Chapter 12
On Structure-Equipment-Piping Interactions Under Earthquake Excitation

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Abstract Generally, seismic risk is discussed with respect to the structures that include lifelines. Less discussed with regard to the equipment and piping that also contribute to the total seismic risk in terms of life and economy. In view of this, in the present paper, the detailed procedure to estimate the design seismic forces in equipment and piping systems is discussed. Focus is given on structure-equipment interaction and equipment-piping interaction. Detailed explanation is made on generation inputs for the design of floor-mounted equipment and piping systems. Also, procedure for evaluating the response of piping system supported at multi locations of structure is explained.

12.1 Introduction

In this article, structure-equipment interaction is discussed considering non-industrial (residences, offices, hospitals and Institutes) and industrial facilities (manufacturing, processing and power industry). In the former case, the equipment (pumps, fans, cup boards, selves, televisions, fridges and low-pressure piping) as shown in Fig. 12.1 are light compared to the structural masses and in the later (machine tools, boilers, high capacity pumps, reactors, high-pressure piping systems) as shown in Fig. 12.2 are heavy and sometimes it has masses comparable to the mass or modal mass of the structure. Details of interaction in terms of the frequency variations of the coupled equipment and structure frequency will be discussed in detail i the forthcoming sections.

The level of risk that is a function of seismic hazard levels, capacity and status of exposure is relatively small in the case of non-industrial facilities compared to the industrial structures and equipment. To avoid failures of equipment in non-industrial facilities, some of the easy fixes those can be easily adopted are illustrated in Fig. 12.3.

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Fig. 12.1 Equipment and piping in non-industrial facilities

Fig. 12.2 Equipment and piping in industrial facilities

Even in the hospitals, such fixes can be adopted for equipment. However, oxygen and water service lines should be anchored on concrete members than on masonry walls for better performance.

In the case of industrial facilities, there are situations where large equipment and complex piping networks will be supported on the structure as shown in Fig. 12.4. This is analogous to the situation where elephant is carrying a large mass of tree trunk as shown in Fig. 12.4. In this case, the structure analogous to elephant will surely feel reactions of the masses being carried or supported. Also, the equipment or the masses on the elephant behave based on the movement or motion of the structure or elephant. If elephant moves very fast and the rope or chain anchorage is not proper, all the material may fall and similar situation can also be seen in the equipment supported

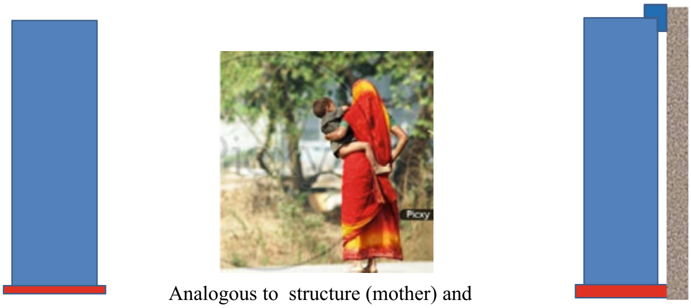


Fig. 12.3 Easy fixes for equipment if non-industrial facilities

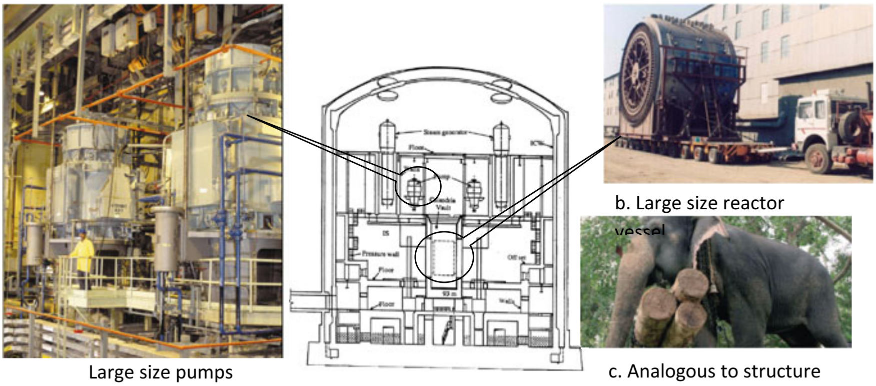


Fig. 12.4 Typical equipment in Industrial system

on the structure when the structure is excited during earthquake. If the design of equipment is made without giving due considerations to these effects, failures of equipment as shown in Fig. 12.5 are inevitable.

These effects are taken care systematically while designing the equipment or piping supported on the structure and are subjected to external excitations such as earthquake. The steps that are followed in generating the input for design of equipment are explained referring to Fig. 12.6 as follows.

Mathematical models of the structure as shown in Fig. 12.6a are developed and analysed for a given design basis earthquake time history as shown in Fig. 12.6b. The basic dynamic equilibrium equation as given below is solved using numerical integration method such as Newmark-β technique.

$$[M]\{\ddot{x}\} + [C]\{\dot{x}\} + [K]\{x\} = [M]\left\{\ddot{x}_g\right\}\{1\} \tag{12.1}$$

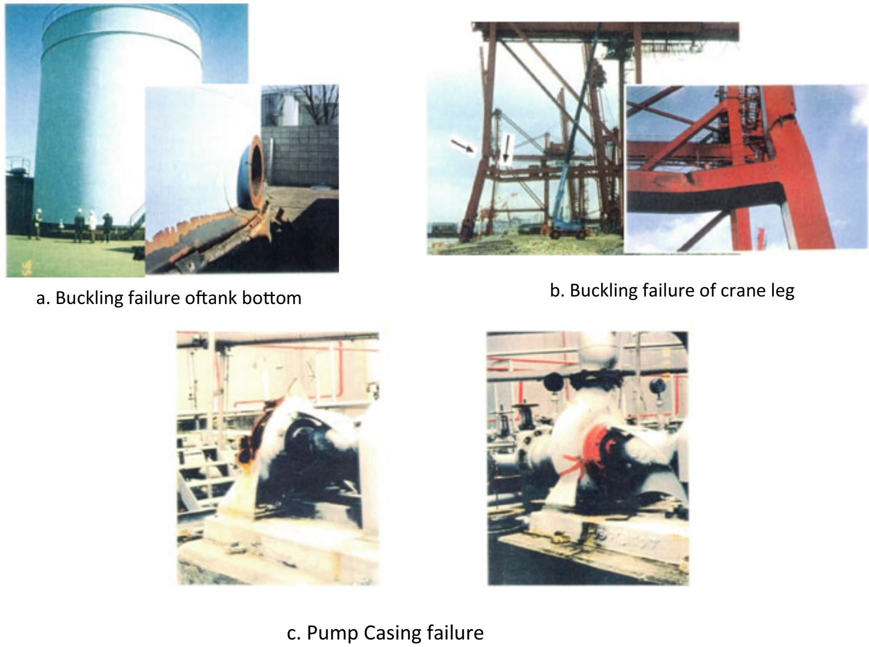


Fig. 12.5 Equipment failure due to earthquake

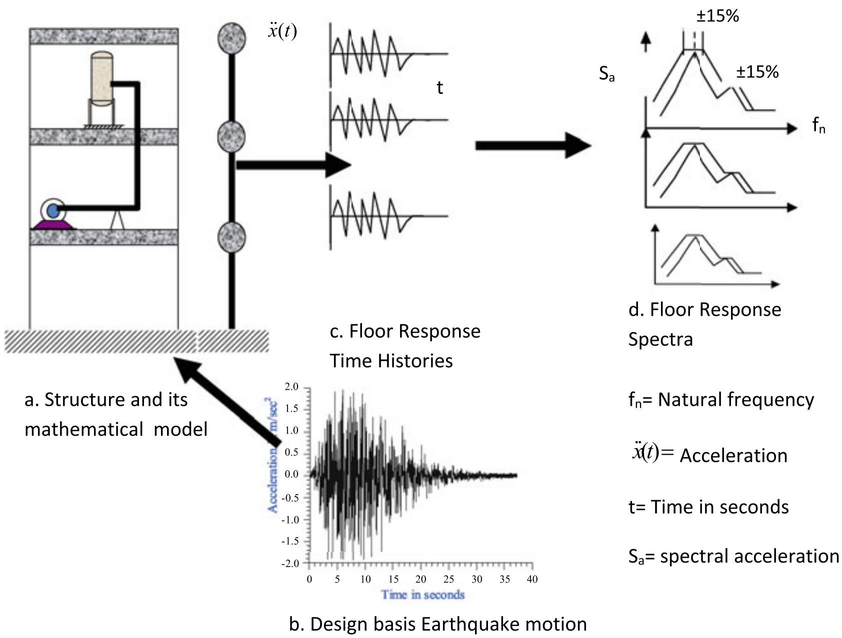


Fig. 12.6 Steps for generation inputs for designing equipment

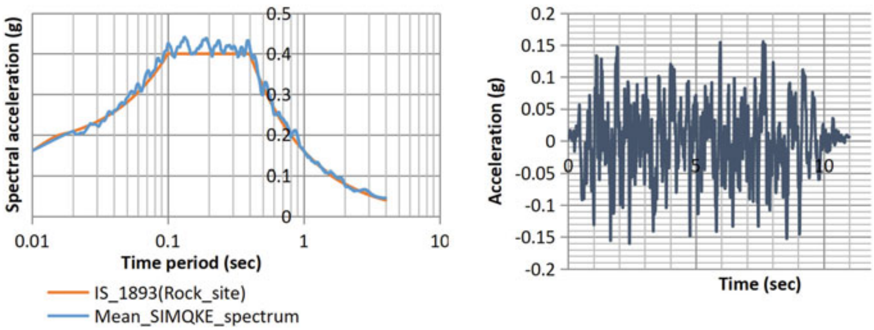


Fig. 12.7 Design Basis Ground Spectrum Compatible time History

where [M] is a mass matrix, [C] is a damping matrix and [K] is a stiffnex matric. x, x with single dot and x with double dot are response displacement, velocity and accelerations respectively as a function of time. Xg with double dot is ground acceleration. IS-1893 spectrum compatible time histories may be generated using the procedure enumerated in the references [1, 2]. Typical one of the three spectrum compatible time histories is shown in Fig. 12.7. The compatibility is checked as per the procedure given in ASCE standard [3]. {1} is the influence vector with unit values along the direction of excitation and zero values along direction of no excitation.

Response absolute accelerations are obtained at different floor levels by solving single degree of freedom (SDOF) equation of motion as given below with different frequencies for a particular damping. Floor response spectra as shown in Fig. 12.6c are obtained as the plot of maximum absolute acceleration versus a frequency for a damping value.

$$\ddot{x}_n + 2\varsigma\omega_n\dot{x}_n + \omega_n^2 x_n = -\ddot{x}_f \qquad (12.2)$$

where ω_n is the natural frequency, ζ_n is the damping ratio of nth SDOF structure. x_n, x_n with single dot and x_n with double dot are response displacement, velocity and accelerations, respectively, with time. X_f with double dot is the floor acceleration.

It is very important to notice that the floor response spectrum has peaks at the natural frequencies of the structure. The frequency of the structure may change due to coupling of the equipment. This coupling effects sometimes called interaction effects and can not be over looked if the equipment and structure are tuned and have large mass (Fig. 12.4) ratio (>10%). In the case of piping systems, interaction with the structure may not affect the natural frequencies due to its light weight and generally treated as an ant sitting on elephant or birds sitting on the tress as shown in Figs. 12.8 and 12.9 respectively.

However, the requirement of coupling equipment and structure is generally decided based on ASCE [3] or ASME [4] criteria as explained in the next section.

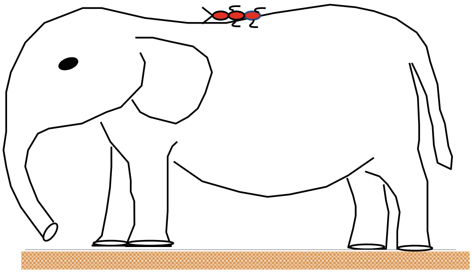


Fig. 12.8 Analogous to the structure (elephant) and piping system (ant)

Fig. 12.9 Analogous to the structure (tree) and piping system (birds)

12.2 Decoupling Criteria

Decoupling criteria are 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 as given below.

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

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

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 $0.8 \geq R_f \geq 1.25$.

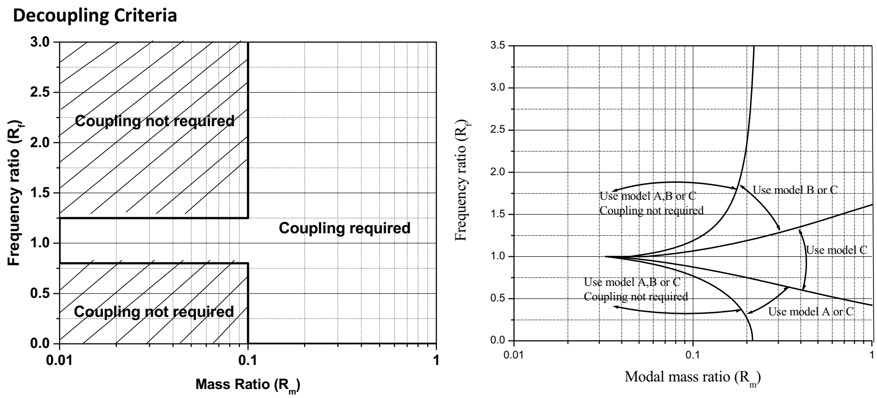


Fig. 12.10 Decoupling criteria for primary and secondary system

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 the above ratios.

Figure 12.10a and b shows the graphical representation of decoupling criteria for primary and secondary system.

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

For multi-degree of freedom structure as shown in Fig. 12.12, modal frequencies and modal mass of the structure are estimated and criteria as explained above are applied considering modes of 20% mass participation. In the case of structures supported on common foundation as shown in Fig. 12.11b and supporting the equipment, degree of freedom (DOF) mass [5, 6] of the substructures are estimated and used to calculate the mass ratios and corresponding frequency ratios and applied decoupling criteria for the requirement of coupling the equipment with the structure.

Based on the coupling requirements, a coupled model is prepared considering structure and equipment and analysis as explained above is performed and inputs for design of equipment are generated. If the damping values are different for soil, structure and equipment, equivalent damping using energy principle is evaluated and used in the analysis [3, 5, 6]. There are direct method and approximate methods to generate inputs for designing floor-mounted equipment and piping systems and are described in the forthcoming sections.

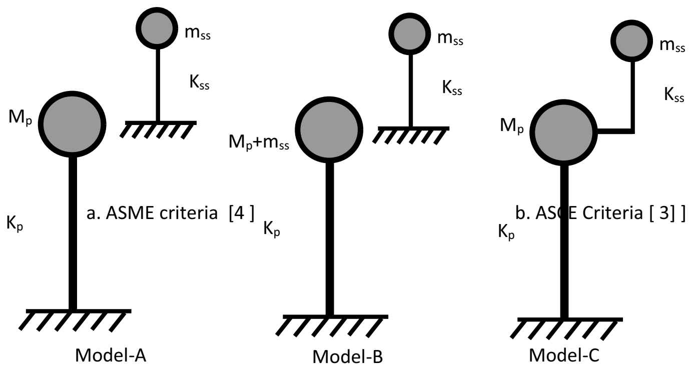


Fig. 12.11 Models adopted in ASCE criteria (Fig. 12.10b)

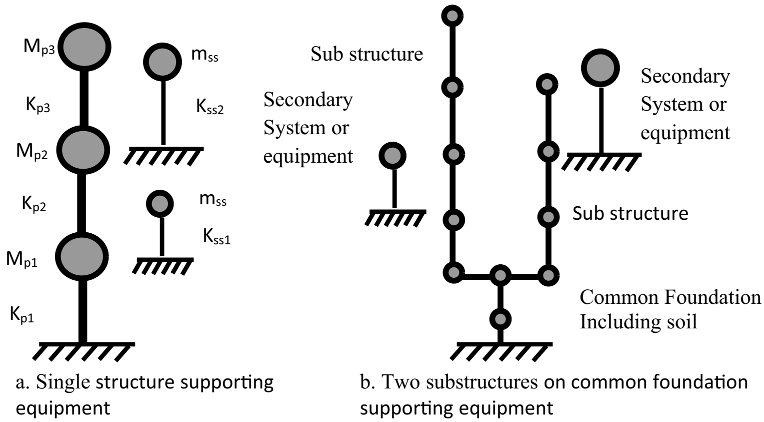


Fig. 12.12 Multi degree of freedom structure supporting equipment

12.3 Direct Method of Evaluating Floor Spectrum Using Design Ground Spectrum

Referring to IAEA-TECDOC-1347 [7], the floor response spectrum may be obtained directly using ground spectra, which correspond to the damping value of the structure including soil, and ground spectra for equipment or piping systems damping and using modal characteristics of the structure obtained in modal analysis. The various steps involved are given below:

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 ith mode of the structure and at jth natural frequency of the equipment is given as follows.

$$Sa_{ij} = \frac{1}{\sqrt{\left\{1-\left(\frac{\omega_{Ej}}{\omega_{Bi}}\right)^2\right\}^2 + 4\left(\xi_{Ej}+\xi_{Bi}\right)^2\left(\frac{\omega_{Ej}}{\omega_{Bi}}\right)^2}} \sqrt{\left\{\left(\frac{\omega_{Ej}}{\omega_{Bi}}\right)^2 Sa(\omega_{Bi},\xi_{Bi})\right\}^2 + Sa\left(\omega_{Ej},\xi_{Ej}\right)^2} \tag{12.3}$$

$$Sa_j = \sqrt{\sum_i^n \left(\Gamma_i \varphi_{ik} \times Sa_{ij}\right)} \tag{12.4}$$

where

Sa_j = Floor response spectrum value at jth frequency of the equipment or piping system taking into account all structural including soil modes (i = 1 to n).

Γ_i = The ith modal participation factor of structure including soil.

ϕ_{ik} = kth floor mode shape in ith mode of structure including soil.

ζ_{Ej} = Damping factor of Equipment or piping system at jth frequency.

ω_{Ej} = jth frequency of the equipment or piping system.

ζ_{Bi} = Damping factor of the structure including soil in ith mode.

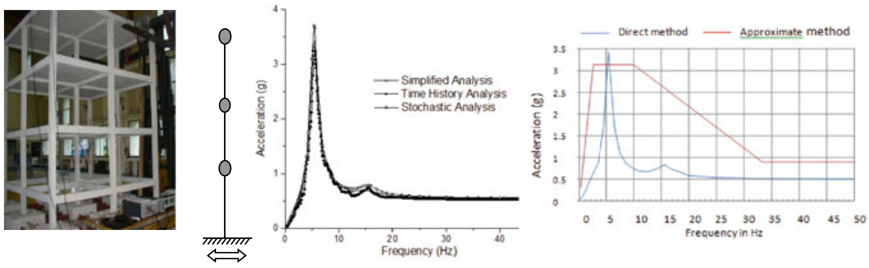
ω_{Bi} = ith modal frequency of the structure including.

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

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

Notes:

(1) The mass or modal mass m_A of the equipment or piping needs to be less than 1% of the mass or modal mass m_{Bi} of the structure.
(2) The floor response spectra, obtained from the above method, need to be broadened by at least 15% to account for the uncertainty in soil-structure-interaction, equipment-structure-interaction and numerical procedures adopted in analysis.



a. Structure b. Beam model c. FRS (direct method) d. FRS (approximate method)

Fig. 12.13 Comparison of floor response spectra of various methods

Figure 12.13 shows the comparison of Floor Response spectra obtained using time history and direct method. For details of stochastic method, reader is requested to see the reference [5, 6].

12.4 Approximate Method of Evaluating Floor Spectrum Using Design Ground Spectrum

12.4.1 Approximate Method

Although not a recommended procedure, the Floor Response Spectrum (FRS) as shown in Fig. 12.13d 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:

$$S_{aj} = S_g\left(1 + c\frac{h}{H}\right) \tag{12.5}$$

where

S_{aj} = Spectral acceleration of FRS at jth equipment/piping frequency.

Sg = Spectral acceleration of Ground response spectra.

h = Height of equipment/piping support element above the ground.

H = Height of the structure.

and c = 3 for 5% damping.

12.4.1.1 Peak Broadening Floor Response Spectra

As mentioned earlier peaks of FRS occur at natural frequency predominantly and these should be evaluated as accurately as possible. However, floor response spectra need to be broadened as explained in Fig. 12.6d 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.

12.4.1.2 Multi-supported Piping Systems

The piping system shown in Fig. 12.6a is independently shown in Fig. 12.14 and has supports at three locations such as one with top equipment and second at bottom equipment and laterally constrained at floor level. For seismic design of this piping system, the basic inputs required are floor response spectra (FRS) at support locations and support displacements. If the supports are effective in three directions, then at each support, three FRS are need to be considered and similarly three support displacements. Support displacements are also called Seismic Anchor Motions (SAM) need to be considered in design and corresponding stresses can be obtained by performing static analysis.

The piping system may be decoupled from the equipment if the following criteria are satisfied.

a. Moment of inertia of equipment is more than 100 times the moment of inertia of the piping system.
b. Equipment side ends of piping system have constraints along three directions. This requirement may be at one location or different locations.

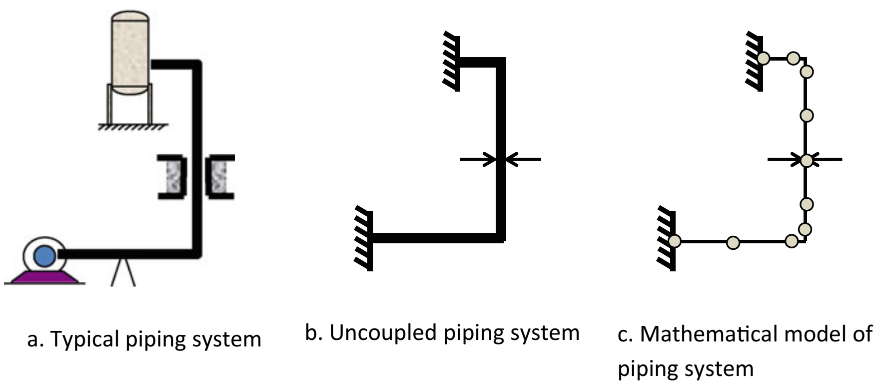


Fig. 12.14 Typical piping system connected to equipment

After finalising the boundaries as shown in Fig. 12.14b, suitable mathematical may be developed as shown in Fig. 12.14c and analysed for the forces, moment and stresses. For selecting number of elements and type of elements such as straight pipe, bend, tee etc., the reader is requested to refer [5, 6] on chapter related to multi-degree of freedom and piping design chapters. After finalising the model, the following equilibrium equation is solved considering the piping subjected to multi-support excitation.

$$[M]\{\ddot{x}\} + [C]\{\dot{x}\} + [K]\{x\} = [M]\left\{\ddot{x}_g\right\}\left\{I_j\right\} \tag{12.6}$$

It is important to note the difference of Eq. 12.6 with respect to Eq. 12.1. In the case of Eq. 12.1 for ground excitation as explained earlier, the influence vector has 1 s and 0 s and whereas the influence vector $\{I_j)$ has static displacements with unit displacement at the support j. It results in number of influence vectors equal to translational supports. Kindly note that the sum of all the influences at given node will result in unity. The above equation cam be solved either for the time wise response or frequency (mode) wise response based on the input in terms of time history and response spectrum respectively. Usually, later procedure is adopted since it is simple and Broadened FRS can be used without variations accounting for soil-structure-interaction, numerical solution variations and structure-equipment interactions. The modal response can be combined using suitable methods such as square root of sum of square, absolute sum, 10% sum or complete quadratic combination rule as explained in the reference [3, 5, 6].

12.5 Discussions and Conclusions

It is very important to perform seismic design of equipment and piping systems of non-industrial and industrial facilities to reduce the risk. Detailed procedures for obtaining the design inputs for equipment and piping system are discussed considering equipment structure interaction and equipment piping interaction. The interactions considered in the present article with respect to the variations of structural frequencies and their importance on the design basis FRS are clearly discussed.

The reader is requested to see the references for more details of the procedures.

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