GUIDE NO. AERB/NPP-PHWR/SG/D-23

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GOVERNMENT OF INDIA

AERB SAFETY GUIDE

SEISMIC QUALIFICATION OF STRUCTURES, SYSTEMS AND COMPONENTS OF PRESSURISED HEAVY WATER REACTORS

ATOMIC ENERGY REGULATORY BOARD

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SEISMIC QUALIFICATION OF STRUCTURES, SYSTEMS AND COMPONENTS OF PRESSURISED HEAVY WATER REACTORS

Atomic Energy Regulatory Board
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FOREWORD

Activities concerning establishment and utilisation of nuclear facilities and use of radioactive sources are to be carried out in India in accordance with the relevant provisions of the Atomic Energy Act, 1962. In pursuance of the objective to ensure safety of members of the public and occupational workers, as well as protection of the environment, the Atomic Energy Regulatory Board has been entrusted with the responsibility of laying down safety standards and framing rules and regulations for such activities. The Board has, therefore, undertaken a programme of developing safety standards, safety codes and related guides and manuals for the purpose. While some of the documents cover aspects such as siting, design, construction, operation, quality assurance and decommissioning, 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 equipment, systems, structures and components of nuclear and radiation facilities. Safety codes establish the safety objectives and set minimum requirements that shall be fulfilled to provide adequate assurance for safety. Safety guides elaborate various 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 fields and are extensively reviewed by Advisory Committees of the Board before they are published. The documents are revised when necessary, in the light of experience and feedback from users as well as new developments in the field.

This safety guide provides methods for seismic qualification of structures, systems and components (SSC) of Pressurised Heavy Water Reactors (PHWR) based nuclear power plants to meet the requirement of assessment of SSC against earthquake loads specified in safety code AERB/SC/D, 'Code of Practice on Design for Safety in Pressurised Heavy Water Based Nuclear Power Plants'. In drafting this guide, information contained in relevant documents published by the International Atomic Energy Agency (IAEA), American Society of Civil Engineers (ASCE), US Department of Energy (US DOE), The Institution of Electrical and Electronics Engineers (IEEE), Japan Electric Association and other international publications have been extensively used. Though this guide is prepared for PHWR based nuclear power plants, it is generally applicable for other types of nuclear power plants also.

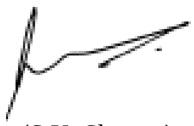
Consistent with the accepted practice, 'shall' and 'should' are used in the document to distinguish between a firm requirement and a desirable option, respectively. Appendices are an integral part of the document, whereas annexures and references are included to provide further information on the subject that might be helpful to the user. Approaches for implementation different to those setout in the Guide may be acceptable, if they provide comparable assurance against undue risk to the health and safety of the occupational workers and the general public and protection of the environment.

The guide applies only for facilities built after the issue of the document. However, during periodic safety review, a review for applicability of current guide for existing facilities would be performed.

For aspects not covered in this guide, applicable national and international standards, codes and guides acceptable to AERB should be followed. Non-radiological aspects such as environmental protection and industrial safety are not explicitly considered. Industrial safety is to be ensured through compliance with the applicable provisions of the Factories Act, 1948 and the Atomic Energy (Factories) Rules, 1996 and the Environmental protection Act, 1984.

This guide has been prepared by specialists in the field drawn from the Atomic Energy Regulatory Board, Bhabha Atomic Research Centre, Indira Gandhi Centre for Atomic Research, Nuclear Power Corporation and other consultants. It has been reviewed by the relevant AERB Advisory Committee on Codes and Guides and the Advisory Committee on Nuclear Safety.

AERB wishes to thank all individuals and organisations who have prepared and reviewed the draft and helped in its finalisation. The list of persons, who have participated in this task, along with their affiliations, is included for information.



(S.K. Sharma)
Chairman, AERB

DEFINITIONS

Analysis

A process of mathematical or other logical reasoning or deduction that leads from stated premises to the conclusion/response/outcome/adequacy of a system or any other item of interest.

Anchor

A structural member embedded in the concrete or attachment to other structures to which a liner, embedment, or surface mounted item is attached.

Component

The smallest part of a system necessary and sufficient to consider for system analysis.

Earthquake

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

Inspection

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.

Model

An analytical representation or quantification of a real system and the ways in which phenomena occur within that system, used to predict or assess the behaviour of the real system under specified (often hypothetical) conditions.

Monitoring

The continuous or periodic measurement of parameters for reasons related to the determination, assessment in respect of structure, system or component in a facility or control of radiation.

Normal Operation

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

Nuclear Power Plant (NPP)

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

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.

Operation

All activities following and prior to commissioning performed to achieve, in a safe manner, the purpose for which a nuclear/radiation facility is constructed, including maintenance.

Review

Documented, comprehensive and systematic evaluation of the fulfillment of requirements, identification of issues, if any.

Safe Shutdown Earthquake (SSE)

The earthquake which is based upon an evaluation of the maximum earthquake potential considering the regional and local geology, seismology and specific characteristics of the local sub-surface material. It is that earthquake which produces the maximum vibratory ground motion for which certain structures, systems and components are designed to remain functional. These structures, systems, and components are those which are necessary to assure

- the integrity of the reactor coolant pressure boundary; or
- the capability to shutdown the reactor and maintain it in a safe shutdown condition; or
- the capability to prevent the accident or to mitigate the consequences of accidents which could result in potential off-site exposures higher than the limits specified by the regulatory body; or
- the capacity to remove residual heat.

Safety Function

A specific purpose that must be accomplished for safety.

Specification

A written statement of requirements to be satisfied by a product, a service, a material or process, indicating the procedure by means of which it may be determined whether the specified requirements are satisfied.

Structure

The assembly of elements which supports/houses the plants, equipment and systems.

Structural integrity

The ability of a structure to withstand prescribed loads.

CONTENTS

1. INTRODUCTION

1.1 General

This Safety Guide has been prepared as a part of AERB's programme for establishing Design Safety Guides relating to Nuclear Power Plants (NPPs). It supplements the other related Safety Guides and suggests methods for designing structures, systems and components (SSCs) against earthquakes loading.

The steps involved in the design of SSCs of NPP to resist seismic loading are:

(a) Generating design ground motion;

(b) Performing analysis to generate response of the SSCs; and

(c) Verification of design of SSCs for the response generated in step (b).

The first step of generating design ground motion is covered in AERB Safety Guide AERB/SG/S-11. The purpose of the present Safety Guide is to give guidelines for the above steps (b) and (c) for the seismic qualification of SSCs of an NPP.

1.2 Objective

AERB Safety Code AERB/SC/D "Code of Practice on Design for Safety in Pressurised Heavy Water Based Nuclear Power Plants" outlines the requirement of protection against natural phenomena as follows : Structures, systems and components necessary to assure the capability for shutdown, residual heat removal and confinement of radioactive material shall be designed to remain functional throughout the plant life in the event of natural phenomena such as earthquakes, cyclones and floods. This guide provides the guidelines for implementation of the same with respect to earthquake loads.

1.3 Scope

The main emphasis in the Safety Guide is to provide guidelines for seismic qualification of SSCs of Pressurised Heavy Water Reactors (PHWRs) by analysis and testing. Though this guide is prepared for PHWR based nuclear power plants, it is generally applicable for other types of nuclear power plants also.

1.4 Structure of the Document in Relation to Earthquake Scenario

Although earthquakes can cause many types of damage, major effects expected at site are related to the vibrations induced in the structures, systems and components. Earthquakes produce random ground motions, which are characterised by simultaneous but statistically independent horizontal and vertical components. The designer is primarily interested in the effects of earthquake ground motion on the SSCs; viz. stresses and deformations. The damage potential of an earthquake (due to excessive stresses and deformations) depends on the magnitude (Richter scale) and the shortest distance of a fault line from the nuclear power plant.

A larger magnitude earthquake may cause higher stresses and larger deformations. On the other hand, probability of such an earthquake event to occur during the life of the NPP is very low. This extreme loading with low probability has led to the seismic design of an NPP for two levels of earthquake. (see sec. 2.1)

An earthquake which is reasonably expected to occur during the life of a structure, is termed as Operating Basis Earthquake (OBE) or S1. The SSCs are expected to resist this level of earthquake within their elastic limits and maintain functionality during and after the earthquake to enable subsequent operation. Seismic Category 1 and 2 SSCs are designed for this level of earthquake (see AERB/NPP-PHWR/SG/D-1 [1] for seismic categorisation).

The most severe earthquake, which could occur with a very low probability, within the life of an NPP, is termed as Safe Shutdown Earthquake (SSE) or S2. Earthquakes beyond S1 limit may result in some damage and deformation beyond elastic limit and subsequent operation may not be possible without repair/replacement of some SSCs. Beyond S1 limit and upto S2 limit the reactor should be capable of being shutdown and maintained in a shutdown state with a coolable geometry. Seismic Category 1 SSCs are designed for this level of earthquake.

Seismic Category 3 structures and components are designed as per the national practice e.g. civil structures of Seismic Category 3 are designed as per the ground motion and the methodology given in IS 1893 [13].

In order to specify the ground motion corresponding to these two different levels of earthquakes; one has to use seismological data, such as magnitude and frequency of occurrence for a specific site supplemented by geological data (e.g., active faults, depth of focus, soil condition, attenuation law etc.)

Peak ground acceleration of the S1 and S2 earthquakes is one possible indicator of the severity of the earthquake, but that alone does not give designer enough information because the frequency content is also important. The form of the seismic motion used for seismic analysis can be described by time history (accelerogram) or response spectrum. Each point on the response spectrum indicates the maximum acceleration (in case of acceleration response spectrum) of a single degree of freedom oscillator with certain frequency and damping.

One way to specify the expected ground motion is to use an accelerogram or response spectrum of a past earthquake with a proper magnitude, which was recorded at an appropriate distance. However, no two earthquakes are ever alike, and there is a big difference between the records of earthquakes with similar magnitude and distance from the source. The scatter among the corresponding structural responses is even greater. This makes the usefulness of this approach, i.e. a single record defining a design earthquake, highly questionable.

To overcome this problem, standard response spectra have been generated by using acceleration records of many past earthquakes and normalising, averaging and smoothing the resultant curves. One such standard response spectrum is the one given in AERB Safety Guide AERB/SG/S-11 [3]. The spectrum is normalised for a Peak Ground Acceleration (PGA) of 1g and it should be scaled in proportion to the PGA of the design earthquake.

By being selective in the usage of past earthquake records in terms of magnitude, distance from epicenter and soil conditions, it is possible to produce site dependent response spectrum. Such site dependent spectra have been generated for a few potential sites in India and the envelope of these may be used.

The ground motion prescribed for a particular site is the ground motion that would occur on the surface of the ground, if the structures were not present, called as control motion or free-field motion. However, the ground motion actually introduced at the base of a structure may be influenced by the motion of the structure itself such that it differs considerably from the free-field motion.

In case of a flexible structure, located on firm ground (rock), the structure can transmit little energy back into the soil and the free-field motion is an adequate measure of the foundation motion (see sec.2.4.1). In case of a stiff structure, located on soft soil, there is considerable exchange of energy between the structure and the soil and base motion may differ drastically from the free-field motion.

It is possible to compute the motion at some depth in the soil profile, such as soil-rock interface. Soil properties required for soil-structure interaction analysis are derived from tests on soil (see sec. 2.4.2). This process of transferring the motion from the surface to the soil-rock interface is called de-convolution. This de-convolved motion may then be used as input to a three dimensional mathematical model of the soil and structure (see sec. 2.4.3). Neglecting this effect of soil-structure interaction will be conservative in most cases, as the actual motion at the base of the structure in presence of soil-structure interaction is less than the free field motion.

The soil-structure interaction introduces one vertical and two orthogonal horizontal translation motions, two orthogonal rocking motions and a torsional motion. These can be accounted for in the analyses by modeling the soil by three translation, two rocking and one torsional springs (see sec. 2.4.4).

A nuclear power plant consists of many SSCs; and a single complete model of the entire plant would be too cumbersome. The mathematical solution of such a single model may also become difficult. Thus the analyst should identify the main systems and subsystems. Major structures, which are considered in conjunction with foundation media to form a soil-structure interaction model, constitute the main system. Other SSCs, attached to the main system, should constitute the subsystems. Certain criteria should be used to decide if a particular subsystem should be taken into account in the analysis of the main system. Such decoupling criteria (see sec. 2.2.8) define some limits on the relative mass ratio between the subsystem and the supporting main system, with more severe limits, when there is a possibility of resonance between the subsystem and the main system.

For design of structures and for ground-mounted equipment, the description of the ground motion in terms of response spectrum is adequate. It is also adequate for large, massive equipment such as calandria and end-shield assembly, which has significant interaction with the supporting structure and has to be modeled along with the primary structure in a coupled analysis. However, for non-interacting or marginally interacting equipment mounted on floors, the ground motion may be filtered and amplified by the intervening structure to produce a narrow band amplified motion. Just as ground response spectra are used for design of structures or ground-supported equipment, floor response spectra are used for designing floor-mounted equipment (see sec. 2.5). Although methods are available for conversion of ground response spectra to floor response spectra (so called spectra to spectra methods), the most frequently used method is the one in which the floor spectra are derived from a time history analysis of the primary structure.

For this purpose, the designer develops synthetic time histories made by the summation of numerous Sine waves of different frequencies. The amplitudes and phase angles of these are adjusted until the response spectrum of the synthetic time history matches the given ground response spectrum (see sec. 2.3.2). This involves certain amount of trial and error; and several iterations are required before a satisfactory synthetic time history can be obtained. Even in this case, a certain amount of residual mismatch between the two spectra is unavoidable. In order to avoid the unconservatism resulting from this, it is necessary to use multiple synthetic time-histories.

Once the input motion has been specified, the response of the structure is obtained by analysing a mathematical model of the structure. The mathematical model consists of stiffness, mass and damping properties of the structure. The structures are often analysed in multiple steps (see sec. 2.2.2).

The first step may use a simplified stick model of the structure and calculate only the response accelerations and displacements. These are used in subsequent detailed analysis of the complete structure. For the simplified stick model, the stiffness properties of the structure are calculated by simple formulas where applicable or from a static analysis of the structure (see sec. 2.2.2). In a Finite Element Model, the stiffness formulation is built-in; needing only the material properties, such as elastic and shear moduli, Poison's ratio (see sec. 2.2.4) and the geometric details.

Modeling of mass, although relatively straightforward in most cases, requires special consideration for SSCs containing liquids (see sec. 2.2.6). When a structure containing liquid (e.g. spent fuel storage bay) is subjected to an earthquake excitation, a certain portion of the liquid acts as if it were a solid mass in contact with the walls. The force exerted by this mass is called the impulsive force. The acceleration also induces oscillations of the liquid, contributing to additional dynamic pressure on the wall and the bottom. This can be thought as a certain portion of the liquid responding as if it were a solid mass connected to the walls through flexible springs. The associated force is called the convective force. Fluids contained within a structure/equipment shall be modeled to represent both impulsive and convective (sloshing) effects.

Damping, as a material property, depends on the stress levels. For S1 earthquake, the stresses are within elastic limit and the damping values are generally lower than those for S2 earthquake, which is expected to result in inelastic deformation (see sec. 2.2.7).

The mathematical model of the structure can be analysed by either time-history method (see sec. 2.3.2) or response spectrum method (see sec. 2.3.3). The response spectrum method calculates only the maximum response of the structure in each mode. Since the maxima in different modes may occur at different times, special techniques are required for combining the modal responses (see sec. 2.3.5). Similar considerations apply to combination of responses from the two horizontal and one vertical component of earthquake motion (see sec. 2.3.6 & 2.3.7).

Response of some components with simple geometry can be calculated by equivalent static method. This method approximates the component as a single degree of freedom structure having frequency equal to the fundamental frequency and accounts for the neglected modes by using a factor of 1.5 on the spectral acceleration (see sec. 2.3.4).

For SSCs, which are not specifically modeled in the dynamic model of the primary structure (i.e. they are decoupled and analysed separately), input motion at their support location is required either in the form of a time history or in the form of floor response spectrum. The floor response spectrum shows peaks at the natural frequencies of the primary structure. These natural frequencies could vary due to uncertainties in the material properties of soil, structure and approximations in modeling. To account for these effects, the floor response spectrum peaks are broadened (see sec. 2.5.2). Equivalent broadening is required in time history also (see sec. 2.5.3). However, the broadening is not required, when equipment (which was coupled with the primary structure) is analysed later using a detailed model (see sec. 2.5.4).

The calculated seismic forces and moments shall be combined with the forces and moments due to other loadings in appropriate load combinations and the SSCs designed as per AERB standards on Civil Engineering Design (see sec. 2.6), or ASME Code for mechanical equipment and piping.

The analytical procedures for evaluating the seismic response of equipment (see section 3) and piping (see section 4) are, in general, same as those for the building/structure.

In most of the equipment used in a nuclear plant, the thickness estimated to resist pressure loading is adequate for resisting seismic loading also. Therefore, seismic design essentially involves design of the supports, which should be firmly fixed to the supporting structure.

For piping, however, the requirements are conflicting. It should be rigid enough to resist seismic loads, but at the same time should be flexible enough to accommodate the thermal expansions. Another complication arises because of the multiple supports. When piping is connected at two or more supports with different earthquake indused displacement and applicable response spectra, the single response spectrum used to define input at a particular support point requires some modification. To account for inertial effects, usually accepted method is to apply at all the support points an envelope spectrum of the inputs at each support. The results of this method are rather conservative. The envelope response spectrum accounts for the inertial effects of the seismic motion. The piping is also subjected to the differential movement between the supports, called the Seismic Anchor Movement, which should also be accounted in the analysis.

The components like buried pipes, earth retaining walls and vertical tanks containing liquids which require special treatment, are addressed in Annexure 1 on Special Structures.

The dynamic analysis or the static analysis, which follows the dynamic analysis, yields the stresses and deflections in the SSCs as well as the reaction loads in the equipment supports. These are checked for acceptability as per the applicable design codes. The design codes provide assurance of structural integrity. For active components, apart from this, an assurance is also required about the functionality of the equipment during and/or after earthquake. The specific requirement should be a part of the component specifications, e.g. for the shutdown system, it should be demonstrated that the shutoff rods can be inserted into the core within a specified time period required for the reactor safety assurance.

Although analytical qualification of functionality is possible, the recommended practice is to subject a prototype of the component to a shake table test and verify its functionality. The procedure for qualification by testing is given in section 5.

Section 6 on “Minimum Contents of Seismic Qualification Report” has been added to facilitate review of the seismic qualification report by Regulatory Authority.

2.- SEISMIC QUALIFICATION OF CIVIL STRUCTURES

2.1 Seismic Categorisation

AERB code of practice on safety in 'Nuclear Power Plant Siting' (AERB/SC/D) requires that structures, systems and components necessary to assure capability for shut down, decay heat removal and confinement of radioactive material shall be designed to remain functional throughout the plant life in the event of natural phenomenon such as earthquakes, cyclones and floods.

As per AERB safety guide on 'Safety Classification and Seismic Categorisation' (AERB/NPP-PHWR/SG/D-1), SSCs are to be categorised in three seismic categories.

2.1.1 Seismic Category-1

All seismic category-1 structures, systems and components shall be designed or qualified for both S1 (OBE) and S2 (SSE).

2.1.2 Seismic Category-2

All seismic category-2 structures, systems, and components shall be designed or qualified for S1 (OBE).

2.1.3 Seismic Category-3

Items under this category should follow national practice; for example, the civil structures under this category can be designed and built as per IS-1893.

2.1.4 Seismic qualification of category 1 and 2 structures shall be performed as per the guidelines of this chapter.

2.2 Modelling of Structures

2.2.1 General Requirements

The seismic response of a structure shall be determined by preparing a mathematical model of the structure and calculating the response of the model to the prescribed seismic input. The model of the structure should include the following:

(a) The hydrodynamic effects of any significant liquid mass interacting with the structure shall be considered in modelling the inertial characteristics (2.2.6).

(b) The model shall adequately account for the effects of soil-structure interaction as given in section 2.4.

(c) The model shall represent the actual locations of the centres of masses and centres of rigidity, thus accounting for the torsional effects caused by the eccentricity.

(d) When calculating forces in various structural elements, the torsional moments due to accidental eccentricity with respect to the centre of rigidity and the effects of non-vertically incident or incoherent waves shall be accounted for. An acceptable means of accounting for these torsional moments is to include an additional torsional moment in the design or evaluation of structural members. This additional torsional moment in the direction of interest shall be taken equal to the corresponding storey shear at the elevation times a moment arm equal to 5% of the building plan dimension perpendicular to the direction of motion in the analysis. This eccentricity is used only in static analysis to increase the magnitude of forces. This additional eccentricity shall not be used for modeling in dynamic analysis.

(e) The relative deformations between structures shall be considered in the analysis of elements connected to or supported from multiple structures and in specifying clearance between structures. Adjacent structure displacements may be combined by the square root of the sum of squares (SRSS) method to obtain relative deformations.

2.2.2 Multi-step Methods of Seismic Response Analysis

(a) Response analysis for both horizontal and vertical components of motion can be performed by either the multi-step or the single-step method. The selection of the method of analysis shall be consistent with the objectives of the analysis and the use of the calculated response.

(b) In the multi-step method, the seismic response analysis is performed in successive steps. In the first step, the overall seismic response : principally the displacement, acceleration; and overall inertial forces of the overall structural system, foundation, and soil is determined. The response obtained in the first step is then used as input to models for the subsequent analyses of the various portions of the structure. The subsequent analyses are performed to obtain the following :

(i) Seismic loads and stresses for the design and evaluation of portions of a structure.

(ii) Seismic response of subsystems, such as equipment and piping subjected to seismic motions, such as accelerations, at various locations of the structural system.

(c) For the first step, a lumped-mass stick model may be used. In many cases the construction of stick model is relatively straightforward with stiffness obtained from formulae, however, when the structure is complex, the stick model is constructed using Finite Element Method.

(d) A detailed model that represents the structural configuration shall be used for determination of stresses. The model shall include gross discontinuities such as large openings (e.g. equipment or personnel hatches in a containment building).

(e) Torsional effects resulting from eccentricity between the centre of mass and the centre of rigidity shall be included.

(f) The stiffness elements are located at the centres of rigidity of the respective groups of elements and the various individual models are properly interconnected.

(g) The storey mass shall be placed at the centre of mass and connected to the centre of rigidity with a rigid link. The torsional mass moment of inertia shall be included when it is significant to response calculations.

(h) Seismic forces from the lumped-mass stick model shall be distributed to the individual members (walls, columns, etc.) in proportion to their contribution to the total stiffness, for determination of stresses using a detailed model. Alternatively, acceleration responses can be used to generate the loading.

(i) Typically separate analytical models for horizontal and vertical excitations may be used. However, if it is seen that there exists significant coupling between horizontal and vertical structural responses, a combined model shall be used for the seismic response analysis. The coupling could be due to the horizontal and vertical frequencies of vibration being close to each other, or due to large vertical responses arising due to horizontal excitations or vice versa.

2.2.3 One Step Method of Seismic Response Analysis

When all seismic responses in a structural system are determined in a single analysis, a plate and shell/solid element model is more appropriate.

2.2.4 Structural Material Properties

(a) Modulus of Elasticity and Poisson's Ratio

The values of the modulus of elasticity (E) and Poisson’s ratio (υ) for concrete and steel are given below. These values are for materials at or near ambient temperatures. Modulus reduction at elevated temperatures shall be considered when relevant.

Concrete

The properties of concrete, E_c and υ_c shall be

$$= \sqrt{\quad} \qquad (2.1)$$

$\upsilon_c = 0.2$

where = characteristic cube compressive strength of concrete at 28 days (MPa)

Steel

The properties of structural steel and reinforcement, E_S and υ_S , shall be

$E_S = 2.1 x 10^5$ MPa

$\upsilon_S = 0.3$

(b) Damping

Damping values are given in Table 2.2.4-1. These values are applicable to all modes of a structure constructed of the same material. Damping value for systems that include two or more structures, such as a combined concrete and steel structure, or soil-structure systems, shall be obtained as described in the subsection 2.2.7.

TABLE 2.2.4-1 DAMPING VALUES AS A PERCENTAGE OF CRITICAL DAMPING

Structure Type	S1	S2
Welded and friction-bolted steel structures	2	4
Bearing-bolted steel structures	4	7
Prestressed concrete structures	2	5
Reinforced concrete structures	4	7

2.2.5 Modelling of Stiffness

(a) Reinforced and prestressed concrete elements are generally modelled as uncracked sections. In order to avoid possible impact between adjacent structures, seismic gaps should be provided. The calculation of the relative displacement for this purpose should be based on a more realistic estimate of the structure stiffness depending on stress levels. In lieu of such an estimate, half of the uncracked stiffness may be used conservatively.

(b) For modelling non-structural elements and fill concrete, best estimate stiffness properties shall be used.

(c) Snubbers are modelled as truss element with stiffness equal to that of a locked snubber.

2.2.6 Modelling of Mass

(a) The inertial mass properties of a structure may be modelled by assuming that the structural mass and associated rotational inertia are discretised and lumped at node points of the model. Alternatively, the consistent mass formulation may be used.

(b) In general, three translations and three rotational degrees of freedom shall be used at each node point. Some degrees of freedom, such as rotational, may be neglected, provided they do not affect the response significantly. The following conditions shall be met:

(i) Structural mass shall be lumped so that the total mass as well as the centre of gravity is preserved, both for the total structure and for any of its major components that respond in the direction of motion.

(ii) The number of dynamic degrees of freedom, and hence the number of lumped masses, shall be selected so that all significant vibration modes of the structure can be evaluated. For a structure with distributed mass, the number of degrees of freedom in a given direction shall be equal to at least twice the number of significant modes in that direction.

(c) The inertial properties shall include all tributary mass expected to be present at the time of the earthquake. This mass will include for example, the effects of dead load, stationary equipment, piping and the appropriate part of the live load.

(d) Building Model Hydrodynamic Mass Effects

For basins with walls that respond as a rigid body (i.e. fundamental frequency > frequency at ZPA) or for walls without local stress concentrations, the entire horizontal impulsive mass may be located at a single height in the model. Similarly, the sloshing mass and associated horizontal spring constant may be located at a single height. The magnitudes and locations along the height of the structure for the masses and convective mode spring constants shall be determined on the basis of engineering mechanics principles. When the basin walls do not respond as a rigid body or when local stresses are of interest, the masses and associated sloshing mode horizontal springs shall be distributed over part of the basin wall height. Guidelines for calculating spring constants, masses and locations of masses for rectangular basins are given in Appendix 1.

2.2.7 Modelling of Damping

(a) Modal Damping

When modal analysis is to be performed for structures with only one type of material (hence single value of damping), the damping values given in Table 2.2.4-1 can directly be used for modal damping. For structural systems that consist of substructures with different damping properties, the equivalent modal damping values may be obtained using strain energy equivalence.

(b) Proportional Damping (Rayleigh Damping)

When a damping matrix is required in a time history analysis, the damping matrix [C] formed by a linear combination of the mass and stiffness matrices may be used :

$$[\quad] = \alpha[\quad] + \beta[\quad] \tag{2.2}$$

where α and β are proportional damping coefficients and are given by

$$\alpha = \frac{\lambda\omega \quad \omega}{\omega \quad + \omega} \tag{2.3}$$

$$\beta = \frac{\lambda}{\omega \quad + \omega}$$

where λ is the damping ratio from Table 2.2.4-1.

The two circular frequencies ω_{max} and ω_{min} are the undamped circular frequencies selected to define the range of frequencies, which contribute to the response of the structure.

2.2.8 Dynamic Decoupling Criteria

(a) The buildings and components of PHWR are complex structural systems, and development of mathematical models requires careful consideration. A single model, which models the soil, building and the equipment within, will be of very large size, leading to computational difficulties. Major structures such as primary containment, secondary containment and internal structure are modelled in conjunction with the foundation. In most cases, the equipment are analysed as a decoupled system. Whether any equipment should also be modelled along with the global model (coupled analysis) or can be analysed separately using the floor motion of the global model (decoupled analysis), depends on the extent of interaction between the building (primary system) and the equipment (secondary system or subsystem). The extent of interaction, in turn, depends on the mass ratio, R_m, and the frequency ratio, R_f, where R_m and R_f are defined as :

$$R_m = \frac{\text{Total mass of the secondary system}}{\text{Total mass of the primary system}} = \frac{M_s}{M_p} \tag{2.4}$$

$$R_f = \frac{\text{Fundamental frequency of the secondary system}}{\text{Fundamental frequency of the primary system}} = \frac{f_s}{f_p} \tag{2.5}$$

If the primary and secondary systems consist of multiple modes, the mass ratio (R_m) will be the modal mass ratio and the frequency ratio (R_f) will be based on the frequencies of these modes. All the modes with modal mass > 20% shall be included.

(b) Following decoupling criteria shall be followed :

(i) If $R_m < 0.01$, decoupling can be done for any R_f

(ii) If $0.01 < R_m < 0.1$, decoupling can be done if $R_f < 0.8$ or $R_f > 1.25$,
Coupling should be done if $0.8 < R_f < 1.25$

(iii) If $R_m > 0.1$, and $R_f > 3.0$, (i.e. the secondary system is rigid compared to the primary system), it is sufficient to include only the mass of the subsystem.

(iv) If $R_m > 0.1$, and $R_f < 0.33$, (i.e. the secondary system is flexible compared to the primary system), decoupling can be done.

(v) If $R_m > 0.1$, and $0.33 < R_f < 3.0$, coupling is required.

(c) The above decoupling criteria are applicable for secondary systems with single point attachment to the primary system. When the secondary system has multiple attachments, the secondary system may restrict the movement of the primary system and may change its frequency. Multi-supported equipment should be reviewed for this possibility, and the criteria of decompling should be based on ASCE 4-98, C3.1.7.3.

2.3 Analysis of Structures

2.3.1 General Requirements

(a) Any one of the following three analysis methods, described in this section, is acceptable for use in seismic response analysis.

(i) The time-history method (see sec. 2.3.2).

(ii) The response-spectrum method (see sec. 2.3.3)

(iii) The equivalent-static method (see sec. 2.3.4)

(b) Seismic analysis shall be performed for the three orthogonal (two horizontal and one vertical) components of earthquake motion in accordance with sec. 2.3.6. The orthogonal axes shall, in general, be aligned with the principal axes of the structure.

(c) Generally, floor systems in building structures of NPP have high in-plane rigidity. Advantage of rigid in-plane floors may be taken in reducing number of degrees of freedom in the mathematical model of the building. But out-of-plane flexibility of the floor systems shall be considered for vertical motion. The model of a structure with non-rigid floors shall include the flexibility of the floor system.

2.3.2 Time-History Method

(a) General Requirements

(i) When more than one set of histories are used for input at the same support in either linear or non-linear analyses, the resulting responses shall be averaged.

(ii) The time step (Δt) of the solution shall be sufficiently small to accurately define the applied dynamic forces and to ensure stability and convergence of the solution. An acceptable rule is that the used be small enough such that the use of ½ Δt does not change the response by more than 10%. For commonly used methods, Δt values are listed in Table 2.3.2-1. Normally, the shortest period of interest need not be less than 0.03 sec.

TABLE 2.3.2-1: MAXIMUM TIME STEP SIZE FOR TIME-HISTORY ANALYSIS

Method	Fraction of Shortest Period of Interest
Houbolt	1/15
Newmark	1/10
Wilson	1/10

(b) Time-histories

(i) One or more recorded, modified recorded, or synthetic earthquake ground motion time-histories may be used to calculate seismic response.

(ii) Time-histories shall be selected, or developed, so that they reasonably represent the ground motion expected for the site (e.g. have amplitude and duration appropriate for magnitude and distance). Ground motion parameters, as defined in Table 2.3.2-2 shall be used, unless otherwise justified.

TABLE 2.3.2-2 : DURATION ENVELOPING FUNCTION PARAMETERS

Magnitude (Richter Scale)	Rise time (s)	Duration of Strong Motion (s)	Decay Time (s)
7.0-7.5	2	13	9
6.5-7.0	1.5	10	7
6.0-6.5	1	7	5
5.5-6.0	1	6	4
5.0-5.5	1	5	4

(iii) Time-histories for each direction shall have the following characteristics :

(A) The mean of the zero-period acceleration (ZPA) values calculated from the individual time-histories shall equal or exceed the design ground acceleration.

(B) In the frequency range of interest for design of structures, systems or components (SSC), the average of the ratios of the mean spectrum (calculated from the individual time-history spectra evaluated at the appropriate damping value, which is generally 5%) to the design spectrum, where the ratios are calculated frequency by frequency, shall be equal to or greater than 1. Response spectral values from any time-history shall be calculated at sufficient frequency points to produce accurate spectra. Table 2.3.2-3 provides suggested frequencies at which spectral ordinates may be calculated. Another acceptable method is to choose frequencies such that each frequency is within 10% of the previous frequency. In addition, the known frequencies of structure and equipment should also be included.

TABLE 2.3.2-3: SUGGESTED FREQUENCIES FOR CALCULATION OF RESPONSE SPECTRA

Frequency Range (Hz)	Increment (Hz)
0.2 - 3.0	0.1
3.0 - 3.6	0.15
3.6 - 5.0	0.20
5.0 - 8.0	0.25
8.0 - 15.0	0.50
15.0 - 18.0	1.00
18.0 - 22.0	2.00
22.0 - 34.0	3.00

(C) Not more than 5 ratios shall be less than 1 and no one point of the mean spectrum (from the time-histories) shall be more than 10% below the design spectrum.

(D) Baseline of the time-history thus generated should be corrected such that the consequent ground velocity and displacement do decay realistically at the end of the duration.

(iv) When responses from the three components of motion are calculated simultaneously, the input motion in the three orthogonal directions shall be statistically independent, and the time-histories shall be different. Shifting the starting time of a single time-history does not constitute the establishment of a different time-history. Two time-histories shall be considered statistically independent if the absolute value of the correlation coefficient does not exceed 0.3.

(c) Linear Method

(i) The response of a multi-degree-of-freedom linear system subjected to seismic excitation can be calculated using the modal superposition or direct integration time-history methods.

(ii) Modal-superposition

The modal-superposition method uses decoupled equation of motion for each mode.

- It shall be sufficient to include all the modes in the analysis having frequencies less than the ZPA frequency, provided that the residual rigid response due to the missing mass is calculated and combined algebraically with the response of modes up to ZPA frequency.
- Alternatively, the number of modes included in the analysis shall be sufficient to ensure at least 90 % mass participation. In this case, if the cutoff frequency is less than 33 Hz, missing mass correction corresponding to spectral acceleration (Sa) value at the cutoff frequency shall be applied.

(iii) Direct Integration

The equations of motion can be directly integrated. Either implicit or explicit methods of numerical integration may be used to solve the equations of motion.

(d) Non-linear Methods

(i) When performing a non-linear analysis, the following shall be considered:

Geometric non-linearity that significantly alter the effective system geometry, such as large displacements or significant gaps;

Material non-linearity, such as plasticity or friction, in the range of response under consideration.

(ii) The direct integration and modal-superposition procedures (when appropriate) are acceptable methods to use for solution.

(iii) Non-linear analyses, shall, in general, consider all three components of earthquake motion, which shall be considered to act simultaneously unless it can be shown that individual component responses are uncoupled.

(iv) In general, more than one set of acceleration time-histories, meeting the requirements of section 2.3.2(b) should be used, and the results of the analyses shall be averaged.

2.3.3 Response-Spectrum Method

(a) Linear Methods

(i) When the response-spectrum method is used, the generalised response of each mode is determined from modal participation factor, modal frequency, spectral acceleration and mode shape vector.

(ii) It shall be sufficient to include all the modes in the analysis having frequencies less than the ZPA frequency provided that the residual rigid response due to the missing mass is added.

Alternatively, the number of modes included in the analysis shall be sufficient to ensure at least 90% mass participation. In this case, if the cutoff frequency is less than 33 Hz, missing mass correction corresponding to Sa value at the cutoff frequency shall be applied.

(iii) For modal combination purposes the residual rigid response shall be considered as an additional mode having a frequency equal to the ZPA.

(iv) Individual modal and component responses shall be combined in accordance with the requirements of section 2.3.5 and section 2.3.6 respectively.

(b) Non-linear Methods

When structures undergo inelastic response, a common means of expressing response is in terms of the displacement ductility ratio, which is defined as the ratio of maximum absolute relative displacement to its yield displacement. For the same input excitation, a non-linear response spectrum is lower than a linear response spectrum. Because ductile structures can exhibit acceptable performance during limited energy earthquake ground motion, the non-linear response spectrum is used as a basis for establishing design seismic forces. The design approach is to determine seismic response by using non-linear response spectrum corresponding to a limited amount of ductility and compare that response to structural capacities. Values of ductility may be selected based on testing and past observations of earthquake damage which correspond to acceptable seismic behaviour of the structure. Larger values may be used for more ductile structures and values at or near unity may be used for brittle or less ductile structures.

The response-spectrum method cannot be applied in a rigorous manner to non-linear multi-degree of freedom systems because superposition of modes is no longer valid. Therefore the use of inelastic response spectra is restricted to structures, which behave as a single degree of freedom system.

2.3.4 Equivalent-Static Method

The equivalent-static method is a simplified method, as compared to other more rigorous analysis methods presented elsewhere in this standard and can be used for certain simple structures.

(a) Cantilever Models with Uniform Mass Distribution

(i) The equivalent static load base shear shall be determined for these models by multiplying the cantilevered structure, equipment, or component masses by an acceleration equal to the peak of the input response spectrum.

(ii) The corresponding base moment shall be determined by using an acceleration equal to 1.1 times the peak of the applicable response spectrum. The resulting load shall be applied at the structure's center of gravity.

(iii) Acceleration values smaller than those given in (i) and (ii) above may be used, if justified. The floor ZPA may be used if it is shown that the fundamental frequency is so high, typically 33 Hz, that no dynamic amplification will occur.

(b) Other Simple Structures

For cantilevers with non-uniform mass distribution and other simple structures in which the maximum response results from loads in the same direction (i.e. no change of sign in mode shape as e.g. in a propped cantilever), the equivalent static load shall be determined by multiplying the structure, equipment, or component masses by an acceleration equal to 1.5 times the peak acceleration of the applicable response spectrum. Smaller values may be used, if justified, or the floor ZPA value may be used if it is shown that the fundamental frequency is so high, typically 33 Hz, that no dynamic amplification will occur.

(c) When the equivalent static method is applied to multiple point of attachment models, the response from the inertial loads shall be combined with the responses obtained from relative motion between points of support.

2.3.5 Combination of Modal Responses

(a) Response-Spectrum Analysis : General Modal Combination Rule

(i) With No Closely Spaced Modes

In a response spectrum analysis, if the modes are not closely spaced (two consecutive modes defined as closely spaced if their frequencies differ from each other by 10% or less of the lower frequency), the representative maximum value of a response (stress, strain, shear, moment, displacement) of a given element of the structure subjected to a single spatial component of a three component earthquake should be obtained by taking the square root of the sum of squares (SRSS) of corresponding maximum values in individual modes.

Mathematically, this can be expressed as :

$$= \sqrt{\sum \quad}$$

(ii) With Closely Spaced Modes

If some or all of the modes are closely spaced, one of the acceptable methods of modal combination is the Grouping Method explained below :

Closely spaced modes should be divided into groups that include all modes having frequencies lying between the lowest frequency in the group and a frequency 10 percent higher. Groups should be formed starting from the lowest frequency and working towards successively higher frequencies. No one frequency is to be in more than one group.

The representative maximum value of a response attributed to each group should first be obtained by taking the sum of absolute values of the response of individual modes within that group. The representative maximum value of this response attributed to all the modes should then be obtained by taking SRSS of corresponding maxima of each group and the maxima of the modes that are not closely spaced.

Mathematically, this can be expressed as :

$$= \sqrt{\sum}$$

(iii) Other methods such as double sum, ten percent or complete quadratic combination are also acceptable.

2.3.6 Combination of Spatial Components

When responses from the three earthquake components are calculated separately, the combined earthquake-induced response shall be obtained by :

$$= \pm\sqrt{\sum}$$

Where, R is any response of interest and R_i (i = 1, 2 and 3) is obtained from sec. 2.3.5 for the two horizontal components and one vertical component of earthquake motion.

Alternatively, the responses may be combined directly, using the assumption that, when the maximum response from one component occurs, the responses from the other two components are 40% of the maximum.

In this method, all possible combinations of the three components, R1, R2, and R3, including variations in sign shall be evaluated.

R = [R1 ± 0.4R2 ± 0.4R3]
OR
R = [R2 ± 0.4R3 ± 0.4R1]
OR
R = [R3 ± 0.4R1 ± 0.4R2]

These rules for combining responses apply to responses in the same direction due to different components of motion.

2.3.7 Combination of Spatial Components for Time-History Analysis

(a) In a linear time-history analysis, the analysis may be performed separately for each of the three components of earthquake motion, or one analysis may be performed by applying all three components simultaneously if the three components of earthquake motion are statistically independent. When the analysis is performed by applying all three components simultaneously, the responses are already combined.

(b) When the analysis is performed separately for each spatial component and three components of earthquake motion are statistically independent, time-history responses for each of the three independent components are combined algebraically at each time step to obtain the combined response time-history.

$$= \sum$$

(c) When linear time-history analyses are performed separately for each component, and three components of earthquake motion are not statistically independent, the combined response for all three components may be obtained using the SRSS rule to combine the maximum responses from each earthquake component :

$$= \pm \sqrt{\sum}$$

Alternatively, the responses can be combined using the 100:40:40 rule explained in sec. 2.3.6.

(d) In a non-linear analysis, the three components of earthquake motion shall be applied simultaneously to the system, consistent with the requirements of sec. 2.3.2, unless it can be shown that the response for one or more of the earthquake motion components can be determined independently.

2.4 Soil-structure Interaction - Modelling and Analysis

2.4.1 General Requirements

(a) Soil-structure interaction (SSI) effects shall be considered for all structures not supported by a rock or rock like soil foundation material.

(b) The two acceptable methods of SSI analysis are the direct method, and the impedance function approach. Requirements for these are given in sec. 2.4.3 and 2.4.4 respectively.

(c) A fixed-base condition may be assumed when the soil behaves in a rock-like manner. In general, a shear waves velocity of 1100 m/s or greater warrants a fixed-base analysis. A fixed-base support may also be assumed in modelling structures for seismic response analysis when the frequency obtained assuming a rigid structure supported on soil springs representing the soil supporting medium, established based on Tables 2.4.4-1, 2.4.4-2, is more than twice the dominant frequency obtained from a fixed base analysis of the flexible structure representation. This frequency check should also be performed for structures with stiff shear walls even when the shear wave velocity is greater than 1100 m/s.

When the soil properties vary along the depth, the values to be used in the analysis are those obtained from a weighted average over the footing influence depth. The weighing factors for this purpose shall be based on the influence zone of the footing in terms of stress levels (i.e. the soil pressure bulb below the footing) and the influence depth shall correspond to the level at which the stress intensity value is not greater than 10% of the initial value in the immediate vicinity of the footing. The values thus derived may be considered as the best estimate value for the purpose of range analysis as per 2.4.1(f).

(d) Adjacent structures on the same foundation should be modelled in the same model. Otherwise, absence of structure-to-structure interaction should be demonstrated.

(e) The effect of mat flexibility for mat foundations and the effect of wall flexibility for embedded walls need not be considered in the SSI analysis performed to establish seismic responses.

(f) The uncertainties in the SSI analysis shall be considered. In lieu of a probabilistic evaluation of uncertainties, an acceptable method to account for uncertainties in SSI analysis is to vary the low strain soil shear modulus. Low strain soil shear modulus shall be varied between the best estimate value times $(1 + C_v)$ and the best estimate value divided by $(1 + C_v)$, where C_v is a factor that accounts for uncertainties in the SSI analysis and soil properties. If sufficient, adequate soil investigation data are available, the mean and standard deviation of the low strain shear modulus shall be established for every soil layer. The C_v shall then be established so that it will cover the mean plus or minus one standard deviation for every layer. The minimum value of C_v shall be 0.5. When insufficient data are available to address uncertainties in soil properties, C_v shall be taken as no less than 1.0.

(g) Structural models defined in sec. 2.2 may be simplified for the SSI analysis. Simplified models may be used provided they adequately represent the mass and stiffness effects of the structure and adequately match the dominant frequencies, related mode shapes, and participation factors of the more detailed structure model.

(h) When a simplified model is used to generate floor response spectra, representative floor response spectra also shall be adequately matched for fixed-base conditions in both the detailed and simplified models.

(i) The potential for reduced lateral soil support of the structure should be considered when accounting for embedment effects. One method to address this concern is to assume no connectivity between structure and lateral soil over the upper half of the embedment or 6m, whichever is less. However, full connection between the structure and lateral soil elements may be assumed if adjacent structures founded at a higher elevation produce a surcharge equivalent to at least 6m of soil. Another method to account for potential partial soil-structure separation is soil property variation.

No credit may be taken for lateral support from back fill.

2.4.2 Subsurface Material Properties

Subsurface material properties shall be determined by field and laboratory tests supplemented as appropriate by experience, empirical relationships and published data for similar materials. The following material properties shall be determined for use in equivalent linear analyses: shear modulus *G*; damping ratio λ; Poisson's ratio υ, total unit weight γ_t, and modulus of subgrade reaction k. Material (hysteretic) damping in soil depends on the strain level. At low strains (< 10 - 4 %) the material damping ratio shall not exceed 2% of critical.

2.4.3 Direct Method

(a) SSI analysis by the direct method is performed in time domain and consists of the following steps :

(i) Locate the bottom and lateral boundaries of the soil-structure model.

(ii) Establish input motion to be applied at the boundaries.

(b) Lower Boundary

The lower boundary shall be located for enough from the structure that the seismic response at points of interest is not significantly affected. The lower boundary of the model may be placed at a layer at which the shear wave velocity equals or exceeds 1,100 m/sec or at a soil layer that has a modulus at least 10 times the modulus of the layer immediately below the structure foundation level. The lower boundaries need not be placed more than 3 times the maximum foundation dimension below the foundation. The lower boundary may be assumed to be rigid.

(c) Lateral Boundaries

The location of lateral boundaries shall be selected such that the effect of the waves reflected by the boundary is relatively small when reaching the structure and, thus, does not significantly affect the structural response at points of interest. Generally the response is properly evaluated if the model's boundary is set at a distance of 2.5 times the maximum foundation dimension from the building centre. Viscous or transmitting boundaries may be used to perform the SSI analysis.

(d) Seismic Input for Model Boundaries

Seismic input motion is normally defined in the free field at the surface of the ground (finished grade). In this case, the seismic input is needed at the level of the lower boundary. This is obtained from the basic earthquake motion defined at the finished grade of the site by a de-convolution analysis. Use of free field motion at lower boundary is generally conservative and acceptable [7].

(e) Time Step

For solution of the SSI analysis in the time domain, the integration time step shall be selected to be small enough (1/10 of the smallest period) to ensure accuracy and stability of the solution.

2.4.4 Impedance Method

(a) SSI analysis by the impedance function approach shall consist of the following steps :

(i) Determine the input motion to the mass-less rigid foundation.

(ii) Determine the foundation impedance functions.

(iii) Analyse the coupled soil structure system.

(b) Determination of Input Motion

The control motion defined at the free-field surface may be input to the mass-less rigid foundation.

(c) Determination of Foundation Impedance Functions

(i) Equivalent Foundation Dimensions

For impedance function calculations all mat foundations may be approximated by equivalent rectangular or circular shapes. The equivalent rectangular or circular dimensions shall be computed by equating basement soil contact area for translational modes of excitation. The equivalent embedment depth shall be determined by equating volumes of soil displaced by the embedded structure.

(ii) Uniform Soil Sites

When the soil below the foundation basement is relatively uniform to a depth equal to the largest foundation dimension, frequency-independent soil spring and dashpot constants, as given in Appendix-2 (Table-1 for circular foundations and Table 2 for rectangular foundations), may be used.

(iii) Layered Soil Sites

Where the soil deposit can be approximated by a number of horizontal layers of uniform soil or where the uniform soil deposit is underlain by bedrock at a depth less than the largest equivalent foundation dimensions, frequency dependent impedance functions shall be developed. An integral equation formulation is acceptable for computing the impedance functions. The use of finite-element or finite-difference formulations is also acceptable.

(iv) Embedded Foundations

- For shallow embedments (depth-to-equivalent-radius ratio less than 0.3), the effect of embedment may be neglected in obtaining the impedance functions, provided the soil profile and properties below the basemat elevation are used for the impedance calculations.
- When the effect of embedment is considered, a simplified formulation may be used that assumes that the soil reactions at the base of the foundation are equal to those of a foundation placed on the soil surface assumed at the foundation elevation and uses lateral soil reactions calculated independently using soil properties of the side soil. There are several simplified methods available for calculating these springs and determining where to place them. More accurate formulations using integral equations, finite-element methods, finite-difference methods, or a combination of these methods may also be used.

(d) Analysis of Coupled Soil-Structural System

(i) The coupled soil-structure system shall include the structure, or its modal representation, and the soil spring and dashpots anchored at the foundation level. The dynamic characteristics of the soil shall be defined by impedance functions computed in accordance with 2.4.4(c). The coupled soil-structure model shall be analysed for input motions as required in 2.4.4(b).

(ii) Following procedures may be used:

- Direct integration time history method in which the energy dissipation associated with the structure is included with the structural elements and the portion associated with the soil is included with the soil elements.
- Modal time history or modal response spectrum methods using composite modal damping values.

2.4.5 Uplift Analysis of Foundation

When tensile force created by the seismic bending moment becomes equal to the compressive force due to vertical load, the foundation mat will be subjected to uplift. A detailed nonlinear analysis can calculate the amount of uplift and the effect of this on stresses in the raft. However, this is a very complex process and it is desirable to have an approximate but conservative estimate and acceptance criterion. One such method (derived for rectangular rafts and applicable to circular rafts with some approximation) is given below :

The condition of uplift is translated into the following equation:

Mo = NL/6

Mo = Bending moment at initiation of uplift

N = Total vertical load due to dead weight

L = Linear dimension of foundation in plan along the direction of motion

Uplift increases with increasing bending moment and the contact ratio decreases.

Contact ratio = D/L = ½ (3 - M/Mo)

These formulas are derived for an infinitely rigid raft but can be conservatively applied to a flexible raft.

A loss of contact less than 30% of the plan dimension (contact ratio > 0.7) is considered acceptable. Under the uplift condition, the raft will see additional bending due to loss of support over a part of area. This shall be evaluated and the raft design shall be checked for the same.

Additionally, if the uplift, as calculated by this formula, is seen to be more than 30% of the raft dimension (i.e. contact ratio less than 0.7), a properly substantiated dynamic analysis can be done to get a realistic and less conservative estimate of uplift. However, if using either method the uplift is seen to exceed 30% of the raft dimension, adequate measure to tie the foundation has to be taken.

2.5 Generation of Input for Floor Mounted Equipment (Subsystem) Analysis

2.5.1 General Requirements

(a) For seismic analysis or testing of floor-mounted equipment, input motion at the support location is required. If the equipment does not satisfy the decoupling criterion as given in 2.2.8, it would be modelled specifically along with the building and this requirement would not arise. This section covers the generation of seismic input for all systems and components that are not specifically modelled in the main building dynamic model i.e. they are decoupled and analysed separately.

(b) Types of Seismic Input for Subsystem Analysis

Seismic input for decoupled subsystem analysis may consist of one or more of the following at subsystem supports :

- Floor response spectra and minimum/maximum displacements and related phase correlation.
- Floor acceleration time-histories and displacement time-histories.

(c) Direction and Locations for Floor Response Spectra or Time-histories

Translational spectra or time-history inputs in each of the two orthogonal horizontal directions and the vertical direction shall be provided at reference locations where input motion to sub-systems is required. A reference location is normally a mass point of the building model. In a stick model, the reference location or the mass point is at the floor level. These translational spectra or time-histories shall consider uncertainties as discussed in sec. 2.5.2(e) and 2.5.3(b), and effects of overall floor rocking and torsional motions.

(d) Subsystem Input Away from Reference Location

The location at which particular equipment is supported does not always coincide with the reference location. In that case, the input motion for the equipment has to be derived from the motion at the reference location.

(e) In the case of a time-history analysis of a soil-structure system subjected simultaneously or individually to the action of three statistically independent spatial components of an earthquake, the resultant translational time histories at subsystem support locations away from the reference location may be obtained by algebraic summation of the translational acceleration time-histories at reference location and the time-history contributions arising from the structural rocking and torsional efforts, as long as the intervening structure between the two locations is rigid. The resultant translational time histories thus obtained may then be used to generate the corresponding spectra.

(f) When the in-plane or transverse flexibility of the intervening structure is significant, the intervening structure shall be included in the subsystem model to analyse the subsystem response. Alternatively, subsystem seismic input spectra and/or time-histories at subsystem support locations may be generated either by using a detailed decoupled model of the flexible intervening structure if the decoupling criteria are met, or by including the flexible intervening structure in the main building system model.

(g) Floor Displacements and Rotations

Minimum/maximum translational displacements and rotations or displacement and rotational time-histories, if significant, shall be specified to determine the effects of relative seismic displacements (Seismic Anchor Movements). The locations and directions for these displacements and rotations shall be the same as those for the floor response spectra or time-histories.

2.5.2 Floor Response Spectra

(a) Floor response spectra shall be developed using the time-history method or by a direct spectra-to-spectra method.

(b) Time-History Method

(i) When the simultaneous action of three statistically independent spatial components of an earthquake is considered, the two horizontal translational components and one vertical translational component of the time-history acceleration responses at the reference location shall be used to compute the corresponding response spectra.

(ii) When the supporting soil-structure system is subjected individually to the action of the three statistically independent spatial components of the earthquake, the resultant time-history at the reference location is obtained by the algebraic summation of the individual responses.

(iii) When time-history analysis of the supporting soil-structure system is performed individually for each of two horizontal spatial components and one vertical spatial component of an earthquake, and the spatial components of the earthquake have not been shown to be statistically independent, the time histories from each individual analysis shall be used to generate response spectra at reference locations. The combined response spectra shall be obtained by combining the codirectional spectra amplitudes from three individual analyses using the SRSS rule.

(iv) When more than one statistically independent time-histories are used in a given direction, the floor response spectrum shall be the average of all the spectra corresponding to the different time-histories. When three statistically independent time-histories (a, b, c) have been generated for the three spatial components, this set of three time-histories can be used to generate three different responses in a given direction by using the combinations (a, b, c), (b, c, a) and (c, a, b) in x, y and z directions respectively.

(c) Direct Spectra to Spectra Method

(i) Direct spectra to spectra generation techniques may be used within the framework of their established range of applicability.

(ii) This method may be adopted only for initial evaluation purpose, which shall be backed up by rigorous analysis subsequently.

(iii) When the response spectrum at a given location and in a given direction has contributions from more than one spatial component of earthquake, these contributions shall be combined by the SRSS rule.

(d) Frequency Interval for Generation of Floor Response Spectra

(i) When generating floor response spectra, the spectrum ordinates shall be computed at sufficiently small frequency intervals to produce accurate response spectra, including significant peaks normally expected at the natural frequencies of the supporting structures.

(ii) One acceptable method is to compute floor response spectra at frequencies listed in Table 2.3.2-3 and at all natural frequencies of the supporting structures within the frequency range of interest. Another acceptable method is to choose a set of frequencies such that each frequency is within 10% of the previous one and then add the natural frequencies of the supporting structures to the set. Alternatively, a set of frequencies such that each frequency is within 5% of the previous one may be chosen.

(iii) The frequency interval may be increased in the frequency range above twice the dominant interaction frequency, or the cut-off frequency.

(e) Treatment of Uncertainties in Generating Floor Response Spectra

(i) Floor response spectra shall account for uncertainties in response due to the uncertainties in supporting structure frequencies and soil-structure interaction analysis.

(ii) One acceptable approach is peak broadening. The minimum broadening shall be 15% at each frequency in the amplified response region for the best estimate soil shear modulus case. In some cases the spectral broadening from variation of soil shear modulus, as described in section 2.4.1, will control. The final spectra shall envelop the upper and lower bounds on the shear modulus. In conjunction with response-spectrum peak broadening, a 15% reduction in peak amplitude is permissible provided the subsystem damping is less than 10%.

(f) Interpolation of Floor Response Spectra for Intermediate Damping

Response Spectra for an intermediate damping value $\bar{\lambda}$ may be generated from spectra for two adjacent damping values λ_1 and λ_2 provided : (i) $\lambda_1 < \bar{\lambda} < \lambda_2 \leq 3\lambda_1$ and (ii) the following relationship between spectral amplitudes and damping is used for all frequencies:

$$S_{\bar{\lambda}} = \sqrt{S_1^2 + \left(S_2^2 - S_1^2\right)\frac{\lambda_2}{\bar{\lambda}}\left(\frac{\bar{\lambda}-\lambda_1}{\lambda_2-\lambda_1}\right)}$$

where, $S_{\bar{\lambda}}$, S_1, S_2 = Spectral Amplitude associated with $\bar{\lambda}$, λ_1 and λ_2 respectively.

The above procedures are to be used for interpolation and not for extrapolation.

2.5.3 Floor Time-History Motions

(a) Methods for Generation of Floor Time-History Motions

Time-histories of floor motion may be used for equipment analysis instead of response spectra. Floor time-history response at the reference locations or subsystem support locations obtained from the time-history analysis of the supporting soil-structure system may be specified as input to singly or multiply-supported subsystems.

(b) Equivalent Broadening and Lowering of Floor Time-History Motions

(i) As in sec. 2.5.2, the effect of uncertainties has to be considered when time-histories of floor motions from the dynamic time-history analysis of the supporting soil-structure system are used. In this case, the frequency content of the time-histories from the structural analysis shall be varied to be consistent with the requirements of sec. 2.5.2.

(ii) An acceptable method to vary the frequency content of the Floor acceleration time-histories for best estimate soil properties is by expanding and shrinking the time-history within $1/(1 \pm 0.15)$ so as to change the frequency content of the time history within $\pm$ 15%.

(iii) Additional variation of frequency content shall be employed, if required, to envelop the upper and lower bound soil property case responses.

(c) Time Interval and Data Precision Requirements for Floor Time-History Motions

Acceleration and displacement data shall be provided in accordance with user requirements, which may be dependent on the subsystem analysis techniques that are to be used. In lieu of specific requirements, the time interval between data points shall not exceed 0.01 sec and acceleration data precise to 0.001g and displacement data precise to 0.0025 mm shall be provided.

2.5.4 Structural Model or Characteristics for Coupled Subsystem Analysis

(a) Equipment/piping (subsystem) satisfying the decoupling criteria (i.e there is no interaction or only marginal interaction between the building and the equipment) are analysed separately using a detailed structural model and subjecting it to the response spectra or time-histories developed in sec. 2.5.2 and sec. 2.5.3 respectively. Uncertainties in modelling are taken into account by the concept of broadening.

(b) Sometimes even the non-interacting or marginally interacting subsystems complying with the decoupling criteria are analysed as part of a coupled model. A detailed analysis of the equipment is then performed using a detailed model of the equipment and a simplified model of the building (supporting structure). The input for this model is the input motion at the base of the building. No intermediate floor motions are developed. In order to take into account the effect of uncertainties in such cases, frequency shifting of the supporting structure or the equipment, equivalent to the requirements of sec.

2.5.2 shall be applied to preclude possible underestimation of equipment response.

(c) Equipment, which do not satisfy the decoupling criteria are analysed as part of the overall building model. A subsequent analysis of the equipment may use a detailed structural model of the equipment and a simplified model of the building, with excitation at its base. In such cases, the frequency shifting as required in (b) above is unnecessary.

(d) The simplified model of the building shall be developed from a detailed model of the building in such a way that the significant frequencies and mode shapes for the fixed-based detailed and simplified models are reasonably matched at the equipment support locations. The adequacy of the simplified model shall be established by a comparison of the floor spectra at equipment support locations in the fixed-base detailed and simplified models.

(e) The base excitation to be used in the detailed equipment analysis shall include the effects of soil-structure interaction, and shall be provided at the base of the supporting structure in the form of translational acceleration and displacement time-histories and/or response spectra in three orthogonal directions.

2.6 Design of Buildings/Structures

(a) Design Check

The seismic forces and moments calculated as per the guidelines in this chapter shall be combined with the forces and moments due to other loadings in appropriate load combinations and the structure be designed as per AERB Safety Standard, AERB/SS/CSE [4] and associated Civil and Structural Engineering Standards for different structures.

3. SEISMIC QUALIFICATION OF EQUIPMENT

3.1 General

The equipment in NPP are designed for various loads viz.:

- Load during design, normal and upset conditions (pressure, temperature, mechanical, cycles, transients); and
- Loads during emergency and faulted conditions (pressure, mechanical test load etc. as applicable) including natural phenomenon like earthquake.

In most of the equipment used in a nuclear plant, the thickness based on pressure loading is adequate for resisting seismic loading also. Therefore, seismic design essentially involves design of the supports, which should be firmly fixed to the supporting structure. A check on stresses resulting from load combinations involving seismic loads still needs to be carried out.

The seismic supports should be arranged in appropriate position and direction so that the thermal expansion of the equipment is restrained as little as possible and there is no excessively large seismic response during an earthquake. If, on the other hand, the thermal expansion is restrained, it is important to confirm that the thermal stresses of the system are within the allowable limit. For the equipment such as large size storage tanks, viz., demineralised water storage tank, fuel tank, the seismic support alone is not adequate. It is necessary to reinforce the earthquake strength of the equipment itself.

3.2 Classification

Depending on the safety function performed by the SSC, various equipment of NPP are classified into three seismic categories as per AERB Safety Guide AERB/NPP-PHWR/SG/D-1. Seismic Category-1 equipment are required to be qualified for both S1 (OBE) and S2 (SSE) earthquake. Seismic Category-2 equipment are required to be qualified for S1(OBE) earthquake and seismic Category-3 equipment may be designed for earthquake resistance as per the national practice for non-nuclear application.

3.3 Structure Equipment Interaction

In most cases, the mechanical and electrical equipment come under the definition of secondary system and are analysed or tested as a decoupled system from the primary system. The seismic input for the equipment is obtained by the analysis of the structure/building (Primary Structure) in which they are housed. Their dynamic coupling to the main building can usually be neglected, provided they meet the general decoupling criteria, in subsection 2.2.8.

The decoupling criteria in sec. 2.2.8 utilise the fundamental frequencies of the structure and the equipment. In general, both the structure and the equipment are multi-degree of freedom systems. In such cases, the frequency and mass ratios can be computed mode wise using the modal frequencies and modal masses. Only the dominant modes need be considered. The number of dominant modes can be identified as those in which modal mass is more than 20% of the total mass.

3.3.1 Decoupling Criteria for Multi Supported Equipment

The decision to decouple the equipment from the building model may need to be revised in case of multi-supported equipment, such as steam generator supported at many elevation of the reactor building. The criteria given in clause 3.1.7.3 of ASCE 4-98 [5] may be adopted for this purpose.

3.4 Equipment Stiffness and Mass Modelling

Seismic analysis of equipment generally uses finite element (FE) methods. Most of the standard, commercially available computer codes have the capability to perform the analysis. In this case, modeling of stiffness and mass is relatively straightforward. One of the following techniques is adopted.

3.4.1 Beam Model or One-Dimensional Finite Element

This modeling is typically applied to beams, columns, frames, ducts, cable trays, conduits, tanks, cabinets, storage racks, which are expressed as a continuous or one dimensional finite element in a two or three- dimensional space. Masses are represented by lumped parameters, which develop a diagonalised elemental mass matrix. Pressure vessels and heat exchangers can also be modelled this way, especially when using the equivalent static method. For the equipment, which has sections of irregular shapes, a beam model of this equipment is generated using energy equivalence between plate or shell type finite element model and beam model.

3.4.2 Plate/Shell Finite Element

This type of modeling is adopted for items whose primary mode of failure is by biaxial bending stress, plane stress or plane strain. Typically included in this category are : cabinets, tanks, pressure vessels and heat exchangers whose shells support significant eccentric loads which would tend to excite shell or local modes of vibration.

3.4.3 Solid Finite Element

In this, the equipment is modeled using solid elements. This type of modeling is expensive and is preferable for local analysis to obtain correct stress picture at openings, nozzle junctions etc.

3.5 Modelling of Damping

Table 3.5.1 shows recommended values of damping for different types of equipment. Damping values higher than given in the table may be used with proper justification based on test results.

Higher damping may exist when there are many sliding supports in the system.

TABLE 3.5.1 : DAMPING VALUES (PERCENTAGE OF CRITICAL DAMPING) FOR EQUIPMENT AND PIPING

System	Earthquake Level	
	OBE	SSE
Welded steel structures	2	4
Bolted steel structures	4	7
Concrete foundations	4	7

Above values include both material and structural damping.

If the equipment, its components and supporting structure are analysed together then a modal damping may be estimated based on the weighted average of strain energy or kinetic energy.

3.6 Analysis Methods

One of the methods described in sec. 2.3 may be followed

3.6.1 Stress Analysis

Stress analysis needs to be performed using appropriate FE models described in sec. 3.4 for various loads viz. pressure, thermal, mechanical, impact loads, weights, wind, vibrations, earthquake, reactions from supports etc..

3.6.2 Codal Qualification

Seismic qualification of equipment is performed by meeting the ASME Boiler and Pressure Vessel (B and PV) Code requirements. The load combinations to be adopted for vessels, components and supports for design and service levels are given in Table 3.6.2-1. S1 (OBE) should be considered in Level B and S2 (SSE) should be considered in level D.

The combined stresses shall meet the relevant codal requirements of ASME B and PV Code section III, Division-1.

The stresses in the base plate and foundation bolts shall be checked as per applicable codes.

TABLE 3.6.2-1 : LOAD COMBINATIONS FOR DESIGN CONDITION AND SERVICE LEVELS FOR EQUIPMENT, PIPING AND SUPPORTS

Plant Classification	Design/Service level	Load Combination
Upset	Service Level B	Pressure + dead weight + sustained loads + OBE + upset condition transients (pressure, temperature, mechanical)[(2)]
Faulted	Service level D	Pressure + dead weight + sustained loads + Temperature[(1)] + faulted condition transients (pressure, mechanical, pipe rupture loads[(3)] or SSE[(2,3)])

Note :

(1) Temperature is used to determine allowable stress only

(2) OBE and SSE include both inertial and seismic anchor movement (SAM)

(3) Pipe rupture loads and SSE need not be combined.

3.6.3 Fatigue Evaluation

Apart from satisfying these limits, a fatigue evaluation shall also be performed considering 50 cycles of peak-to-peak acceleration loading corresponding to S1(OBE) level earthquake (this effectively accounts for 5 S1(OBE) events with 10 cycles in each event).

4. SEISMIC QUALIFICATION OF PIPING

4.1 General

There is an essential difference between the design of equipment and piping. The piping needs to be rigid enough to resist seismic loading. But, at the same time, extra rigidity is also harmful as it will hamper its ability to absorb thermal expansion.

4.2 Classification

NPP piping are classified into three seismic categories as per Design Safety Guide AERB/SG/D-1. Seismic category-1 piping are those required to be qualified for S1(OBE) earthquake and S2 (SSE) earthquake. Seismic category-2 piping are required to be qualified for S1(OBE) earthquake. Seismic category-3 piping are designed for earthquake resistance as per the national practice for non-nuclear application.

4.3 Structure-Equipment-Piping Interaction

The piping is normally analysed as an uncoupled system. For the uncoupled model, the input motion is required at the support points and is derived from the results of previous analysis of the supporting primary system.

It is also possible to analyse the piping along with a simplified model of the equipment. For the combined model, the input motion is the one at the base of the supporting equipment.

However, if the piping is rigid and the decoupling criterion as given in sec. 2.2.8 are not satisfied, it should be analysed along with the connected equipment and supporting primary structure. This is done to account for the interaction between the supporting structure and the supported piping.

A branch pipe can be decoupled if the ratio of moment of inertia of the branch pipe to the moment of inertia of the run pipe is more than 20. If branch pipe is decoupled from run pipe, the displacements of the run pipe at the branch to run intersection shall be treated as Seismic Anchor Movement (SAM) for branch pipe analysis. However, in this case, the branch pipe will be analysed using the spectra generated at the point of intersection.

4.4 Mathematical Idealisation of Piping System

In most of the cases, mathematical idealisation of piping system is based on linear elastic model, using 3-D line (beam or pipe) elements for idealisation of tangent pipe, bend/pipe elbows, tees, concentric/eccentric reducers, valves, pipe supports with mass or mass moment of inertia lumped at discrete nodal points.

In certain cases, 3-D continuum (shell) elements, 3-D solid elements may also be used for idealisation of piping system in linear elastic domains. This may be restricted to equipment-piping junctions for obtaining local stresses.

Similarly, in some special cases, mathematical idealisation of piping system calls for a geometric and/or material non-linear model to account for non-linear pipe support stiffnesses, sizable gaps at pipe support etc.

4.4.1 Modelling of Stiffness

Mathematical idealisation of piping element and pipe support stiffness should be in conformance with following principles :

(a) The piping is represented by a 3-D model with stiffnesses determined by accounting for axial, shear, torsional and flexural forces.

(b) Requisite input values for evaluation of piping stiffness are: outside diameter, pipe wall thickness, Young's modulus of elasticity and Poison's ratio. In additions to this, stiffness of safety class 1 pipe bend/elbow is also influenced by internal pressure (ASME B and PV Code, section III, subsection NB).

  (i) Nominal value of outside diameter is used.

  (ii) Value of nominal wall thickness minus design corrosion allowance is used.

  (iii) In principle, the values of Young's modulus used in the stiffness evaluation of piping are those at the temperatures when the seismic motion is considered acting concurrently. Since, the probaility of concurrent occurrence of a temperature transient and an earthquake is very small, the highest temperature of the piping in the normal operation may be used for evaluation of properties.

  (iv) Similarly, the value of internal pressure used in the stiffness evaluation of safety class 1 pipe bend/elbows is the normal operating pressure.

(c) The pipe supports are idealised with following boundary conditions.

Restraint : The stiffness in the restraining direction is considered.
Anchor : The stiffness for the six degrees of freedom are considered.
Snubber : The stiffness in the restraining direction is considered.
Spring Hanger : Stiffness is not considered.

4.4.2 Modelling of Mass

Mathematical idealisation of piping mass should be in conformance with following principles.

(a) The nodal points in the piping model are set with an appropriate spacing to enable full representation of the typical vibration modes upto cut-off frequency.

(b) In addition to mass of piping itself, masses of fluid in pipes, masses of thermal insulation and concentrated masses of the valves and flanges are also taken into consideration.

(c) Extended mass of valves or other eccentric masses should be idealised appropriately to account for the torsional effect associated with the eccentricity.

(d) For submerged pipe, the mass of the displaced water will be added to the mass of the pipe.

4.4.3 Modelling of Damping

The damping value used in the analysis of piping shall be limited to 4% of critical damping for SSE and 3% of critical damping for OBE irrespective of the size of piping. This includes both material and structural damping [14].

As an alternative for response spectrum analyses using an envelope of the SSE or OBE response spectra at all support points (uniform support motion), frequency-dependent damping values given below may be used, subject to certain restrictions stated subsequently [14] :

Freqency (Hz)	**Damping (% of critical)**
upto 10	5
more than 10 but less than 20	linearly varying between 5 and 2
20 and higher	2

The following restrictions apply for use of the alternative damping values stated above:

(a) Frequency-dependent damping should be used completely and consistently, if at all.

(b) Use of the specified damping values is limited only to response spectral analyses. Acceptance of the use of the specified damping values with other types of dynamic analyses (e.g., time-history analyses or independent support motion method) requires further justification.

(c) When used for reconciliation or support optimisation of existing designs, the effects of increased motion on existing clearances and online mounted equipment should be checked.

(d) Frequency-dependent damping is not appropriate for analysing the dynamic response of piping systems using supports designed to dissipate energy by yielding.

(e) Frequency-dependent damping is not applicable to piping in which stress corrosion cracking has occurred, unless a case-specific evaluation is provided and reviewed and found acceptable.

For specified seismic input motion, response of piping system is controlled by damping. Damping may be increased by using viscous dampers etc. In such cases energy dissipation capacity of viscous damper should be accounted appropriately in seismic analysis of piping system.

4.5 Dynamic Analysis Methods

4.5.1 Time-History Analysis

The Response Spectrum method (see sec. 4.5.2) is generally used for analysis of piping. This method is valid only for linear behaviour. When nonlinearities occur due to nonlinear pipe support stiffness or due to sizeable gaps at supports, time history analysis is required for evaluation of dynamic response. It is also required for generation of Required Response Spectrum (RRS) for seismic testing of safety related valves in linear piping systems, with three components of seismic motions acting concurrently.

Interpretation of vast amount of output data and cost factor prohibit the use of time-history analysis for linear piping systems. But in principle time-history analysis of linear piping system may be performed for some special cases.

The time-history used as input for the piping analysis is the floor time-history derived from the analysis of the supporting structure. When the two ends of the piping are supported on the same floor, the input motion is the motion of that floor. In case of long pipes, if the two points on the same floor have different motion, appropriately different motion shall be used in the analysis. In many cases, the piping is supported at two or more number of floors. In that case, appropriately different input motion has to be used at the different supports.

4.5.2 Response Spectrum Analysis

In general, the piping is supported at two or more number of floors. Response spectra are determined for each support motion. The two methods of Response Spectrum Analysis with multiple support input are :

(a) Envelope Response Spectrum Method (or, uniform support motion method)

(b) Multiple Response Spectrum Method (or, independednt support motion method)

4.5.2.1 Envelope Response Spectrum Method

The response spectrum to be used in this method is the single response spectrum that envelopes each of the relevant spectra at the support locations. This envelope spectrum is used at all of the support locations.

Modal and component responses are combined as follows:

(a) Modal Combination : Depending on numerical values of natural frequencies, modes can be classified as far spaced modes or closely spaced modes.

Responses should be combined by Square Root of Sum of Squares (SRSS) method for far spaced modes only.

For closely spaced modes, the responses should be combined by any of the acceptable method as per RG 1.92, Revision 1, February 1976 (Combining Modal Responses and Spatical Components in Seismic Response Analyis) viz. ten percent method, double sum method, complete quadratic combination (CQC) etc.. In lieu of this, if on the basis of study of all the mode shapes upto 33 Hz, it is demonstrated that so called closely spaced modes excite the different segments/spans of piping system which are not the adjacent segments/spans, use of SRSS method is admissible for closely spaced modes also.

(b) Combination of Spatial Components - A modal combination shall be followed by spatial combination. Directional responses should be combined by SRSS method.

4.5.2.2 Independent Support Motion RS Analysis

(a) By this technique, different supports are first separated into different groups, so that supports within a group are subjected to the same motion. A single response spectrum is applied to a group of supports, but different input spectra are applied to different groups of supports.

(b) Modal combination is performed as per sec. 4.5.2.1(a).

(c) The contributions from each support within a group are algebraically combined, consistent with the assumption of same motion.

(d) To obtain the response due to input applied at all supports, individual group responses should be combined. When no phasing information is available, they are combined using the Absolute Sum method. This method is consistently conservative when compared with the exact time history results.

However, sometimes it is excessively conservative.

(e) Algebraic combination of group responses is acceptable if it can be shown that responses of all supports are essentially in-phase.

(f) SRSS combination of individual grouped responses is acceptable if it can be shown that each of the independent spectra are un-correlated. Since the primary system (structure/equipment) is common for all supports, it leads to considerable phase correlation, and therefore, SRSS method should generally not be used.

(g) A modal combination shall be followed by spatial combination. Directional responses should be combined by SRSS method.

4.5.3 Rigid Body Response

In the analysis of piping systems, solution of eigen values problem is generally carried out upto cut-off frequency. Dynamic rsponse due to modes having natural frequencies more than the cut-off frequency is called Rigid-Body Response or Missing Mass response. This should be added to the computed response using SRSS method.

4.5.4 Seismic Anchor Movement Analysis

Response calculated in 4.5.1, 4.5.2 and 4.5.3 is the inertial response of the piping. Piping system supported from two or more number of floors in a building or between two buildings is also subjected to differential movements during seismic event. Experience of past earthquakes show that piping have failed at a number of places due to seismic anchor movement because of lack of flexibility to account for differential movements. Therefore, seismic anchor movement should be properly accounted for. This is accomplished by a static analysis in which the relative movements at supports locations are specified. If phase information is available, relative movement will be the algebraic difference between the support movements. If phase information is not available, the supports shall be assumed to move in opposite direction and the relative movement shall be the absolute sum of support movements.

Combination rules for seismic anchor movement analysis responses with inertial responses are as follows.

(a) Time-history Analysis :

At each time step, evaluate the seismic anchor movement and inertial response. Total response is obtained by algebric addition method.

(b) Response Spectrum Analysis :

Total response should be combined using SRSS method.

4.5.5 Simplified Dynamic Analysis

A simplified seismic load coefficient method as given in ASME B and PV Code, Section III, Appendix- N, may be used for calculating seismic inertia induced piping stresses, displacements, loads and support reaction loads.

4.6 Codal Qualification

Piping with safety classification 1, 2, 3, and 4 (as per AERB SG-D-1) is designed as per the requirements of ASME Section III Boiler and Pressure Vessel Code, subsection NB-3000, NC-3000, ND-3000 and national practice respectively. These requirements assure structural integrity of pressure boundary and subsection NF-3000 addresses design of piping supports.

OBE should be considered in Level B and SSE should be considered in level D.

Loading combinations for ASME class 1 components and component supports involving seismic loads are given in the following Table 4.6.1

TABLE 4.6.1 : LOADING COMBINATIONS FOR PIPING AND PIPING SUPPORTS

Design/service level	Loading Combinations	Equation to be satisfied
Service Level B	Operating pressure + dead weight + OBE (inertial part)	Eq. 9 with 1.8 Sm
Service Level B	Upset condition pressure + dead weight + OBE(1)	Eq. 10
Service Level D	Faulted condition pressure(1) + dead weight + SSE(1) OR pipe rupture loads(2)	Limits given in sec. III Appendices

Notes :

(1) The OBE and SSE loadings include the effects of inertial loading and seismic anchor movement loadings, combined using SRSS summation method

(2) For faulted condition evaluations, the effects of SSE & LOCA need not be combined.

4.6.1 Fatigue Evaluation

Apart from satisfying these limits, a fatigue evaluation shall also be performed considering 50 cycles of peak-to-peak acceleration loading corresponding to S1 level earthquake (this effectively accounts for 5 S1 events with 10 cycles in each event).

5. SEISMIC QUALIFICATION BY TESTING

5.1 General

Many of the mechanical, electrical and instrumentation and control equipment involve mechanical motion, and as such functional operability becomes an additional qualification requirement along with structural and pressure boundary integrity as required for the structure and system respectively. In general, seismic test qualification program is recommended for equipment, which are having close gaps/clearances between moving components for their functional performance, closure of these gaps/clearances can result into a possible malfunction jeopardising the functional operability of the equipment.

Active equipment viz. reactor control and shutdown devices; valves; rotating equipment viz. pumps, fans, blowers, motors; reciprocating equipment viz. compressors, diesel generators, reciprocating pumps; panels having devices like relays, contactors, recorders, switches, beepers etc. performing a mechanical motion and having close gaps/clearances between moving components fall in this category.

The equipment like pumps, fans, blowers, motors; compressors, diesel generators, reciprocating pumps, have close gaps/clearances between the moving and stationary components. The components of these equipment viz., shafts-bearings, impeller-casing, piston-cylinder, are large components and can be modelled and analysed by finite element method to demonstrate their functional operability based on deflection of the moving components during seismic events to be within the allowable gaps/clearances, as well as by demonstrating that the forces at the bearing location are less than the bearing design load. However, it may be noted here that even for these equipment, seismic qualification by testing is more reliable method to demonstrate their functional operability.

Instrumentation and control and electrical panels have devices like relays, contactors, recorders, switches, beepers etc., which have very close gaps clearances and have complex geometries, uncommon materials making it difficult to model and analyse. Valves also fall in the category of devices and equipment, which are complex in nature and cannot be modelled/analysed to demonstrate their functional operability, and have to be seismically qualified by testing. It is preferable to test the devices for their fragility so that the limiting value for their operability is known and is required to be demonstrated to be less than the one to be seen by the device in a panel at plant for the designed earthquake motion.

In general, the seismic qualification test should be conducted by mounting the equipment on a shake table. While a seismic motion is given to the shake table, the equipment should be checked for its intended functional operability. During the test, the operating conditions/loads of the equipment should also be simulated adequately. The test should conservatively simulate the seismic event at the equipment mounting location. In particular, the multidirectional and broadband nature of the seismic motion should be simulated.

Normally, the residual life of the equipment may not be significantly affected due to the shake table test, however, an equipment that has been shake table tested should, in general, not be installed in a plant, unless it can be demonstrated that accumulated stress cycles experienced by the equipment during the test will not degrade its ability to perform its intended function.

5.2 Equipment Seismic Test Qualification Specification

In order to meet the functional operability requirement of the equipment, various functions to be performed by many devices and sub-devices in the equipment and associated parameters, which are to be monitored during the shake table test shall be brought out in the equipment specification. These functions and associated parameters may include the timings of opening and closing of valves; making and breaking of electrical contacts; relay position and allowable chattering time, change of state during seismic transient; pressure, temperature, voltage, current, humidity, radiation and chemical and other load conditions/settings; characteristics of seals, gaskets and insulation and their functional requirements; the descriptions of complete operating cycle and number of operating cycles; duration and, ranges of operating loads; environmental aging requirements; and any other requirement peculiar to specific equipment etc. as applicable and as given in the general specification of the equipment.

5.3 Seismic Qualification Test Plan

The seismic qualification test plan generally includes the following elements as applicable :

(a) Seismic loads;

(b) Input motion;

(c) Mounting;

(d) Concurrent loads;

(e) Monitoring;

(f) Refurbishment;

(g) Seismic qualification test; and

(h) Test acceptance criteria.

5.3.1 Seismic Loads

5.3.1.1 Required Response Spectrum

Generally, the seismic motion expected at the place of installation of equipment in two horizontal and vertical directions are given in the form of required response spectra (RRS) in horizontal and vertical direction for 5% damping. For the equipment, which are mounted on floor, the applicable RRS are the floor response spectra of the floor on which equipment is mounted. In case the equipment is mounted on a wall, then the RRS is the envelope of the two floors connected by the wall. The RRS shall be generated by 15% broadening of the acceleration spectrum at all the frequency points of the response spectrum. The duration of the test should be equal to duration of the strong motion portion of the original time history. If the information on this is not available, the equipment should be tested for 30 seconds. If equipment is used on different floors of a plant building(s) then envelope of respective floor response spectra shall be used. The orientation of equipment with respect to two horizontal axes should be considered while giving two specific horizontal spectra or envelope of both horizontal spectra shall be given if equipment orientation is uncertain.

For the line-mounted equipment like valves or instruments mounted in panels etc. the peak acceleration or acceleration time-history or the acceleration response spectrum seen by devices shall be analytically determined and shall be used for seismic qualification testing of these devices.

If the supporting structure (piping, wall, panel or instrument support stand or panel etc.) of the device (valve, instrument, actuator etc) is demonstrated to be rigid i.e. natural frequency of the supporting structure being greater than or equal to 33 Hz, then floor response spectra may be used as RRS.

In case of rigid valves equivalent seismic loading test in lieu of shake table is also permitted. In the equivalent seismic loading test of valves, the valve assembly is rigidly mounted in the fixture. The equivalent seismic force equal to the peak acceleration value of the floor response spectrum multiplied by 1.5 times (to account for the higher mode behaviour) the valve mass is to be applied to the valve assembly at the C.G. location in weakest direction and operability of valve under this load is to be demonstrated.

5.3.2 Input Motion

5.3.2.1 Test Response Spectrum

The test facility shall generate suitable input motion to the shake table so that seismic loads as defined by RRS or acceleration levels at different frequencies as per the expected seismic loading defined above are achieved. Single frequency, multi frequency or single axis, biaxial or triaxial input motions can be employed with proper justification in such a way that earthquake environment is appropriately simulated.

The input motion shall be derived from the RRS in order to satisfy the test response spectra acceptability requirements.

5.3.2.2 Test Response Spectra (TRS) Acceptability

(a) For any waveform employed, the motion of the shake table must be adjusted so that [11]

(i) The TRS envelops the RRS over the frequency range from 1 to 33 Hz.

(ii) For comparison of the TRS and the RRS the TRS is computed with a damping value equal to or greater than that of the RRS.

(iii) It is recommended that the TRS be computed with 1/6 octave or narrower bandwidth resolution.

(iv) The shake table maximum peak acceleration is at least equal to the Zero Period Acceleration (ZPA) of the RRS.

(v) The total test duration for multi frequency testing shall be 30 sec., the strong motion portion shall be 15 sec., peak-to-peak cycles shall be 10 cycles in number, and for single frequency testing the test duration shall be 15 sec. at each frequency.

(b) The RRS occasionally requires high acceleration levels at the lowest frequencies that require very high test-table displacement capability. The general requirement for enveloping the RRS by the TRS can be modified under the following criteria [11].

(i) In those cases where it can be shown by a resonance search that no resonance response phenomena exist below 5 Hz, it is required to envelop the RRS only down to 3.5 Hz. Excitation must continue to be maintained in the range of 1 Hz to 3.5 Hz to the capability of the test facility.

(ii) When resonance phenomena exist below 5 Hz, it is required to envelop the RRS only down to 70% of the lowest frequency of resonance.

(iii) In the absence of resonance response phenomena or malfunction below 5 Hz cannot be justified, the general requirement applies and the low frequency enveloping should be satisfied down to 1 Hz.

(iv) Under any circumstances, failure to envelop the RRS at, or above, 3.5 Hz must be justified.

(c) In the performance of a test program, the TRS may, on occasion, not fully envelop the RRS. The general requirement for a retest may be exempted if the following criteria are met [11] :

(i) A point of the TRS may fall below the RRS by 10% or less, provided the adjacent 1/6 octave points are at least equal to the RRS and the adjacent 1/3 octave points are at least 10% above.

(ii) A maximum of 5 of the 1/6 octave analysis points may be below the RRS, provided they are at least one octave apart.

(iii) It is acceptable that the TRS stays below the RRS according to the limit of the vibration table provided that an additional test is performed using equivalent excitation methods (such as sinusoidal excitation), and their equivalence is demonstrated.

5.3.2.3 Triaxial Testing

Seismic ground motion occurs simultaneously in all directions in a random fashion. As such shake table test on triaxial table is a complete test. However, for test purposes, if single-axis, biaxial tests are used to simulate the three-dimensional environment, they should be applied in a conservative manner to account for the absence of input motion in the other orthogonal direction(s). Three cases may be encountered according to the type of installation available.

5.3.2.3.1 Triaxial Installation

The test is performed with simultaneous but independent input waveform into the three preferred axes of the specimen.

5.3.2.3.2 Biaxial Installation (Vertical - Horizontal)

The use of a biaxial vibration table with independent simultaneous excitation signals in the horizontal and vertical plane is acceptable.

Since in this case the motion along the two horizontal directions is not independent, two tests are then performed in order to test in and out of phase. The equipment should be installed on the vibration table in the positions indicated below:

(i) Position 1 : The equipment should be mounted and tested on the vibration table with its preferred horizontal axes at 45º to the direction of excitation of the table.

(ii) Position 2 : With preferred horizontal axes at 135º to the direction of excitation of the table.

The excitation level in the horizontal plane shall be 1.41 times the RRS along the two chosen orthogonal horizontal axes of the equipment.

5.3.2.3.4 Single Axis Installation

Single axis testing applied successively in three preferred axes of the equipment is acceptable. Since in this case the motion along the vertical direction is not applied during the application of the horizontal motion and horizontal motion not applied during the vertical motion four tests are performed. The equipment should be installed on a horizontal vibration table in the positions indicated below :

(i) Position 1 : The equipment should be mounted and tested on the vibration table with its preferred horizontal axes at 45º to the direction of excitation of the table, which is in a horizontal plane.

(ii) Position 2 : With preferred horizontal axes at 135º to the direction of excitation of the table.

(iii) Position 3 : With preferred horizontal axes at 225º to the direction of excitation of the table.

(iv) Position 4 : With preferred horizontal axes at 315º to the direction of excitation of the table.

(v) Position 5 : In addition, the equipment is mounted with its vertical axis along the direction of excitation of the table and tested.

The excitation level in each of the horizontal and vertical direction shall be 1.73 times the RRS along the horizontal and vertical axes of the equipment respectively

5.3.2.4 Testing Waveforms

5.3.2.4.1 General

Whichever test waveform is used, it shall:

(i) produce a TRS that envelops the RRS over the test frequency range-TRS and RRS shall be compared to the same damping value or with a damping value of TRS greater than that of the RRS;

(ii) possess a peak acceleration value equal or greater than the ZPA of the RRS;

(iii) ideally not include any frequency greater than the maximum specified by the RRS.

5.3.2.4.2 Time-History Test

The test is performed by applying a previously synthesised time-history to the specimen to simulate the specimen's probable excitation. The signal consists of a summation of multiple sine waves at distinct frequencies controlled in amplitude and randomly phased in order to meet the requirements of sec. 5.3.2.2.

5.3.2.4.3 Single Frequency Testing

Taking into account that the RRS is usually broadened in the amplified region, it is acceptable to carry out the test at the center frequency of the broadened region and at frequencies spaced 1/3 octave interval apart (or closer) until the amplified area of the spectra is covered.

5.3.3 Mounting

The equipment to be tested shall be mounted on the vibration table in such a way that it simulates the intended service mounting. Any interposing fixtures if used shall be such that their use will not alter the input motion. The effect of electrical connections, conduit, sensing lines, and any other interfaces etc., shall be considered and included in the setup unless otherwise justified.

5.3.4 Concurrent Loading

In principle, seismic qualification tests on equipment should be performed with the equipment subjected to normal operating loading. These include electrical loads, mechanical loads, thermal loads, pressure and all such other plant conditions. However, practically it is very difficult to include all the normal operating loads. It is therefore required that the loads which significantly affect the intended functional performance of the equipment should be included.

5.3.4.1 Environmental and Aging Simulation

Whenever required, as per the equipment's general specification requirement the equipment should be aged and irradiated. These tests are required to be performed prior to the seismic qualification test. Basic assurance is required against loss of operability from environmental aging effects such as radiation, pressure, temperature, humidity, corrosion, erosion and fatigue etc. Aging may not be significant when the equipment component is made of metal, glass or ceramic material. However, for qualification of equipment consisting of organic materials viz. plastics, elastomeric materials, epoxies, lubricants etc., which are susceptible to damage by radiation, humidity and temperature, pressure etc., environmental and aging simulation are required.

5.3.4.2 Vibration Aging

Seismic qualification tests on equipment designed to show adequacy of performance during and following a SSE must be preceded by tests that produce the equivalent fatigue effect of the five number of OBEs (seismic aging) and the equivalent fatigue effects of specified in-plant vibration resulting from normal and transient plant operating conditions.

5.3.5 Monitoring

Sufficient vibration monitoring instrumentation shall be used to determine the applied vibration levels. This data can also be used for structural analysis, functionality failure analysis, for future design changes or device change or for qualification of devices mounted on the equipment (for example instruments mounted on panel). It is also recommended that strain gauges be mounted to determine the response of the equipment at those points within the structure of the equipment which reflect the equipment response associated with its structural integrity. Sufficient monitoring instrumentation shall be used to evaluate the functional performance of the equipment before, during (when required) and after the test, viz. opening or closing timings of electrical contacts, opening or closing timings of valves, various output indications on volt meter/ ampere meters etc., operation of limit switches, actuation of mechanical/ electrical operations etc.. Any other peculiar functional characteristic of an equipment/component as per the general specification of equipment/component e.g. in case of shut down system the drop time and in case of relays, the permitted chatter time, should be mentioned. In some cases, transient response monitoring may require fast recorders.

5.3.5.1 Pretest and Intermediate Inspection

This inspection as a minimum shall include thorough visual examination of the equipment to ensure correct assembly of all the components, proper calibration of the assembly, proper calibration of test equipment, security of fasteners, adequacy of power supply and appropriateness of all control settings etc.. Intermediate inspection shall be carried out as above, on similar lines.

5.3.5.2 Functional Checks [Pre, Post, Intermediate]

In order to establish base line functional values for the equipment, pretest functional checks shall be performed as per the performance specification of the equipment. These base line functional values will then be compared with the post-test inspection values upon completion of the test sequence.

Functional checks may include following elements :

(a) Opening or closing of electrical contacts and timing.

(b) Opening or closing of valves and timing.

(c) Various outputs indications on volt meter/ampere meter etc..

(d) Operation of limit switches.

(e) Actuation of mechanical/electrical operation etc..

(f) Logic changes, changes of state.

(g) Any other peculiar function to be performed by equipment and or component as per the general specification of equipment/component e.g. in case of shutdown system, control rod drop time should be monitored.

5.3.5.3 Post Test Inspection

Upon completion of testing equipment shall be dismantled as far as necessary for the inspection to permit all parts to be appropriately tested and visually inspected. The condition of electrical insulation, mechanical parts, bearings, lubricants, electrical contacts, wiring, gear drive trains, linkages and other related constituents shall be recorded.

5.3.6 Refurbishment

Any refurbishment performed on equipment during a test program may be classified into maintenance or repair according to its degree. Examples of maintenance activities include calibration of relays and retorquing of hardware. Examples of repairs include welding or re-welding of portions of equipment, replacing damaged components such as sheared bolts and retightening loose electrical terminals. When repairs are necessary during the OBE or SSE test, retest is required unless justified otherwise.

Maintenance may be performed and testing continued. When maintenance is performed during OBE testing, it becomes part of the post earthquake field maintenance checks and procedures for the equipment.

5.3.7 Seismic Qualification Test

In general, the seismic qualification test should be conducted by mounting the equipment on a shake table. After performing the pre test inspection the equipment may be subjected to vibration response investigations to determine the natural frequencies, and the damping of the equipment. The test may be performed in the frequency range of 1-100 Hz. The exploratory test can be performed by base excitation with continuous sinusoidal sweep or by exciting the structure with movable shaker or by impact hammer testing.

Depending on the application of the test the seismic qualification test methods are classified as below and one of the following four methods can be followed.

5.3.7.1 Proof Testing

Proof testing is used to qualify equipment for a particular application or requirement. The equipment is subjected to the particular response spectrum, time-history or other parameters as defined for the mounting location of the equipment.

5.3.7.2 Generic Test

Generic testing may be considered as a special case of proof testing. Specification is usually written to encompass most, or all of the known requirements. Narrow band spectra testing leads to equipment qualification for only one power plant site at a time. A generic test encompassing two or more power plant spectra with a broadband frequency content and the equipment or the devices need not be separately qualified for each plant. If the RRS for a specified plant is enveloped by the FTRS, there is no need to test the equipment or the device again.

5.3.7.3 Fragility Testing

Fragility testing is used to qualify equipment by determining its ultimate capability; such information may be used to prove adequacy for a given requirement. The input random motion is increased till malfunction occurrence. The test response spectrum is called Fragility Test Response Spectra (FTRS). During qualification of a device, it is adequate to demonstrate that the calculated Required Response Spectrum (RRS) is enveloped by the FTRS.

5.3.7.4 Validation of Finite Element Model

Finite element models of some complex structures which can not be modelled without some approximations, can be validated for the mode shapes and modal frequency values of a few of the modes by carrying out shaketable tests.

The test methods can also be classified as follows :

5.3.7.5 Assembly Testing

A large complex assembly is subjected to the required seismic input motion while the normal operating conditions experienced by the assembly are applied or simulated and its performance recorded during the test.

5.3.7.6 Devices Testing

Shake table tests are impracticable in case of multi-cabinet assembly or large panel or equipment, which cannot be mounted on a shake table. Even for the panels which otherwise can be mounted on the shake table can also be qualified by a combination of analysis and testing. In such cases the active devices in the panel or equipment can be separately tested on a shake table. The device is fixed to the vibration table in a manner that simulates the mounting in the panel.

The input motion to be given to the table can be obtained by time history analysis of the finite element model of the panel with the device mass appropriately incorporated in the model. Subsequently a test should be performed with TRS at the base of the device location enveloping RRS.

A response spectrum analysis of the assembly can be performed to get the peak response at the base of the device. The device can then be tested on a shake table with a flat spectrum with an acceleration equal to the peak acceleration between 1-50 Hz. A universal value of 3.5 g is currently being specified for such a test. A combination of single frequency tests can also be employed for this purpose.

As device is tested using analytically determined values of acceleration, the tests should be extended beyond 33 Hz (up to 50 Hz as a minimum), to account for possible effects of impact and rattling between racks and cabinets, or between inter cabinets, which generate high frequency response.

5.3.8 Test Acceptance Criteria

Inspection shall be made to check the integrity and performance of the equipment before, during and after the test (according to the type of equipment).

The acceptance criteria shall be specified in advance. Apart from the specific functional requirements pertaining to the equipment, in general the acceptance criteria shall be prepared with the following conditions whichever are applicable.

(a) Structural failure or deflection which would inhibit or prevent intended performance of the equipment is not acceptable;

(b) Loss of output signal; for example open or short circuit;

(c) Spurious or unwanted output; for example relay contact bounce exceeding the specified limits;

(d) Change of set-point or trip setting greater than the specified accuracy over the full range;

(e) Calibration shift greater than the specified accuracy over the full range; this parameter need not be determined during vibratory excitation;

(f) Loss of required performance characteristics; for example inability to change state;

(g) Loss of pressure boundary integrity of instrumentation piping; for example leakage;

Sufficient instrumentation shall be provided to monitor and record device performance during vibratory excitation; i.e. in order to show that each of the above desired criteria have been satisfied.

Whenever these criteria are not met, the specific deviation data shall be evaluated according to the relevant specification of the equipment to suggest refurbishment.

Equipment assemblies or devices, which fail to give satisfactory test results, shall be repaired, modified, or replaced but in any case the entire test of the equipment shall be repeated and satisfactory results obtained. If devices are replaced during a test, they shall be replaced according to the general criteria of equipment specification and aged if necessary.

6. MINIMUM CONTENTS OF SEISMIC QUALIFICATION REPORT

6.1 General

A seismic qualification report should contain the following information.

6.2 Safety Classifications and Seismic Categorisation

Identify the safety class and seismic category to which the SSC belongs.

6.3 Design Specification

6.3.1 Structural Integrity

Structural integrity of SSC is assured by compliance with requirements of a design code. The design code, the load combinations involving seismic loads and the prescribed codal limits on stresses/strains shall be identified.

6.3.2 Functional Requirements

In addition, a component may be required to remain functional during/after an earthquake. These requirements should be identified along with means of checking the same by calculations (e.g. relative displacement less than clearance available etc.) or by testing.

6.4 Seismic Input

6.4.1 Design Response Spectra

Design response spectra corresponding to S1 and S2 levels should be provided to permit comparison with the site independent acceptable spectra given in AERB Safety Guide AERB/SG/S-11. Basis for any response spectra that differ from AERB Safety Guide AERB/SG/S-11 should be included.

Location/level at which the spectra are applied should also be specified (e.g. finished grade level in free field, or foundation level in free field or base of the soil-structure interaction system). Normally the spectra are provided at the finished grade level in free field.

6.4.2 Design Time-History

Time-history parameters (see sec. 2.3.2 (b)) shall be submitted. For the time-history analyses, the response spectra derived from the actual or synthetic earthquake time-motion records should be provided. A comparison of the derived response spectra with the design response spectra should be submitted for each of the damping values to be used in the design. This comparison should be made at period intervals specified in sec. 2.3.2 (b) and the enveloping requirements given therein should be satisfied.

6.4.3 Damping Values

The specific percentage of critical damping values used for structures, systems, components and soil should be provided for both S1 and S2 to permit comparison with the damping values specified in this guide. Any proposed damping values that differ from those given in the guide should be justified.

6.4.4 Supporting Media for Seismic Category 1 Structures

Foundation embedment depth, depth of soil over bedrock, soil layering characteristics, width of structural foundation, total structural height, soil properties (such as shear modulus, shear wave velocity and density) shall be included. This information is needed to assess suitability of the finite element or the lumped spring model for soil/structure interaction analysis (see sec. 2.4.2, 2.4.3 and 2.4.4) and describe treatment of uncertainties (see sec. 2.4.1 (f))

6.4.5 Soil-structure Interaction

If not considered, the basis for not using soil-structure interaction analysis should be provided. (section 2.4.1).

If the method used is the direct method (finite element method) provide:

- location of bottom boundary (see sec. 2.4.3 (b))
- location of side boundary (see sec. 2.4.3 (c))
- Seismic input at model boundaries (see sec.2.4.3 (d))

If lumped spring method is used, the parameters used in the analysis (see sec.2.4.4) should be discussed.

6.4.6 Uplift Analysis

Uplift effects (see sec. 2.4.5) should be calculated.

6.5 Seismic Analysis

6.5.1 Analysis Model

Description and sketches of the mathematical models should be provided. The purpose of the model, i.e. whether it will be used for determining the stresses or it is only the first step in a multi-step analysis, should be provided. The number of degrees of freedom and number of modes selected should be justified.

Information about computer code and its validation shall be included.

6.5.2 Method Used to Account for Torsional Effects

Torsional effects are introduced in structures with an unsymmetric layout.

These have to be accounted for by a combined vertical, horizontal and torsional dynamic analysis.

In addition consideration has to be given to accidental torsion (see sec. 2.2.1(d)).

6.5.3 Seismic Analysis Methods

The applicable seismic analysis method (e.g. response spectrum method (see sec. 2.3.3), time history analysis, direct or modal superposition (section 2.3.2), equivalent static load (see sec. 2.3.4) should be identified.

6.5.4 Application of Decoupling Criteria

Criteria for determining whether a component should be analyzed as part of a system analysis or independently as a subsystem (see sec. 2.2.8) should be included.

6.5.5 Natural Frequencies and Mode Shapes

Significant natural frequencies and mode shapes should be provided.

6.5.6 Three Components of Earthquake Motion

The response due to three components of earthquake motion has to be combined suitably. Compliance with sec. 2.3.6 shall be demonstrated.

6.5.7 Combination of Modal Responses

The modal responses (forces, moments, stresses, deflections, accelerations) have to be combined as per sec. 2.3.5.

6.5.8 Development of Floor Response Spectra

The following shall be identified:

(a) Frequencies at which the spectra are calculated (see sec. 2.5.2(d)),

(b) Consideration given to multiple time histories used during time history analysis of the system,

(c) Procedure for calculating spectra at a point on a floor, which is away from the centerline, and

(d) Consideration given to three spatial components of seismic motion.

6.5.8.1 Peak Broadening of Floor Response Spectra

To account for uncertainties in the structural properties, damping, soil properties, soil/structure interaction etc. the spectra have to be broadened as per sec. 2.5.2(e).

(a) The raw and broadened spectra to enable comparison should be provided.

(b) When floor time-histories are used in analysis the equivalent broadening has to be performed (see sec. 2.5.3).

6.6 Acceptance Criteria

6.6.1 Structural Integrity Requirements

Compliance of codal limits identified in design specifications shall be demonstrated.

6.6.2 Functional Requirements

6.6.2.1 Demonstration by Analysis

Demonstrate compliance with the functional requirements identified in design specifications. Use of analytical methods is justified only if it is possible to relate the functional requirement to calculated parameter, e.g. gap between stator and rotor or the gap between impeller and casing (should be more than the calculated relative displacement); reaction at bearing location should be less than the bearing load capacity.

6.6.2.2 Demonstration by Test

When functional requirements are satisfied by performing a shake table test, following information shall be supplied:

(a) Demonstrate acceptability of Test Response Spectra (TRS) vis-à-vis Required Response Spectra (RRS).

(b) If the test is carried out on an installation other than triaxial, testing is required to be done in different orientations and the excitation level is required to be higher. Demonstrate compliance with relevant clauses of the guide.

(c) Generally test is performed with synthesised time-history compatible with RRS. However, sometimes it may be done with multiple single frequency excitations. Show that the broadened region of RRS is covered by the frequencies selected.

(d) Provide details of mounting to show similarity with actual mounting in the plant.

(e) Provide details of concurrent loading applied during seismic test.

(f) If the general specification of the equipment calls for environmental simulation, prior environmental or vibration ageing, demonstrate compliance with the same.

(g) Provide details of instrumentation used for monitoring.

(h) Results of pre-test inspection, intermediate functional checks, post-test functional checks and post-test inspection shall be provided.

(i) Enumerate the acceptance criteria and demonstrate that these are met.

6.7 Compliance to Quality Assurance Plan

A quality assurance plan should be prepared and followed for all the activities pertaining to seismic qualification by testing. A typical checklist given below may be useful in this respect.

Project					
Equipment: Name/ Manufacturer/ Supplier					
Equipment Safety class	Electrical class		Seismic category		
Equipment mounting details	Bldg	Floor	Piping	Other	
If Equipment is mounted on floor in a building, verify that the RRS for testing is the appropriate floor response spectrum					
Hor OBE		OBE X	SSE X		
Hor SSE		OBE Y	SSE Y		
Ver OBE		OBE Z	SSE Z		
Ver SSE		Mark X,Y,Z On Mounting Drg.			
If equipment is mounted on piping or on panel or on rack etc. give the acceleration levels expected at mounting location of the equipment	OBE X		SSE X		
	OBE Y		SSE Y		
	OBE Z		SSE Z		
Reference No of the analysis report from which the floor response spectra or response at the mounting location on the piping/panel/ rack/etc. is taken					
Test Waveform	Sinusoidal		Time-History		
Test Axes	One		Two		Three
Application of seismic motion in 3 axes of equipment	Separately		Hor. and Ver.		
	All together		any other		
Is mounting of equipment on shake table simulating the site condition ?					
Are resonance search parameters acceptable ? Frequency and damping must be determined using resonance search results. Up and down sweep both shall be done.					
Location of strain gauges and accelerometers shall be checked to verify structural integrity and vibration response characteristics of equipment					
Are transducer locations acceptable ?					
Perform post test inspection and functional checks.					
Are pre-test criteria acceptable ?					
Perform post test inspection/functional checks					
Are post-test inspection acceptable ?					
Is test sequence given correctly (Pre-test, resonance (X, Y, Z) (up, down), intermediate), 5 (obe, intermediate), See , post test as applicable) ?					
Warning clause on use of tested equipment in plant given ?					

APPENDIX 1

GUIDELINES FOR CALCULATING SPRING CONSTANTS, MASSES AND LOCATIONS OF MASSES FOR RECTANGULAR BASINS

Case-1 : For rigid walls and/or without local stress concentration effects.

(a) For rectangular basins having $H/L \leq 0.75$:

$$M_o = \frac{\tanh(0.866\ L/H)}{(0.866\ L/H)} M_t$$

$$H_o = 0.375\ H$$

$$M_1 = 0.265.\ (L/H) \tanh(3.16.H/L)\ M_t$$

$$H_1 = \left[1.0 - \frac{[\cosh(3.16.H/L) - 1.0]}{(3.16.H/L) \sinh(3.16\ H/L)}\right] H$$

$$\omega^2 = (3.16\ g/L) . \tanh(3.16\ H/L)$$

$$A = Sa/\omega^2$$

$$\theta = (3.16\ A/L) . \tanh(3.16\ H/L)$$

$$\text{Slosh height (Dmax)} = \frac{0.265\ L \coth(3.16\ H/L)}{(2g/(\omega^2 . \theta L) - 1.0)}$$

$$K = \omega^2 . M_1$$

Where,

M_o = Impulsive mass

H_o = Height above basin bottom where M_o is attached

M_1 = Convective mass

H_1 = Height above basin bottom where M_1 is attached

Sa = Spectral acceleration corresponding to 'ω'

A = Max. amplitude of oscillation

θ = Angle of free oscillation

g = Acceleration due to gravity

K = Spring stiffness of convective mass 'M_1'

H, L and M_t are liquid height in the basin, basin length along the direction of motion and total liquid mass respectively.

(b) For rectangular basins having H/L > 0.75 :

In a rectangular tank where depth of the fluid exceeds three fourths of the length L, the entire mass of the fluid below the surface, equal to three fourths of 'L' from the top surface of liquid tends to respond as a rigid mass rigidly attached to the walls, in so far as impulsive pressures are concerned.

Total Mass (M_t) = L. H. B. ρ

Rigid mass (M_r) = $\frac{-}{\quad}$

Point of action (H_r) = $\frac{-}{\quad}$

Remaining mass (M) = M_t - M_r

Where, ρ = Mass density of the fluid.

This mass 'M_r' is lumped at a height 'H_r' above the bottom of the basin. For calculation of effect of mass M, the basin can be regarded as a tank with a fictitious bottom at a datum of 0.75 L below the fluid surface and supported on a solid mass extended from this fictitious bottom to the actual bottom. The formulae given in (a) above are applicable for determining the masses M_o, M_1 and other parameters.

Case-2 : For flexible walls and/or with local stress concentration effects

The impulsive mass may be uniformly distributed over a height equal to twice the distance from the bottom of the basin to the center of mass (as determined for the case of a single impulsive mass). Similarly, the horizontal springs for the sloshing effect shall be distributed over a height from the top of the water surface to the center of mass (as determined for the case of single sloshing mass). The sloshing mass shall be attached through a rigid link to the distributed springs.

The effects of water mass in the vertical direction shall be included in the building model. For water depths less than 15 m, the entire water mass may be lumped at the bottom of the basin. For water depths greater than 15 m, the effects due to the compressibility of water shall be determined on the basis of engineering mechanics principles.

Incase of basins with roofs, if the roof is located below 50% of the slosh height above the free liquid surface, the basin shall be treated as completely filled and total liquid mass may be considered as rigid mass. Sloshing effect need not be considered in such cases. If the roof is located above 50% of the slosh height, the hydrodynamic effects shall be considered in terms of both rigidly connected and flexibly connected masses as given above.

APPENDIX 2

SOIL SPRING AND DASHPOT CONSTANTS

Table 1 : Lumped Representation of Structure-Foundation Interaction at Surface for Circular Base

Motion	**Equivalent Spring Constant**	**Equivalent Damping Coefficient***
Horizontal	$= \frac{-\upsilon}{-\ \upsilon}$	$= \sqrt{\frac{\rho}{}}$
Rocking	$_{\psi} = \frac{}{-\upsilon}$	$_{\psi} = \frac{}{+\ _{\psi}}\ _{\psi}\sqrt{\frac{\rho}{}}$
Vertical	$= \frac{}{-\upsilon}$	$= \sqrt{\frac{\rho}{}}$
Torsion	$= \frac{}{}$	$= \frac{\sqrt{\ }}{+\ /\rho}$

In which υ = Poisson's ratio of foundation medium

G = shear modulus of foundation medium

R = radius of circular basement

ρ = mass density of foundation medium

$_{\psi} = \frac{-\upsilon}{\rho\ \ ^{5}}$

I_o = total mass moment of inertia of structure and basemat about the rocking axis at the base

I_t = polar mass moment of inertia of structure and basemat

Table 2 : Lumped Representation of Structure-Foundation Interaction at Surface for Rectangular Base

Motion	**Equivalent Spring Constant**	**Equivalent Damping Coefficient***
Horizontal	$= \ +\upsilon\ \ \beta\ \sqrt{\ }$	Use the results for circular base with the following equivalent radius R:
Rocking	$_{\psi} = \frac{}{-\upsilon}\beta_{\psi'}$	
Vertical	$= \frac{}{-\upsilon}\beta\ \sqrt{\ }$	(1) $= \sqrt{\ \ \pi}$ (2) $= \sqrt{\ \ \pi}$
Torsion	Use Table 1 with $= \sqrt{\ \ +\ \ \pi}$	

In which υ and G are as defined previously, and

B = width of the basemat perpendicular to the direction of horizontal excitation

L = length of basemat in the direction of horizontal excitation

β_x, β_ψ, β_z = constants that are functions of the dimensional ratio, L/B (from Figure 1)

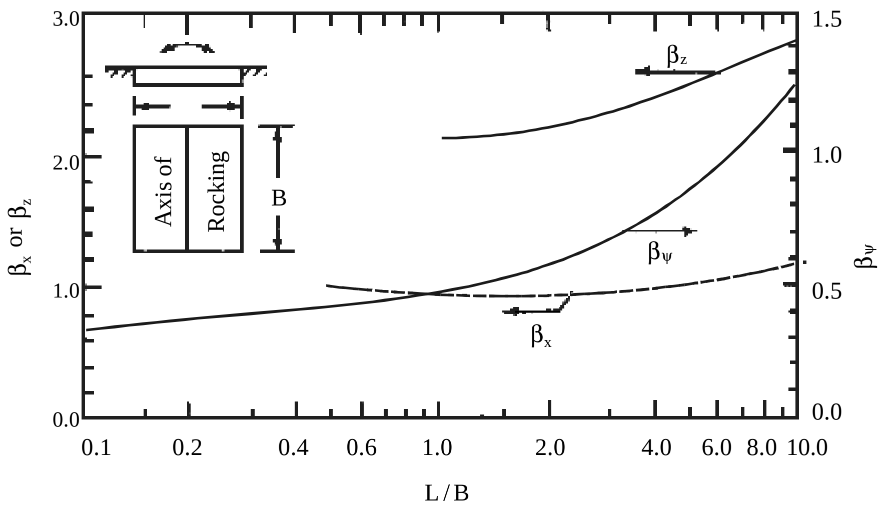


Fig. 1

* The damping calculated from these formulae shall be restricted to 7%, 20% and 30% in rocking, horizontal and vertical directions respectively.

The equivalent modal damping derived from these damping values shall not exceed 20%.

These soil springs are concentrated at the base of a beam model of the structure. When the structure is modelled differently, using plate/shell or solid elements, the vertical soil springs may be uniformly distributed over the plan area of the raft. The rotational springs need not be considered in such a model.

ANNEXURE 1

SPECIAL STRUCTURES

A1.1 Buried Pipes

Long, buried structures are primarily subjected to strains induced by ground deformation due to seismic wave passage and by differential displacement between an anchor point to a building and the surrounding ground. Inertial effects are unimportant for design of such structures. Important considerations for design of such structures are given below. For more details on response calculations, ASCE 4-98 may be referred.

A1.1.1 Straight sections away from anchor points, sharp bends or intersections.

Such sections are designed to withstand maximum axial strain and maximum bending strain induced due to seismic wave passage, assuming each point on the structure moves with the ground. Upper bound of the axial strain may be calculated considering slippage between the structure and the ground based on the maximum friction force at the interface.

Flexible joints in straight segments should withstand the maximum relative joint displacement and joint rotation calculated on the basis of maximum ground motion parameters and spacing between the joints. Generally, such displacement/rotation are negligible and are often ignored.

A1.1.2 Forces on bends, intersections and anchor points.

Axial force is calculated on the basis of the maximum strain calculated as per A1.1.2. Bending moments and shears are calculated by considering the buried structure as a beam on an elastic foundation subjected to the axial force stated above.

A1.1.3 Anchor point movement.

Forces and strains due to the maximum relative dynamic movement between anchor points and the adjacent soil shall be calculated. The motion of adjacent anchor points shall be considered to be out of phase in such calculations.

Forces and strains associated with the relative movement of anchor points shall be combined with thecorresponding forces and strains from wave propagation effects using the SRSS method.

A1.2 Earth Retaining Walls

A1.2.1 General Requirements

(a) Earth-retaining walls including basements of building structures shall be analysed for seismic-induced soil pressures.

(b) For cantilever retaining walls, the active solution may be used.

(c) For basements of building structures elastic solution should be used for earth pressure calculations.

(d) The summation of dynamic seismic soil pressures and static earth pressure shall not exceed soil static passive earth pressure.

A1.2.2 Elastic Solution

A conservative estimate of dynamic soil pressures and the corresponding resultant force and overturning moment may be obtained from ASCE 4-98. For design purpose, static soil pressure shall be calculated separately and combined with the dynamic soil pressure calculated above with appropriate load factors.

A1.2.3 Active Solution

Total of the static and dynamic soil pressures (P_{AE}) may be established as per the Mononobe - Okabe method using ASCE 4-98. In order to allow for the use of different load factors for the static and dynamic earth pressures, the overall soil pressure during a seismic event is separated into the static component (P_A) and the dynamic increment (ΔP_{AE}). The dynamic soil pressure (ΔP_{AE}) is applied at two-third of the soil embedment height from the bottom. The variation of dynamic soil pressures along the height of the wall may be represented by an inverted triangle with the maximum pressure at the ground surface.

A1.3 Vertical Tanks with Free Liquid Surface

When a vertical tank containing liquid is accelerated in a horizontal direction, a certain portion of the liquid acts as if it were a solid mass in contact with the walls. The force exerted by this mass is called the impulsive force. The acceleration also induces oscillations of the liquid, contributing to additional dynamic pressure on the wall and the bottom. This can be thought as a certain portion of the liquid responding as if it were a solid mass connected to the walls through flexible springs. The associated force is called the convective force. Important considerations for including both impulsive and convective (sloshing) effects in the design of such tanks are given below. For more details on response calculations, ASCE-4-98 may be referred.

The horizontal response analysis shall include at least one impulsive mode. The effective fluid weight (only a portion of the total weight), the height at which it is attached to the tank can be computed using formulas in ASCE-4-98. The fundamental horizontal frequency of vibration of the tank shell including the impulsive contained fluid weight can be determined using the methods which account for the flexibility of the tank shell and the effective impulsive fluid mass. The horizontal impulsive mode spectral acceleration shall be determined using this impulsive mode frequency and tank shell damping. In lieu of determining the impulsive mode fundamental frequency, it is permissible to use the peak horizontal spectral acceleration for the tank shell damping value. The spectral acceleration is used in calculating the overturning moment and hydrodynamic pressures acting on the tank shell. The overturning moment at the base of the tank due to the fundamental impulsive mode shall include the effects of the impulsive mode effective fluid weight and the effects of the weight of the tank shell acting in phase.

Similarly, in the fundamental horizontal convective mode for a vertical cylindrical tank, the effective fluid weight and height from the bottom of the cylindrical shell to the centroid of the sloshing weight as well as the fundamental sloshing mode frequency can be obtained using formulas in ASCE-4-98. The horizontal sloshing mode spectral acceleration shall be determined using the above sloshing mode fundamental frequency and damping ratio equal to 0.5% of critical damping. The spectral acceleration is used in calculating the overturning moment and hydrodynamic pressures acting on the tank shell. For the sloshing mode, the additional quantity of importance is the slosh height. If the tank top is not located above the slosh height, it shall be analyzed for the contact pressures and impact force that result from fluid sloshing against it.

If the distance form the top head to the water surface is less than 50% of the slosh height above the top of the fluid, the tank shall be treated as being full. For a full tank, 100% of the fluid weight shall be incorporated into the horizontal impulsive mode. In this case, a horizontal sloshing mode need not be considered.

The contribution of the vertical motion to hydrodynamic pressure shall also be considered. The spectral acceleration needed for this purpose, shall be calculated at the vertical fluid response mode natural frequency and damping equal to shell material damping.

The maximum overturning moment at the base of the tank shall include the effects of the impulsive and sloshing horizontal moments. An acceptable method of combining these effects is the SRSS method.

The tank shall also be evaluated for buckling considering seismically induced longitudinal compressive loads. French Code RCC-MR (2002) (Design and Construction Rules for FBR Nuclear Islands, section-I, sub-section-Z (Other Technical Appendices), AFCEN, Paris, 2002) may be referred for more details.

The seismic-induced hydrodynamic pressure on the tank shell at any level may be determined by the SRSS combination of the horizontal impulsive, horizontal sloshing, and vertical hydrodynamic pressures. The hydrodynamic pressure at any level shall be added to the hydrostatic pressure at that level to determine the hoop tension in the tank shell. ASME/BPVC-2003, Section-III, Div. 1, Appendix-N titled 'Dynamik Analysis Methods' may be referred for damping values and modal damping calculations for coupled fluid-structure analysis.

ANNEXURE 2

GENERAL DESIGN GUIDELINES FOR STRUCTURES, EQUIPMENT AND PIPING

A2.1 General Design Guidelines for Structures

A2.1.1 Layout Selection

Seismic effects should be minimised by:

(i) Locating the centre of gravity of all structures as low as possible;

(ii) Selecting a plan and elevation that is as simple and regular as possible;

(iii) Avoiding protruding sections (lack of symmetry) as far as possible;

(iv) Making the centre of rigidity at the various elevations as close to the centre of gravity as practicable.

(v) To reduce undesirable differential movements between structures, consideration should be given to locate the structures, to the extent practicable, on a common foundation structure, or at least, avoiding different embedment depths.

A2.1.2 Design Guidelines

(i) Brittle failure in shear and/or bond, or in the compressive zones of concrete should be prevented in RC structures;

(ii) An appropriate minimum compressive strength of concrete should be fixed to ensure the ultimate strength of the structural members is governed by the reinforcement;

(iii) For rebars, an appropriate minimum ratio between UTS and YS (~1.25) should be defined, to guarantee a minimum ductility (~10 %);

(iv) Appropriate design of structural joints, particularly in RC structures should provide a high ductility and a capability to accommodate high displacements and rotations. Guidelines of IS 13920-1993 (Code of Practice - Ductile Detailing of Reinforced Concrete Structures Subjected to Seismic Forces) may be followed in this regard.

A2.2 General Design Guidelines for Equipment and Piping

Following points should be taken into account to improve the resistance of equipment to an earthquake-induced vibration:

(a) For the portions of the equipment with a certain degree of freedom in design, the position of the center of gravity should be made as low as possible, and the mounting should be as stable as possible.

(b) In case when equipment with a lower safety class is closely located to equipment with a higher safety class, it is necessary to check the configuration plan to make sure that the damage to the equipment with a lower safety class due to earthquake does not affect the equipment with a higher safety class.

(c) As far as the pressure vessel itself is concerned, usually the plate thickness is controlled by the pressure (and not by seismic load) and the effect of the seismic force on the equipment is relatively small in comparison with the normal stress during operation. However, for the support structure, since the seismic force is dominant, appropriate strength check should be made considering the seismic force. It is also necessary to ensure enough stiffness for the support, particularly, in the design of the anchorage, where there is a likelihood of damage. It is of particular importance to ensure that base plates are sufficiently stiff to avoid prying effects and that anchor bolts are adequately tightened to avoid rocking effects, lowered frequencies, increased response levels, higher-than-design loads and increased risk of loosening, pull-out or fatigue. Over-designed or redundant bolts, pre-loaded on installation to the tensile force expected during a seismic event are therefore recommended.

(d) In addition, the seismic supports should be such that they do not cause difficulties in the maintenance and servicing of the machines/ equipment.

(e) It is important to avoid, as far as practicable, resonance of equipment, piping, instrumentation and core internals at the frequency of the dominant modes of supporting structures. In most cases, stiffness can be increased to avoid resonance. In some cases, when systems are made stiffer, the effect of thermal stresses, other dynamic loads and differential motions of supporting points may become significant.

(f) For S2 Level earthquake ground motion, equipment may enter the range of nonlinear/elasto-plastic behavior. In this case, it is necessary to make sure that the required ductility is present in the system, particularly in the embedded parts (EPs). The design of the embedded part (EP) of the support should be such that the failure in concrete is avoided. Therefore, the strength of the load path through concrete should be much more than the strength of the anchorage rod of the EP.

(g) Particular attention should be paid to the possibility of collision between adjacent components, or between components and adjacent parts of a building, as a consequence of their dynamic displacement.

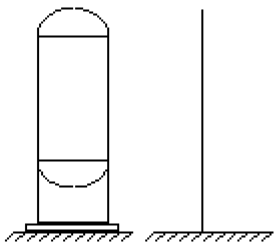
It is also important to allow for flexibility of connections between such components, between components and building penetrations and underground connections to buildings, as well as between buildings.

A2.2.1 Component Specific Guidelines

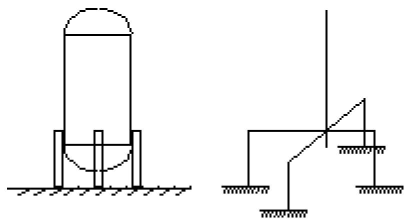
A2.2.1.1 Auxiliary Mechanical Equipment

(a) All safety related mechanical equipment, such as tanks, vessels and heat exchangers, piping and supports must be qualified to demonstrate structural integrity and pressure boundary integrity when subjected to earthquake loads. Dynamic modal analysis using time history or floor response spectrum (floor response spectrum in this case) method is certainly the most accurate procedure, but equivalent static method is also acceptable.

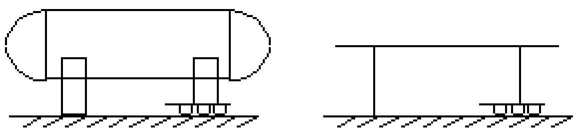
(b) For equipment such as (i) Vertical vessel with skirt support, (ii) Vertical vessel with leg support, and (iii) Horizontal vessel on two saddle type supports; an equivalent beam model can be constructed as shown in the following figure. The seismic response is predominantly associated with the first mode. Hence, it is sufficient to use spectral acceleration at the first frequency to calculate the equivalent static loads (equipment mass x spectral acceleration). A static analysis is then performed by applying this force to calculate the stresses in vessel as well as in supports.



Vertical vessel with skirt support



Vertical vessel with leg support



Horizontal vessel on saddle supports

(c) The equivalent static force together with the overturning moment acts on the anchorage system and should be designed to withstand them.

(d) For horizontal Pumps, fans and motor generators, the driver and the driven component should be connected by a rigid base or common skid to avoid differential displacement between the driver and the driven component, which could cause shaft misalignment.

(e) Avoid long unsupported pipe or a heavy valve attached to the pipe near the equipment, which may cause excessive nozzle loads resulting in damage to the pump nozzle or pump casing distortion causing bending.

(f) For vertical pumps, the impeller shaft and casing should not be cantilevered for more than 6 m below the pump mounting flange. It should have a radial bearing at the bottom of the casing to support the impeller shaft. Otherwise, there is a possibility of misalignment and bearing damage due to excessive lateral loads, damage to the impeller due to excessive displacement and damage due to interfloor displacement on multi-floor supported pumps.

A2.2.1.2 Vertical Tanks Containing Liquids

Liquid containing vertical tanks, in which the upper liquid surface is essentially unconstrained (free), are subjected to additional loading due to the motion of the liquid. Part of the liquid moves in an impulsive mode, in which the liquid moves in unison with the tank shell; while the remaining portion of the liquid moves in a convective (sloshing) mode, independent of the tank shell.

Guidelines given in Annexure 1 along with ASCE 4-98 can be followed for the seismic qualification of these tanks.

A2.2.1.3 Active Components

The guidelines provided for design of structures, systems and component (SSC) by analytical method provide assurance of structural integrity and pressure boundary integrity.

For active components, viz., valves, pumps, fans, blowers, motors, compressors, diesel generators; electrical; and instrumentation panels devices viz. relays, pushbuttons, switches, circuit breakers etc. apart from structural and pressure boundary integrity, an assurance is also required about the functionality of the equipment during and/or after earthquake.

The performance of some ‘active’ equipment (e.g. pumps, valves and diesel generator sets) under earthquake conditions can be calculated with adequate confidence by analysis, when their potential failure modes can be identified and described in terms of stress, deformation (including clearances) or loads. Typically this would involve calculating the relative displacement between the members likely to rub against each other and showing existence of adequate clearance to justify its functionability. The integrity of shaft bearings should also be assessed for the seismic loads. This specific requirement should be a part of the component specifications. It should be understood that a high level of analytical sophistication requires a number of assumptions and produces at best only an indicator of seismic behavior. Therefore, it is recommended that test or experiment be conducted to validate such analytical results, particularly with regard to functionality of the equipment.

For components such as electrical and instrumentation panels, devices viz. relays, pushbuttons, switches, circuit breakers etc. seismic qualification by testing is the recommended method.

For the shutdown system, it should be demonstrated by testing that the shutoff rods can be inserted into the core within a period required to meet the intended function.

When functionality of typical equipment has been demonstrated by analytical or experimental means for an earthquake motion, similar equipment can be considered qualified.

A2.2.1.4 Cranes

(a) For the main body (girder) of the crane, evaluation is performed for a beam model having its both ends simply supported. Since the vibration characteristics and stress generated depend on the trolley's position, it is necessary that the analysis be performed for different trolleys positions. For the strength calculation in the running direction at the support position, seismic acceleration equal to the gravitation constant multiplied by friction coefficients between the rail and wheel should be taken. For the transverse direction (direction perpendicular to the running rails), since the girder is taken as a rigid body, the seismic response acceleration is equal to the seismic motion of the building at the mounting position. Apart from structural integrity check, it is necessary to provide a mechanism to prevent the jumping of the crane from rails.

(b) Make design provisions for tethering or clamping cranes/hoists in a safe position when out of service.

(c) Lower loads onto safe areas when hoisting/handling operations are over (administrative).

A2.2.1.5 HEPA Filters

HEPA filters are generally lightweight and firmly held in position to a frame by some type of restraining mechanism. The frame should be evaluated for overall stability. No permanent deformation should take place that can affect the function of the filter bank. The restraining mechanism should restrain the filters from coming loose during an earthquake. HEPA filter needs to be functionally qualified.

A2.2.1.6 Ventilation Ducts

Seismic design of a ventilation duct consists of structural integrity check and is usually performed using one of the following methods :

(a) Dynamic analysis is performed using the modal response spectrum method to calculate the seismic load and to evaluate the strength.

(b) Alternatively, equivalent static seismic force is calculated depending on the natural frequency of the first mode of vibration and corresponding spectral acceleration. The natural frequency is calculated using the theoretical formula derived under the assumption that the duct is a beam with its two ends simply supported.

In either case, the span of the support should be shorter than the allowable limit from buckling considerations. The allowable span is calculated using the theoretical formula derived under the assumption that the duct is a beam with its two ends simply supported.

A2.2.1.7 Cable Trays

Cable trays and the supports should continue to maintain overhead support for the cables during and after the seismic event. Cable tray supports are mounted on a cantilever beam from an adjacent structural wall or are suspended from ceiling. The mounting configuration should be rigid for lateral response (braced against the wall), so dynamic amplification of seismic motion is minimal. Where rigidity cannot be achieved without an excessive increase in support member sizes, it becomes necessary to design the supports on the basis of amplified seismic loads obtained from the floor response spectra.

Following are some of the good design practices to aid the design process :

(i) The length of the unsupported cable tray between adjacent supports should not exceed 3 m in the direction of the run. Beyond the last support, the cable tray should not cantilever out by more than 1.5 m.

(ii) There should be sufficient distance between adjacent systems so that there is no seismic interaction with other systems.

(iii) Cable trays should be secured to their supports so the trays or conduit cannot slide and fall off the supports.

(iv) Cables above the top of the sides of the tray should be restrained to keep them in the tray to prevent them from flopping or falling out of the trays and being pinched or cut.

(v) All cable tray supports should pass a vertical capacity check of 4 times the dead load.

(vi) Consideration should be given to the seismic adequacy of the wall to which the cable tray and conduit raceway supports are attached. Reinforced concrete walls are not a concern.

A2.2.1.8 Electrical Systems, Control and Instrumentation Devices, Panels and Racks

The active components of electrical and control and instrumentation systems get qualified by testing. If the panel/rack is not part of the test, it is essential that the panel/rack be checked for structural integrity by analysis. If the device is qualified for a 3.5 g flat spectrum, it is necessary to show that the acceleration at device location is less than 3.5 g.

It has been observed that a significant cause of these systems failing to function properly during and after an earthquake, is lack of anchorage or inadequate anchorage. Analyses should be performed to compare the anchorage capacity to the demand imposed by the seismic loading. This capacity evaluation should extend down to the embedded parts and the concrete structure.

A2.2.1.9 Good Practices

It has been observed that failures have occurred because seemingly minor things were ignored during detailing. Following guidelines are provided to preclude such occurrences :

(a) Oversized washers or reinforcing plates are recommended for thin equipment bases. Lock washers are recommended where even low-level vibration exists.

(b) There should be no gap at the bolt or stud anchor locations for equipment containing essential relays, since they have the potential for opening and closing due to the load reversals during earthquake. This may cause impact loading on the equipment leading to generation of high frequency vibrations and may result in chatter of essential relays mounted therein.

(c) Lack of adequate stiffness in the anchorage raises two concerns. First, the natural frequency could be lowered into the resonance range. Second, it could cause lift up of the cabinet off the floor during an earthquake resulting in high frequency impact loading and chatter of relays. Such inadequate stiffness may arise due to use of thin frame members and clip angles in the construction of motor control centers, switchgear, and instrumentation and control cabinets. Stiff load paths with little eccentricity are preferable for anchorages.

(d) Battery racks should have close-fitting, crush-resistant spacers between the cells, which fill about two-thirds of the vertical space between the cells, to avoid rocking and colliding during the earthquake causing malfunction and damage. The battery racks should also have end and side rails, which are close fitting against the cells (with shims, if needed) to avoid tipping the batteries or sliding off the rack.

(e) Adjacent cabinets of motor control centers, switchgear, distribution panels, transformers which are close enough to impact each other should be bolted together to avoid unbolted cabinets responding out of phase to one another and impacting each other during an earthquake. The resulting high frequency vibration loadings could cause essential relays to chatter.

(f) Cabinets for the above mentioned items should not have large size (> 150 mm wide and 300 mm high) cutouts in the lower half of the cabinet. The concern is that the shear load from the earthquake will not be able to be transferred through the shear walls to the anchorage. Alternatively, the cutouts should be adequately reinforced.

(g) All doors and drawout panels should be secured by a latch or a fastener. The concern addressed is that the doors or drawout panels could open during an earthquake and repeatedly impact the housing, causing internal components such as relays and contactors to malfunction or chatter.

(h) For floor-mounted units such as battery chargers and inverters, the transformer, which is the heaviest component of this equipment, should be positively anchored and mounted near the base of the cabinet.

(i) For temperature sensors, the detrimental differential displacement between the mounting of the connection head and the mounting of the temperature sensor should not occur so as to prevent the wiring to be pulled out of the sensor.

(j) Valves with heavy operators should not be mounted on small lines (< 1” dia) or, valve, operator and the line should be well supported and anchored to the same support structure to avoid overstressing of adjacent piping.

(k) Valve operator cantilever length (distance between centerline of pipe to the top of the operator) should not be too large.

(l) The valve actuator and the yoke should not be independently braced to the structure unless the pipe is also braced to the same structure immediately adjacent to the valve. If the operator is independently supported from the valve and attached piping, it may act as a pipe support and attract considerable load through yoke and possibly fail or bind the shaft. If both the operator and the valve/pipe are restrained, and if they are both not tied to the same support structure, then differential motion may lead to high seismic loads.

A2.3 General Design Considerations for Piping

(a) To provide seismic restraints for piping and components and at the same time allow for thermal deformations, dampers or motion limiting stops should be used. Excessive use of snubbers should be avoided due to their implications on operation and maintenance.

(b) Realistic damping values should be used to define seismic design input, since over design for seismic loads can reduce design margins for thermal loads.

(c) When a concentrated mass, such as a valve, is attached to the piping, there is a possibility of large torsional moment getting generated due to eccentric mass. This can be avoided by placing a support as near the discrete mass as possible.

A2.3.1 Span between Vertical Supports

Piping shall be well supported vertically. A piping system may be considered well supported for deadweight if the equivalent span length between vertical supports, for liquid or gas service, is as given in ASME B31.1 Table 121.5, Suggested pipe support spacing). These values are based on a bending stress of 160 kg/sq.cm and maximum sag of 2.5 mm

A2.3.2 Span between Lateral Supports

Piping shall be sufficiently restrained in the lateral direction. In general, a piping system may be considered sufficiently restrained in the lateral direction if the equivalent lateral span length for liquid or gas service does not exceed three times the spans for vertical supports. Lateral restraint may be provided either by an engineered lateral support or by other means such as :

(a) U-Bolts - provides significant lateral restraint but no longitudinal restraint along pipe axis.

(b) Saddles - simple saddle without yoke or strap does not provide horizontal restraint. A deep saddle will provide restraint even without straps.

(c) Floor and Wall penetrations - provide restraint when gaps close.

A2.3.3 Anchor Motion

Piping must have sufficient flexibility to accommodate the seismic motions of structures, equipment and headers to which it is attached.

One of the most common causes of piping failure in strong motion earthquakes is Seismic Anchor Movement (SAM) resulting from:

(a) large displacement of unanchored tanks or equipment

(b) large displacement due to flexibility of the tank or equipment anchorage

(c) large differential motions of structures to which the piping is attached

(d) large motions of header piping induced into smaller branch piping

Suggested remedies are :

(i) Tanks and equipment to which piping attaches, must be properly anchored to prevent sliding, rocking or overturning.

(ii) Tanks and equipment to which piping attaches, and the supports should be relatively stiff to minimize SAM. When vibration isolators are present, they are a source of SAM. If there are no seismic stops built into the isolators, the equipment will require the addition of seismic restraints to limit motion.

(iii) Piping rigidly attached to two different buildings or substructures within a building must be sufficiently flexible to accommodate the differential motion. Pay attention to piping that has its axial motion restrained at supports points in two different structures.

(iv) Header motion imposed on small branches must be assessed, or the header must be restrained near the branch.

A2.3.4 Equipment Nozzle Loads

Equipment and component nozzles, except for valves that are stronger than the pipe, should be protected, by appropriate restraints, from excessive seismic loads. Piping layout should be reviewed to evaluate that large seismic loads are not reacted at the equipment nozzle. One potential problem is a long axial run of pipe not restrained from axial movement except at the equipment nozzle.

Piping reaction loads at the nozzles of rotating equipment may affect their function. The seismic reaction loads imparted by the piping on the nozzle of the active (rotating) equipment shall be within the estimated capability of the equipment.

A2.3.5 Interaction with other Structures

A piping system subjected to seismic loads will displace or swing laterally, and may impact adjacent components. Lateral displacements or swing deflections of piping spans shall be estimated. An approximate formula is :

$$S_d = \frac{1.3\ S_a}{(2\pi f)^2}$$

S_d = lateral displacement

f = natural frequency Hz

S_a = spectral acceleration at f

Impact must be avoided if it affects the following components :

- Active components
- Instrumentation tubing
- Unstable or light weight structures
- Electrical cabinets and panels

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LIST OF PARTICIPANTS

WORKING GROUP

Dates of meeting:		
	May 05, 2003	March 01, 2004
	June 02, 2003	April 05, 2004
	July 07, 2003	May 03, 2004
	August 04, 2003	June 07, 2004
	September 01, 2003	July 05, 2004
	October 06, 2003	August 02, 2004
	November 03, 2003	September 06, 2004
	December 01, 2003	October 04, 2004
	January 05, 2004	November 01, 2004
	February 02, 2004	December 06, 2004

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ADVISORY COMMITTEE ON CODES, GUIDES AND ASSOCIATED MANUALS FOR SAFETY IN DESIGN OF NUCLEAR POWER PLANTS (ACCGD)

Dates of meeting:	March 14, 2004	May 15, 2005
	January 09, 2005	April 13, 2007

Members of ACCGD:

Shri V.K. Mehra (Chairman)	:	BARC
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ADVISORY COMMITTEE ON NUCLEAR SAFETY (ACNS)

Dates of meeting: January 25, 2008

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Shri S.S. Bajaj	:	NPCIL (Former)
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Shri D.S.C. Purushottam	:	BARC (Former)
Shri A.K. Anand	:	BARC (Former)
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PROVISIONAL LIST OF SAFETY CODES, GUIDES AND MANUALS ON DESIGN OF PRESSURISED HEAVY WATER REACTOR

Safety Series No.	Provisional Titles
AERB/SC/D	Code of Practice on Design for Safety in Pressurised Heavy Water Based Nuclear Power Plants
AERB/NPP-PHWR/ SC/D (Rev.1)	Design for Safety in Pressurised Heavy Water Based Nuclear Power Plants
AERB/NPP-PHWR/ SG/D-1	Safety Classification and Seismic Categorisation for Structures Systems and Components of Pressurised Heavy Water Reactor
AERB/SG/D-2	Structural Design of Irradiated Componenets
AERB/SG/D-3	Protection Against Internally Generated Missiles and Associated Environmental Conditions
AERB/SG/D-4	Fire Protection in Pressurised Heavy Water Based Nuclear Power Plants
AERB/SG/D-5	Design Basis Events for Pressurised Heavy Water Reactor
AERB/NPP-PHWR/ SG/D-6	Fuel Design for Pressurised Heavy Water Reactors
AERB/SG/D-7	Core Reactivity Control in Pressurised Heavy Water Reactor
AERB/NPP-PHWR/ SG/D-8	Primary Heat Transport System for Pressurised Heavy Water Reactors
AER/SG/D-9	Process Design
AERB/NPP-PHWR/ SG/D-10	Safety Systems for Pressurised Heavy Water Reactors
AERB/SG/D-11	Emergency Electric Power Supply Systems for Pressurised Heavy Water Reactor
AERB/NPP-PHWR/ SG/D-12	Radiation Protection Aspects in Design for Pressurised Heavy Water Based Nuclear Power Plants
AERB/SG/D-13	Liquid and Solid Radwaste Management in Pressurised Heavy Water Based Nuclear Power Plants
AERB/SG/D-14	Control of Air-borne Radioactive Materials in Pressurised Heavy Water Reactors

PROVISIONAL LIST OF SAFETY CODES, GUIDES AND MANUALS ON DESIGN OF PRESSURISED HEAVY WATER REACTOR (CONTD.)

Safety Series No.	Provisional Titles
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AERB/SG/D-18	Loss of Coolant Accident Analysis for Pressurised Heavy Water Reactor
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