Inputs for seismic Design of Equipment and Piping Systems

Dr. G.R. Reddy, Ph.D (TMU,Japan)
Professor Emeritus, Applied Mechanics Department, VNIT Nagpur,
Adjunct Professor, VJTI Mumbai.

An equipment or cascaded series of Equipment perform variety of task(s) in industry. Some of these equipment may be connected by Piping Systems, which hold and circulate fluids and gases. These Piping Systems themselves are supported within the same floor, across the floors or across the buildings, staging or supporting structures. Similarly, the equipment may be supported within the same floor, across the floor. The Equipment and Piping System along with their normal intended design functions shall be designed and constructed to resist the earthquake effects during and after an earthquake in accordance with the requirements and provisions of relevant standards. This guidelines describes the primarily the procedures for generating earthquake inputs to design and provides steps to be followed to estimate earthquake forces for design of such Equipment and Piping System.

A systematic design for earthquake loads ensures high safety of the plant and protects the industrial personnel and public around the plant.

The performance of Equipment and Piping System under normal design conditions are taken care by the applicable design code for its normal intended design performance. However, safety of the industry depends on the performance of Equipment and Piping System under accidental loads such as earthquake, wind, etc. Since, earthquake, wind etc., loads are low probable events, therefore, these loads are not considered to be occurring together at the same time. Only one of these types of accidental load is considered to be occurring at any time and accordingly, is combined with the normal design loads.

The guidelines deals with seismic design parameters, specific seismic design requirements for the design and analysis of above ground metallic equipment and piping systems. For non-metallic equipment and piping, seismic loads may be evaluated using these guidelines.

Like some of the structure/ buildings, equipment is complex. It may consist of all stationary parts or it may have parts, which are themselves moving. Hence, we need to classify the equipment such as stationary/ static in nature, like heaters/ coolers/ transformers/ circuit breaker/ etc. and here also may be mechanical, electrical etc. as their treatment may be different. Similarly, classify the equipment such as that with moving parts/ dynamic in nature, pump/ fan/ turbine/ motor/ generator/etc. and here also may be mechanical, electrical etc. as again their treatment may be different. For all such equipment and systems, design inputs shall be evaluated using these standards.

DESIGN INPUTS

For ground mounted equipment

For ground mounted equipment, the response spectrum analysis shall be carried out using Design Response Spectrum corresponding to seismic hazard as per the seismic categorization.

Seismic categorization of static equipment and piping systems

Categorization of the equipment and piping systems shall be based on the hazard potential, possible scenarios and consequences in the case of failures under normal and accidental loads. Depending on the seismic importance the equipment and piping systems shall be classified to various categories. For each specific category, it is necessary to ensure that it is safe with respect to the designed seismic force. The objective of categorization is to identify those equipment and systems from the point of view of earthquake, which needs to considered for safety in the event of an earthquake. In case of equipment/ piping systems, designer has to include few more complexities, such as when earthquake is anticipated the equipment can be made to shut down and need not perform or it is of type where its performance is necessary and it cannot be shut down. The purpose of this categorization is to facilitate the protection of public and environment against release of toxic gases, fire, etc. through following demands:

a. that equipment/piping needs to be in position, hence, check the adequacy of its support system for additional forces induced on account of earthquake.

b. that equipment and piping are designed with adequate margins to perform its intended functions during/ after the earthquake event.

c. To prevent accidents due to failure of Piping / equipment

d. To mitigate the consequences of accidents

In this guidelines, categorization is made considering seismic hazard and safety requirements.

Seismic Category I

Category-I shall include the equipment and piping systems whose failure can cause conditions that can lead directly or indirectly to extensive loss of life/ property to population at large in the areas adjacent to the plant complex (referred as '**off-site condition'**). Equipment and piping systems under this category shall be designed and demonstrated to withstand the consequences of ground motion associated with return period of 2475 years.

Seismic Category II

Category-II shall include the equipment and piping systems whose failure can cause conditions that can lead directly/ indirectly to serious fire hazards/ extensive damage within the plant complex (referred as 'on-site condition'). The items categorized under this category shall be designed with suitable importance factor to withstand consequences of ground motion associated with DBE with return period of 1475 years

Seismic Category III

Category III shall include the equipment and piping systems whose failure, although expensive, does not lead to serious risk within the plant complex. The items categorized under this category shall be designed with to withstand consequences of ground motion associated with DBE with return period of 975 years.

Seismic Category IV

All other equipment and piping systems shall be considered into this category. The items categorized under this category shall be designed with suitable importance factor to withstand consequences of ground motion associated with DBE with return period of 475 years.

Simplified models can be used for evaluating the forces in Category IV equipment and piping systems.

Equipment

Ground seismic response spectra shall be used for all the equipment supported directly on ground.

Industrial floor mounted equipment are supported at different elevations of the structure. This equipment shall be designed using Floor Time History (FTH) or Floor Response Spectrum (FRS). From structural analysis, FRS shall be obtained at various floor levels and at the locations where equipment and piping are supported. FRS shall be generated for damping of the equipment and piping systems using time history analysis or stochastic analysis or direct simplified methods as explained in these guidelines and Commentary 2 and 3.

Piping systems

Seismic response spectra applicable for the piping can either be ground response spectra or a floor spectra obtained as explained in these guidelines and Commentary 2 and 3. Further, the design ground response spectra for the seismic qualification shall be either site specific spectra or the spectra from IS 1893 (Part 1).

Ground seismic response spectra shall be used for all the piping supported directly on ground.

Floor seismic response spectra shall be generated from ground seismic response spectra for each elevation of the supporting structure as explained in this guideline. In case the entire piping loop spread within a single floor, floor spectra of the respective floor shall be used for the design.

In case the piping is connected to more than one floor, in addition to the floor response spectra, data regarding peak floor displacements shall also be made available for the purpose of Seismic Anchor Moment (SAM) analysis to account for the differential support movements.

In case of piping running in multi floor levels of building or multiple buildings, multi support excitation as explained in Annexure 3 and SAM should be considered in the analysis.

Generation of spectrum compatible time histories

Spectrum compatible time history is generated from Power spectral density function (PSDF) which is compatible with Design Response Spectrum (DRS). The DRS compatible time history is called Design Basis Time History (DBTH) can be generated directly from response spectrum using two methods as described in Annexure-1 or from ensemble of actual earthquake. The procedure for generation of time histories is also provided in this annexure. Other suitable methods may be adopted meeting the compatibility requirement as explained in annexure 4. IS 1893:2002 spectrum compatible time histories were generated using above mentioned procedure and given in Commentary 3. Other similar suitable methods of generating time histories ensuring the compatibility may also be used.

Generation of floor response spectra

The floor response spectra shall be generated using any of the following methods.

1. Time history method
2. Direct method
3. Approximate method

For details with examples Commentary 3 may be referred.

Floor response spectra generation using time history method

Generally time history (time domain) methods are used for generating Floor response spectra (FRS) from Floor Time Histories (FTH). Frequency domain methods, called stochastic methods are also used sometimes for generating FRS. Designers/utility engineers generally prefer to use former method because the codal design inputs are in time domain.

The various steps shall be followed in time history analysis are:

1. Generate design basis ground motion called DBTH.
2. Generate mathematical model of the structure. The model could be beam model or 3D finite element (FE) model.
3. Generate floor time histories from the structural analysis using DBTH as explained in Annexure 1. Time history data compatible with IS 1893 spectrum are provided in commentary 3 may be used for generating FRS.

4. Generate FRS using floor time histories. While generating FRS, 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 structure. One acceptable frequency intervals to compute FRS is, at frequencies listed in the following Table.1 In addition it is suggested to include the frequencies of the structure also.

Table 1: Frequency steps for FRS generation

Frequency Range (Hz)	Increment (Hz)
0.1-0.5	0.10
0.5-3.0	0.10
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	1.0
18.0-22.0	2.0
22.0-34.0	3.0

Direct method of evaluating floor spectrum using Design Ground spectrum

The FRS may be obtained directly from the two design ground spectra which correspond to the damping value of the structure and the equipment or piping systems, using modal characteristics of the structure obtained in modal analysis. The various steps involved in generating FRS are:

1. Obtain the design basis ground motion called design basis response spectra corresponding to the damping value of the structure and the equipment or piping systems.

2. Generate mathematical model of the structure. The model could be beam model or 3D FE model.
3. Obtain the eigen values and eigen vectors of the structure by modal analysis.
4. Generate FRS by using the eigen values and eigen vectors of the structure.

Spectral acceleration at i^{th} mode of the structure and at j^{th} natural frequency of the equipment is given as follows.

$$Sa_{ij} = \frac{1}{\sqrt{\left\{1-\left(\frac{\omega_{Ej}}{\omega_{Bi}}\right)^2\right\}^2 + 4\left(\xi_{Ej}+\xi_{Bi}\right)^2\left(\frac{\omega_{Ej}}{\omega_{Bi}}\right)^2}}\sqrt{\left\{\left(\frac{\omega_{Ej}}{\omega_{Bi}}\right)^2 Sa\left(\omega_{Bi},\xi_{Bi}\right)\right\}^2 + Sa\left(\omega_{Ej},\xi_{Ej}\right)^2} \quad (1)$$

$$S_{aj} = \sqrt{\sum_{i}^{n}\left(\Gamma_i \emptyset_{ik} \times S_{ij}\right)^2} \quad (2)$$

Where (abbreviations)

Sa_j = Floor response spectrum value at j^{th}frequency of the equipment or system idealized as SDOF and taking into account all building modes (i=1 to n)

Γ_i = The i^{th} modal participation factor of building

ϕ_{ik} = k^{th} floor mode shape in i^{th} mode of building

ζ_{Ej} = Damping factor of Equipment or system at j^{th} frequency

ω_{Ej} = j^{th} frequency of the equipment or system

ζ_{Bi} = Damping factor of the building in i^{th} mode

ω_{Bi} = i^{th} modal frequency of the building

$Sa(\omega_{Bi},\zeta_{Bi})$ = The standard design ground spectral value corresponding to ω_{Bi},ζ_{Bi} of the building.

$Sa(\omega_{Ej},\zeta_{Ej})$ = The standard design ground spectral value corresponding to ω_{Ej}, $\zeta_{Ej}$of the equipment or systems idealized as SDOF.

Notes:

(1) The mass or modal mass of the equipment or piping needs to be less than 1% of the mass or modal mass of the structure.

(2) The floor response spectra, obtained from the above method, shall be broadened by at least 15% to account for the uncertainty in soil-structure-interaction, equipment-structure-interaction and numerical procedures adopted in analysis.

(3) Commentary 2 gives simple case study for generating FRS using direct method. It also gives comparison of FRS generated using approximate and time history methods.

Approximate method of evaluating floor spectrum using Design Ground spectrum

, The Floor Response Spectrum (FRS) at a particular floor within a structure may be obtained by directly multiplying the design Ground Response Spectrum (GRS) by a factor depending on the height of the floor with respect to the total height of the structure. The FRS is given by:

$$S_{aF} = S_a\left(1 + c\frac{h}{H}\right)$$

Where

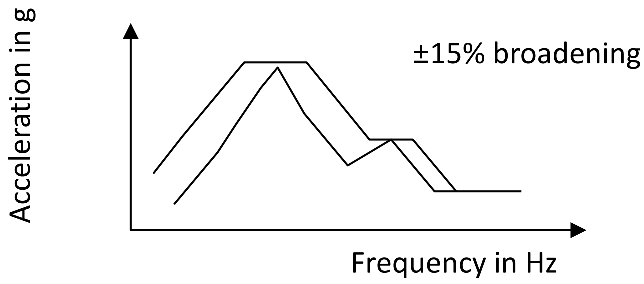
S_{aF} = Spectral acceleration of FRS

S_a = Spectral acceleration of GRS
h= Height of equipment/ piping support element above the grade
H= Height of the structure
and c=3 for 5% damping.

Peak Broadening Floor Response Spectra

Peaks of FRS occur at natural frequency predominantly and these should be evaluated as accurately as possible. However, floor response spectra shall be broadened (±15%) before using in design to account for variations of Frequencies due to uncertainty in the following.

a. Soil-structure interaction
b. Equipment-structure interaction
c. Numerical structural modelling and analysis procedures in estimating the natural frequencies**.**



If the building frequencies evaluated by numerical analysis are complied with in situ testing, ±10% peak broadening is adequate.

Development of numerical models and analysis

It is a common practice to carry out finite element analysis for qualification of equipment and piping systems. Either stick models or detailed three dimensional models shall be used for analysis and the details are given in Commentary 1. Some of the equipment of the industry is supported on a foundation resting on a soil column or rock depending on the site soil condition. The soil-equipment-interaction is required to be considered and the details are provided in subsequent section. Also, whether coupled or de-coupled models of equipment, supporting structure are to be used depends on frequency and mass ratios as detailed below.

Checking coupling effects- Decoupling criteria

Decoupling criteria is based on the frequency/modal frequency ratio R_f and mass/modal mass ratio R_m of the secondary system (SS) called equipment to the primary system (PS) called structure and given as:

$$R_f = \frac{Frequency\ of\ Secondary\ system}{Frequency\ of\ primary\ system}$$

$$R_m = \frac{Mass\ of\ Secondary\ system}{Mass\ of\ primary\ system}$$

Where R_f is the ratio of frequency or modal frequency of uncoupled SS to the uncoupled PS and R_m is the ratio of mass or modal mass of the uncoupled SS to the uncoupled PS.

i) Decoupling can be done for any R_f, if $R_m < 0.01$

ii) If $0.01 \leq R_m \leq 0.1$ decoupling can be done provided $0.8 \geq R_f \geq 1.25$

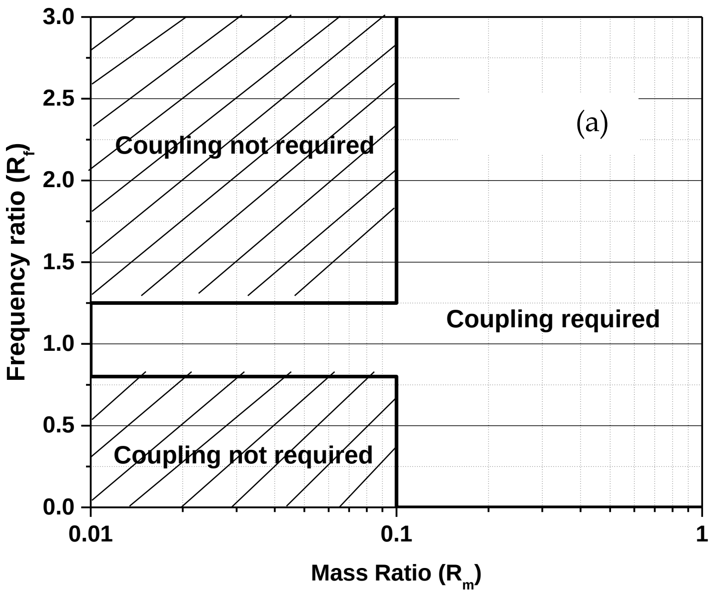
iii) If $R_m \geq 0.1$ and $R_f \geq 3$ (i.e. rigid secondary structure) It is sufficient to include only the mass of the system in the primary structure.

iv) If $R_m \geq 0.1$ and $R_f < 0.33$ (Flexible secondary system) decoupling can be done.

v) If $R_m \geq 0.1$ and $0.33 < R_f < 3$, coupled system analysis is required.

Note that the modes whose participation is more than 20% need to be considered in evaluating above ratios.

Fig. 1 (a) and (b) shows the graphical representation of decoupling criteria for Primary and secondary system.



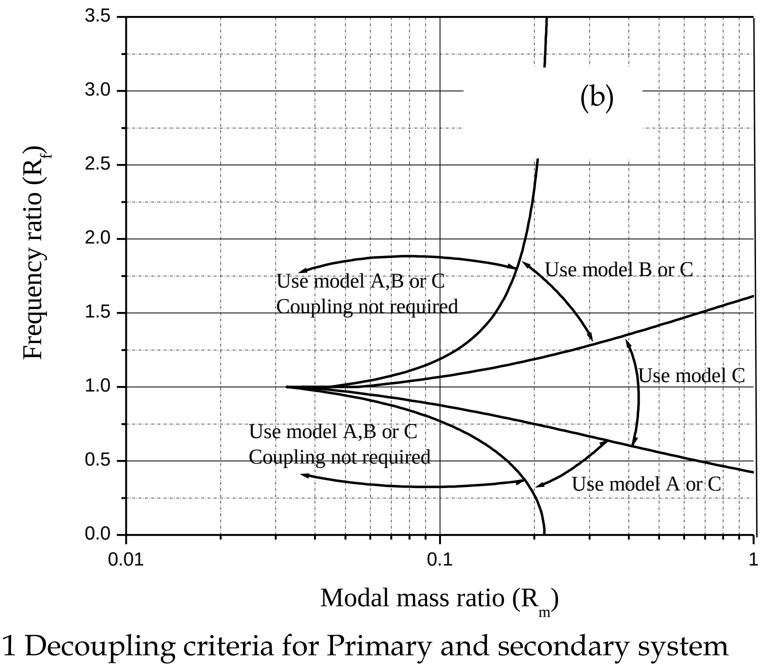
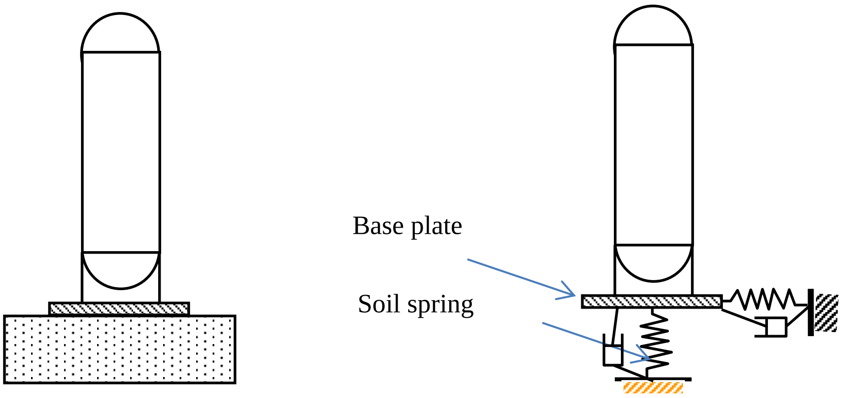


Fig. 1 Decoupling criteria for Primary and secondary system

One of the above criteria shall be adopted for checking the requirements of coupling the equipment to the structures.

Soil-Equipment Interaction

Soil-Equipment interaction effects shall suitably be modeled using soil springs below the equipment. The procedure is same as that of soil-structure interaction and the details of Foundation. Soil and Foundation Pile Group Stiffness are provided in Table 13 of IS 1893: Part-4 . An example for a vessel on soil springs is shown in Fig. 2.



a. Skirt supported

b. Model of vessel with soil springs

Fig. 2: Example for a vessel on soil springs

Selection of number of nodes and elements

Number of nodes shall be selected based on the response output desired and accuracy of results. For example in the stick models a node is required where the piping or equipment are supported, a node is needed at each floor level etc.. Nodes are also added suitably based on the number of modes to be evaluated up to rigid frequencies. The rigid frequency is generally considered as ≥ 33 Hz. The number of modes required within the 33 Hz shall be evaluated approximately using the classical formulae. For example in the piping system, span between the two supports can be isolated and number of modes within 33 Hz can be evaluated and accordingly number of nodes can be fixed. Similarly in the cantilever type of structures and equipment, number of nodes can be fixed for evaluating appropriate frequencies within 33 Hz. Minimum number of nodes can be obtained using the following equation:

$N=2m+1$

where, 'N' is number of nodes and 'm' is number of modes

It is recommended to consider twice this minimum number of nodes for analysis. Similar approach may be followed if the structure/equipment has simply supported end conditions, fixed-pinned end conditions or other combinations. For more details Commentary 1 for number of nodes and Annexure-2 for number of modes may be referred.

Modelling of Mass

The inertial mass properties of structure, equipment or piping may be modeled using lumped formulation or alternatively, the consistent mass formulation may be used. Generally, mass and mass moment of inertia shall be lumped respectively along three translational and rotational degrees of freedom. Some degrees of freedom such as rotation may be neglected provided that their exclusion does not affect response significantly. The following conditions shall be met:

1. Structural mass shall be lumped so that the total mass, as well as the center of gravity is preserved.
2. 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.
3. To ensure 100% mass contribution in the response, missing mass correction may be performed as explained in Annexure 2. It may be not required for structures designed based on 90% mass participation. Nevertheless, it is must for piping and also may be needed for equipment with large internals.

Modelling of Damping

Damping is a common designation for all kinds of energy dissipation of vibratory equipment. In equipment, energy dissipation takes place due to internal material friction, sliding/impact at the joints and connections.
The critical damping of a material is a value for which the oscillatory motion gets seized.
Damping ratios for equipment materials are generally less than 20% and for different materials damping values are different.
(a) Damping coefficients listed in Table 2 and Table 3 may be used for equipment composed of the same material.
(b) When modal analysis is to be performed for equipment and piping with only one type of material (hence single value of damping), the damping values given in Table 2 shall directly be used for modal damping. For equipment that consist of subcomponents with different damping properties, the equivalent modal damping values may be obtained using the method given in next section which is based on strain energy equivalence.

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:

$$[C] = \alpha[M] + \beta[K]$$

Where, α and β are proportional damping coefficients and are given by

$$\alpha = \frac{2\xi\omega_{max}\omega_{min}}{\omega_{max} + \omega_{min}}$$

$$\beta = \frac{2\xi}{\omega_{max} + \omega_{min}}$$

Where, ξ is the damping ratio from Table 2.

The two circular frequencies ω_{max} and ω_{min} are the un-damped circular frequencies selected to define the range of frequencies which contribute to the response of the equipment or piping or together. The ω_{min} is the first modal frequency and the ω_{max} is the maximum frequency corresponding to final significant mode which is usually considered to be 207 radian/s (33 Hz). In certain cases, it may be the value where the spectral acceleration is constant.
For non-proportional damping, the damping values corresponding to the modes may suitably be added in the damping matrix.

Evaluation of Modal Damping

There may be different damping values because of variation in material, due to soil damping, or due change in geometry. One of the examples is a beam model of a vessel as shown in Fig. 3 resting on foundation. In the model the foundation stiffness and damping can also be added.

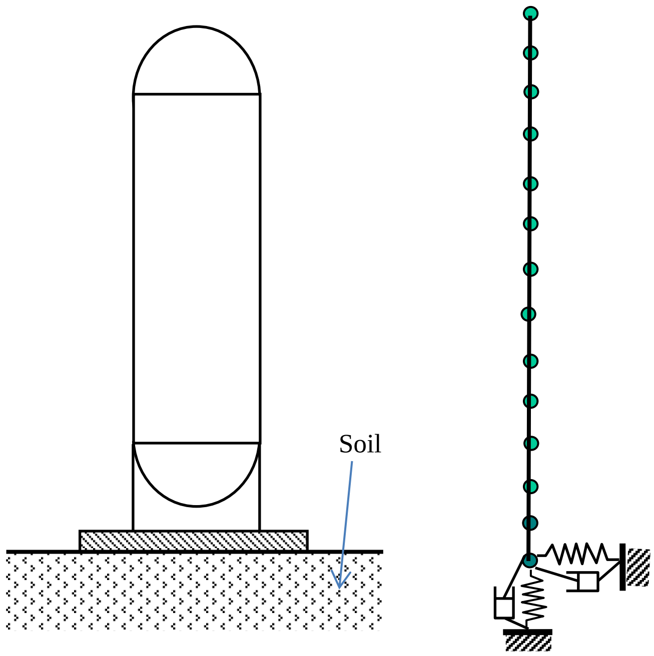


Fig. 3 Vessel on foundation

In this cases, the percentage of critical damping in each mode evaluated using the weighted strain energy principle has been described below.

Strain energy of the equivalent system in mode j is equal to sum of the strain energy of the individual element

$$\xi_j \{\Phi\}^T \sum_{i=1}^{N} [K]_i \{\Phi\} = \{\Phi\}^T \sum_{i=1}^{N} [\xi K]_i \{\Phi\}$$

$$\xi_J = \frac{(\phi_J)^T \left[\sum_{i=1}^{N} [\xi K]_i \right] (\phi_J)}{\omega_j^{\ 2}}$$

The following equation may be used for the mass-weighted damping based upon kinetic energy principle:

$$\xi_j = \{\Phi\}^T \sum_{i=1}^{N} [\xi M]_i \{\Phi\}$$

Where (abbreviations)

ξ_i = damping ratio of the element (subsystem)

$[K]_i$ = stiffness matrix of the i^{th} element (subcomponent)

$[M]_i$ = mass stiffness matrix of the i^{th} element subcomponent

Φ = Mass normalized mode shapes

The uncertainty in evaluation of damping matrix using Rayleigh coefficients can be eliminated considering modal damping based on strain energy principle in modal superposition technique.

Table 2: Damping values for various equipment and piping systems in percentage of critical damping

Type		Category I,II &III
Welded equipment		4%

Bolted equipment.		7%
RCC foundation		7%
Piping systems		4%

Note: If the equipment is bolted to foundation, it can be considered as bolted equipment. If the equipment is welded to the foundation, it may be considered as welded equipment.

Table 3: Damping ratio for various supports

Type of support		Category I,II,III & IV
Steel support structure		4%
Concrete support structure including Foundation (consider Soil Structure Interaction (SSI) as explained above)		7%

Note:

Above information is suggestive. However, the damping values specified by design code may also be adopted.

QUALIFICATION OF ACTIVE EQUIPMENT

The general methods of seismic qualification of equipment shall be based on analysis, testing and combination of analysis and testing. The choice should be based on the practicality of the method for the type, size, shape and complexity of the equipment.

Need for testing

Structural integrity, certain serviceability requirements such as leak tightness can be fulfilled by analysis but the functional requirements of equipment specially rotating mechanical components, electrical components may be difficult in most cases. In addition to this, conforming the performance levels of the equipment in plastic conditions become sometimes difficult. In these situations testing or combination of analysis and testing of active equipment shall be performed to qualify the equipment.

Methods of testing

The standard IEEE 344 discusses the details of testing for seismic qualification of Class 1E equipment for nuclear power generating stations. However, the procedures described in the standard shall be followed in general for all the equipment and the important aspects that shall be considered are:

i. Some equipment such as tall process columns are generally very large in size and weight and it is not possible to test full equipment on existing shake tables. In addition, simulation of boundary conditions on the test table is difficult (which depend on the foundations and the soil/rock supporting it). Due to these reasons equipment shall generally qualified using well established and proven analytical/numerical procedures.

ii. To find out the ultimate capacity of the equipment, scaled models of equipment shall be used. While scaling, the dynamic characteristics like frequencies, mode shapes shall be simulated using similitude principles(e.g Buckingham pi-theorem).

iii. The natural frequencies of the model are generally higher than the actual equipment. In these situations if the frequency of the test model need to be matched with the actual equipment for having the same response rate effect on the behavior, sufficient mass may be added to the model. Otherwise the response spectra may be shifted to see the same response acceleration as that of full equipment at the model frequencies.

iv. In case of active equipment, systems like electrical and control systems, it may be possible to test full scale model.

Required and Test response spectrum

For testing of equipment mounted at the ground and at different elevations of the structure, artificial time history compatible with Required Response Spectrum (RRS) is to be generated. The RRS at different floors of the structure, which supports equipment and systems, is same as Floor Response Spectrum. Time histories shall be selected or developed, so that they reasonably represent/ envelope the RRS. The response spectrum of the test time history is called Test Response Spectrum (TRS). Compatibility checks as explained Annexure 4 shall be adopted.

Measurements

Dynamic/vibration signals such as displacement, velocity, accelerations, strains and loads shall be measured Suitable sensors to measure these vibration/dynamic parameters shall be used. The various sensors to record these signals are called displacement, velocity and acceleration sensors.

Documentation

A detailed document shall be prepared. The document should contain natural frequencies, mass participation of the tested equipment, RRS, TRS, displacement, velocity, acceleration, loads and strains recorded during the test. The document should also contain the comparison of equipment response with permissible/performance limits.

Acknowledgements

Some of the information is taken from draft IS code on seismic design of Equipment and piping systems. We acknowledge the respective working group efforts. Also, efforts of Scientists from Bhabha Atomic Research centers who contributed for generating compatible time histories are highly acknowledged.

If you have questions or wanted to have two / three days workshop

Contact: 1. Dr. G R Reddy (9757085116)

2. Dr. R K Ingle (9822574061)

3. Dr Sachin Bakre (9922659179)