear and radiation facilities. Safety codes establish the objectives and set requirements that shall be fulfilled to provide adequate assurance for safety of nuclear and radiation facilities. Safety guides elaborate the requirements and furnish approaches for their implementation. Safety manuals deal with specific topics and contain detailed scientific and technical information on the subject. These documents are prepared by experts in the relevant field and are extensively reviewed by Advisory Committee of the Board before they are published. The regulatory safety documents are revised when necessary in the light of experience gained, feedback from users as well as new developments in the field.

AERB safety code on 'Site Evaluation of Nuclear Facilities', AERB/SC/S (Rev.1), stipulates the requirements to be met by nuclear facilities, to qualify for grant of siting consent. The Safety Guide on 'Seismic Studies and Design Basis Ground Motion for Nuclear Power Plant Site', AERB/NPP/SG/S-11, 1990 provides guidance to meet the requirements stipulated in the safety code. Owing to the developments in the field of seismic hazard assessment, and changes in national/ international regulations, revision of the safety guide was taken up. During the revision, the scope of the safety guide was increased to all nuclear facilities. The revised guide includes probabilistic approach of Design Basis Ground Motion (DBGM) estimation, assessment of tsunami hazard, evaluation of DBGM parameters for soil sites using site response analysis. This revised safety guide supersedes its 1991 edition.

Appendices are an integral part of the document, whereas annexures, references and bibliography are included to provide further information on the subject that might be helpful to the user. Consistent with the accepted practice, 'shall' and 'should' are used to distinguish between a requirement and a desirable option respectively.

The draft of the revised safety guide has been prepared in-house. Experts have reviewed the draft and the Advisory Committee on Nuclear and Radiation Safety vetted it. In drafting this safety guide, regulatory experience gained during consenting process of Indian NPPs and lessons learnt from accident at Fukushima Daiichi NPP have been taken into account. Also, the relevant safety standards published by International Atomic Energy Agency and other regulatory agencies were extensively referred.

AERB acknowledges the efforts of all individuals and organisations who have prepared and reviewed the draft and helped in its finalisation.

22-7-2022
(G. Nageswara Rao)
Chairman, AERB

Definitions

Applicant
An ‘employer’ or a ‘person’ authorised by employer under Atomic Energy (Radiation Protection) Rules, 2004, or ‘Occupier’ under Factory Rules, 1996, or ‘applicant’ under Atomic Energy (Safe Disposal of Radioactive Wastes) Rules, 1987 who applies to the competent authority for obtaining, ‘License’, ‘Authorisation’, ‘Registration’ ‘Consent or ‘Approval’ as appropriate, to undertake any activity for which Regulatory instrument (Licence/Authorisation/ Registration/Consent/Approval) is required.

Commissioning
The process by means of which systems and components of nuclear and radiation facilities, having been constructed, are made operational and verified to be in accordance with the design intent and to have met the required performance criteria.

Decommissioning
The process by which the use of radiation equipment or installation is discontinued on a Permanent basis, with or without dismantling the equipment, including removal or containment of radioactive materials.

Deterministic Method
A method for which the parameters and their values are mathematically definable and may be explained by physical relationship and are not dependent on random statistical events.

Inspection (QA)
Quality Control actions which by means of examination, observation or measurement determine the conformance of materials, parts, components, systems, structures, as well as processes and procedures, with predetermined quality requirements.

Normal operation
Operation of a plant or equipment within specific operational limits and conditions. In case of a nuclear power plant, this includes, start-up, power operation, shutting down, shutdown state, maintenance, testing and refueling.

Nuclear facility
All nuclear fuel cycle and associated installations encompassing the activities from the front end to the back end of nuclear fuel cycle processes and also the associated industrial facilities such as heavy water plants, beryllium extraction plants, zirconium plants, etc.

Nuclear Power Plant
A nuclear reactor or a group of reactors together with all the associated structures, systems, equipment and components necessary for safe generation of electricity.

Operation
All activities following commissioning (after initial fuel loading) performed to achieve, in a safe manner, the purpose for which a nuclear/radiation facility is constructed. For nuclear power plants, this includes maintenance, refueling, in-service inspection and other associated activities performed during initial operation, regular operation or long term operation.

Operating Basis Earthquake (OBE)
An earthquake which, considering the regional and local geology and seismology and specific characteristics of local sub-surface material, could reasonably be expected to affect the plant site during the operating life of the plant. The features of a nuclear power plant necessary for continued safe operation are designed to remain functional, during and after the vibratory ground motion caused by the earthquake.

Atomic Energy Regulatory Board (AERB)

The national authority designated by the Government of India having the legal authority for issuing regulatory consent for various activities related to the nuclear and radiation facility and to perform safety and regulatory functions, including their enforcement for the protection of site personnel, the public and the environment against undue radiation hazards.

Site

The area defined by a boundary, containing facility or source and are under effective control of the management of the facility or activity.

Siting

The process of selecting a suitable site for a facility including appropriate assessment and derivation of the related design bases. The selected site is evaluated throughout the lifetime of facility.

Special Definitions

Bedrock
The uppermost strongly consolidated, hardened and homogeneous geological formation, above the base rock/basement and which exhibits contrast in mechanical properties to overlying deposits/materials if any.

Capable Fault
A fault which has a significant potential for relative displacement at or near the ground surface.

Design Basis Ground Motion
The ground motion parameters of a given level of earthquake severity and representing the potential effects of earthquakes, which are used in the design and/or assessment of a facility. Examples of these parameters are Peak Ground Acceleration (PGA), response spectrum, and acceleration time history **of** the ground motion. Examples of severity levels of earthquakes are safe Shutdown Earthquake (SSE), Operating Basis Earthquake (OBE), and Extreme Earthquake (EE) used in the design and/or assessment of a Nuclear Facility, as applicable.

Earthquake
Vibration of earth caused by the passage of seismic waves radiating from the source of elastic energy.

Epicentre
The geographical point on the surface of earth vertically above the focus of earthquake.

Fault
A fracture or fracture zone in the earth crust along which there has been displacement of the two sides relative to one another parallel to the fracture.

Foundation Input Response Spectra
This is the site-specific motion developed at the foundation elevation of the structure in the free-field.

Free Field Ground Motion
The motion which appears at a given point of the ground due to earthquake when vibratory characteristics are not affected by structures and facilities.

Ground Motion Intensity
A general expression charactersing the level of ground motion at a given point, it may refer to acceleration, velocity, displacement, macroseismic intensity or spectral intensity.

Hypocentre

The location where the slip responsible for an earthquake commences, the focus of an earthquake.

In Layer Motion
The ground motion estimated within a soil/ rock layer using appropriate techniques or recorded at a particular depth below free field are referred as in-layer motion.

Intensity of Earthquake
The intensity of an earthquake at a place is a measure of the effects of the earthquake and is indicated by a number according to the Modified Mercalli Scale of Seismic Intensities.

Interferometry
It is a subsurface imaging technique using ambient noise or controlled-source data by cross correlating seismic observations at different receiver locations.

Isoseismal
Contour drawn to separate one level of seismic intensity from another.

Karstic Phenomena
Formation of sinks or caverns in soluble rocks by the action of water.

Microearthquakes
Microearthquakes have magnitudes less than 3.0, other earthquakes or macroearthquakes have magnitudes equal to or greater than 3.0.

Macroseismic Epicentre
The best estimate made of the position of the epicentre (i.e., the point on the Earth's surface above the focus of the earthquake) without using instrumental data. This may be derived from any or all of the following as circumstances dictate: position of highest intensities; shape of isoseismals; location of reports of foreshocks or aftershocks; calculations based on distribution of intensity points; local geological knowledge; analogical comparisons with other earthquakes, and so on. This is a rather judgmental process with subjectivity.

Microtremor
An ambient ground vibration with extremely small amplitude (of a few micrometers). This vibration can be produced by natural and/or artificial causes such as wind, sea-waves, sonic booms due to supersonic flights, and traffic disturbances.

Neotectonics
For seismic regions, the tectonics of the Quaternary era.

Response Spectrum
Response Spectrum is plot of the maximum absolute value response of a single degree freedom system with respect to its undamped natural frequency.

Seismotectonic Province
A geographic area characterized by similarity of geological, structural and earthquake characteristics.

Seismogenic Structure
A geological structure that displays earthquake activity or that manifests historical surface rupture or the effects of palaeoseismicity, and is likely to generate macro-earthquakes within a time period of concern.

Seismic Site Response
The amplification of earthquake ground motion by rock and/or soil near the earth's surface in the vicinity of the site of interest. Topographic effects, the effect of the water table, and basin edge wave propagation effects are sometimes also included under site response.

Surface Faulting
Permanent deformation or tearing of the ground surface by differential movement across or along a fault plane or a fault zone in an earthquake.

Tectonic province
(refer seismotectonic province)

Tsunamis
Long period seismic sea waves generated in a sea or ocean by an impulsive disturbance such as an abrupt bottom displacement caused by an earthquake, a volcanic eruption or a submarine landslide

Tsunami
A wave train produced by impulsive disturbances in a body of water caused by displacements associated with submarine earthquakes, volcanic eruptions, submarine slumps or shoreline slides.

Uniform Hazard Spectra (UHS)
Response spectra derived so that the annual probability of exceeding the response quantity (acceleration, displacement, etc.) is the same for any spectral frequency.

CONTENTS

1.0 INTRODUCTION

1.1. General

1.1.1 In any Nuclear Facility (NF), to mitigate the effects of the hazards on account of earthquakes, appropriate engineering approach is required to be adopted. The AERB Safety Code on 'Site Evaluation of Nuclear Facilities' [1] provides criteria for evaluation of external events including earthquakes and associated hazards based on hazard category of the NF.

1.1.2 The vibratory effects of ground motion, the main perceived hazard from an earthquake, can be mitigated by engineering solutions. If potential for ground failure exists at a site, adequate and reliable engineering solutions are required to be provided for establishment of facility [1]. Also, the site should be evaluated for the potential consequences arising from a seismically induced flood and water waves. If the evaluation shows that the consequences are not acceptable, appropriate engineering solution should be implemented to mitigate their effects.

1.1.3 This safety guide provides guidance on seismic studies, establishment of design basis ground motion and assessment of related hazards at nuclear facility sites to fulfil requirements specified in the code [1].

1.2. Objective

1.2.1. The objective of this safety guide is to provide guidance on evaluating seismic hazards for a nuclear facility and approaches to determine:

a. The vibratory ground motion hazards to establish the design basis ground motions and other relevant parameters
b. Correlated hazard such as, surface faulting, ground deformation, potential for liquefaction, ground failure, slope instability
c. Seismically induced flood and water waves: tsunamis, dam failure, failure of reservoir, seiches, flash floods consequent to failure of natural dams etc.

1.3. Scope

1.3.1. The safety guide provides methodology to be adopted in deriving the design basis ground motion parameters for safety evaluation of NFs. Investigations and studies which are required to be undertaken during site evaluation for acceptability of the site as well as methodologies for estimation of seismic design bases are covered. Guidance is also included on secondary hazards associated with earthquake such as, surface faulting, potential for liquefaction, ground failure, and slope instability. Also, guidance on establishment of micro-earthquake (MEQ) network, seismic instrumentation, pre and post-earthquake action are provided. In addition, the Safety Guide covers the aspects of assessment of hazard due to seismically generated water waves and related flood hazard.

1.3.2. The provisions of the safety guide are applicable to all categories of nuclear facilities. The methodologies provided for nuclear power plants and other hazard category-I [1] nuclear facilities are applicable to other lower hazard category nuclear installations by means of a graded approach in accordance with its hazard potential. Also, guidance is provided on implementation of graded approach. Ground motion parameters for safety assessment of non-nuclear structures, such as dams, whose failure may affect safety of NF, should also be estimated using the provisions of this Safety Guide.

2.0 GENERAL CRITERIA FOR DESIGN BASIS GROUND MOTION

2.1 General

2.1.1 To ensure seismic safety, Nuclear Facilities shall be designed to withstand the effects of vibratory ground motion and other effects arising from earthquakes. The evaluation of DBGM for this purpose should capture impact of local site/ strata conditions as deemed necessary. For this purpose, comprehensive geological, seismological, geophysical, and geotechnical investigations of the site area and region need to be performed. This section presents guidance on general aspects related to establishment of DBGM parameters.

2.2 Levels of Design Basis Ground Motion

2.2.1 Design basis ground motion adopted for a nuclear facility shall be commensurate with its hazard categorization as per AERB Safety Code on 'Site Evaluation of Nuclear Facilities', AERB/SC/S (Rev.1) [1]. To ensure seismic safety, nuclear facilities shall be designed to withstand different levels of vibratory ground motion and other effects arising from earthquakes depending up on its hazard category.

2.2.2 For NPPs, the design basis ground motion shall be evaluated for two levels of severity i.e. S1 and S2. In addition, an extreme earthquake level, termed as S3, shall be estimated for margin assessment purpose.

a. S1 level ground motion is referred as the Operating Basis Earthquake (OBE). There is no specific requirement regarding the minimum level of ground motion for S1. The S1 level ground motion shall be specified by the applicant. For this specified S1 level of ground motion, seismic category I & II structures, systems and components (SSCs) shall be designed and qualified.

   If the NPP experiences ground motion equal to or above S1 level (refer appendix B.2), the plant shall be safely shutdown and maintained in safe shutdown condition. Restart of the NPP after exceedance of S1 level of ground motion shall be taken up after inspection, safety review and approval by AERB.

b. S2 level ground motion is referred to as the Safe Shutdown Earthquake (SSE). S2 level of ground motion is based on evaluation of the maximum earthquake potential considering the regional and local geology, seismology and specific characteristics of the local sub-surface material. Seismic category I structures, systems and components shall be designed for this level of ground motion.

c. S3 level ground motion is referred to as Extreme Earthquake (EE). S3 level of ground motion is assessed by maximizing the intensity of shaking at site while adopting deterministic methods. While using probabilistic method, one order higher return period (compared to S2 level ground motion) should be considered for estimation of S3 level ground motion (refer 2.11). Due consideration to a wider regional seismotectonic settings, surface and sub-surface characteristics should be given for arriving at S3 level ground motion. All identified SSCs including that required to fulfil the key safety functions of shutdown, maintaining core cooling, containment integrity, and spent fuel pool cooling as well as accident management as a result of extreme events should be evaluated for their functional/ structural safety, as the case may be, with respect to S3 level of ground motion.

2.2.3 Hazard Category I facilities other than NPPs shall be designed for S2 level ground motion. In addition, a lower level of ground motion (S1) for which the plant is capable of continued operation also needs to be defined. In case of exceedance of this lower level ground motion, plant shall be shut down and inspected. The restart of the plant shall be after the approval of AERB [1]. In addition, an extreme earthquake level, termed as S3, shall be estimated for margin assessment purpose. All identified SSCs, including that required to fulfil key safety functions as applicable, as well as, accident management as a result of extreme event shall be evaluated for their functional/ structural safety, as the case may be, with respect to S3 level of ground motion.

2.2.4 For Hazard Category II and III nuclear facilities, design basis ground motion shall be derived/ defined as per the requirements spelt out in AERB safety code on 'Site Evaluation of Nuclear Facilities' [1] and section 9 of this safety guide.

2.3 Specification of Design Basis Ground Motion

2.3.1 The DBGM is specified as free field motion. In case it is defined as input motion at foundation level, it shall represent hypothetical free field condition commensurate with the strata characteristics below founding level. For the purpose of detailed soil-structure interaction analysis and for structures supported on piles, additional in-layer spectra may be specified. These spectra shall be consistent with the target free field spectra.

2.3.2 For NFs founded on soft strata, the impact of the strata on seismic wave propagation from geological bedrock should be accounted through site response analysis considering site specific soil properties. Site response analysis should account for non-linear effects of seismic wave propagation on strata characteristics and uncertainties in various inputs. Approach for site response analysis is given in Appendix A. Site response studies should provide necessary details on strain levels in soil for dynamic analysis of structures. In exceptional cases, if site response analysis cannot be performed from geological bedrock due to lack of data, selection of strata from which convolution of ground motion is conducted should be justified.

2.3.3 For sites where subsurface structure does not represent one dimensional or flat layering, two or three-dimensional analysis models should be adopted in site response studies. Appropriateness of adopted analysis models (1D/2D/3D) should be justified. Radiation boundaries should be adequately represented in 2D/3D model.

2.3.4 For large sites with spatially separated facilities or in sites where founding media characteristics differ significantly, modifications in specified DBGM should be accounted for, or need for facility specific assessment should be studied, as applicable.

2.3.5 Long, buried structures (e.g. duct, piping, etc.) are primarily subjected to relative displacement-induced strain due to seismic wave passage effects. For such structures, response spectra, time histories, and/ or induced displacements, as appropriate, should be developed in coordination with the structural designer. For such structures, soil structure interaction should be considered, if required.

2.4 Design Basis Ground Motion Parameters

2.4.1 The DBGM parameters should be evaluated preferably by using both probabilistic and deterministic methods of seismic hazard analysis. The probabilistic results allow deterministic values to be evaluated within a probabilistic framework so that the annual frequency of exceedance is known for each spectral ordinate of the response spectrum.

2.4.2 The parameters that can be used to characterize ground motion include (a) response spectral acceleration, velocity or displacement at specified damping levels, (b) spectral frequencies, (c) peak ground acceleration, velocity or displacement, and (d) Fourier amplitude spectrum and power spectral density. In general, the design basis ground motion parameters for a nuclear facility are specified in terms of design response spectra and spectrum compatible time histories. The selection of the ground motion parameters should be consistent with the requirements of analysis and design.

2.4.3 For category-I facilities, site-specific design basis ground motion parameters of S2 level shall not be less conservative than corresponding ground motion level specified in national standards for industrial facilities of highest safety or hazard category [1]. It may also be pertinent to note that as per BIS 1893 (2016) [2], the earthquake effects specified by Indian Standard [2] shall be taken as the minimum.

Design response spectra

2.4.4 The Design Response Spectra (DRS) should be derived from site specific strong motion data. However, in case adequate number of records are not available from the site, the records from places having similar seismic, geological and soil characteristics may be used. The method used to derive the site specific response spectra should capture the effects of seismogenic source characteristics, seismic attenuation characteristics, and effects of subsurface geology on seismic wave transmission. The bedrock spectra may be developed using validated frequency dependent site specific ground motion prediction equations and/or following simulation based approaches.

2.4.5 Numerical simulation of ground motion, including fault rupture, wave propagation, path and site effects (e.g., by use of Empirical Green’s Function Methods/ stochastic simulation) can be employed to complement the more traditional methods, like use of Ground Motion Prediction Equation (GMPE), in regions for which pertinent parameters are available. These approaches should be applied cautiously, and should undergo extensive validation studies using records from the site or sites with similar seismotectonic environment. Sensitivity of key input parameters of numerical simulation should be studied. Uncertainty in key input parameters should be accounted in numerical simulation in order to capture variations consistent with those in recorded strong motion data. While adopting numerical simulations, a number of simulated time histories used for generation of response spectra should be sufficient to capture uncertainties in all associated parameters. Use of these methods is not recommended for soils that are expected to respond non-linearly.

2.4.6 Outcome of hazard assessment in terms of response spectra shall be provided for a minimum of 30 frequencies, approximately equally spaced between 0.2 Hz to 100 Hz, considering a logarithmic frequency axis. The design response spectra corresponding to 5% damping shall be used for representation of DBGM and derivation of spectrum compatible time histories. Also, the spectra should be specified at other damping values considered relevant for analyses.

2.4.7 While depicting PGA in response spectrum, the PGA may be considered to represent spectral acceleration at 50 Hz frequency for soil sites and 100 Hz for rock sites (typically associated with $V_{s_{30}} > 1500$m/s) [3].

Acceleration Time histories

2.4.8 A suit of Acceleration Time Histories (ATHs) shall be derived for use in site response analysis and structural analysis, as applicable. They shall reflect all the prescribed ground motion parameters as embodied in the response spectra or other spectral representation (namely power spectra) in addition to other parameters, such as duration, phase and coherence.

2.4.9 The number of ATHs to be used in the detailed analyses and the procedure used in generating these time histories will depend on the type of analysis to be performed. Coordination with the designer should be ensured to understand and respond to the needs of the particular type of engineering analysis. The number and characteristics of ATHs should be adequate for performing particular types of engineering analyses required for design of the plant. For plant structure, systems and components sensitive to low frequency motions, time histories should be examined and, if necessary, modified to take related effects into account.

2.5 DBGM in Two Orthogonal Horizontal Directions

2.5.1 The ground motion in two orthogonal horizontal directions are not same. The difference may be quantified by ratio between the two orthogonal horizontal motions. If the considered source-distance couplets are devoid of related characteristics, such as near source and directivity effects, the ground motion in the two orthogonal horizontal directions may be considered equal.

2.5.2 When a site is located in the near-field region of a fault, the characteristics of the ground motion at the site depend on how the rupture propagates relative to the site. One of such ground motion characteristics is termed the rupture directivity effect. A near-fault site may experience forward directivity when the fault rupture propagates towards the site with a velocity almost equal to the shear-wave velocity. The resulting ground motion typically exhibits a large velocity pulse. Forward directivity is generally characterized by the presence of a two-sided, long-period, large-amplitude velocity pulse in the Fault-Normal (FN) direction. Backward directivity occurs when the fault rupture propagates away from the site. The resulting ground motion tends to be of low intensity and long duration. The fling step is caused by the permanent displacement of the fault and is usually characterized by a one-sided velocity pulse in the Fault-Parallel (FP) direction. These effects need to be accounted appropriately in the assessment of design basis ground motion.

2.6 DBGM in Vertical Direction

2.6.1 Vertical design ground motion (response spectra and time histories) should be developed by using the same methods used for developing horizontal ground motions. Empirical evidence has shown that the ratio of vertical to horizontal spectra values varies typically from 0.5 to 1.0, and is largest for large magnitudes, close distances and high frequencies. Also, in certain cases (large magnitudes, and close distances), the ratio of vertical to horizontal spectra values are observed to be more than 1.0.

2.6.2 If sufficient data are not available, the motion in vertical direction may be defined by the ratio between peak accelerations in vertical and horizontal directions. Under such situations, recommended value of the ratio is 2/3 and the same spectral shape and normalized ATHs developed for the horizontal motion may be used for vertical motion.

2.7 Review Basis Ground Motion

2.7.1 In the context of existing/ operating NFs which undergo periodic safety evaluation, the S2 level ground motion is derived considering updated seismotectonic data, state-of-the-art methodologies and regulatory requirements applicable at the time of periodic safety evaluation. The S2 level ground motion, thus generated is commonly termed as Review Basis Ground Motion (RBGM). The requirements for generation of RBGM is same as that for DBGM.

2.8 Pre and Post-Earthquake Actions

2.8.1 To address the consequences of a possible exceedance of earthquake design levels and to follow structured actions subsequent to an earthquake event, all NFs are required to be equipped with appropriate pre-earthquake planning and post-earthquake action plan.

2.8.2 Before start of operation, the NF shall establish earthquake exceedance criteria along with applicable seismic instrumentation based on the approved DBGM parameters for the site.

2.8.3 The NF shall prepare a list of pre-selected SSCs (representative of SSCs important to safety) along with baseline data on their condition towards future evaluation of the impact of an earthquake greater than the design basis of the NF.

2.8.4 In case of an earthquake greater than exceedance criteria, the NF shall be shut down. Restart of the NF shall be after inspection, evaluation and approval by AERB. Related guidance is provided in Appendix B.

2.9 Evaluation of other hazards associated with earthquakes

2.9.1 The inputs and results, as applicable, for a seismic hazard analysis should be used in the assessment and mitigation of other hazards associated with earthquakes that may be significant for the safety of a NF. These hazards include tsunamis, liquefaction, slope instability, subsidence, subsurface cavities, karstic processes and the failure of man-made or natural water retaining structures, initiated either by ground motion or surface faulting.

2.9.2 For assessment of these associated hazards, fault rupture and ground motion parameters consistent with the assessment should be used. Guidance on these aspects are provided in Sections 7 and 8.

2.10 Requirements for SSCs sensitive to low frequency motion

2.10.1 The methodology described in this safety guide for deriving the design basis ground motions for the S1 and S2 levels has been developed for plant structures having conventional foundations. For Structures, Systems and Components (SSCs) sensitive to low frequency motion, e.g. base isolated systems and liquid storage tanks where ground motion calculations may be needed for frequencies less than 0.2 Hz, the preferred approach is to develop appropriate displacement estimates consistent with seismic hazard for the site.

2.10.2 The matching criteria for spectra compatible acceleration time histories given in sub-section 5.5 of this safety guide should be extended down to lower frequencies of interest.

2.11 Extreme Earthquake for margin assessment

2.11.1 The AERB code on ‘Site Evaluation of Nuclear Facilities’ [1] specifies requirement for consideration of exceedance of design basis parameters and provision of additional safety margin in design of a nuclear facility. To address this aspect, an extreme earthquake above design basis shall be estimated using method acceptable to AERB for margin assessment of SSCs.

2.11.2 The derived S3 level ground motion should be limited by the physical upper bounds commensurate with tectonic characteristics of the region and justifiable assumptions. Due consideration to regional seismotectonic settings, surface and sub-surface characteristics should be given in this assessment.

2.11.3 All SSCs important for basic safety functions of NPP and spent fuel pool should be evaluated for their functional/ structural safety, as the case may be, using S3 level of ground motion. Broad guidelines for estimation of extreme earthquake are given in Annexure II.

3.0 GEOLOGICAL, GEOPHYSICAL, SEISMOLOGICAL AND GEOTEHCNICAL INVESTIGATIONS

3.1 General

3.1.1 Comprehensive geological, seismological, geophysical and geotechnical investigations of the site area and surrounding region shall be performed to develop an integrated database providing input parameters for evaluation of design basis ground motion and associated hazards.

3.1.2 The integrated database should include all relevant information related to geological, geophysical, geotechnical and seismological data and any other information that is relevant for evaluating the ground motion, faulting and geological hazards at the site. Also, it should be ensured that all the seismotectonic features, relevant to the site have been considered in a coherent form for development of seismotectonic model.

3.1.3 Based on the investigations and studies as brought out in the following sub-sections, seismogenic faults and tectonic structures should be associated with appropriate earthquake potential. Guidance provided in this section is applicable to Hazard Category-I facilities. For other hazard category facilities, a graded approach should be followed in deciding on the level of investigation in line with the guidance given in section-9.

3.2 Requirement of Information

3.2.1 To develop the seismotectonic model consisting of discrete set of seismogenic features, the seismological and geological database should be established and considered along with the current knowledge of neo-tectonics and crustal dynamics. Seismicity and geology of the region around the site should be investigated. Essential information required to be generated/ collected are given in sub-sections 3.2.2, 3.2.3 and 3.2.4.

3.2.2 Seismological Information

a. Description of the site including geographical coordinates for estimating distances from the site to the seismic sources of potential hazards
b. Pre-historic and historical data on earthquakes
c. Global instrumental data and the national network recorded earthquake data
d. Data from regional and site specific instrumentation

3.2.3 Geological and Geophysical Information

a. Information on geological and geophysical (e.g. gravity and magnetic data) characteristics of the region including offshore area, as applicable
b. Detailed information on lineaments, faults, sub-surface features, and active crustal volume

c. Ground truth data on lineaments (with respect to its existence, its expression on ground surface, whether a tectonic or non-tectonic feature, expression of its activity, etc.)
d. Information on inactive faults and lineaments
e. Ground displacement data
f. Evidences of fault movement to evaluate potential for surface faulting, dimensions of faults / fault zones, and information on their nature and degree of faulting

3.2.4 Geotechnical data

a. General stratification of strata at the site including depth to bedrock
b. Engineering properties of the soil and/or rock at site from field and lab investigations

3.3 Development of Seismological Database

3.3.1 Information on pre-historical, historical and instrumentally recorded earthquakes in the region should be collected and documented.

Pre-historic and Historical Earthquake Information

3.3.2 All pre-instrumental data on historical earthquakes should be collected, extending as far back in time as possible. Also, paleoseismic and archaeological information on historical and prehistoric earthquakes should be taken into account, if available.

3.3.3 Where appropriate, paleoseismic studies should be performed for the following purposes:

a. Identification of seismogenic structures on the basis of the recognition of effects of past earthquakes in the region
b. Improvement on completeness of the earthquake catalogues for large events, using identification and age dating of fossil/ palaeo earthquakes. For example, observations of trenching across an identified capable fault may be useful in estimating the amount of displacement (say, from the thickness of alluvial wedges) and its rate of occurrence (by using age dating of the sediments). Regional studies of paleo-liquefaction can provide evidence of the recurrence and intensity of earthquakes
c. Estimation of the maximum potential magnitude of a given seismogenic structure, typically on the basis of the maximal length of the structure and displacement per event (trenching) as well as of the cumulative effect
d. Calibration of probabilistic seismic hazard analyses, using the recurrence intervals of large earthquakes

3.3.4 The following information on all pre-historic and historical earthquakes should be collected, to the extent possible:

a. Date, time, location and duration of earthquake shaking as reported
b. Location of the macroseismic epicenter
c. Intensity at the macroseismic epicentre or maximum intensity, as appropriate, with a description of local conditions and observed damage
d. Intensity at the site, together with available details of effects on the soil and the landscape
e. Isoseismal contours
f. Estimated magnitude along with the type of magnitude (e.g. moment magnitude, surface wave magnitude, body wave magnitude, local magnitude or duration magnitude or macroseismic magnitude) and documentation of the methods used to estimate magnitude from the macroseismic intensity
g. Estimated depth of focus
h. Estimates of uncertainty for all of the applicable parameters mentioned above
i. An assessment of the quality and quantity of data on the basis of which such parameters have been estimated
j. Information on felt foreshocks and aftershocks
k. Information on the causative fault
l. Source of reported information

3.3.5 The Intensity scale used should be noted. The magnitude and depth estimates for each earthquake should be based on relevant empirical relationships between instrumental data and macroseismic information, which may be developed from the database directly from intensity data or by using isoseismals.

Instrumental Earthquake Information

3.3.6 All available instrumental earthquake data recorded by the global and national networks should be collected. Existing information on crustal models should be obtained in order to locate earthquakes, if necessary.

3.3.7 The information to be obtained for each earthquake should include:

a. Date, duration and origin time
b. Coordinates of the epicenter
c. Focal depth
d. Magnitude(s) (on different scales) and information on seismic moment
e. Fault plane solution(s) (determined by local and global networks)
f. Information on observed foreshocks and aftershocks, to estimate rupture area and geometry of main-shock, where possible

g. Other information that may be helpful in understanding the seismotectonics of the region, such as inferred fault, stress drop and other seismic source parameters like b-value, aftershock attenuation factor (p-value), fractal dimension etc.
h. Asperity location and size, to the extent possible
i. Dimensions and geometry of the aftershock zone
j. Macroseismic Intensity data including maximum intensity, isoseismal map, intensity at the site and the location of the macroseismic epicenter, information on the causative fault, directivity and duration of rupture, to the extent possible estimates of uncertainty for each of the parameters mentioned
k. Records from both broadband seismograph and strong motion accelerograph
l. Source of reported information

Preparation of Earthquake Catalogue

3.3.8 A site specific earthquake catalogue shall be prepared by compiling all earthquake related information pertinent to the project covering temporal scales. The catalogue should include pre-historic, historic and instrumental earthquake data to the extent possible. Assessment of the completeness and reliability of the catalogue, particularly in terms of macroseismic (intensity) data, magnitude, date, location and focal depth should be conducted using appropriate methods (e.g. 'Stepp' method, and 'Tinti and Mulargia' method).

3.3.9 Regional and local strong ground motion data should be collected. The data can be used for deriving/ selecting/ validating appropriate Ground Motion Prediction Equations (GMPEs) and also in developing ground response spectra.

Site-Specific Instrumentation

3.3.10 A network of Micro-earthquake (MEQ) sensitive seismographs having capability of recording micro-earthquakes ($M_w \geq 1.0$) shall be installed and operated in the site region of a Hazard Category I facility to acquire detailed information on potential seismic sources/ seismically active faults, hypocentres, local crustal stress condition and other aspects of seismotectonics. The network should be installed as part of seismotectonic characterization of the site, say, three to five years before the start of the project and continue to operate throughout the lifetime of the facility to obtain necessary data for seismotectonic interpretation. Earthquakes recorded within and near such a network should be carefully analyzed, interpreted, and reviewed in connection with seismotectonic studies of the near site region. Details of MEQ seismic instrumentation are given in Appendix C.

3.3.11 Strong motion (SM) accelerograph(s) shall be installed permanently within the site area for each NPP to record ground acceleration. It is advisable to have at least one SM accelerograph installed (along with MEQ network establishment) at the site or in the adjacent surrounding region at site selection stage. For characterization of site response, seismic instrumentation in deep borehole should be provided for soil sites. Strong motion instrumentation using vertical arrays should be used for a better understanding of site response. Seismic instrumentation shall also be provided to automatically trip the NPP upon exceedance of specified level of ground motion (acceleration) not exceeding S1 level.

3.3.12 For Hazard Category I facilities other than NPPs and Hazard Category II & III facilities, unless required otherwise, at least one strong motion recorder at free field should be available. Specifics of the strong motion instrumentation are described in Appendix D. The stratigraphic profile should be obtained with dynamic soil properties below the network stations.

3.3.13 This site specific instrumentation should be appropriately and periodically upgraded and calibrated to provide adequate information in line with state-of-the-art operational practices.

3.4 Geological, Geophysical and Geotechnical Investigations

3.4.1 Investigations of the site and surrounding region including offshore, are necessary to identify capable tectonic sources that could generate earthquakes and surface deformation. These aspects should be assessed using geological, geophysical, seismological and geodetic methods to determine their significance. Appendix E elaborates the relevant geological, geophysical and geodetic investigations.

3.4.2 The investigations should be carried out in sufficient detail and in spatial and temporal extents so as to enable detailed characterization of seismotectonic information along with associated uncertainties.

Levels of Investigation

3.4.3 The investigations should be carried out at four levels, namely:

a. Regional investigations
b. Intermediate region investigations
c. Site vicinity investigations
d. Site area investigations

Regional investigations

3.4.4 The regional investigations should be undertaken to identify seismic sources and describe the tectonic regime in line with requirements specified in AERB Safety Code on ‘Site Evaluation of Nuclear Facilities’, AERB/SC/S (Rev.1). The radial extent of regional investigation should cover minimum 300 km radius around the site. The areas of investigation may need to be expanded beyond those specified above in regions that has active/ capable tectonic sources, relatively high seismicity, and complex geology or in regions that shows record of a large earthquake in recent years, or in historical time, or in paleoseismic records.

3.4.5 Preliminary investigation in a region should include a comprehensive literature review/ survey supplemented by focused geological reconnaissance based on the results of the literature study including topographic, geologic, lithologic, aeromagnetic, and gravity maps, seismicity, satellite image and aerial photos for preparing a seismotectonic map at a scale of 1:500,000 or larger with appropriate cross-sections.

3.4.6 Detailed investigations at specific locations within the region including ground truth reconnaissance may be necessary, if potential seismic sources that may be significant for determining the S2 level of ground motion are identified, and/ or existing data with respect to seismic sources are deficient. Where the existing information is insufficient, it may be necessary to verify and complete the database by acquiring new data. The data, as far as possible, should be obtained from national expert agencies, which may be supplemented with information from other authentic publications.

Intermediate Region Investigations

3.4.7 Intermediate region investigations, covering a radial distance of 50 km from the site, should include studies of structural geology, stratigraphy and tectonic history of the region. All lineaments, faults and geological features identified in the regional seismotectonic map should be investigated in detail by field verification and integrated subsurface geophysical investigations. Emphasis should also be given to the tectonic features outside this region, which have the potential to control the design basis ground motion of the site. Sites with capable tectonic sources (i.e. sources which can produce deformation on the surface or near surface during an earthquake) within a radius of 50 km require more extensive and detailed geological, geophysical, geodetic, and seismological investigations and analyses, at par with requirements specified for site vicinity investigations.

3.4.8 To identify and characterize the seismic and surface deformation potential of any capable tectonic and seismogenic sources, geological, seismological, geodetic, and other geophysical investigations in intermediate region should be carried out in greater detail than the regional investigations. Reconnaissance-level investigations, should be supplemented at specific locations by more detailed explorations such as geological mapping, geophysical surveying (namely refraction and reflection, electrical imaging, gravity and magnetic mapping methods), borings, and trenching. The Reservoir Induced Seismicity (RIS), if any, in this zone, should also be incorporated in the study.

3.4.9 For geodetic investigation to study rate and type of ground deformation, the Global Positioning System (GPS), interferometry and strain rate measurements data should be used. Seismological data (all events with Mw > 3.0) from all sources, particularly from the national and local network, need to be studied to identify seismically active fault(s), if any. The data should have a resolution consistent with the prepared seismotectonic map on a scale of 1:50,000 or larger.

3.4.10 Light Detection and Ranging (LIDAR) studies should be carried out in the intermediate region which should encompass site vicinity region also. The study should provide details of morphology and the existing faults on a regional scale. For further detailing of the faults, above mentioned geophysical methods can be employed.

3.4.11 All investigations should be conducted in sufficient detail so that the causes of each recent (in terms of the pertinent time window for the specific local tectonic environment) geological and geomorphological feature that is relevant (e.g., linear topographic or structural features as found in photographs, remote sensing imagery or geophysical data) can be properly included in a model of the recent geological evolution of the area.

Site Vicinity Investigations

3.4.12 The site vicinity investigations should cover a geographical area not less than 5 km in radius around the site and need to be rigorous. In this area, additional studies to that undertaken in intermediate region are required to obtain database which should be in more detail than that developed in the regional and intermediate region studies. Data obtained should be presented with resolution consistent with a map developed on a scale of 1:5,000 or larger.

3.4.13 The investigations in site vicinity region should be carried out for the following information:

a. Detailed mapping of geological and morphotectonic attributes occurring within a minimum of 5.0 km radius of the NF site on scale 1:5,000 or larger in order to identify the structural (faults, shears, folds, joints, etc.), lithological and stratigraphic features of the area.

b. Surface information including detailed tectonic history including the ages of the lineaments/ faults, dislocations based on trenching and age dating, identification of rock outcrops, tectonic features, fracture traces, geological contacts, lineaments, and soil conditions. Classification of faults and characterization of the active-capable faults should be carried out by shallow subsurface explorations, dating of Quaternary sediments and fault zone material. Evidences of (palaeo-) liquefaction and (palaeo-) landslides, if any, should also be documented and ages determined;

c. Subsurface information including but not limited to magnetic and gravity structures, seismic reflection and seismic refraction images, resistivity images, borehole geophysics records (line density, resistivity, and sonic velocity), ground-penetrating radar images, and Multi-channel Analysis of Surface Waves (MASW) images. Selection of these methods should be commensurate with characteristics of the region. Such surveys would also be helpful in the delineation of any hidden seismic source zone not detected during the course of surface investigations;

d. Microseismic data (Mw > 1.0) need to be recorded by at least a five-station MEQ network, 3 to 5 years before the project starts, and should continue till the life of the project;

e. Characterization of slope stability, soil, and strata based on geomorphic, physiomorphic and hydrological data (e.g. drainage, vegetation, and water table); and

f. The potential of ground collapse due to geological hazards such as differential erosion, karstic phenomena, fractures fissuring/subsidence/caving-in of ground on account of excessive withdrawal of groundwater in some alluvial terrain, and unstable material.

Site Area Investigations

3.4.14 Site area studies should include the entire area covered by the nuclear facility, which is typically one square kilometer. For multiunit sites, the area of investigation should be appropriately augmented. The primary objective of these investigations is to obtain knowledge of the potential for permanent ground displacement (e.g., fault capability, subsidence or collapse due to subsurface cavities, and liquefaction) and to provide information down to the required depth on the static and dynamic properties of sub strata, such as P-wave and S-wave velocities, shear modulus and damping curves, as applicable. Investigations in site area should have a resolution consistent with a map developed on a scale of 1:500 or larger.

3.4.15 In addition to geological, geophysical, and seismological investigations, detailed geotechnical investigations as described in AERB Safety Guide on ‘Geotechnical Aspects and Safety of Foundation for Buildings and Structures Important to Safety of Nuclear Power Plants’, AERB/NPP/SG/CSE-2 [4], should be conducted at the site. The investigations to be performed, by using field and laboratory techniques within the site area include:

1) Geological and Geotechnical Investigations

Investigations using boreholes or in-situ pit excavations (including in-situ testing), geophysical techniques and laboratory test should be conducted to develop database for the sub surface layer of the site area. The information which should be collected from these tests include:

a. Stratigraphy and geological structure
b. For soil sites, estimation of depth to bedrock using deep boreholes, to the extent practicable
c. Thickness, depth and dip of the subsurface layers

d. Engineering properties and index properties of subsurface layers like Young’s modulus, shear modulus, Poisson’s ratio, consolidation and swelling characteristics, grain size distribution, SPT N-value, density, dynamic soil properties, etc.

2) Geophysical Investigations

a. Seismic refraction/reflection imaging
b. Seismic cross hole imaging
c. Electrical resistivity imaging of the layers
d. Multi-channel Analysis of Surface Waves (MASW) imaging

3) Hydrogeological Investigations

Investigations using boreholes, borehole geophysics, and other techniques, should be conducted to define the physical properties of the aquifers in the site area (e.g., thickness, porosity, physiochemical constituents), and steady state behavior (recharge, transmissivity), with specific purpose of determining the stability of soils/ layers and how they interact with the foundation.

4) Ground response Investigations

a. For soil sites, appropriate investigations should be carried out to characterize subsurface properties down to bedrock for use in site response study such as P-wave and S-wave velocities, shear modulus and damping curves, density, soil strata characteristics, etc. as applicable;
b. The dynamic behavior of the rock or soil columns at the site should be assessed using instrumental data and borehole lithological as well as geophysical data including deep borehole data; and
c. Determination of the Predominant Frequency (PF) of ground using micro tremor (ambient noise) technique.

Investigations for Marine Region

3.4.16 In addition to investigations on land, adequate investigations should be conducted in offshore regions also, to fully analyse the tectonic characteristics of the region. Mapping of features should include seismotectonic features, topography, geomorphology (particularly mapping marine and fluvial terraces), bathymetry, submarine landslides, geophysics (such as seismic reflection) and hydrographic surveys to the extent needed to describe the features.

3.4.17 Analysis should be performed to determine the tectonic significance of offset, displaced or anomalous landforms, such as displaced stream channels or changes in stream profiles or the upstream migration of knick points, abrupt changes in fluvial deposits or terraces, changes in paleo channels across a fault, or uplifted, down-dropped, or laterally displaced marine terraces.

3.5 **Stages of Investigations**

3.5.1 In general, investigations are required to be carried out in four stages, namely:

a. Investigations for acceptability of the site
b. Investigations to establish design basis
c. Confirmatory investigations
d. Investigations as part of lifetime monitoring

Investigations for Acceptability of the Site

3.5.2 The main objective of the investigations during site evaluation stage is to determine the engineerability and acceptability of site as per the stipulations of AERB safety code on 'Site Evaluation of Nuclear Facilities', AERB/SC/S (Rev.1), [1]. Information required to be collected include:

a. Records on pre-historic, historic, and instrumental seismicity in the region and in particular in the site vicinity (within 5 km).

b. Geological and geophysical investigations in site vicinity area (as per clauses 3.4.12 and 3.4.13) to rule out existence of active/ capable faults within 5 km for Hazard Category I facilities.

c. Study on existence of an active/capable fault within intermediate region that can cause potential surface deformation and faulting at the site.

d. Evaluation of potential for permanent ground displacement, such as surface faulting or folding, fault creep, and subsidence or collapse at the site.

e. Collection and study of necessary information from geotechnical investigations based on limited number of boreholes augmented with geophysical investigation in the site area (as per clauses 3.4.14 and 3.4.15) to confirm availability of competent strata.

f. Preliminary assessment of earthquake induced liquefaction or any other seismic hazard capable of producing ground failure using conservative earthquake parameters (in absence of design basis ground motion parameters) to establish engineerability of the site.

g. Evaluation of the site and its vicinity for slope instability, if any, using conservative earthquake parameters (in absence of design basis ground motion parameters) to demonstrate engineerability of the site.

h. Geographical coordinates of site for establishing seismic zone as per IS 1893 [2].

i. Preliminary information on seismicity within 300 km radius.

Detailed Investigations to establish Design Basis

3.5.3 In this stage, the detailed regional, intermediate region, and site area investigations should be completed to establish design basis ground motion parameters. Investigation of all four levels and earthquake data collection should commensurate with requirement specified in sub-sections 3.2, 3.3, and 3.4. For sites vulnerable to tsunamis, and far field tsunamis in particular, investigations should encompass all potential far field sources as specified in section 8.

Confirmatory Investigations

3.5.4 There are some important investigations which need to be carried out for a longer period, such as seismological networks (MEQ), Strong Motion (SM) accelerometers at the proposed site and about 3-4 campaign mode GPS stations to measure the rate of deformation. Similar to the MEQ network, the campaign mode GPS stations may be established 3 to 5 years before the start of the project and continue till the life of the project. The MEQ network would monitor microseismicity, the SM accelerometer would provide ground acceleration and the GPS would provide ground deformation data at the site for any large / strong earthquake in the region. These informations would confirm the assumptions for design basis.

3.5.5 Confirmatory investigations should be conducted to demonstrate that deformation features, if any, discovered during excavation (e.g., fractures, potential soft zones, and other features of engineering significance) do not have the potential to compromise the safety of the facility. The identified features, should be mapped and appropriately assessed. As a minimum, this should apply to excavations for construction of all Hazard Category I facilities [1].

Investigations as part of Lifetime Monitoring

3.5.6 Seismotectonic hazard shall be monitored and assessed throughout the lifetime of all Hazard Category I facilities [1]. In addition to MEQ network, site specific instrumentation consisting of broad band and strong motion equipment should be employed for the above purpose. For lower hazard category facilities, need for lifetime monitoring may be decided on a case to case basis. Data collected by site specific instrumentation and by various other national institutes and competent agencies using state-of-the-art technology should be considered. The monitoring program should be established before commissioning and continued till decommissioning of the facility.

3.5.7 When a seismic hazard (and other correlated hazard) analysis are performed during the operating lifetime of the NPP as part of periodic safety review or a probabilistic seismic hazard analysis for a seismic probabilistic safety assessment, the existing integrated database should be updated and used.

4.0 REGIONAL SEISMOTECTONIC MODEL

4.1 General

4.1.1 For estimation of the seismic hazard, a regional seismotectonic model should be developed through a coherent merging of geological, geophysical, geotechnical and seismological databases. In the development of such a model, all relevant interpretations of the seismotectonics of the region should be taken into account. As seismogenic structures may exist without recognized surface or subsurface manifestations, and because of the timescales involved; any seismotectonic model should in general consist of two types of seismic sources [5] namely:

a. Those seismogenic structures that can be identified by using the available database
b. Diffused seismicity (consisting usually, but not always, of small to moderate earthquakes) that is not attributable to specific structures identified by using the available database

4.1.2 The evaluation and characterization of seismic sources of both types involve assessments of uncertainty. But seismic sources of the second type, i.e., those of diffused seismicity, generally involve greater uncertainty because the causative faults of earthquakes are not well understood.

4.1.3 Attempts should be made to define all parameters of each element in a seismotectonic model. Primarily, the construction of the model should be data driven. Information on source parameters should be collected using literature surveys and from agencies/organizations with relevant expertise and should conform to requirements of section 3.

4.1.4 When it is possible to construct alternative models that can explain the observed geological, geophysical and seismological data, and the differences in these models cannot be resolved by means of additional investigations, all such models should be considered in the final hazard estimation, with due weightage given to each model [5]. The epistemic uncertainty (e.g., the uncertainty associated with the modelling process) should be adequately assessed to capture the full range of hypotheses regarding the characterization of the seismic sources, the frequencies of the earthquakes and wave propagation models. If applicable, the effects of induced seismicity should also be accounted by adopting appropriate representation of seismogenic structures and maximum earthquake magnitude.

4.1.5 Experts in the relevant fields may be consulted for confirmation of input parameters for construction of seismotectonic model. However, expert elicitation should not be considered as a substitute for new data collection, investigations or additional analyses.

4.2 Seismogenic Structures

Identification

4.2.1 All seismogenic structures/ active faults which may contribute to the ground motion and/ or fault displacement hazard at the site shall be included in the seismotectonic model. With regard to the fault displacement hazard, specific attention should be paid to those seismogenic structures close to the site that have a potential for displacement at or near the ground surface (i.e. capable faults).

4.2.2 Based on investigations carried out as per section 3, identification of seismogenic structures should be made from the geological, geophysical, geotechnical and seismological databases on the basis of those features for which there is direct or indirect evidences of a seismic source within the tectonic regime. The definition of activity of a seismogenic structure with respect to the tectonic regime should be as per AERB Safety Code on ‘Site Evaluation of Nuclear Facilities’, AERB/SC/S (Rev.1).

4.2.3 The correlation of historical and instrumental recordings of earthquakes with geological and geophysical features is important in identifying seismogenic structures. However, a lack of correlation does not necessarily indicate that a structure is not seismogenic. Whenever the investigations show that an earthquake hypocenter or a group of earthquake hypocenters can potentially be associated with a geological feature, the rationale for this association should be developed by considering the characteristics of the feature, its geometry and geographical extent, and its structural relationship to the regional tectonic framework.

4.2.4 Other available seismological information, such as information on uncertainties in hypocentral parameters and the earthquakes’ focal mechanisms, stress environments and foreshock and aftershock distributions should also be used in interpretation of the seismogenic feature.

4.2.5 When specific information on a particular geological feature is lacking or sparse, a detailed comparison of this feature with other analogous geological features in the region should be made in terms of their age of origin, sense of movement and history of movement, in the development of regional tectonic model.

4.2.6 On the basis of the compiled information, the seismogenic structure(s) should be incorporated into a seismotectonic model along with uncertainties associated in the identification of these structures as well as interpretation. Unsupported assumptions or opinions with regard to the association between earthquakes and geological features, should not be considered. When information on a geological feature is insufficient, it should be considered as seismogenic.

Characterization

4.2.7 For seismogenic structures that have been identified as being pertinent while determining the exposure of the site to earthquake hazards, their associated characteristics should be determined. The dimensions of the structure (length, down-dip, width), its orientation (strike, dip), amount and direction of displacement, rate of deformation, maximum historical intensity and magnitude, paleoseismic data, geological complexity (segmentation, branching, structural relationships, etc.), and earthquake data should be used in this determination. Comparison with similar structures for which historical data are available also should be made, if available. The investigations carried out as per section 3 should be sufficiently detailed to enable such characterization.

4.3 Zones of Diffused Seismicity

Identification

4.3.1 Zones of diffused seismicity should be identified. A zone is considered to encompass an area having equal seismic potential (i.e. a geographically uniform rate of seismicity). A geographically non-uniform distribution of seismicity should be used, if the available data support this assumption.

4.3.2 When conducting seismic hazard analysis, knowledge about the depth distribution of the diffused seismicity (e.g. derived from the seismological database) should be incorporated. Significant differences in rates of earthquake occurrence may suggest different tectonic conditions and may be used in defining the boundaries of the seismotectonic zones. Also, significant differences in focal depths (e.g. crustal versus sub-crustal earthquakes), focal mechanisms, state of stress, tectonic characteristics, and seismic b-values characteristic may be used to differentiate between the zones.

Characterization

4.3.3 The maximum potential earthquake magnitude (M_{max}) in the region not associated with identified seismogenic structures should be evaluated on the basis of historical data and the seismotectonic characteristics of the zone. Comparison with similar regions for which extensive historical information are available may be useful, but considerable judgment may have to be used in such an evaluation. Often the value of maximum potential magnitude have significant uncertainty owing to the historical information of relatively short time period with respect to the processes of ongoing deformation. This uncertainty should be appropriately represented in the seismotectonic model.

4.3.4 Determination of the ‘b-value’ for seismic sources that have few earthquakes may involve a different approach. The approach may include adopting a value that represents the regional tectonic setting of the seismic source; for example, a stable continental tectonic setting, also considering available literature. Regardless of the approach used to determine the 'b-value' of the magnitude-frequency relationship, uncertainty in the parameter should be appropriately assessed and incorporated into the seismic hazard analysis. Guidelines for determining seismic parameters, like 'b' and 'a' values for such regions is provided in Annexure III.

4.4 Background Seismicity

4.4.1 In Stable Continental Regions (SCR), due to sparse seismicity and absence of any recorded event in the short period of observation compared to geological time scale of seismic activity, seismicity in the region should not be construed as 'zero', which may influence the DBGM parameters. Background seismicity needs to be considered to represent possible seismicity, where no recorded event in the time window is available. The maximum magnitude will depend on sensitivity of regional seismic instrumentation in operation during the time window considered and its minimum detectable magnitude. Broad guidelines on consideration of background seismicity in seismic hazard analysis is provided in Annexure III.

4.5 Components of Seismotectonic Model

Processing of Earthquake Catalogue

4.5.1 Prior to assessment of the frequency-magnitude relationship for a seismic source and maximum potential magnitude, the catalogue should be evaluated and processed. This should include:

a. Selection of a consistent magnitude scale for use in the seismic hazard analysis;
b. Determination of the consistent magnitude of each event in the catalogue on the selected magnitude scale;
c. Identification of main shocks (for de-clustering of aftershocks);
d. Estimation of completeness of the catalogue as a function of magnitude, location and time period; and
e. Quality assessment of the derived data, with uncertainty estimates of all parameters.

4.5.2 The magnitude scale selected should be consistent with the magnitude scale used in the ground motion prediction equations (GMPE) that are utilized in the hazard calculations and in any relationships used to derive the earthquake magnitude from intensity data. In deriving frequency-magnitude relationship, the selected magnitude scale should vary linearly with the moment magnitude (Mw) scale across the magnitude range of interest, in order to avoid magnitude saturation effects.

Identifying Source Geometry

4.5.3 Estimation of source geometry and its uncertainty should be based on detailed studies carried out on seismogenic structures and zones of diffused seismicity as elaborated in the section 4. For delineation of source geometry, information should be considered from geological, geophysical, lithological, seismological data etc. In general, owing to the impact on estimated DBGM, more efforts are required on delineation of source geometry for those sources located closer to the site. The consideration of source geometry also depends on the method of hazard analysis, e.g. in deterministic analysis, location of the source which is at the closest distance to site is more critical, whereas in PSHA source geometries are required to be defined with more diligence. Well defined seismic sources are more amenable to be modelled as line sources. For such cases, fault dip, strike and depth of earthquakes should be explicitly captured in the calculations.

4.5.4 Aerial sources can be used, when there is a spatial distribution of earthquake events corresponding to a seismogenic structure, namely the events occurring along a fault plane, background seismicity, etc. Selection of source geometry should account for uncertainties in collected data as well as in alternate interpretations. Alternate interpretations on source geometry may be considered as epistemic uncertainty and captured through logic tree analyses. Identified source geometry should account for errors in locations of earthquake epicentre and focus and depend on the distribution and density of station coverage. In general, epicentral determinations are more accurate (generally accurate to one-tenth of the average station spacing) than hypocentral determinations.

Estimating M_{max}

4.5.5 The maximum potential magnitude (M_{max}) associated with each seismic source should be specified, and the uncertainty in M_{max} described with a probability distribution. For each seismic source, the value of M_{max} is used as the upper limit of integration in a probabilistic seismic hazard analysis. It is also used in the derivation of frequency-magnitude relation, and in deterministic seismic hazard evaluation.

4.5.6 Due to lack of adequate span of recorded data, the largest recorded earthquake is not considered as a good estimate of M_{max}.The information from region of similar seismotectonic characteristics should be taken into consideration. However, appropriateness of seismotectonic analogue should be justified. The sensitivity of the resulting hazard to the selection of the M_{max} distributions should be checked.

4.5.7 When sufficient information on seismological and geological history of a seismogenic source (such as segmentation, average stress drop, rupture area and fault width etc.) is available to estimate the maximum rupture dimensions and/or displacements of future earthquakes, this information may be used to evaluate the maximum potential magnitude using the appropriate empirical relation. A number of other data such as data on heat flow, crustal thickness and strain rate etc. that may be used to construct a rheological profile are also important in M_{max} estimation. In absence of the above information, the M_{max} of a seismogenic structure can be estimated from its dimensions. For a fault source, M_{max} can be estimated using the fault's length and depth and its stress regime. At locations where a fault zone comprises multiple fault segments, each fault should be considered independently. Since the recent studies show remote triggering of faults by other earthquakes, the possibility of the multiple fault segments rupturing simultaneously during a single large earthquake also should be considered. To deal with M_{max} uncertainties, a suite of possible fault rupture length scenarios should be postulated and used to determine the best estimate of M_{max} .

4.5.8 Among other approaches for estimating M_{max}, statistical analysis of the b-value for earthquakes associated with a particular structure may be adopted. Results of all the methods should be, however, consistent. Further, the selected M_{max} should be atleast higher by one intensity equivalent of the observed maximum magnitude in the region.

4.5.9 Regardless of the approach or combination of approaches used, the determination of the maximum potential magnitude may have uncertainty, which should be incorporated to the extent that it is consistent with geological, geomorphological data and seismotectonic setting of the fault.

Fixing minimum magnitude, M_{min}

4.5.10 In seismic hazard analysis, there is a need to consider a lower bound or minimum magnitude owing to constraints in the seismological database and less damage potential of smaller earthquake. The selected lower bound magnitude should not exceed Mw 5.0.

Deriving Frequency-Magnitude Relations

4.5.11 Frequency-magnitude relationship of earthquakes should be derived for each seismogenic structure in the seismotectonic model, to determine: (a) the rate of earthquake activity; (b) an appropriate type of magnitude-frequency relationship (e.g. characteristic or exponential); and (c) the uncertainty in this relationship and its parameters. Each relationship should include the M_{max} for each structure. The relationship may be derived using earthquake data of adequate size or data of crustal strains buildup/ fault slip rate. Uncertainty in the parameters of the magnitude-frequency relationship should be defined accounting for any correlation between the parameters.

Selecting Ground Motion Prediction Equations

4.5.12 The Ground Motion Prediction Equations (GMPEs) published in internationally peer reviewed and well established literature only should be adopted. More emphasis should be given to GMPEs that have attributes to their functional form that is considered desirable, including saturation with magnitude, magnitude-dependent distance scaling and terms that contain the effects of anelastic attenuation. As a minimum, GMPEs that represent the source, propagation characteristics and regional/site characteristic may be used for evaluation of seismic hazard. Additional phenomena, such as style of faulting, hanging wall effects, also may be considered on a case to case basis.

4.5.13 If there are multiple GMPEs that are well constrained by data, but exhibit different trends, it is desirable to capture those trends in the selected GMPEs to properly represent epistemic uncertainty. In stable continental regions (SCRs), GMPEs are derived generally from the results of numerical simulations. In such situations, the manner in which the limited available data is used to constrain the input parameters for the simulations, should be critically evaluated. In SCRs, additional uncertainty due to numerical simulations may be captured by considering GMPEs that use alternate simulation methodologies. Also, it should be ensured that appropriate site specific constraints to all inputs used by GMPEs including those terms which are generally difficult to evaluate (e.g., basin depth terms) are available. The performance of GMPEs to regional characteristics should be preferably evaluated using available site/regional instrumental and intensity data from past earthquake events. Distance measures used in GMPEs should be consistent with the seismic source configuration.

5.0 **DETERMINISTIC SEISMIC HAZARD ANALYSIS**

5.1 **General**

5.1.1 This section covers estimation of DBGM parameters adopting deterministic approach and provides general guidance for estimating the S1 level and S2 level events.

5.2 **Methodology**

5.2.1 The assessment of seismic hazard by the Deterministic Method should include:

a. Collection of data and its assessment as per section 3 and 4 respectively

b. Development of the seismotectonic model for the region (the minimum distance for source identification should not be less than 300 km from the site, refer clause 3.4.4) in terms of the seismic sources identified on the basis of tectonic characteristics

c. For each seismic source, establishment of source geometry and determination of the maximum potential magnitude

d. Selection of the GMPEs appropriate for the site region and assessment of the mean and variability of the ground motion parameters as a function of earthquake magnitude and seismic source to site distance

e. Estimation of the hazard taking into account both aleatory and epistemic uncertainties at each step of the evaluation

f. Consideration of site amplification

5.3 **S2 Level Ground Motion**

5.3.1 Evaluation of the S2 level ground motion requires that the maximum earthquake potential associated with each tectonic zone/fault is estimated. The maximum earthquake potential should be assigned on the basis of maximization of historical earthquake data and seismotectonic model (also see sub-section 4.5). For each of these tectonic zone/ fault, a S2 level ground motion should be defined considering the following points:

1) For each active fault, the maximum earthquake potential, M_{max}, should be moved to a point on the fault closest to the site. While doing so, consideration may be given to the size and depth of the earthquake source.

For the tectonic zone in which the site lies, the M_{max}associated with this tectonic zone should be considered to occur at a certain distance from the site, within which it has been confirmed through detailed investigations that no active tectonic structure exists. It is desirable to demonstrate through actual earthquake monitoring that no earthquake was occurring within that distance.

For other tectonic zones, the M_{max} should be a point nearest to the site on the boundary of the tectonic zone.

2) Effect of Induced Seismicity (IS)

An estimate should be made of the M_{max} due to its possible origination from impounding of reservoir (existing or proposed) or withdrawal of fluid or hydrocarbon (from existing or proposed facilities) associated with tectonic units, for which there exists the possibility of faults being reactivated. The potential will be placed on such structures at a point closest to the site.

5.4 Design Response Spectra

5.4.1 In deterministic seismic hazard analysis, design response spectra should be derived as mean response spectra and uncertainty in the process of evaluation should be duly accounted. Recommended approach to consider uncertainty is by adding one sigma to all spectral ordinates. Any other approach to account for uncertainty should be confirmed with detailed probabilistic seismic hazard analysis as outlined in section 6. In this case, probabilistic seismic hazard analysis is mandatory to confirm the results of DSHA.

5.4.2 The design response spectra should be derived from an ensemble of accelerograms recorded on similar sites and covering a broad range of source and transmission path characteristics. At least 25 accelerograms should be taken in developing the response spectra. The magnitude and distance of these records should cover the corresponding ranges considered for S2 level ground motion. Alternately/ additionally, numerical simulation approach for generation of time histories or GMPEs may be adopted for establishing design response spectra (refer clauses 2.4.4 to 2.4.7 and 4.5.12 to 4.5.13).

5.4.3 Envelope of design response spectra corresponding to all seismotectonic sources should be considered as site specific design spectra.

5.5 Site Amplification

5.5.1 For sites located on soil strata, studies to capture amplification of seismic wave due to propagation through soil media should be conducted following the guidance provided in Appendix A.

5.6 Spectra Compatible Ground Acceleration Time Histories

5.6.1 There are various methods that can be used to develop design ground acceleration time histories, depending on the available data. In all cases, these ground acceleration time histories should be compatible with the characteristics of the design earthquakes, the amplitude and spectral shape of the response spectra, and the expected duration of the design ground motions. The common methods for developing design acceleration ground motion time histories are:

a. Based on appropriately selected and scaled recorded acceleration time histories, for which the scaling factor is within the range 0.5 - 2.0
b. Appropriately selected recorded time histories modified using spectral matching techniques in which the phase characteristics of the ground motion are taken into account
c. Generation of artificial time histories, usually having random phase
d. Simulated time histories based on numerical modelling methods

5.6.2 The Time History generated Response Spectra (THRS) should be compatible [6] with the Specified Response Spectra (SRS)[1] for the same values of damping, i.e. THRS should not deviate significantly from the SRS over the frequency range of interest [6 7]. The matching should be attempted at all points where the SRS has been specified. The baseline of the time history thus generated should be modified to ensure that the consequent ground velocity and displacement do decay realistically at the end of the duration. In addition to compatibility requirements given in [6], it is desirable that the time history satisfies the constraints on specified values of: (1) Peak ground acceleration, (2) Peak velocity and displacement, (3) Rise-time to peak acceleration, (4) Duration of strong motion, and (5) Rate of zero crossing. These constraint parameters should be determined from the relevant data set and should be consistent with the source and wave propagation characteristics.

5.6.3 The duration of ground motion is determined by many factors, including the length and width of fault rupture (generally characterized by magnitude), crustal parameters along the propagation path (generally characterized by distance), conditions beneath the site and the presence of a sedimentary basin. A consistent definition of duration should be used throughout the evaluation. In determining an appropriate duration for the time histories, due weightage should be given to any empirical evidence provided by the regional database. As a minimum, the strong motion duration specified in AERB Safety Guide on 'Seismic Qualification of Structures, Systems and Components of Pressurised Heavy Water Reactors', AERB/NPP-PHWR/SG/D-23 [6] should be considered.

5.6.4 For liquefaction hazard assessment, time histories used should be consistent with source magnitude-distance couplets. In some sites, relatively low amplitude motions from distant, large earthquakes may pose a liquefaction hazard. When this condition applies, time histories required to be used for liquefaction assessment should include such low amplitude time histories over an appropriate duration.

5.6.5 For the acceleration time histories, the strong motion duration may be defined by: (i) Time interval (bracketed duration) between the first and the last peak of strong ground motion above a specified threshold value, generally, taken as 0.05g, or (ii) Time

[1] SRS may refer to spectra at bedrock for soil sites and free field for rock sites

intervals between 95th and 5th percentiles of the integral of the mean square value of the acceleration.

5.6.6 For a site where a site specific response analysis to capture local site conditions is required, two different sets of time histories could exist. The first set corresponds to spectra derived at strata of impedance contrast/ bedrock and used for convolution studies through soil strata. The second set corresponds to spectrum compatible time histories derived from the DBGM spectra defined at appropriate levels of soil strata including hypothetical free field and used for structural analysis.

5.6.7 Selection of number of time histories and their characteristics (amplitude, frequency content, phase, duration, strong motion, etc.) should be justified. For sites where near-field events could be of concern, adequate number of velocity pulses may also need to be introduced.

5.7 Treatment of uncertainties

5.7.1 In the seismic hazard evaluation, all uncertainties, both aleatory and epistemic, should be taken into account. A conservative process should be adopted for magnitude, distance, spectral shape, etc. and for epistemic uncertainty, a weighing scheme with alternate scenario/ models should be considered.

5.8 S1 Level Ground Motion

5.8.1 For NPPs, the S1 level ground motion can be derived on the basis of historical earthquakes that have affected the region. The potential of induced seismicity may be considered in deriving S1 level ground motion when the site is located near to any artificial reservoir (existing or proposed) or place of extraction (existing or proposed) of fluid or hydrocarbon from the earth. Details of the proposed method for fixing the S1 level ground motion are left to the applicant.

6.0 PROBABILISTIC SEISMIC HAZARD ANALYSIS

6.1 General

6.1.1 Probabilistic Seismic Hazard Analysis (PSHA) is carried out to assess the hazard level in a probabilistic sense and probability of exceeding a level of earthquake vibratory ground motions at site in a specific period of time. This approach allows users to handle uncertainty in seismic hazard analysis in a structured manner. The major input parameters for PSHA are: seismic source geometry, recurrence of earthquakes within seismic sources, maximum magnitude of earthquakes within a seismic source and estimation of earthquake ground motion through GMPE or attenuation relationship. In case of estimation of Design Basis Ground Motion, peak ground acceleration and response spectral accelerations are generally considered as ground motion parameters for PSHA.

6.1.2 A PSHA, based on state-of-the-art approaches, should be conducted to complement DSHA in determination of DBGM parameters for a site. In addition to hazard curves corresponding to different spectral periods/ frequencies, PSHA should provide uniform hazard spectra (UHS) corresponding to the specified mean annual frequency. The ground motion parameters, i.e., intensity measure (IM) should be selected based on the objectives of PSHA and considering input requirements.

6.2 Methodology

6.2.1 The major steps in PSHA are:

a. Collect information as per section 3 and its assessment as per section 4
b. Evaluate the seismotectonic model for the site region in terms of the definition of seismic sources, including uncertainties in their geometries, dimensions, and other characteristics, as applicable. PSHA should also account for background seismicity
c. For each seismic source, evaluate the maximum potential magnitude, the rate of earthquake occurrence and the type of magnitude-frequency relationship, together with the uncertainty associated with each evaluation
d. Select the applicable GMPEs for the site region, and assessment of the uncertainty in both the mean and the variability of the ground motion as a function of earthquake magnitude and seismic source to site distance
e. Evaluate the outcrop motion at the bedrock by integrating the distributed hazard

$$\lambda(IM > x) = \sum_{i=1}^{N} \lambda_i \left(M_{min}^i\right) \int_{M_{min}^i}^{M_{max}^i} \int_{R_{min}^i}^{R_{max}^i} P\left(IM > x|m,r\right) f_i(r|m) f_i(m) dr dm \qquad (6.1)$$

where,

N = Number of seismogenic sources in the PSHA source model

IM = Intensity measure used in PSHA for evaluation of ground motion at site

M_{min}^{i} = Minimum magnitude of earthquake of source i that has engineering significance

M_{max}^{i} = Magnitude of maximum potential earthquake from a source i

R_{min}^{i} = Minimum distance to seismic source i. The R_{min}^{i} value for background seismic sources should be based on level of investigation as per section 3

R_{max}^{i} = Maximum distance to seismic source i

$\lambda_i(M_{min}^{i})$ - Frequency of earthquakes on seismic source i above a minimum magnitude of engineering significance M_{min}^{i}

$f_i(m)$ = Probability density function of event size on source i between m_{min} and a maximum earthquake size for the source M_{max}

$f_i(r|m)$ = Probability density function for distance to earthquake rupture on source i, which may be conditional on the earthquake size

$P(IM > x|m,r)$ = Probability that a given magnitude m earthquake at a distance r from the site, the ground motion (IM) exceeds a value x

$\lambda(IM > x)$ = Frequency of exceedance of the ground motion (IM) beyond a value x

f. In case of soil sites, evaluate free field ground motion considering the local site effect as per Appendix A.

6.2.2 In line with guidance provided in Section 4.5, the earthquake source parameters (like maximum earthquake magnitude M_{max}, the magnitude-frequency relationship, and the temporal occurrence model) should be evaluated from seismotectonic and seismicity data considering uncertainties. The geometry of seismic sources (like line, area or volumetric source), should be identified and characterized by probability distributions for earthquake locations. The minimum distance for source identification should not be less than 300 km from the site. Need should be evaluated for alternate scenarios of source models as well as consideration of recurrence relations based on strain build-up.

6.2.3 The lower magnitude M_{min} selected for use in the hazard integration equation (6.1) should be so chosen that earthquakes of magnitude less than M_{min} will not cause significant damage to structures, systems or components. Selection of M_{min} should account for potential bias in the hazard calculation of high frequencies (refer clause 4.5.10). The GMPEs used for the evaluation of ground motion exceedance probability $P(IM > x|m,r)$ should be selected as per clauses 4.5.12 and 4.5.13. In case of GMPE having additional input parameters other than magnitude and distance, their sensitivity on ground motion also needs to be studied. The hazard integration equation (6.1) for such GMPEs also should incorporate these parameters. Given an estimated frequency of exceedance of the ground motion (IM) (λ), the probability that the ground motion (IM) exceeds a value of x ($P(IM > x)$), in a time window of Tp years is given by following equation 6.2:

$$(IM>x)=1- e^{-\lambda Tp} \qquad (6.2)$$

6.2.4 For DBGM estimation, Tp is considered as one year. For the NPPs and hazard category I NFs, all six steps are mandatory to establish free field ground motion. For other nuclear facilities, free-field motion could be established using Steps 1-5, by considering local site effects as incorporated in GMPEs. .

6.3 Uncertainties

6.3.1 The PSHA should consider uncertainties associated with seismic sources, ground motion, the state of knowledge of earthquake process, etc. These uncertainties can be categorized into aleatory and epistemic uncertainties. Aleatory uncertainty results from natural variability in the physical process. The size, location, time of the future earthquake in a source region and the ground motion at site are some of the characteristics that may be captured in aleatory uncertainty. The aleatory uncertainties should be incorporated into seismic ground motion evaluation through hazard integrations equation (6.1).

6.3.2 The epistemic uncertainty results from the uncertainties due to the insufficient knowledge like seismogenic characteristics of the faults, etc., and should be incorporated using either logic tree or Monte Carlo simulations. In case of logic tree analysis, weights of each branches should be established based on variability of parameters and state of knowledge. The resulting suit of hazard curves should be presented as curves showing statistical summaries, like mean, median, fractiles.

6.3.3 In case of analysis of propagation of uncertainty using logic tree or Monte Carlo simulation, a sensitivity analysis should be performed to determine the relative degree of contribution of each uncertain parameter on the final results. As a minimum, uncertainties should be considered in source model, recurrence rate, maximum magnitude, and GMPE. In each logic tree, minimum of three representative cases should be used in analysis for applicable parameters. Unrealistically narrow or broad estimates of uncertainty by ignoring or misinterpretation of data should be avoided.

6.3.4 The mean of distribution of hazard due to epistemic uncertainty should be used for final evaluation of hazard level at site. In addition, the fractal hazard curves should be reported to derive uncertainty in the determination of the hazard.

6.4 S1 and S2 Level of Ground Motion

6.4.1 S1 and S2 level of ground motion should be established as per sub-section 2.2. The S2 level ground motion can be established from PSHA by deriving UHS corresponding to specified annual frequency.

6.5 Site Amplification

6.5.1 In case of soil sites, where local site effect study is warranted, bedrock UHS corresponding to specified annual frequency should be propagated to free-field as per Appendix A, and mean free-field spectra should be considered as S2 level ground motion.

7.0 POTENTIAL FOR GROUND FAILURE

7.1 General

7.1.1 Potential for ground failure at a site could result from various phenomena, such as fault rupture, liquefaction of soils, slope failure, ground subsidence, and ground collapse. These phenomena are generally associated with differential ground movements or initiated by vibratory motion resulting in irreversible damage to facilities at the site. Investigations to characterize required input parameters and for assessment of these hazards should be performed in sufficient detail. This should be followed by assessment and documentation of their presence or absence and safety implications.

7.2 Fault displacement

7.2.1 The concern with regard to fault displacement at surface is whether a fault (buried or outcropping) at or near the site is active/ capable and can result in surface/ near surface displacement that can endanger safety of nuclear facility. The assessment should be carried out for both primary faults that reach the ground surface as well as subsurface faults that do not reach the ground surface. The database as incorporated in the seismotectonic model, together with additional specific data as needed, may be used for assessment of fault displacement. General guidelines with respect to the investigation of a site and its vicinity for surface faulting include identification and assessment for potential active faults around the site or trending towards the site.

7.2.2 The types of studies and areas of investigation for evaluating potential for surface rupture hazard should be based on the tectonic, geological, and seismological setting of the site (refer section 3). If found necessary, fault displacement2 associated with each feature under investigation should be determined. The assessment may be carried out by deterministic or probabilistic approach.

7.3 Liquefaction

7.3.1 Evaluation of the liquefaction potential of soil at the site is an important part of the overall assessment of the seismic hazard. The physical attributes controlling the liquefaction phenomena are:

a. Composition of the soil at the site
b. Ground water conditions and drainage pattern
c. Behavior of the soil under dynamic earthquake loading
d. Duration and level of the vibratory ground motion

[2]IAEA Safety Standard Series 85

7.3.2 Soil strata at site can be categorized as potentially liquefiable, if any one of the following conditions are met with at the site:

a. Presence of Alluvial/ Aeolian sands and silts, Beach sands, Reclaimed land, Un-engineered fills
b. Low penetration resistance, as measured by Standard Penetration Test (SPT) or Cone Penetration Test (CPT)
c. Persistent inability to retain soil samples in conventional sampling devices
d. Presence of saturated zones of granular soil with impeded drainage
e. Presence of any clean, fine sand below ground water table

7.3.3 If preliminary assessment based on the above indicates potentially liquefiable strata at site, further assessment to evaluate safety and engineer the site to eliminate potential for liquefaction is required. This evaluation should be conducted following established state-of-the-art methods and using site specific parameters. Unless specified otherwise, a factor of safety of at least 1.4 should be demonstrated against liquefaction hazard to ensure there is no modification in characteristics of founding medium.

7.3.4 To address uncertainties in methods of assessment, multiple approaches (based on different field/ lab investigation techniques) should be adopted. Details on methods of assessment are provided in AERB Safety Guide on 'Geotechnical Aspects and Safety of Foundation for Buildings and Structures Important to Safety of Nuclear Power Plants', AERB/NPP/SG/CSE-2 [4].

7.3.5 If potential for soil liquefaction exists, proven engineering solutions should be implemented to mitigate liquefaction hazard at site with sufficient margin. Using appropriate confirmatory tests/ investigation, it should be demonstrated that application of engineering solution results in mitigation of liquefaction hazard at site. The site shall be deemed unsuitable unless engineering solutions are demonstrated to be available.

7.4 Slope Instability

7.4.1 The site and its vicinity should be evaluated for potential of seismic induced slope instability (such as land and rock slides and land erosion) which could affect the safety of NF. If such a potential exists, the hazard should be evaluated using site specific design basis ground motion parameters. In addition to the basic data acquired in the investigations (see section 3), the following data are needed to analyse the potential of slope instability:

a. Geometry, extent and distribution of drift deposits (debris, soil, etc.) or rock formations within or around the site as well as slope angle

b. For rock slopes, details of form and features, such as zones of fracturing, the orientation of the strata and their localized weathering, lithology, geological structures and rock mass rating (RMR) which might affect their stability
c. Static and dynamic characteristics of the soil or rock including densities, strengths, and deformabilities
d. Hydrological conditions and their variations
e. Evidence of past slope failures

7.4.2 The assessment should be carried out using well validated numerical models and design basis ground motion parameters, as applicable to the strata for which the particular analysis is carried out. The site shall be rejected, if suitable engineering solution against slope instability is not feasible.

7.5 **Ground Subsidence and Collapse**

7.5.1 Ground subsidence and collapse under dynamic loads, change of ground water conditions, soil expansion, soil collapse, erosion, and other causes should be evaluated. In general, subsidence and collapse due to ground shaking are owing to either compaction of dry or partially saturated sands or dissipation of dynamic pore water pressure. Conditions such as the existence of a thick aquifer in the site vicinity, the extraction of fluids, or the existence of mining activities in the vicinity, may indicate potential for subsidence, particularly in case where contact zone between hard and soft rock/ soil exists.

7.5.2 Subsurface features associated with geological /geochemical process (namely Existence of caverns or karstic networks in calcareous deposits, Potential for solution phenomena in salt formations, Joint and fracture patterns, and spatial extent and slope of strata especially aquifers) and/ or human activities (namely Existence of tunnels, existence of mine galleries or cavities in or out of operation, mineral extraction (for instance by dissolution techniques), withdrawal of subsurface fluids, and injection or ingress of fluids) may create conditions for ground collapse which can adversely affect the safety of the site. In addition to the above basic data acquired in the investigations (section 3), the following factors should be evaluated:

a. The total reduction of the groundwater level that could occur during the operating life of the nuclear facility
b. The differential change in groundwater level that could develop across the site
c. The pertinent physical parameters of the aquifer, such as consolidation coefficient, degree of lateral homogeneity

7.5.3 If the consequences of potential subsidence or collapse cannot be mitigated by engineering solutions, the site should be considered as unacceptable.

8.0 SEISMICALLY GENERATED WATER WAVES AND FLOODS

8.1 General

8.1.1 A tsunami is a series of travelling waves of long wavelengths (kilometers to hundreds of kilometers) and long periods (several minutes to tens of minutes and exceptionally hours). It is generated by sudden movement in the sea floor, whereby large volumes of water are impulsively displaced, such as in the event of a deep sea earthquake, sediment slump, volcanic eruption or even meteorite impact. During the propagation, submarine topography and depth affects the speed and height of the tsunami wave. Refraction, reflection from a sea mount or its chain (archipelago) and diffraction are important factors affecting the propagation of tsunami waves in deep water.

8.1.2 In the coastal zone, local topography and bathymetry, such as a peninsula or submarine canyon, may cause an additional increase in wave heights. Also, the wave heights could be amplified by the presence of a bay, an estuary, a harbour or lagoon funnels as the tsunami moves inland. The above aspects should be considered appropriately during tsunami hazard assessment. The possibility that first wave may not be the largest, should also be accounted for.

8.1.3 For purpose of hazard assessment, an earthquake induced tsunami may be considered only for a seafloor deformation associated with submarine and near-coast earthquakes with shallow depth ($<$ 50 km), large magnitude (M $>$ 6.5) and dip-slip mechanism [8]. Tsunamis may be considered to be generated by volcanic phenomena when voluminous (e.g. $> 10^6 m^3$) landslides, pyroclastic flows or debris avalanches rapidly enter the sea or large lakes, or by the eruption of underwater volcanoes.

8.1.4 Underwater and coastal (sub-aerial or sub-aerial-underwater) landslides, rock falls and cliff failures also may generate tsunamis, some of which are locally more disastrous than earthquake induced tsunamis. These landslides may or may not be triggered by an earthquake or by volcanic activity. Possibility of such phenomena to generate a tsunami around the site should also be looked into.

8.1.5 Phenomena of generation and propagation of tsunami wave should be captured using appropriate mathematical models and inputs. Based on the assessment, various coastal phenomena associated with arrival of tsunami wave at the site should be evaluated.

8.1.6 The run-up, which is defined as the maximum ground elevation that the tsunami waves reach above a standard datum, is the parameter used to define the high-water level. The run-up is obtained as an output from the inundation model. Along with the maximum run-up, the areal extent of the tsunami run-up also should be considered. Apart from flooding, other hazards posed by tsunami include dry intakes during drawdown, scouring, deposition, hydrostatic and hydrodynamic forces, debris and projectiles, and tidal bores [9]. In all scenarios, the required volume of cooling water should be shown to be available, because of the potential for low water level to affect the intake water system for several hours.

8.2 Information Collection

8.2.1 A comprehensive survey and assessment of tsunamigenic sources should be performed to determine the potential that a tsunami may pose a hazard to the site. The assessment should include all potential near and far-field sources (i.e. trans-oceanic) and mechanisms that generate tsunamis. Available information on earthquake induced tsunami sources, as applicable, collected as part of section - 3 needs to be augmented (to address far field tsunamigenic sources) for the purpose of tsunami hazard assessment.

8.2.2 A comprehensive search should be carried out of the national and international (wherever needed) information repositories to list all historical tsunamis that occurred in the region. When available, information should be collected on wave height, inundation extent, run-up, and drawdown associated with these events. Paleotsunami information and inferences drawn by experts from these information should also be collected because these datasets extend the historical record and may include some events which may be more severe than those actually recorded. The fact that no historical tsunami records can be found for a region does not necessarily result in a conclusion that the region is free of tsunami hazards. A comprehensive search for potential tsunamigenic sources that may create a tsunami in regional water bodies should also be carried out.

8.2.3 An analysis should be carried out using all tsunami information to determine the potential mechanisms that may generate a tsunami capable of affecting the site. The analysis should specify tsunami characteristics and its effects at the site. The frequency and severity of tsunamis at the site from historical and pre-historical data, if available, should be estimated. Both near- and far-field tsunamis require investigation.

8.2.4 Based on the collected historical data, tsunami activity at and near the site should be brought out. It should list all observed source mechanisms, the ranges of source parameters and characteristics, the ranges of tsunami run-up and inundation, and the extent of damage suffered.

8.3 Preliminary Screening

8.3.1 As an initial assessment, a simplified screening criterion is recommended. No specific further investigations and studies need to be performed to analyse the tsunami hazard for the plant site, provided that the site is located in an area that shows no evidence of past occurrences of tsunamis, and is located [8]:

a. At more than 10 km away from the sea or ocean shoreline, or more than 1 km from a lake or fjord shoreline, as appropriate; or
b. At more than 50 m elevation from the mean water level.

8.3.2 In situations other than above, a detailed hazard assessment for tsunamis should be performed.

8.3.3 If the specific studies and investigations performed and compiled in the geological, geophysical, seismological and tsunami databases, demonstrate that there is no potential for occurrence of tsunamis at the site, no further assessment of the tsunami hazard is necessary. In other cases, a site specific tsunami hazard analysis should be performed through a detailed numerical simulation to derive the design basis flood level.

8.4 Characterization of Tsunamigenic Sources

8.4.1 For Site-Specific tsunami analysis, compilation of tsunami data including paleotsunami data covering both far field and near field sources should be done. All tsunamigenic source mechanisms should be investigated. Information on source parameters should be collected using literature surveys and organizations with relevant expertise. Experts in the relevant fields may need to be consulted for estimation of parameters when no published values exist. But, expert elicitation should not be considered as a substitute for new data collection, investigations or additional analyses.

8.4.2 The source parameters required for a tsunamigenic earthquakes are [9]:

a. Location (latitude, longitude, and depth)
b. Moment magnitude, Mw estimated following clauses 4.5.5 to 4.5.9
c. Fault dimensions (rupture length and width)
d. Dip, strike, and slip distribution
e. Shear modulus

8.4.3 In addition to compiling the above parameters (known or estimated), attention should be given to the orientation of the source with respect to the proposed site, as the orientation of the source, can strongly affect the directivity of the tsunami waves.

8.5 Numerical Modelling

8.5.1 For assessing the tsunami hazard for all types of tsunami source, the numerical simulation should cover the generation, propagation and coastal processes, with appropriate initial conditions and boundary conditions, and should use appropriate bathymetry and coastal or near shore topography data.

8.5.2 For earthquake induced tsunamis, the elastic model of the earthquake source [10] should be used as initial condition to provide the sea floor deformation due to the earthquake. Then this should be used as the initial water wave field. For landslide induced tsunamis and tsunamis induced by volcanic phenomena, the generation mechanisms are fundamentally different from that for seismic sources, with much longer duration. For this reason, the dynamics of interactions between sources and water waves should be taken into account.

8.5.3 The long wave or shallow water theory, integrated from the sea floor to the water surface, can be applied for tsunami wave propagation, including run-up and drawdown. The nonlinear and bottom friction terms can be neglected for deep water (more than 100 m). For small scale sources or long distance propagation, the dispersion effect with wave frequency may need to be considered.

8.5.4 The resolution and accuracy of the near shore bathymetric and topographic information have a vital effect on the computed results. The spatial grid size should be small enough to represent properly the terrain, coastal, and underwater morphology near the site. Spatial grid size, time steps and connecting borders between meshes of different size should be specified to provide stability to the numerical computation.

8.5.5 In deep waters, where the tsunami waves have long wavelengths, a relatively low resolution relief data may be acceptable. In shallow waters, accurate and high-resolution relief data is needed to resolve the wave and to ensure accuracy of model predictions. Resolution of topography data may become more important because inundation models typically have the most uncertainty in their predictions.

8.5.6 The high tide and low tide levels should be considered appropriately for generating conservative scenarios (e.g. high tide and flooding, low tide and draw down).

8.5.7 The numerical models should undergo rigorous validation and verification processes considering analytical solutions and outcome of laboratory experiments. In addition, capability of model to perform in real world scenario and validity of predictions in terms of time of arrivals and water levels also should be assessed. For this purpose, comparison may be made between simulated data and observed datasets.

8.6 Hazard Assessment

8.6.1 For earthquake induced tsunamis, the hazard should be assessed by using either a deterministic hazard analysis or a probabilistic hazard analysis, or preferably both methods [8]. Whichever method is used, a quantitative estimate should be made of the uncertainties in the results of the hazard assessment. The overall uncertainty will involve both aleatory uncertainty as well as epistemic uncertainty arising as a result of differences in interpretation of tsunami sources and run-up heights by subject experts. Such interpretations should be treated in the tsunami hazard analysis in a consistent manner, providing for a suitable representation of current thinking on tsunami sources, propagation modelling and coastal processes. Particular care should be taken to avoid bias in these interpretations. Expert opinion should not be used as a substitute for acquiring new data.

8.6.2 Due to uncertainty that exists in predictions from inundation models, care should be taken in application of these models and use of their predictions to specify design bases with respect to the location of SSCs important to safety as well as their grade elevations. Wherever possible, inundation models should be verified with locally available run-up data. Sufficient margins should be provided for these uncertainties in all design bases that may be derived from such simulations.

8.6.3 Low-water level can lead to a dry intake, compromising the safety of a nuclear power plant. Ambient conditions, such as low tide, can affect the low-water level. Care should be taken in interpretation of drawdown predictions from inundation models, and sufficient margins should be provided in all design bases that may be affected by these predictions. For evaluation of other related hazards, namely scouring, deposition, hydrostatic and dynamic pressure, appropriate methodology/numerical models may be used.

Deterministic Methods

8.6.4 The numerical simulation may be performed using a deterministic approach using the following steps [8]:

1) Select numerical propagation model, which has undergone rigorous validation exercise following both analytical solution and laboratory experiments;

2) Construct and validate the numerical simulation model on the basis of records of observed historical tsunamis:

   a. Select the largest historical tsunamis in the near field and far field that have affected the site region
   b. Identify and validate the corresponding run-up heights and time of arrival at various observation stations in the coastal region near the site
   c. Identify the corresponding seismogenic fault parameters
   d. Develop and execute the numerical model including generation, propagation and coastal processes for all selected historical tsunamis
   e. Compare the simulation results with the historical run-up heights
   f. Adjust the model, if required, with justification

3) Apply the numerical model based on seismogenic sources and the associated fault parameters for the assessment of tsunami hazards:

   a. Select tsunami sources and estimate the related maximum earthquake magnitude and associated fault parameters and their range of variation, in accordance with the seismic hazard assessment

b. Consider multi segment ruptures to accurately capture source configuration (e.g. Andaman-Sumatra region), heterogeneous distribution of slip, etc. may be considered

c. Perform numerical calculations for all the possible seismogenic sources along with related uncertainties in input parameters to examine the range of tsunami heights

d. Select the maximum and minimum water levels

8.6.5 Both aleatory and the epistemic uncertainties should be captured. In particular, the uncertainties related to following should be considered:

a. Tsunami source
b. Numerical calculation
c. Submarine and coastal topography

Probabilistic Methods

8.6.6 Though several methods are proposed for the assessment of tsunami hazards using probabilistic approaches, standard evaluation procedures have not yet been developed. For regions with sparse observed records of tsunamigenic events such as Indian coast, a Probabilistic Tsunami Hazard Assessment (PTHA) may be developed analogous to Probabilistic Seismic Hazard Assessment (PSHA), using unit source method [11].

8.6.7 During application of unit source method, in addition to characterization of seismotectonic sources following the guidance already provided in previous sections/sub-sections of this guide, due consideration should be given for nonlinear amplification of tsunami waves. As tsunami waves are sensitive to site specific bathymetry and source directivity, use of empirical equations is not recommended for tsunami run-up in PTHA.

8.6.8 While adopting Probabilistic methods, both the aleatory and the epistemic part should be taken into account. Results of the PTHA should be typically displayed as the mean annual frequency of exceedance of run-up height and draw down values, estimated through a logic tree approach.

8.7 Seiches

General

8.7.1 When a site is located on the shore of an enclosed or semi-enclosed body of water, the potential for seiches should be taken into consideration. Free oscillations of a water body (seiche) can be excited by earthquakes, storm surges, variations in wind speed, variations in the atmospheric pressure field, wave interactions, earthquake induced tsunamis, landslides into water, underwater volcanic eruptions and other disturbances (such as a local seismic displacement that could produce an extreme 'sloshing' of the entire basin). Also, forced oscillations of the water body may arise from a continuous application of an excitation to the water column at an entrance to an embayment or canal or from periodic winds at the water surface.

Hazard Assessment

8.7.2 For flooding by seiches, the hazard may be assessed by using a Deterministic Hazard Analysis. The modes of oscillation due to a seiche depend on the surface geometry and bathymetry of the water body, and the amplitudes of the oscillation depend on the magnitude of the exciting force and on friction.

8.8 Dam-Break Assessment

8.8.1 Potential for dam failure should be assessed against the DBGM determined specifically for the dam site determined using the same methodology corresponding to the hazard category of NF under consideration. If found necessary, the site should be evaluated for potential consequences arising from the seismically induced failure of the upstream and downstream dams (existing and proposed).

8.8.2 For numerical assessment of flood waves arising out of dam break scenarios, AERB guide on 'Design Basis Flood for Nuclear Power Plants on Inland Sites', AERB/NPP/SG/S-6A [12] may be referred to. Based on outcome of evaluation, mitigatory measures, as applicable, may be implemented.

8.8.3 The river courses could be blocked due to seismically induced landslides. Also, potential for flash floods due to failure of such structure should be given due consideration.

9.0 EVALUATION OF SEISMIC HAZARD FOR NUCLEAR INSTALLATIONS OTHER THAN HAZARD CATEGORY I FACILITIES

9.1 General

9.1.1 Evaluation of seismic hazard for nuclear facilities other than NPP can be performed following a graded approach. The hazard categorization of these facilities, based on their potential for radiological and other hazards is provided in AERB Safety Code on 'Site Evaluation of Nuclear Facilities', AERB/SC/S (Rev.1), Appendix 1 [1]. The level of investigation and seismic hazard evaluation of these facilities should be performed following a graded approach, in accordance with their respective categories.

9.1.2 Prior to categorizing an installation for the purpose of adopting a graded approach, a conservative screening process should be applied assuming that the entire radioactive inventory of the installation is released by the postulated initiating event, either due to internal or external events.

9.1.3 If the conservative screening process shows that the potential consequences of such releases from any facility would result in off-site, on-site or within plant boundary radiological impact, it should be categorized as Hazard Category I, II or III facility, respectively, and the mean annual frequency of exceedance as stipulated in AERB Safety Code on 'Site Evaluation of Nuclear Facilities', AERB/SC/S (Rev.1) [1], Appendix 1 should be used for estimation of DBGM and site related hazards. For other facilities/ structures not falling into above category, national seismic codes for hazardous and/or industrial facilities should be used.

9.2 Evaluation of Ground Motion

Hazard Category II Facilities

9.2.1 In case of nuclear facilities belonging to Hazard Category II, to the extent possible, seismotectonic investigation, modelling and characterization should be carried out in line with requirements specified for hazard category-I facilities. As a minimum, all published literature should be referred and assessed for estimation of DBGM.

9.2.2 Notwithstanding above, for Hazard Category II facilities located in Seismic Zone IV or V [2], site specific studies as required in section 3 and 4 should be conducted for intermediate region (50 km radius of facility). Uncertainty due to lack of site-specific investigations should be accounted for by appropriate methods (e.g. conservative assessment of magnitude, consideration of all seismotectonic features as active, and by range analysis of input parameters).

9.2.3 The design basis ground motion for these facilities can be evaluated using probabilistic method for specified annual frequency of exceedance [1]. In absence of detailed investigation, design basis input corresponding to maximum considered earthquake (MCE) as defined in [13] can be adopted.

9.2.4 For category-II facilities, the DBGM parameters shall not be less than half of S2 level DBGM parameters applicable for category-I facilities. In either case, as a minimum, design basis input corresponding to maximum credible earthquake (MCE) as defined in [13] should be used.

Hazard Category III and Other Facilities

9.2.5 For nuclear facilities other than Hazard Category I & II, ground motion definition should be in line with requirements specified in AERB safety code on 'Site Evaluation of Nuclear Facilities', AERB/SC/S (Rev.1), Appendix 1. Details on earthquake ground motion to be considered for such facility is given in Table 9.1 [1].

Table- 9.1 Details on earthquake ground motion to be considered for Hazard Category-III facility

Category	General Characteristics	Earthquake Ground Motion
III	Potential for radiological impact within plant boundary	DBE[3] using BIS 1893 (Part-4) with I=1.5 and R' = 2.0 (0.67 x Response reduction factor defined in IS 1893 for structures without any special provisions for seismic resistance).
	Potential for radiological impact within plant boundary and/or offsite chemical hazard	MCE[4] using BIS 1893 (Part-4) with I=1.5 and R' = 2.0 (0.67 x value of response reduction factor defined in BIS 1893 for structures without any special provisions for seismic resistance.)
General	Conventional or industrial buildings	DBE using BIS 1893 (Part-4) with I=1.0 and R' = 2.0 (0.67 x value of response reduction factor defined in BIS 1893).

[3] This scenario represents earthquake ground motion parameters corresponding to 10% exceedance in 50 years (i.e., return period of 475 years)

[4] This scenario represents earthquake ground motion parameters corresponding to 2% exceedance in 50 years (i.e., return period of 2475 years)

10.0 QUALITY ASSURANCE

10.1 General

10.1.1 A Quality Assurance (QA) program should be established and implemented for all the activities covered under this safety guide including data collection, data processing, and field and laboratory tests and investigations.

10.1.2 The study report on estimation of design basis ground motion and correlated hazards as well as supporting documents should be prepared in a manner and details that enables independent evaluation. A suggested format for report on seismic studies and estimation of DBGM is provided in Annexure I.

10.1.3 The QA program should be developed on the basis of the philosophy adopted in the AERB safety code on 'Quality Assurance for Safety in Nuclear Power Plants', AERB/NPP/SC/QA (Rev-1) [14] and applicable safety guides on quality assurance published by AERB.

REFERENCES

1. Atomic Energy Regulatory Board, Site Evaluation of Nuclear Facilities. AERB Safety Code No. AERB/NF/SC/S (Rev. 1), Mumbai, India, 2014.
2. Bureau of Indian Standards, Criteria for Earthquake Resistant Design of Structures: Part 1 General Provisions for All Structures and Specific Provisions for Buildings. BIS 1893, Part 1, New Delhi, India, 2016.
3. United States Nuclear Regulatory Commission, A Performance-Based Approach to define the Site-Specific Earthquake Ground Motion, RG 1.208, USNRC, USA, 2007.
4. Atomic Energy Regulatory Board, Geotechnical Aspects and Safety of Foundations for Buildings and Structures Important to Safety of Nuclear Power Plants. AERB Safety Guide No. AERB/NPP/SG/CSE-2, Mumbai, India, 2008.
5. International Atomic Energy Agency, Seismic Hazards in Site Evaluation for Nuclear Installations, IAEA SSG-9, IAEA, Vienna, 2010
6. Atomic Energy Regulatory Board, Seismic Qualification of Structures, Systems and Components of Pressurised Heavy Water Reactors. AERB Safety Guide No. AERB/NPP-PHWR/SG/D-23, Mumbai, India, 2009.
7. American Society of Civil Engineers, Seismic Analysis of Safety-related Nuclear Structures, ASCE/SEI-4, 2017
8. International Atomic Energy Agency, Meteorological and Hydrological Hazards in Site Evaluation for Nuclear Installations, IAEA SSG-18, IAEA, Vienna, 2011
9. United States Nuclear Regulatory Commission, Tsunami Hazard Assessment at Nuclear Power Plant Sites in the United States of America, NUREG/CR-6966, USNRC, USA, 2009.
10. Okada, Y. (1985), “Surface deformation due to shear and tensile faults in a half-space.” Bulletin of Seismological Society of America, 75(4), 1135-1154.
11. Burbidge, D., Cummins, P. R., Mleczko, R., and Thio, H. K. (2008), “A probabilistic Tsunami Hazard Assessment for Western Australia.” Pure and Applied Geophysics, 165, 2059-2088.
12. Atomic Energy Regulatory Board, Design Basis Flood for Nuclear Power Plants on Inland Sites. AERB Safety Guide No. AERB/NPP/SG/S-6A, Mumbai, India, 1998.
13. Bureau of Indian Standards, Criteria for Earthquake Resistant Design of Structures: Part 4 Industrial structures including Stack like structures. BIS 1893, Part 4, New Delhi, India, 2015.
14. Atomic Energy Regulatory Board, Quality Assurance in Nuclear Power Plants. AERB Safety Code No. AERB/NPP/SC/QA (Rev-1), Mumbai, India, 2009.

15. U.S. Nuclear Regulatory Commission, SRP 3.7.2, Seismic System Analysis, Washington, USA, 2013.

16. International Atomic Energy Agency, Earthquake Preparedness and Response for Nuclear Power Plants, Safety Reports Series No. 66, IAEA, Vienna (2011).

17. American Nuclear Society, Criteria for Investigations of Nuclear Facility Sites for Seismic Hazard Assessments. ANS Standard, ANSI/ANS-2.27-2008, Illinois, USA, 2008.

18. Atomic Energy Regulatory Board, Design of Light Water Reactor Based Nuclear Power Plants. AERB Safety Code No. AERB/ NPP-LWR/SC/D, Mumbai, India, 2015.

BIBLIOGRAPHY

Completeness Check of Earthquake Catalogue

1. Stepp, J. (1973). Analysis of completeness of the earthquake sample in the puget sound area. Technical report, NOAA Tech. Report ERL 267-ESL30, Boulder, Colorado.

2. Tinti, S. and F. Mulargia, Completeness analysis of a seismic catalog. In Annales geophysicae (1983), volume 3, 1985.

Estimation of Mmax

3. R. L. Wheeler, (2009), "Methods of Mmax Estimation East of the Rocky Mountains", USGS open file report 2009-1018.

Expert Elicitation

4. Budnitz, R.J., G. Apostolakis, D.M. Boore, L.S. Cluff, K.J. Coppersmith, C.A. Cornell and P.A. Morris: Senior Seismic Hazard Analysis Committee (SSHAC), "Recommendations for Probabilistic Seismic Hazard Analysis: Guidance on Uncertainty and Use of Experts", NUREG/CR-6372, Volumes 1 and 2, 1997.

5. Kammerer, A.M. and J.P. Ake, "Practical Implementation Guidelines for SSHAC Level 3 and 4 Hazard Studies", NUREG-2117 Revision 1, 2012.

Fault Displacement Hazard

6. International Atomic Energy Agency, Ground Motion Simulation Based on Fault Rupture Modelling for Seismic Hazard Assessment in Site Evaluation for Nuclear Installations, IAEA Safety Standards Series No. 85, IAEA (2015).

Fault Directivity effects

7. Dabaghi, Mayssa. Stochastic modeling and simulation of near-fault ground motions for performance-based earthquake engineering. Diss. UC Berkeley, 2014.

Ground Motion Prediction Equations

8. Ground motion prediction equations 1964-2018; John Douglas, Department of Civil and Environmental Engineering, University of Strathclyde; April, 2018.

Induced Seismicity

9. Gupta, I.D. and V.J. Shende (2003).RIS potential of some important reservoirs in Peninsular India - A statistical estimation, Procs.National Confs. On Hydraulics and Water Resources, HYDRO-2003, 416-420.

10. Jaiswal, K. and R. Sinha (2007).Probabilistic seismic hazard estimation for Peninsular India, Bull.Seism. Soc. Am., Vol. 97 (1B), 318-330.

11. Baker, J.W. and A. Gupta (2016). Bayesian Treatment of Induced Seismicity in Probabilistic Seismic-Hazard Analysis, Bulletin of the Seismological Society of America, Vol. 106, No. 3, pp. 860–870, doi: 10.1785/0120150258 .

Tsunami Fault Deformation

12. Okada, Y. (1985). “Surface deformation due to shear and tensile faults in a half-space.” Bulletin of Seismological Society of America, 75(4), 1135-1154.

13. Mansinha L and Smylie D. E. (1971). “The displacement fields of inclined faults.” Bulletin of Seismological Society of America, 61(5), 1433-1440.

Unit Source Method for PTHA

14. Burbidge, D., Cummins, P. R., Mleczko, R., and Thio, H. K. (2008). “A probabilistic Tsunami Hazard Assessment for Western Australia.” Pure and Applied Geophysics, 165, 2059-2088.

15. Burbidge, D.R, Cummins P.R, Mleczko R, Latief H, Mokhtari M, Natawidjaja D, Rajendran C.P and Thomas C. (2009). “A Probabilistic Tsunami Hazard Assessment of the Indian Ocean Nations”, Geoscience Australia Professional Opinion. No.2009/11

16. Hoechner, A., Babeyko, A. Y., and Zamora, N. (2015). “Probabilistic tsunami hazard assessment for the Makran region with focus on maximum magnitude assumption.” Natural Hazards and Earth System Science, 5191–5208.

Probabilistic Seismic Hazard Analysis

17. McGuire, R K. Seismic Hazard and Risk Analysis. Earthquake Engineering Research Institute, USA 2004.

18. US Army Corps of Engineers, Response Spectra and Seismic Analysis for Concrete Hydraulic Structures, EM 1110-2-6050, (1999).

Site Response Analysis

19. Kramer, Steven L. Geotechnical Earthquake Engineering. Prentice-Hall, New Jersey, USA (1996).

Appendix A：SITE RESPONSE ANALYSIS FOR GROUND MOTION EVALUATION AT SOIL SITES

A.1. General

A.1.1 The Design Basis Ground Motion (DBGM) should correspond to the free field or the hypothetical outcrop corresponding to foundation level. For soil sites, a site specific wave propagation analysis should be performed. Generally, the input ground motion used in the analyses are specified based on GMPEs, which assume that an outcrop exists at the free-field surface. If required, this input may be converted to within layer motion for site response analysis. The following procedure should be adopted for the site specific amplification or de-amplification analysis:

a. Conduct required field investigations including boreholes to establish strata characteristics including its dynamic behavior
b. Develop the site-specific soil profile
c. Develop appropriate modified earthquake time histories to be used in site response analysis
d. Perform a suit of site response analysis to determine mean site amplification function for a range of frequencies
e. Develop the spectra at the free ground surface based on the outcrop based PSHA and mean site amplification functions

A.1.2 For direct generation of hazard curves at free field, the amplification or de-amplification characteristics should be developed for various levels of ground motions ranging from those causing very small strain to those consistent with higher strain level anticipated in the design basis ground motion. For first order estimates, site amplification evaluation based on empirical function should be conducted.

A.2. Development of Site-Specific Soil Profile

A.2.1 The static and dynamic engineering properties of soil and rock and their spatial distribution should be established through field and laboratory investigations. The seismic wave propagation characteristics of the materials overlying bedrock at the site should be described over a range of frequencies that include the significant structural frequencies. For each soil layer, the following material properties should be established through in situ or laboratory investigations:

a. Thickness of soil layer and their spatial variation
b. Compressional and shear wave velocity
c. Soil density
d. Soil index properties and classification
e. Variation of shear modulus and damping with respect to strain level and associated dispersion/ uncertainty in evaluation parameters

f. Water table elevation and its variation throughout the site
g. Bedrock material properties
h. Internal friction angle, cohesive strength and over-consolidation ratio for clay

A.3. Site Response Analysis

A.3.1 The strain-dependent shear modulus and damping curves should be developed based on site-specific test results. A statistically significant number of tests should be performed for establishing strain-dependent shear modulus and damping curves and associated dispersion. The processing of test results for development of these curves should be conducted as per state-of-the-art practice. In case of sparse test numbers, as a minimum, dispersion as reported in appropriate literature on soil dynamic models need to be considered for establishing standard deviation of the curves. These variability in the soil properties should be accounted for in site response analyses by considering a range of input parameters. Special attention should be given to damping values estimated at very low and very high shear strains and to ensure its compatibility with shear modulus reduction curves. The effect of confining pressures (reflecting effect of overburden) on these strain-dependent soil dynamic characteristics should be assessed and considered in site response analyses.

A.3.2 Due to the nonlinear nature of site response, the choice of input ground motion has a significant impact on the amplification of motion observed in the soil column. Hence, recorded earthquake time histories selected and modified based on DSHA/ PSHA results should be used for Site Response Analysis (SRA). In such cases, sufficient number of input motions should be considered for SRA to establish variability in amplification function. In addition, the spectra of these time histories should be compared with fundamental frequency of soil to ensure that the spectra has sufficient energy content at the natural frequency of the site.

A.3.3 If the recorded earthquake time histories are not available, spectra compatible accelerograms with significant strong motion duration may be used for SRA. These accelerograms generated from base rock spectra should be in line with compatibility and duration criteria provided in AERB Safety Guide on 'Seismic Qualification of Structures, Systems and Components of Pressurised Heavy Water Reactors', AERB/NPP-PHWR/NPP-PHWR/SG/D-23 [6].

A.3.4 The fundamental frequency of the site can be approximated prior to analysis using simplified methods. In the case of analysis using equivalent linear frequency domain method, strain level up to which the method is valid should be established. Similarly, for analysis using nonlinear time domain method, input time history should have a sufficiently small time increment and material models should be compatible with strain dependent shear modulus and damping curves. The spatial discretization of domain should be selected based on the maximum frequency of interest. In case of sites with available instrumented data, the method used for site amplification study should be validated using observed free field motions.

A.3.5 Heterogeneity of the soil should be captured appropriately by using randomized variations in soil depth, shear wave velocity, layer thickness, and strain dependent non-linear material properties. Randomization of soil properties should be guided by the actual field investigation data collected, and the number of randomizations should be commensurate with the amount of data collected and its variability. It should be ensured that the number of randomizations considered for each soil parameter is statistically adequate and sufficient to represent the considered probability density function of the variables. As a minimum, 60 randomizations per soil profile should be considered. The variation in shear modulus and damping curves may be taken in a paired manner (i.e. higher G-γ curve may correspond to lower D-γ curve and vice-versa.).

A.3.6 Based on the randomized profiles and properties, the Best Estimate [BE], Lower Bound [LB] and Upper Bound [UB] iterated site properties shall be established for use in soil structure interaction analyses. The best estimate properties are determined from the mean of the resulting properties and the UB and LB values selected from the +/- one sigma values. In no case should the LB shear modulus be less than that value consistent with standard foundation analysis that yields foundation settlement under static loads exceeding design allowable. The UB shear modulus should not be less than the BE shear modulus defined at low strain and as determined from the geophysical testing program. In no case should the soil material damping as expressed by the hysteretic damping ratio exceed 15 percent [15]. Using the Foundation Input Response Spectra (FIRS) as input to each of the deterministic soil profiles, the envelope of the computed response spectra at the ground surface should be shown to equal or exceed the mean spectra at the surface at all frequencies of interest.

Appendix B : PRE AND POST EARTHQUAKE ACTIONS

B.1. General

B.1.1 This appendix provides guidance on approaches to be adopted for pre-earthquake preparedness and post-earthquake actions. For further guidance IAEA safety standard series 66 [16] may be referred. Though, guidance in this section is oriented towards Hazard category-I facilities (as per AERB/NF/SC/S Rev.1 [1]) and NPPs in particular, the provisions may be applied to other lower hazard category facilities following a graded approach.

B.1.2 In case of an earthquake greater than the exceedance criteria set for the facility, the NF shall be shut down. Restart of the NF shall be after inspection, evaluation and approval by AERB.

B.2. Exceedance levels of ground motion

B.2.1 Evaluation of ground motion exceedance should be based on data from free field instrumentation. For immediate action following an earthquake, free field PGA may be used as a basis. However, detailed evaluation and subsequent restart of the plant should be based on complete evaluation of response spectra. For hazard category-I facilities, levels to be considered are:

a. Level 1: Instrumental records indicate non exceedance of S1 level ground motion
b. Level 2: Instrumental records indicate exceedance of S1 level ground motion and non exceedance of S2 level ground motion
c. Level 3: Instrumental records indicate exceedance of S2 level ground motion

B.2.2. For NFs with only one defined level of earthquake input (hazard category II & III), related Levels will be:

a. Level 1: Instrumental records indicate non exceedance of 1/3rd of design earthquake level
b. Level 2: Instrumental records indicate exceedance of 1/3rd of design earthquake level and non exceedance of design earthquake level
c. Level 3: Instrumental records indicate exceedance of design earthquake level

B.2.3 Facility should prepare specific procedures bringing out post-earthquake actions considering three Levels, as applicable.

B.3. Pre-earthquake Actions

B.3.1 Before start of operation of facility, the earthquake exceedance criteria (to be used in decision making for shutdown and restart corresponding to design basis ground motion of facility) along with applicable seismic instrumentation should be established based on the approved DBGM parameters for the site and different levels mentioned in previous section. The calibration standards, if any, required for the seismic instrumentation, computer software and record analysers should be prepared in advance so as to enable the engineering assessments to be performed within a reasonable time frame, for example, within eight hours of the occurrence of an earthquake.

B.3.2 To perform the post-earthquake safety assessment of SSCs including evaluation of in-structure response in a timely fashion, the dynamic models of the SSCs of interest reflecting 'as is' conditions of the NF should be readily available and executable in computer software currently available to the responsible engineering staff.

B.3.3 A record collection log should be maintained at the plant, and all data should be identifiable and traceable with respect to:

a. The date and time of collection
b. The make, model, serial number, location, and orientation of the instrument (sensor) from which the record was collected.

B.3.4 Only competent personnel should be allowed to collect the data and this activity should be planned and performed in accordance with established procedures. During data collection, caution should be exercised to prevent accidental damage to the recording media and instruments.

B.3.5 In the event of plant experiencing an earthquake which caused triggering of seismic instrumentation, a quick survey of the various SSCs (safety related as well as non-safety related) is required to be carried out. For this initial post-earthquake inspections which allows to generate a preliminary understanding of earthquake impact, facility in consultation with designer and AERB should prepare a pre-selected set of SSCs, encompassing the SSCs of interest based on characteristics such as the number of like components, location, vulnerability to damage due to earthquake motion, accessibility after the earthquake and other considerations.

B.3.6 The pre-selected SSCs should be chosen to be representative of SSCs important to safety and also include SSCs that experience has shown to most likely be damaged during an earthquake. The SSCs selected should also include typical items not important to safety, which experience has shown to be of low seismic capacity: these items may be damage indicators that will assist experienced seismic engineers in evaluating the state of the plant.

B.3.7 The set of pre-selected SSCs identified for pre-earthquake actions should also be baseline inspected as part of periodic inspections and their 'as is' properties documented. The seismic design/ qualification information for the SSCs should also be available so as to be conveniently accessed if an earthquake occurs.

B.3.8 Periodic inspections of the items selected for post-earthquake shutdown inspections also should be performed to identify and document any changes in the condition of the pre-selected items. Any significant cracks in reinforced concrete structures are to be included and documented in the baseline inspections so that their condition after an earthquake can be properly evaluated.

B.4. Post-earthquake Actions

B.4.1 A well-documented procedure should be prepared for post-earthquake action plan based on the guidelines given in this section. Post-earthquake event, as part of immediate actions, visual inspections should be performed of all SSCs that are selected for post-earthquake inspections, and the results of the inspections documented in written reports, including sketches and photographs of abnormalities as appropriate. During collection of data from seismic instruments in the post-earthquake event, instrument specific report also should contain condition of the instrument and its installation, for example, instrument flooded, mounting surface tilted, or objects that fell and struck the instrument or the instrument mounting surface, etc. Records should be analyzed according to the manufacturer's specifications and the results of the analysis should be evaluated. Any record anomalies, invalid data, and non-pertinent signals should be noted, along with any known causes. Outcome of evaluation of data collected from seismic instrumentation should be reported along with the inputs, as applicable used during the design stage.

B.4.2 In response spectrum, comparison with design should be based on 5% damped spectra. The three components of recorded free field ground motion should be used for comparison with corresponding design inputs. For this purpose, the response spectral ordinates should be checked at frequencies for which design basis spectra has been defined covering the entire frequency range of the spectra. The response spectra for motions recorded on the foundations and in-structure also should be used for purposes of additional comparison and generation of information on structure wise and elevation wise performance of SSCs.

B.4.3 In case of Level-3 exceedance as given in section B.2, need to separate Level 3 further into Levels 3a, 3b and 3c according to the frequency characteristics of the ground motion, i.e. exceedance in high frequency region only, exceedance in mid-amplified frequency range and exceedance in low frequency range; may be examined. This classification may be used for detailed examination of damage that could be generated by ground motion. The sub-categorization into Levels 3a, 3b and 3c is intended to allow for identification and refinement of short term and long term actions which are also dependent on the ground motion frequency characteristics with respect to the soil-structure system frequencies. If exceedance occurs in multiple frequency ranges, it should be properly taken into account and corresponding response actions should be controlled by the segment that requires maximum assessment.

B.4.4 In general, exceedance only in high frequency range (Level 3a) is expected to have minimal adverse effects on NPPs and other industrial facilities. Thus, significantly fewer post-earthquake actions may be required for Level 3a; fewer post-earthquake actions may be needed for Level 3c; but continued extensive evaluations are required for Level 3b. In general, the specific frequency ranges defining Levels 3a, 3b and 3c are dependent on the dynamic characteristics of the SSCs and Level 3b requires extensive evaluations. If such a classification is planned to be used for a particular facility, the classification along with applicable frequency ranges would require prior approval from the AERB. In absence of any guidance, frequency range of 1-10 Hz may be considered as applicable range for Level 3b.

B.4.5 Additional safety analyses and investigations commensurate with the level of exceedance and addressing review observations by AERB should also be conducted as part of post-earthquake event assessment. In performing visual inspections associated with the post-earthquake inspections, it is important to keep in mind the possibility of the existence of 'hidden damage', i.e., damage to the SSCs that cannot be identified visually. Other approaches (e.g. non-destructive examinations) should be adopted to identify the possibility of hidden damage. Damage due to earthquake does not follow a standard pattern and surprises are expected. Investigation, as it progresses, is expected to point to further course of action. The post-earthquake actions should also include assessment of the terrain surrounding the NF site, including geodetic measurements, slope stability, etc.

B.4.6 Immediate actions following an earthquake of different levels for different category facilities is given in Table B-1.

Table B-1: Immediate actions following an earthquake

<table>
<tr><th></th><th>Level 1</th><th>Level 2</th><th>Level 3</th></tr>
<tr><td>CAT-I[#]</td><td>EL[*] < S1</td><td>S1 <= EL < S2</td><td>EL >= S2</td></tr>
<tr><td>CAT-II&III[#]</td><td>EL < DBE/3</td><td>DBE/3 <= EL < DBE</td><td>EL >= DBE</td></tr>
<tr><td rowspan="4">Immediate Actions</td><td colspan="3">1 - Processing of recorded motion and determination of ground motion parameters like PGA, spectral acceleration, etc. from in-structure as well as on site instrumentation and collection of earthquake parameters like magnitude, location of epicenter, etc.
2 - Assessment of exceedance or non-exceedance of S1 or S2 levels</td></tr>
<tr><td rowspan="3">General walk down of the facility for any visual sign of damage</td><td>Implementation of action plan according to earthquake level.</td><td>Implementation of action plan according to earthquake level</td></tr>
<tr><td>Initial focused visual Inspection of all SSCs that are selected for post-earthquake as per section B.3 and conduct further post-earthquake assessment as per section B.4.</td><td>Initial focused visual Inspection of all SSCs that are selected for post-earthquake as per Section B.3.
Identify the frequency range where the free-field earthquake level is exceeded above S2 level ground motion and conduct further post-earthquake assessment as per section B.4.</td></tr>
<tr><td>Restart of the plant after approval of AERB</td><td>Restart of the plant after approval of AERB</td></tr>
</table>

Hazard categorization of the facility

* Exceedance of spectral ordinates at any or set of frequencies including PGA

Appendix C : MICROEARTHQUAKE SURVEY

C.1. General

C.1.1 Comprehensive assessment of local seismicity and seismotectonics in the region of a NF shall be ensured on a continuous basis. This can be accomplished by uninterrupted monitoring of seismic activity in the vicinity of the NF site by means of continuously operating a microearthquake network.

C.1.2 Generally, Microearthquakes (MEQs) are referred to as local earthquakes of magnitude not exceeding 3.0 M_w. Such weak tremors have low intensity, and normally ground vibrations produced by them are neither felt by human beings, nor are their strength adequate to cause damage to surface structures. MEQs can be detected only by sensitive seismometers.

C.1.3 MEQ networks help in the investigation of earthquake source zones / active faults and geodynamical behavior of a given region. The objectives of the MEQ network are to:

c. Identify both seismogenic sources and active/ capable faults and to determine their potential for generating larger earthquakes;
d. Provide confirmatory evidence of the presence (or the absence) of potentially active geological faults along with their depth wise extension, which may not have perceptible surface expressions or reveal such details while examining pertinent imageries of lineaments;
e. Evaluate fault plane solutions of the events (with magnitude more than 2.0) by waveform inversion;
f. Investigate the characteristics of seismic sources and obtain preliminary estimate of b-value of the Gutenberg-Richter (GR) frequency-magnitude relation to examine its temporal variation which provides earthquake precursory diagnostics;
g. Enhance understanding of seismic wave attenuation model in the region and evaluate energy transfer function at a given location to predict intensity of ground motion at that location due to a local earthquake;
h. Progressively supplement and update seismological information available from historical records and regional catalogues of earthquakes;
i. Acquire data to periodically review seismic evaluation of the site that may have been carried out using some macroseismic data during the early phases of site evaluation;
j. Model structural response to lend support to what is constructed using strong motion accelerograph data obtained largely from historic records;
k. Analyse the homogeneity (or the heterogeneity) of the region from the status of stress distribution using foreshock-aftershock patterns obtained from microearthquake data;
l. Keep vigil (seismic surveillance) on any abnormal seismic activity indicating either sudden increase or decrease in it which has a bearing on a future earthquake impending in the region;
m. Provide valuable inputs required for the estimation of seismic hazard in the region followed by periodic assessment of seismic hazard; and

n. Analyse the problem of “floating earthquake” (an earthquake which cannot be associated with any known lineament but is considered for the purpose of aseismic design a probable earthquake that is likely to occur anywhere within the region of interest) to verify if there is a definite pattern of seismic activity in the neighbourhood of the epicenter of the floating event.

o. For characterization of site response, the above MEQ instruments can be used for ambient noise survey in the site area. Close spaced (say 100 m) ambient noise records in the site area (say 1 km x 1 km) can provide the site characteristics in terms of amplification factor of the ground soil and its predominant frequency (PF). This can help design of the project in the site. The MEQ instruments in vertical arrays in a borehole can also be used for the site response at depth (say at bed rock depth), if required.

C.2. Establishment of a Typical Microearthquake (MEQ) Network

C.2.1 The seismograph field stations should be placed within a radial distance of 30 km from the NPP with one seismometer at a suitable location within NPP site. The inter-station spacing should have a fair uniform distribution of stations with the NPP as reference point. Although, a minimum of three stations are required to locate seismic sources, at least five to seven station network should be established for redundancy. Larger network (say, ten station networks) covering bigger area around the NPP site with better azimuthal coverage would help to determine the hypocentral parameters more precisely. In any case, number of stations should not be less than five. The geometry of the network can be finalized by a theoretical exercise involving simulation of observing stations and hypothetical seismic sources and iteratively evaluating network response until the desired accuracy is achieved of location of those sources that lie within the outermost boundary of the net. But, focal depth is better constrained if one or two stations are much close to the epicenter and some reliable S-phase data are used for hypocenter location of the earthquake. As a minimum the network should be capable of recording Micro earthquakes, Mw >= 1.0.

C.2.2 The locations of stations should be such that the background noise is minimum. Typically, a site with 5 nanometers peak displacement at 1 Hz due to the background noise is considered to be a reasonably quiet site, ideal for establishing an MEQ station. In this respect, the stations should be sited far away from all cultural sources of noise, such as airfield, rail tracks, highways, agricultural fields, thick forest with tall trees, crowded human settlements, large water bodies, heavy machine industry, and stone quarries etc. At the same time, a site has to be accessible for routine maintenance.

C.2.3 The seismic stations should be selected on hard rocks or strata composed of reasonably well consolidated materials (or bedrock) at 1-2 meters depth at which seismic sensor (seismometer) can be placed with Plaster of Paris to achieve proper coupling with the hard rock/ bedrock. In regions of thick alluvial sediments, precast RC pits should be constructed for sensor installation. The sensor is placed on a concrete plinth constructed on the rocky base of the pit excavating the top soil down to a depth of 5 – 10m and enclosed in a vault with water-tight lid and proper drainage for surface water flow. Installation of broadband sensor would require specially constructed thermally insulated vault grouted over bedrock. The instruments should be rugged, compact and transportable over rough terrain by vehicle, and be able to withstand extremes of humidity, dust, temperature and waterproof.

C.2.4 At least one seismograph should be provided at NPP site. All the field stations should have battery backup.

C.3. Sequential Steps for Microearthquake Survey

C.3.1 The seismic monitoring should be started well (say, three to five years) before the construction of a hazard category I nuclear facility and should continue monitoring throughout the operating life of the plant.

C.3.2 With the help of detailed topo sheets, road maps and other relevant maps, a reconnaissance survey should be conducted to examine logistics before establishing a MEQ network. This should be followed by, instrumental survey to ensure line of sight between proposed control center and each field station, if applicable (say, telemetric network), and actual measurement of background noise to ensure suitability (remoteness from sources of background high frequency noise that interferes with the detection of microearthquake signals).

C.3.4 Considering the objectives listed in Section C.1, the data collected should be processed and analyzed using standard techniques and tools by competent personnel (seismologist) within specified timeframe.

Appendix D : STRONG MOTION SEISMIC INSTRUMENTATION

D.1. General

D.1.1 Strong motion seismic instrument (accelerometer) should be deployed at the NPP site to study ground acceleration during earthquakes and to compare the same with that used as the design basis. The comparison should be made for deciding amongst other things: (i) whether the NPP can continue to be operated safely and to permit such other timely action as may be appropriate, and (ii) whether the mathematical models are applicable, which are used in the seismic analysis of NPP and equipment.

D.2. Instrumentation

The following instrumentation should be deployed:

a. Triaxial acceleration sensors or accelerographs (which record time history of acceleration during earthquakes), which are self-contained instruments (accelerographs) or acceleration sensors with the data transmitted to remote control recorders
b. Seismic Switches (SS), which provide inputs on specified values of the earthquake design parameters to take instantaneous action to deal with the situation. In general, these instruments should be deployed at several locations for better assessment of exceedance.

D.3. Selection and actuation criteria of Instruments

D.3.1 The choice of instruments of each category should be done by plant design engineer, seismologist and instrumentation specialist, who should jointly select relevant and proper instrumentation with suitable dynamic range, trigger level, frequency band, damping, recording speed, recording duration, pre-event memory, etc., needed to specially assess acceleration time history, and structural response, specific to seismic environment and structural features of the NPP. The following general recommendations are made for seismic instrumentation at NPP:

a. Preference may be given for central recording. Provision for remote access and download of data should also be available
b. The trigger level should not exceed 0.01g. A lower value of trigger level can be used based on the judgment of the designer. The actuation of trigger in any direction should initiate sensors in all directions. Also, it is recommended that the initiation of recording in one instrument kept at free field, containment foundation or foundation of the seismic category I structure, should actuate all other strong motion instrumentation provided in the plant

c. Specified actuation level of acceleration for seismic switch for the purpose of alarm should not be more than 50 % of expected peak ground acceleration (PGA) of S1 level ground motion up to a maximum of 0.1 g at any site
d. Upon actuation of seismic switch, a remote indicator alarm in the control room, should be activated and manual/automatic actions as per corresponding Standard Operating Procedures (SOPs) should be followed
e. Instruments should be rugged, compact, waterproof, and should be able to withstand extremes of humidity, dust, temperature and other conditions expected during normal operation of NPP

D.4. Installation of Instruments

D.4.1 The instrument stations should be firmly anchored and should be accessible for periodic servicing. Triaxial instruments in an instrument station should be oriented so that one horizontal axis component is parallel to the major horizontal axis assumed in the seismic analysis.

D.5. Maintenance of Instruments

D.5.1 The NPP should have a periodic maintenance programme to ensure that the instruments perform as required. Technical and testing procedures should be defined and documented in advance and updated periodically. It should be ensured that minimum number of instruments, as specified by designer, are in operation during all plant states.

D.5.2 Maintenance procedures should be preplanned and performed in accordance with documented instructions or drawings appropriate to the instrument. Periodic channel checks, functional tests and calibration should be performed to provide data for evaluating instrumental status and effectiveness of the maintenance programme. Records of maintenance data should be established and maintained for each seismic instrument, and should include calibration data, operational status, recommendations for follow up work and certification of person who performed the work.

D.5.3 Items that have specified lifetime and have been found to be defective, should be immediately replaced. Maintenance records and operational status of the instruments should be reviewed at the appropriate administrative level of the NPP periodically to maintain maximum effectiveness of the seismic instruments.

D.6. Location and Number of Seismic Instruments

A. Requirement for NPPs

D.6.1 Choice of locations and number of seismic instruments at NPP and their installations, should be made by the plant design engineer, seismologist and instrumentation specialist who jointly should select proper locations and install various instruments mentioned in Section D.2, so that maximum information about free field ground motion and response of the NPP are obtained through optimum installation. However, as a minimum, the following recommendations for installations are made:

a. Digital tri-axial time-history accelerographs should be installed at appropriate locations in free field, containment and other seismic category I structure. They should be located such that the output can be compared with design basis, i.e. they should be oriented such that one horizontal axis component is parallel to the major horizontal axis considered in the analysis
b. Plan views and vertical sections showing the location of each seismic instrument and the orientation of the instrument components with respect to plant reference axes should be prepared. Moreover, the mandatory locations are:
   (i) Free-field
   (ii) Containment foundation
   (iii) Two elevations (excluding the foundation) on a structure inside the containment
   (iv) An independent Seismic Category I structure foundation where the response is different from that of the containment structure
   (v) At an elevation on independent Seismic Category I structure selected above

In case isolators are used, the instrumentation should be placed on both the rigid and isolated portions of the same or on an adjacent structure as appropriate at approximately at the same elevations. Additional installation should be made, if considered necessary during safety review.

c. The additional instrumentation required at soil sites are:
   Through instrumentation in borehole, the soil sites should have provisions for measurement of wave modification across depth for evaluation of wave amplification across soil strata and assessment of impact on sub-structures. The number of boreholes, depth of boreholes, type and spacing of instruments, etc., are site dependent and should be based on inputs from plant design engineer, geotechnical engineer, seismologist and instrumentation specialist

B. Nuclear Facilities other than NPPs

For hazard category-I facility other than NPP and category-II and III facilities, unless required otherwise, at least one strong motion instrument shall be deployed at free field.

D.7. Quality Assurance in Instrumentation

The NFs are required to keep the following information related to the seismic instrumentation:

D.7.1 Information of the Instrumentation: Information on each instrument type including requirements, e.g., for maintenance, operation, or installation, details about the location of each instrument in the structure and the orientation of its components with respect to plant reference axes

D.7.2 Maintenance history of the Instrumentation: The service and testing interval for each instrument should be decided based upon the information obtained from manufacturer and behavior of the surrounding environment. The testing and calibration of these instruments should be done at least once in a year. The healthiness of the communication and electrical cables used and the joints provided in the system should be tested more frequently than the testing interval of the instrument itself; and

D.7.3 Manufacturer's calibration standard should be available. If required, personnel should be identified and trained for maintenance, calibration of the instruments and data collection.

D.7.4 The seismic instrumentation should be operated at all times including the shutdown conditions.

D.8. Processing of Acceleration Records

The following should be undertaken:

1) Identification of earthquake events

   A collection log should be maintained at the plant, and all events should be identifiable and traceable with respect to the date and time of collection, and make/ model.

2) Collection of Records

   The following should be ensured:

   a. Only competent personnel in the operation of the instrument should collect the acceleration data
   b. The steps for removing and storing records from each seismic instrument should be planned and performed in accordance with established procedures
   c. Extreme caution should be exercised to prevent accidental damage to the recording media and instruments during data collection and subsequent handling
   d. Notes should be made regarding the condition of the instrument and its installation during inspection
   e. If the instrument's operation appears to have been normal, the instrument should remain in service without readjustment or change

3) Evaluation of Records

   Records should be analyzed according to the manufacturer's specifications and the results of the analysis should be evaluated. Any record anomalies, invalid data, and non-pertinent signals should be noted, along with any known causes.

Appendix B may be referred to for further guidance on post-earthquake actions.

Appendix E : FIELD INVESTIGATIONS

E.1. General

E.1.1 The geological and geophysical investigations shall be carried out to develop the database on following aspects pertaining to seismic studies as discussed in this Guide:

1) Subsurface characteristics, stratigraphy and lithology, depth to bedrock, ground water level, shallow cavities, etc.
2) Rock mass properties, shear and compressive wave velocities, engineering properties of rock materials, etc.
3) Geological features, faults, folds, joints, shear zones, dykes, buried channel, etc.

E.1.2 In general, seismic sources should be identified and characterized based on available information on location, activity, length, dip, depth style, and area of fault rupture. Different methods may be included but not limited to:

1) Geological/ remote sensing methods: Detailed mapping, Geomorphic information, Quaternary surface rupture, Fault trenching information, Paleo-liquefaction information, Borehole information, Aerial photography, Low sun-angle photography, Satellite imagery, Digital elevation model (DEM), Regional structure, and Balanced cross section

2) Geophysical/ geodetic methods: Regional potential field information, Local potential field information, High-resolution refraction information, Standard reflection information, Deep crustal reflection information, Tectonic geodetic/strain information, and Regional stress information

3) Seismological methods: Reflected crustal phase information, Pre-instrumental earthquake information, Tele-seismic earthquake information, Regional network seismicity information, Local network seismicity information, Focal mechanism information, etc. If an event occurs within the seismic network, and if the P-phases are well read and at least a few S-phases are fairly well read then the epicenter and depth estimates are much reliable. If an event, however, occurs outside the network, say with an epicentral distance to the nearest station less than twice the seismic-station spacing, then the hypocenter location (i.e. epicenter and depth) may be acceptable if located within an error limit, say < 10 km, in the region beyond 50 km radius of the site. On the other hand, to understand the seismogenic sources in the 50 km radius (Intermediate) region, the hypocenter locations need to be within an error $\pm$ 5 km

E.1.3 The geological and geophysical investigations when used judiciously can give detailed subsurface information within a very short span of time. It is important and necessary to corroborate geophysical results with that from a few boreholes in the area and any discrepancies could be remedied through modified techniques.

E.1.4 Subsurface investigations are helpful in providing definitive information on fault location and fault behavior and should be conducted as needed to identify and characterize faults that could contribute to ground motion or fault displacement hazard at the site. Subsurface investigations may include exploratory trenching, large and small-diameter boreholes, and geophysical profiling. Boreholes are drilled to define depth and type of bedrock and thickness and properties of subsurface layers.

E.1.5 Site-specific geophysical studies e.g., seismic reflection and refraction surveys for profiling of subsurface layers at various depth intervals, ground-penetrating radar, magnetic surveys, and other types of electromagnetic surveys can be used to identify and characterize faults, folds, or fault-related deposits in the subsurface that do not exhibit substantial ground disturbance. Information derived from these profiles can be used for deciding specific locations for exploratory trenching. Sites for trenching should be selected after preliminary geological observation and mapping. For information on general data types and their primary applications for identifying and characterizing tectonic sources, information covered in American Nuclear Society document, ANS-2.27 (2008) [17] may also be referred to.

E.2. Geological/ Geophysical Investigations

Some of the suggested methods for the investigations are briefly described below. These methods could be used for both reconnaissance and intensive exploration purposes.

E.2.1. Geophysical methods

Geophysical methods that can be considered for exploration purposes include:

(i) Seismic refraction method
(ii) Seismic reflection method
(iii) Electrical resistivity method
(iv) Magnetic method
(v) Magnetotelluric (MT) method
(vi) Borehole logging method
(vii) Cross-hole method
(viii) Gravity method
(ix) Microtremor method
(x) Radon Measurements
(xi) Very Low Frequency Electromagnetic (VLFEM) Method
(xii) Time-domain Electromagnetic (TDEM)
(xiii) Multichannel Analysis of Surface Waves (MASW)
(xiv) Ground Penetrating Radar (GPR)

E.2.2. Investigations on Ground Water

Investigations should be undertaken to ascertain the ground water conditions in local area (covering a radial distance of 10 km) surrounding the site. These should include well inventory and resistivity surveys.

E.2.3. Boreholes

The lithology and structure of site area should be thoroughly evaluated on the basis of grid-drilling to a depth of at least 100 meters. Depth should also follow guidance provided in AERB Safety Guide on ‘Geotechnical Aspects and Safety of Foundation for Buildings and Structures Important to Safety of Nuclear Power Plants’ AERB/NPP/SG/CSE-2 [4]. After evaluating these borehole information it may be necessary to drill a few deeper drill holes (up to seismic bedrock). Lithologic logs will be prepared and evaluated. Particular attention will be directed to identify possible fault gouge and/or clay horizons, etc. and karsts or other cavities, as these would require special attention while planning construction.

E.3. Geodetic Measurements/ Investigations

E.3.1 The geodetic measurements complement other geophysical studies by providing data on a continuous basis for ascertaining the seismic status of the site identifying anomalous precursory crustal movements, strain accumulation and gravity variations. Geodetic investigations may be required to be carried out during various stages of site evaluation, pre-construction to both during and post construction period at the local and/ or site area.

Investigations through Geodetic Survey

E.3.2 Existing state high precision survey control points and gravity stations are first located as close to the target area as possible. These control points would be in the form of at least two first order triangulation or traverse stations (for plan control), two high precision benchmarks (for elevation control) and two order gravity stations.

E.3.3 Although the target area is expected to be free of any geological faults or lineaments, the existence of these close to the target area, cannot be completely ruled out. Such features, if any, should be located on the ground by joint teams of geodesists and geologists.

E.3.4 Sites for ground monuments are then suitably located and monuments erected by joint teams of geodesists and geologists. These monuments serve the roles of geodetic investigations both during and post construction periods. Monuments, 200 to 300 meters apart, in a suitable pattern, inside the target area an astride the suspect lineament, would be adequate. Depending on topography, the monuments for plan and elevation control may or may not be the same. However, the monuments for elevation control can also serve as the monuments for gravity survey. The monuments should be in the form of suitable pillars founded on bedrock. The design of the pillar would depend largely on the depth of the bedrock. This is necessary to ensure that any movements subsequently detected are not attributed to loose overburden. For deep soil sites, the monument foundation should be wider and be founded on competent soil strata. This is necessary to ensure that any movements subsequently detected are not attributed to loose overburden.

E.3.5 The stage is now set for the first set of geodetic observations. After ascertaining the stability of the two existing plan control points near the target area (as envisaged in E.3.2) horizontal control survey (triangulation and/or Electromagnetic Distance Measurement (E.D.M.) traverse is carried out) to provide co-ordinates of the monuments with an accuracy of at least 1:40,000. Similarly after ascertaining the stability of two existing benchmarks near the target area, high precision levelling is carried out to provide heights of the monuments with an accuracy of $(1/k)^{-}0.5$ m.m. where, k is the length of the line in kilometre. Similarly gravity values at the monuments are provided by microgravity surveys, to an accuracy of a few microgals.

E.3.6 At least, two more sets of repeat observations to the specifications given in E.3.5 are then required to be carried out at intervals of 6 to 9 months.

E.3.7 Analysis of data from the operations indicated in paras E.3.2 and E.3.3 will provide the following information:

1. Horizontal co-ordinates and heights of the monuments required for subsequent detailed topographical surveys if the target area is selected.
2. Horizontal and vertical movements at the monuments along with the trend of the movements. Strain parameters for the target area and their trend. Only those values are to be accepted which are subjected to appropriate statistical tests and found acceptable.
3. Gravity values, their variations and trend.

E.3.8 Other geophysical studies suggested by geologists, geophysicist and seismologists, to complement the above and ascertain the seismic status of the target area.

E.3.9 With the advancement of technology, precise GPS based methods could be used for geodetic measurements to ascertain crustal movements and strain built-up.

E.3.10 Depending on the outcome of initial evaluation, need for confirmatory/ continued geodetic measurements/ investigations may also be looked into.

Annexure I: TYPICAL CONTENT OF THE REPORT ON SEISMIC STUDIES AND ESTIMATION OF DESIGN GROUND MOTION PARAMETERS

I.1. General

I.1.1 The reports on Seismic Studies and Design Basis Ground Motion/ Design Ground Motion should provide information regarding the seismic, tectonic and geologic characteristics of the site and the region surrounding the site and establishment of design basis ground motion. The application and its supporting information should enable reviewer to logically progress from data and assumption to conclusions drawn without the need for an extensive independent literature review.

I.1.2 The information on studies, investigations and other related work which need to be provided for the review by AERB are categorised into three groups.

1) Preliminary Investigation

2) Detailed Investigation including:

   a. Geological and geophysical investigations
   b. Geodetic Measurement
   c. Microearthquake Survey
   d. Development of database
   e. Design Basis Ground Motion
   f. Evaluation of co-seismic hazards such as liquefaction, ground deformation, surface rupture, ground failure, slope failures (earthquake triggered or induced landslides), water waves, floods/flash floods and dam failures.

3) Confirmatory Investigation

I.1.3 All the relevant information pertaining to each of the above subjects should be furnished in detail. Each report should be self-contained and self-explanatory.

I.1.4 Presentation of the above information may be structured in one report or in a number of reports as desired by the applicant and according to the information requirements of corresponding consenting stage (i.e. site evaluation, construction/ periodic safety review). As a minimum, information as required in Group-I reports need to be reviewed during site evaluation stage of a hazard category-I facility and Group-II and Group-III reports are required as part of subsequent stage of consent. Related reports for Hazard category-II facilities may be presented in a similar manner but following a graded approach, also taking into account guidance provided in section -10.

I.2. CONTENT FOR THE DOCUMENTATION

I.2.1 Each report should have a title, document number, and should contain the name and signature of the persons preparing, reviewing and approving it.

1) The documentation of the report should be done chapter wise, and each chapter should be numbered.

2) A table of contents should be provided. When a document consists of several volumes, the complete table of contents should be included in each volume.

3) The chapters of the report should be planned according to the contents of the report. Each chapter of the document should cover a particular topic and be self-contained to the extent possible.

   For systematic presentation, each chapter may be subdivided into a number of sections, sub-sections and so on.

4) The first chapter of the report should be the introduction, which will contain objective of the report, scope of the report and the structure of the report.

5) The last chapter of the report should contain the summary and concluding remarks.

6) Abbreviations and symbols should be consistent with general usage and should be defined in each volume where they are used first.

7) All information presented in the drawings, maps, diagrams, sketches and chats should be numbered, should be legible and the symbols should be defined and the drawings should not be to a scale that necessitates the use of visual aids.

8) The information presented in the main body of the document should be supplemented as necessary by appendices.

9) A complete list of references should be included at the end of main body of the report.

   If certain references are found important pertaining to the content of the report and is not commonly used, copy of the relevant portion of those references or full should be attached to the report as annexures with numbering.

10) All pages should be numbered.

   Equation number should be assigned to each equation or mathematical expression.

11) Outdated text and data should be removed and replaced by inserting revised pages issued with updated text and data. All pages submitted to update, revise or add information to the document should show the date of issue and a change or amended number. In lieu of the same, complete document may be resubmitted after revision. Changes should be highlighted by a vertical line in the margin or some other effective indication.

I.3. CONTENTS OF REPORT OF GROUP I INVESTIGATIONS

The report should include but not necessarily be limited to, the following information pertaining to preliminary investigation:

1) Objective, scope of the document and its limitation.

2) Brief description of the site
3) The sources and database
4) Geological maps developed for 4 different ranges of studies (cl.No.3.4) along with commentaries.
5) Results of investigations undertaken in line with requirements specified in section-3.5.1 on investigations during site evaluation.
6) Identification of important issues which should be studied in detailed investigation stage.
7) Discussion on the acceptability considering rejection criteria specified in [1] and engineerability of the site.
8) Conclusion
9) Reference

I.4. CONTENT OF DOCUMENT ON GROUP-II INVESTIGATIONS

This document should include but not necessarily be limited to the information discussed below. It should contain all the information upon which the decision on the acceptability and engineerability of the site could be taken.

I.4.1. Evaluation of Database

The information should be extracted from the published reports, maps, private communication, other existing sources and the investigations carried out in four ranges. For each range of studies, the report should contain:

1) Objective, scope and limitation;
2) The geological map highlighting all deformation zones such as shears, joints, fractures, folds, faults, lineaments, and tectonic structures;
3) Commentary on the geological map;
4) Identification of new data required, and identification of investigations/studies to be carried out in downstream activity;
5) Information on the investigations and studies;
    a. Name of the investigation and the agency which carried out the investigation,
    b. Objectives of the investigation,
    c. Description of the investigation,
    d. Result: field data, test data, and
    e. Analysis of the result and data and their interpretation.
6) Summary of the complete work

1. Has instrumental, historical, pre-historical/paleo-seismic earthquake data been collected from all available sources? Yes/No

2. Has evidence been looked into for historical surface faulting? Yes/No.

3. Have studies been carried out to describe the potential of surface faulting? Yes/No.

4. Are all known lineaments listed? Yes/No.

5. Are all known faults in the region listed? Yes/No.

6. Are dead/inactive faults identified? Yes/No.

7. If yes, whether adequate studies have been carried out to support the finding? Yes/No.

8. Have the remaining faults been classified as active faults? Yes/No.

9. Do the available earthquake data reasonably reflect the earthquake history of the region? Yes/No.

10. Were additional investigations undertaken and completed for improving the data base:

11. Examination of satellite imageries Yes/No

    a. Examination of aerial photographs Yes/No

    b. Ground check of lineaments Yes/No

    c. Microearthquake studies Yes/No

    d. Gravity studies Yes/No

    e. Magnetotelluric studies Yes/No

    f. Seismic reflection studies Yes/No

    g. Multichannel Analysis of Surface Waves Yes/No

    h. Any other geophysical studies Yes/No

    i. Relevant Geotechnical investigations Yes/No

12. Whatever investigations were considered necessary for arriving at optimum design basis have been completed? Yes/No

13. Are the basis of engineering and geological judgements and their limitations described in the report? Yes/No

14. Are additional investigations likely to alter the postulated earthquake design basis? Yes/No

15. If the answer to any of these questions is “yes”, then the details of the investigations, the methodology used and the conclusions arrived at have been given? Yes/No

16. If the answer to any of the questions is ‘no’, the implications of the answer and the basis of the judgement applied and the associated limitation have been examined? Yes/No

7) Uncertainties in collected data and Unresolved issues, if any;

8) Identification of investigations to be carried out;

9) Conclusion; and

10) References.

I.4.2. Estimation of Design Basis Ground Motion

1) Short description of site;

2) Description of geological set up;

3) Seismic data, faults, tectonic structures and crustal volume to be considered in model;

4) Development of seismotectonic map and its depiction;

5) Identification of inactive faults, structures and crustal volume based on detailed study in line with section-3;

6) Establishment of seismotectonic model including geometric characterization of sources, selection of inputs for numerical modeling of wave propagation, selection of GMPEs, etc.;

7) Evaluation of maximum earthquake potential, recurrence relationships, etc.;

8) Discussion of uncertainties associated with various inputs and incorporation of uncertainties in computational model;

9) Estimation of DBGM, presentation of total hazard as well as source wise contribution;

10) Methods, numerical model adopted, inputs used and outcome of site amplification studies, if applicable and estimation of DBGM at free field;

11) Evaluation of spectrum compatible time histories;

12) Recommendations for design input;

1. Design response spectral graphs at various damping; and

2. Digitized values of design response spectra and Spectrum compatible Design time history.

   The above parameters should be specified for all three directions (two orthogonal horizontal and vertical. For applicable NFs, the outcome should be reported for both S1 and S2 levels.

13) Deviations, if any, from recommendations of the guide;

14) Identification of further investigations/studies;

15) Unresolved issues; and

16) References.

I.4.3. Seismically Induced Ground Failure, Water Waves and Flood

The seismically induced water waves, flood, various types of ground failure specific to the safety of the site should be addressed highlighting the following,

1) Identification of type of the hazard and their location to be shown in the map developed during the investigation.
2) Data required and their acquisition.
3) Detailed description of the methodology adopted to evaluate the potential of the particular hazard and associated uncertainties in inputs and methodology.
4) Analysis of the data obtained from the investigation and interpretation of the result
5) Deviation, if any, from the recommendation of the Guide
6) Comparison with outcome of similar works, if available
7) Identification of further investigations
8) Unresolved issues
9) Conclusion
10) Reference

I.5. CONTENT OF DOCUMENT ON GROUP III INVESTIGATION

The document should include but not necessarily be limited to the information mentioned below:

I.5.1. Confirmatory Investigation

1) Name of the investigation and the agency which carried out the investigation.
2) Objective of the investigation.

3) Description of investigation.

4) Result: field and test data.

5) Analysis of data and result and their interpretation.

6) Impact of Confirmatory study(ies) on assumptions made, inputs used and outcome of applicable Group-II studies.

7) Unresolved issues.

8) Conclusion.

9) Reference.

Annexure-II Estimation of Extreme Earthquake for Margin Assessment

II.1 The AERB code on site evaluation of NF [1] and regulatory documents on design of NPP [18] requires provision of additional safety margins in design of nuclear facility from consideration of possible exceedance of design basis parameters. Towards evaluating the adequacy of safety margins for seismic scenario, an extreme earthquake is postulated.

II.2 The parameters of extreme earthquake (S3 level earthquake) could be defined based on a postulated level of maximum acceleration/intensity of shaking that can be expected at site, taking into account regional seismicity and local site conditions, irrespective of earthquake source location. However, the derived S3 level motion should be limited by the physical upper bounds commensurate with tectonic characteristics of the region and justifiable assumptions. All SSCs important for basic safety functions of NPP and spent fuel pool should be evaluated for their functional/ structural safety, as the case may be, using extreme earthquake parameters.

II.3 The approaches for estimating the parameters of extreme earthquake are:

A. S3 level ground motion parameters for assessment of SSCs

(i) Using probabilistic methods: One order higher return period compared to what is required to be considered as design basis shall be considered for specifying parameters of ground motion (spectra) representing extreme earthquake.

(ii) Using deterministic methods: A combined magnitude-intensity based approach can be adopted for estimating the ground motion parameters. In this method, epicentral intensity representing extreme earthquake is postulated for the site region based on study of historical seismicity. Depending on the location of site in region of low seismicity, moderate seismicity or high seismicity, the maximum site intensities (MSK) considered are of VII, VIII and IX, respectively. Current considerations with respect to demarcation of these regions is as follows:

a. Kachchh region in Gujarat, areas in Gangetic alluvium close to Himalayan Frontal fault as well as entire Himalayas and North-East India are expected to experience a maximum intensity of IX.
b. Bundelkahnd region surrounding Kota/Rawatbhata are classified for a maximum intensity of VII.
c. Rest of India is assigned a maximum site intensity of VIII.

Assuming that the site could be subjected to this intensity level, several sets of earthquake magnitude-distance combination are worked out utilizing intensity-Magnitude-distance empirical equations (applicable to the region) to yield this intensity at the site. As detailed investigations are carried out to rule out active fault within 5 km radius of NPP, minimum distance to earthquake source location need not be lower than 5 km from site. For each magnitude and distance combination, response spectra should be generated using validated numerical simulation software taking into account uncertainties in source and wave propagation modelling, site amplification, etc. The response spectral ordinates corresponding to 84% non-exceedance should be considered to represent the spectra corresponding to extreme earthquake for margin assessment.

B. S3 level ground motion parameters for seismic induced water waves

For evaluation of earthquake potential in tsunamigenic regions, unlike the above method, a more specific (in terms of earthquake sources, e.g. only subduction zones to be considered) earthquake source model needs to be adopted. Considering the large time gap between extreme tsunamigenic earthquakes, apart from available earthquake records, information from paleo-tsunami deposits along the coast, convergence rate of plates, maximum rupture length and width possible for the zone combined with numerical simulation/ empirical relations correlating these parameters with earthquake magnitude may be used to derive the upper bound magnitude.

The dislocation of sea surface due to the earthquake should be used as input for numerical model. Alternate source scenarios to address uncertainties in source model (e.g. location of rupture, distribution of displacement, etc.) should also be captured. Information from observed tsunami events may be used as an input to evaluate variation in these parameters. Numerical simulation adopting a validated numerical code and site specific topographic/ bathymetry data should be used to estimate tsunami levels (at site and its impact on various SSCs). Inputs of flooding and related phenomena (See section 8) as well as draw down should be evaluated.

While adopting probabilistic methods, one order higher return period compared to what is required to be considered for design basis shall be used to evaluate extreme tsunami levels and assessment of margins in identified SSCs.

Annexure-III Background Seismicity in Seismic Hazard Assessment

III.1 Background seismicity needs to be considered in seismic hazard assessment to take into account subsurface/ hidden features and lack of information on past seismicity. For Hazard Category-I facilities, detailed investigation need to be undertaken in 5km radius to rule out existence of active/capable seismogenic feature. Hence, possibility of any subsurface/ hidden feature is ruled out. But, for the region between 5 to 50 kms, such detailed investigation is done on a case to case basis. Hence, it is recommended that background seismicity should be considered in intermediate region (5 to 50km) in probabilistic seismic hazard analysis. Based on judgment obtained from experts in the field, maximum magnitude for background seismicity can be taken as M 5.5.In deterministic analysis, M 5.5 at a distance of 20km can be considered as background seismicity. The distance of 20km is average of 5 to 50km considered in PSHA. In general, for M 5.5 earthquake, depth of focus is observed to be 5 to 15km. Hence, depth of focus can be taken as 10km for the assessment.

III.2 In case of investigation being carried out for a larger region in as much of details as done within 5km, or in case of site having information/ records from MEQ network for a longer period, the above specified numbers may be revisited considering the knowledge of seismicity of the site.

III.3 For evaluating parameters used in hazard analysis (*a-* & *b-values*) for background seismicity, following is recommended:

(i) In general, results of seismic hazard analysis is not that sensitive to *b-value*. Hence, average *b-value* for the site region can be used for assessment.

(ii) For *a-value*, approach based on strain rates can be adopted. Strain rates can be used to derive earthquake activity for any region where seismicity is sparse. Other approach is to consider a Poissonian model of earthquake occurrence corresponding to a zero occurrence of considered magnitude within the time window of observation.

LIST OF PARTICIPANTS

IN-HOUSE GROUP

Period of meetings

May 2017 to March 2018

Members In-House Group:

1.	Dr. A. D. Roshan, NPSD, AERB	:Convener
2.	Dr. P Shylamoni, RDD, AERB	:Member
3.	Shri Somnath Jha, NPSD, AERB	:Member
4.	Shri Anis M., NPSD, AERB	:Member- Secretary

TASK FORCE (AERB-TF/SG/S11)

Dates of meeting

May 25, 2018	July 17, 2018
June 01, 2018	August 03, 2018
June 06, 2018	August 08, 2018
June 13, 2018	August 11, 2018
June 22, 2018	September 14, 2018
July 04, 2018	October 23, 2018
July 11, 2018	November 27, 2018

Members of the Task Force:

1.	Shri H. S. Kushwaha, Rtd. BARC	: Convener
2.	Shri K. K. Vaze, Rtd. BARC	: Co-Convener
3.	Shri S. M. Ingole, NPCIL	: Member
4.	Shri L. Swamy Raju, CCE (FBR-1&2)	: Member
5.	Shri Abhijit Harshan, NPCIL	: Member
6.	Shri. U. P. Singh, NPCIL	: Member
7.	Dr M. Hariprasad, BARC	: Member
8.	Shri C. Harikumar, IGCAR	: Member
9.	Dr. Srinagesh, NGRI, Hyderabad	: Member
10.	Dr. A. S. Pisharady, AERB	: Member
11.	Shri Somnath Jha, AERB	: Member-Secretary
12.	Dr. A. D. Roshan, AERB	: Invitee
13.	Dr. P. Shylamoni, AERB	: Invitee
14.	Shri. Anis M., AERB	: Invitee

ADVISORY COMMITTEE FOR NUCLEAR AND RADIOLOGICAL SAFETY (ACNRS)

ACNRS Mtg. No. 4 held on March 04, 2017
ACNRS Mtg. No. 14 held on February 09, 2019
ACNRS Mtg. No. 25 held on May 27, 2021 and November 18, 2021

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Shri K. K. Vaze, Former Dir (RD&D Group), BARC	-	Member
Dr. N.Ramamoorthy, Former CE, BRIT & AD, BARC	-	Member
Shri A. R. Sundararajan, Former Dir (RSD), AERB	-	Member
Shri Atul Bhandarkar, Director (T), NPCIL	-	Member
Shri Sanjay Kumar, Director (T-LWR), NPCIL	-	Member
Dr. A. N. Nandakumar, Former Head, RSD, AERB	-	Member
Shri A Jyothish Kumar, Director (O), BHAVINI	-	Member
Shri H.Ansari, Head, RDS, R&DD, AERB	-	Member Secretary

EXPERTS and STAKEHOLDERS

Dr. Prabhash Pande, Former DDG, GSI
Dr. D.B. Yedekar, Former GSI
Dr. J.R. Kayal, Ex. Dy. Director General, GSI, & Emeritus Professor, CSIR
Prof. D. K. Paul, Ex-IIT Roorkee
Dr. A.K.Bhaduri, Director, IGCAR
Dr. Sumer Chopra, Institute of Seismological Research, Ahmedabad

TECHNICAL EDITING AND COPY EDITING

Dr. A. S. Pisharady, AERB
Shri H.Ansari, AERB
Ms. Sonal Gandhi, AERB