4.0 SESIMIC ANALYSIS TECHNIQUES

4.1 Seismic Input

The input to the seismic analysis of a piping system may be either dynamic (time history or response spectra) or static (static coefficient). In either case, the seismic input is obtained, as described later in this section, from building code seismic maps or from a detailed geotechnical and seismological investigation of the site (referred to as "site specific" seismic input).

4.1.1 Time History

The time history input consists in one or a series of seismic motions (displacement, velocity or accelerations) as a function of time, that last for the full extent of ground shaking (typically in the order of 20 to 60 seconds), as illustrated in Figure 4.1.1-1. The maximum ground acceleration reached during the earthquake (approximately 0.25g in Figure 4.1.1-1) is the peak ground acceleration. The seismic time history ground motion (displacement, velocity or acceleration vs. time) is established for each of three directions, typically east-west, north-south and vertical up-down. These three time histories are then applied to a finite element model of a building structure to obtain, as output, the time history excitations at each floor in the structure. The excitation typically increases with elevation in the structure. Time history seismic input is rarely used for design or retrofit of equipment or piping systems. It is used to generate facility specific response spectra analyses, or as a research tool, to study in detail the behavior of a component or system as a function of time.

4.1.2 Response Spectra

Seismic response spectra are plots of acceleration or velocity or displacement vs. frequency or period (typically, acceleration vs. frequency is the most common form of seismic response spectrum used in piping and equipment analysis). Figure 4.1.2-1 illustrates a set of acceleration vs. frequency in-structure response spectra (spectra at a certain elevation within a structure) at 2%, 5% and 10% damping. For a given frequency "f_N", the seismic response spectrum at damping ζ gives the maximum acceleration reached by a single degree of freedom (a "lollipop" of natural frequency f_N with dash pot of damping ζ) subject to the input excitation represented by the response spectrum.

The higher the damping of the single degree of freedom, the lower its acceleration, as can be intuitively expected. This is illustrated in Figure 4.1.2-1. The constant acceleration at high frequency (the right hand side horizontal tail in Figure 4.1.2-1) is the peak ground acceleration. A rigid single degree of freedom oscillator (an oscillator with a natural frequency in the order of 30 Hz or more) will follow the ground motion, without amplification, its maximum acceleration will therefore be the maximum ground acceleration, or "peak ground acceleration".

Other terms commonly used in seismic analysis are listed at the end of the report, in section "Terms and Definitions".

4.1.3 Static Coefficient

The static coefficient is typically a single horizontal acceleration value and a single vertical acceleration value, specified as a fraction or multiple of "g". For example a horizontal static coefficient $a_H = 0.3g$ and a vertical static coefficient $a_V = 0.2g$.

Static coefficients are usually obtained from seismic contour maps in building codes. Until recently, the building codes defined seismic "zones" from 0 to 4, each zone corresponding to a level of seismic acceleration. The concept of seismic zones was however abandoned by the United States Geological Survey (USGS) in 1969, in favor of probabilistic based seismic contour maps. The building codes continued using seismic zones until recently. In its 2000 issue, the International Building Code followed the USGS lead and abandoned the seismic zones in favor of seismic contour maps. These maps provide horizontal ground accelerations with a 98% non-exceedance probability (NEP) in an exposure period (T) of 50 years. In other words, there is a 98% chance that a particular site will not see a seismic acceleration larger than the acceleration shown on the contour map, in 50 years. This probability can also be expressed as a return period

$$RP = T / r^*$$

$$r^* = - \log_e (NEP) \sim r (1 + 0.5r)$$

RP = return period
r = exceedance probability = 1 – NEP
NEP = non-exceedance probability
T = exposure period, years

For example, for the IBC-2000 maps, NEP = 0.98 and T = 50 years, which leads to a return period RP = 2475 years ~ 2500 years. In other words, the seismic accelerations in the IBC 2000 maps may be experienced once every 2500 years. The longer the return period, the larger the projected seismic acceleration.

4.1.4 Seismic Anchor Motion

Seismic anchor motion (or "SAM") is the differential motion between pipe support attachment points (for example, supports attached to an upper floor would sway with the building, with a larger amplitude than supports attached at a lower elevation), or the differential motion between equipment nozzles and pipe supports. Seismic anchor movements are input as displacements (translations and rotations) at the support attachments or at equipment nozzles. The resulting stresses and loads in the piping system are then combined by square root sum of the squares (SRSS) to the stress and loads due to inertia (seismic induced sway or vibration of the pipe).

4.2 Choosing the Type of Seismic Analysis

The type of seismic analysis may be (a) a "cook-book" approach, (b) a static hand calculation technique, (c) a static analysis of a piping model, or (d) a computerized response spectrum analysis of a piping model.

4.2.1 Cook Book

In a "cook-book" approach, the designer selects seismic restraint locations at fixed intervals, following a "recipe", for example: a lateral "sway brace" (seismic restraint) is placed every 40 ft along the pipe and a longitudinal restraint every 80 ft. The braces may be pre-designed based on the specified spacing. The technique has the advantage of simplicity, but has two important drawbacks:

(1) In order to cover all practical configurations, the cook-book methods tend to be "conservative", in other words they will over-predict the number and size of seismic supports.

(2) Cook books can be so simple that they may have been developed and may be used by engineers who have little, if any, understanding of piping systems and seismic design.

4.2.2 Static Hand Calculations

For a static hand calculation approach, the pipe is divided into individual spans or into a series of simple U, T or Z configurations. The peak acceleration from the response spectrum is applied as a lateral force distributed along the span, and bending stresses and support reactions are calculated using beam formulas. This technique was useful throughout the 1960's and 1970's; however, with the advent of user-friendly PC-based piping design software, computerized system analysis is now preferred, as more accurate and faster than the hand calculations. The hand calculation techniques are still useful as a tool to intuitively interpret the output of a computer analysis.

As a refinement in hand calculation techniques, the span natural frequency can be calculated. In this case, the spectral acceleration at the calculated span natural frequency may be applied to predict the load and displacement distribution along the span [Pickey, Blevins].

4.2.3 Static System Analysis

Another analysis technique consists in preparing a piping model of the system, using PC-based piping analysis software. The use of general finite element analysis software is not recommended in piping design, except in the very rare case where an elastic-plastic analysis is needed, or in the case of research to calculate detailed stress distributions in particular pipe fittings.

The seismic static coefficient is applied statically and uniformly in each of three directions (typically east-west, north-south and vertical) to the computer model of the whole system, providing the full distribution of stresses and support loads in the system.

4.2.4 Response Spectra Analysis

To perform a seismic response spectra analysis of a piping system, a computer model representing the piping system is first created. As in 4.2.3, the model should be created with a special purpose piping analysis software, rather than a general purpose finite element software. The model needs to be sufficiently accurate to properly reflect the dynamic characteristics of the system since the analysis results will depend on the accuracy of the computed natural frequencies of the system.

Three seismic response spectra are input into the program: east-west, north-south and vertical spectra, typically in the form of accelerations vs. frequency, from very low frequencies up to the ZPA. The computer program will calculate displacements and loads separately for each natural frequency (mode) of the system and for each of three directions (north-south, east-west, vertical). The modal results and directional results are then combined to obtain a total, resultant response of the system. The engineer has a choice of modal and directional combination techniques. In the early days of modal analysis, the resultant response the square root sum of squares of the individual modal responses ("response" here means loads or displacements at the various points along the piping system) [Newmark]:

$$R = \sqrt{\sum_{1}^{N} R_i^{\,2}}$$

R = resultant response
R_i = response in mode i

Studies by Singh et. al. concluded that the SRSS combination could underestimate the total response if some modal frequencies of the equipment were "closely spaced"; as a result, more elaborate modal combination techniques have been developed and applied [Singh, R.G. 1.92].

The resulting loads and displacements of the piping system are typically obtained by taking the square root sum of squares of the response (loads and displacements) in each of the three directions

$$R = [(R_{EW})^2 + (R_{NS})^2 + (R_V)^2]^{0.5}$$

R = resultant response
R_{EW} = east-west response
R_{NS} = north-south response
R_V = vertical response

As a less common alternative, the response in each direction may be combined by the "100-40-40" technique:

$$R_{100,40,40} = 100\%\ R_{EW} + 40\%\ R_{NS} + 40\%\ R_V$$

$$R = \max\ \{R_{100\text{-}40\text{-}40}\ ;\ R_{40\text{-}100\text{-}40}\ ;\ R_{40\text{-}40\text{-}100}\}$$

4.3 IBC Seismic Input

The International Building Code provides a procedure to determine seismic input applicable to a facility. Two types of input can be obtained: A static coefficient for static analysis, or a seismic response spectrum for dynamic analysis.

The IBC technique for developing the seismic input to equipment and piping systems consists of three parts:

(1) The input acceleration at ground level, based on seismic maps and soil characteristics.
(2) The amplified seismic load for equipment and piping located inside a structure.
(3) The seismic load for tall equipment located at grade, for example in the plant yard.

These three parts will be described step by step in the following sections.

4.3.1 Site Ground Motion

The first step in the International Building Code procedure [IBC-2000] is to determine the site ground motion at the facility, given its geographic location and soil characteristic, as illustrated by the nine steps in the logic diagram of Figure 4.3.1-1. It will be applied, as an example, to a facility.

Step-1: The site ground motion will be selected from the IBC seismic maps, and not from a site-specific seismicity study.

Step-2: To obtain the IBC site ground motion, the facility location is first placed on the IBC map (IBC-2000, Figures F1615(1) to (10)), and the mapped maximum considered earthquake spectral acceleration (MCESRA) is read from the contour intervals as

$$S_S$$
$$S_1$$

S_S = MCESRA at short period, 5% damping in a site class B.
S_1 = MCESRA at 1 sec, 5% damping in a site class B.

Step-3: The soil is characterized as hard rock, dense clay, sand, etc; and the shear wave velocity v_S is estimated.

Step-4: According to IBC Table 1615.1.1 the soil is classified as class A to E.

Step-5: The site coefficients F_A and F_V are determined from IBC Tables 1615.1.2(1) and (2), given the site class and the MCESRA S_S and S_1

Step-6: The mapped spectral acceleration for short period $S_{MS}$and the mapped spectral acceleration for 1-second period $S_{M1}$are calculated as

$$S_{MS} = F_a \, S_S$$
$$S_{M1} = F_V \, S_1$$

Step-7: The design spectral response accelerations (DSRA) for short period and 1-second are calculated as

$$S_{DS} = (2/3) \, S_{MS}$$
$$S_{D1} = (2/3) \, S_{M1}$$

To understand this multiplication by 2/3 we refer to “NEHRP Recommended Provisions for Seismic Regulations for New Buildings and Other Structures”, Part 2 Commentary, Chapter 4 Ground Motion, 1997 Edition, Building Seismic Safety Council, Washington, DC., which states “The design ground motions are based on a lower bound estimate of margin against collapse inherent in structures designed to the Provisions. This lower bound was judged, based on experience, to be about a factor of 1.5 in ground motion. Consequently, the design earthquake ground motion was selected at a ground shaking level that is 1/1.5 (2/3) of the maximum considered earthquake ground motion”.

Step-8: Two reference spectral periods are defined as

$$T_o = 0.2 \, S_{D1}/S_{DS}$$
$$T_S = S_{D1}/S_{DS}$$

Step-9: The design response spectrum (DRS) of the facility, at 5% damping, can now be traced. It consists of three regions:

Period Range T(sec)	Spectral Acceleration S(g)
0 to T_o	$0.6 \, (S_{DS}/T_o) \, T + 0.4 \, S_{DS}$
T_o to T_S	S_{DS}
T_S to infinite	S_{D1} / T

Table 4.3.1-1 IBC-2000 Response Spectrum

4.3.2 Seismic Load In-Structure

The seismic load applied to equipment and piping inside a building or structure, above ground level, is larger than the load at ground level. The steps followed to calculate the seismic load applied to a piping system contained inside a structure (building or steel frame structure), referred to as “in-structure” seismic load, are illustrated in the logic diagram of Figure 4.3.2-1.

Step – 1: Based on the consequence of failure of the system (failure effect), the system is assigned a Seismic Use Group I, II or III (IBC 1616.2), and an importance factor I = 1.0 or 1.5 (IBC 1621.1.6).

Step – 2: Given the Seismic Use Group (SUG I, II or III) and the values of S_{DS}, $S_{D1}$and S_1, the system is assigned a Seismic Design Category (SDC) A to F (IBC 1616.3). The extent of detail in seismic design and qualification will increase from SDC A to SDC F.

Step – 3: At this point, several types of systems or components can be exempted from seismic design, according to IBC (IBC 1621.1.1), as summarized in table 4.3.2-1.

SDC	I	W	FC	H
A, B	any	any	any	any
C	1.0	any	any	any
D,E,F	1.0	20 lb	Yes	any
All	1.0	400 lb	Yes	4 ft

Table 4.3.2-1 Exemption from Seismic Design

I =importance factor (1.0 or 1.5)
W = maximum weight, component below this weight can be exempted.
FC = only distributed systems (piping, duct, etc.) with flexible connections exempted if "Yes".
H = maximum height above floor, component below this height can be exempted.

Step – 4: The horizontal seismic load applies separately in the longitudinal and lateral directions, it is given by F_P where (IBC 1621.1.4)

$$0.3\ S_{DS}\ I\ W \leq F_P = [0.4\ a_P\ S_{DS}\ W\ I\ /\ R_P]\ (1 + 2\ z/h) \leq 1.6\ S_{DS}\ I\ W$$

S_{DS} = Project Spectral acceleration for short period
I = importance factor (1.0 or 1.5)
W = weight
F_P = horizontal load
a_P = component amplification factor (1.0 to 2.5)
a_P = 1.0 for any piping system
R_P = component response modification factor (1.0 to 5.0)
R_P = 1.25 for low deformability piping systems, 2.5 for limited deformability piping system, 3.5 for high deformability piping systems
z = height of attachment to structure
h = height of structure

It is useful, at this stage, to dissect the above F_P equation.

The term 0.4 S_{DS} is the zero period acceleration input to the piping system. It is the acceleration that would be applied to a very rigid system.

The term a_P amplifies the ZPA acceleration from 1.0 x $0.4S_{DS}$, which would logically apply to a rigid piping system, up to 2.5 x $0.4S_{DS} = S_{DS}$, which is the peak spectral acceleration. A value a_P = 2.5 would therefore logically apply to a system that would have a natural frequency that falls within the range of frequencies where the seismic excitation is at its maximum value S_{DS}.

The term R_P accounts for the “ductility” of the system, its ability to absorb and redistribute the imparted seismic excitation, without failure [WRC 379]. This term is closely related to the ability to of the system to yield locally, without breaking.

The term (1 + 2z/h) amplifies the ground acceleration as a function of elevation. For example, a pipe atop a 20-ft tall rack will see an acceleration that is (1 + 2(20’ / 20’)) = 3 times larger than a pipe at ground. On the other hand, a pipe that is half-way up a 40-ft tall rack, i.e. still 20-ft above ground, will experience an acceleration that is (1 + 2(20’ / 40’)) = 2 times larger than a pipe at ground.

Step – 5: The effect of the horizontal seismic load F_P (applied separately in the lateral and longitudinal direction) is added to the effect of the vertical seismic load F_V given by (IBC 1617.1.1, 1621.1.4)

$$F_V = 0.2\ S_{DS}\ W$$

F_P = vertical component of seismic load

The total seismic load is therefore the horizontal load F_P plus the vertical load F_V. This is a vectorial addition, in other words, the effects of the horizontal load are added to the effects of the vertical load to obtain the total seismic effect on the system (IBC 1617.1.1, 1621.1.4)

$$E = F_P + F_V$$

Step – 6: The total load is the sum of the seismic load E and the weight W. If the allowable stress design method (also called working stress design method) is used to qualify the piping system, as is the common practice, then the seismic load E should be divided by 1.4 (IBC 1605.3.2), the total load is therefore.

$$F_T = W + E/1.4$$

4.3.3 Seismic Load At-Grade

The seismic lateral load on equipment at grade is given by a different method than used for in-structure equipment. In fact, the at-grade procedure follows very closely the method for calculating shear forces and base shear in buildings. It is to be applied to tall towers and vessels but is not readily applicable to piping systems or equipment with a low center of gravity (such as pumps, compressors, horizontal tanks and heat exchangers).

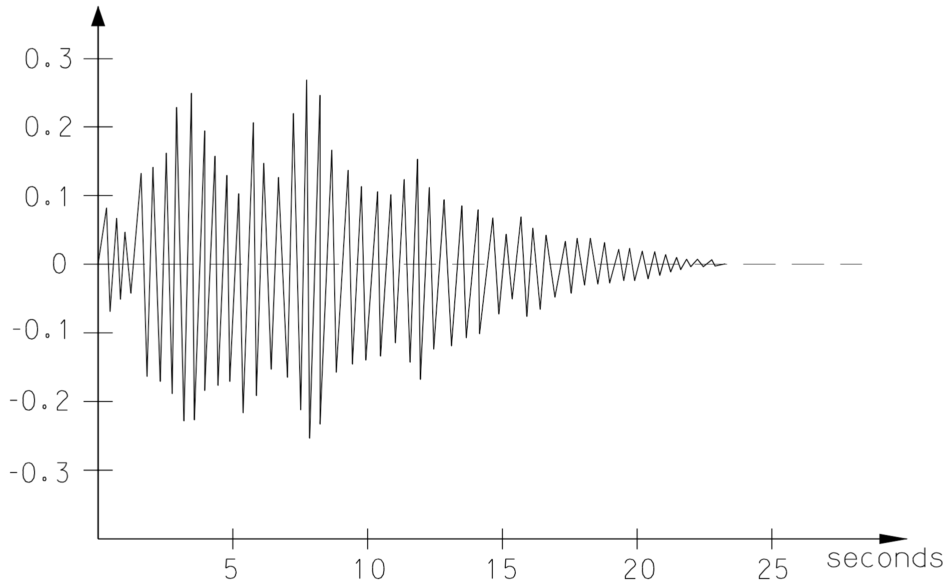

Figure 4.1.1-1 Illustration of a Seismic Time History Acceleration

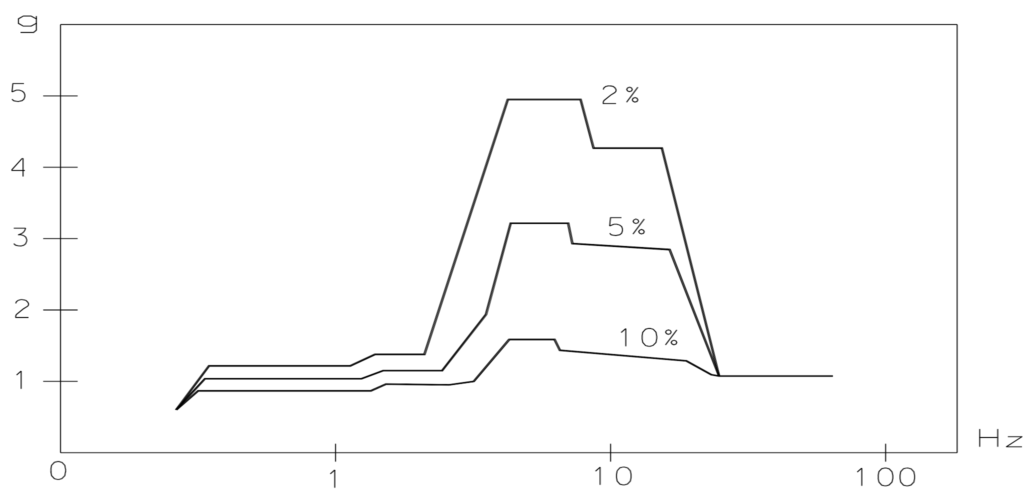

Figure 4.1.2-1 In-Structure Seismic Response Spectra

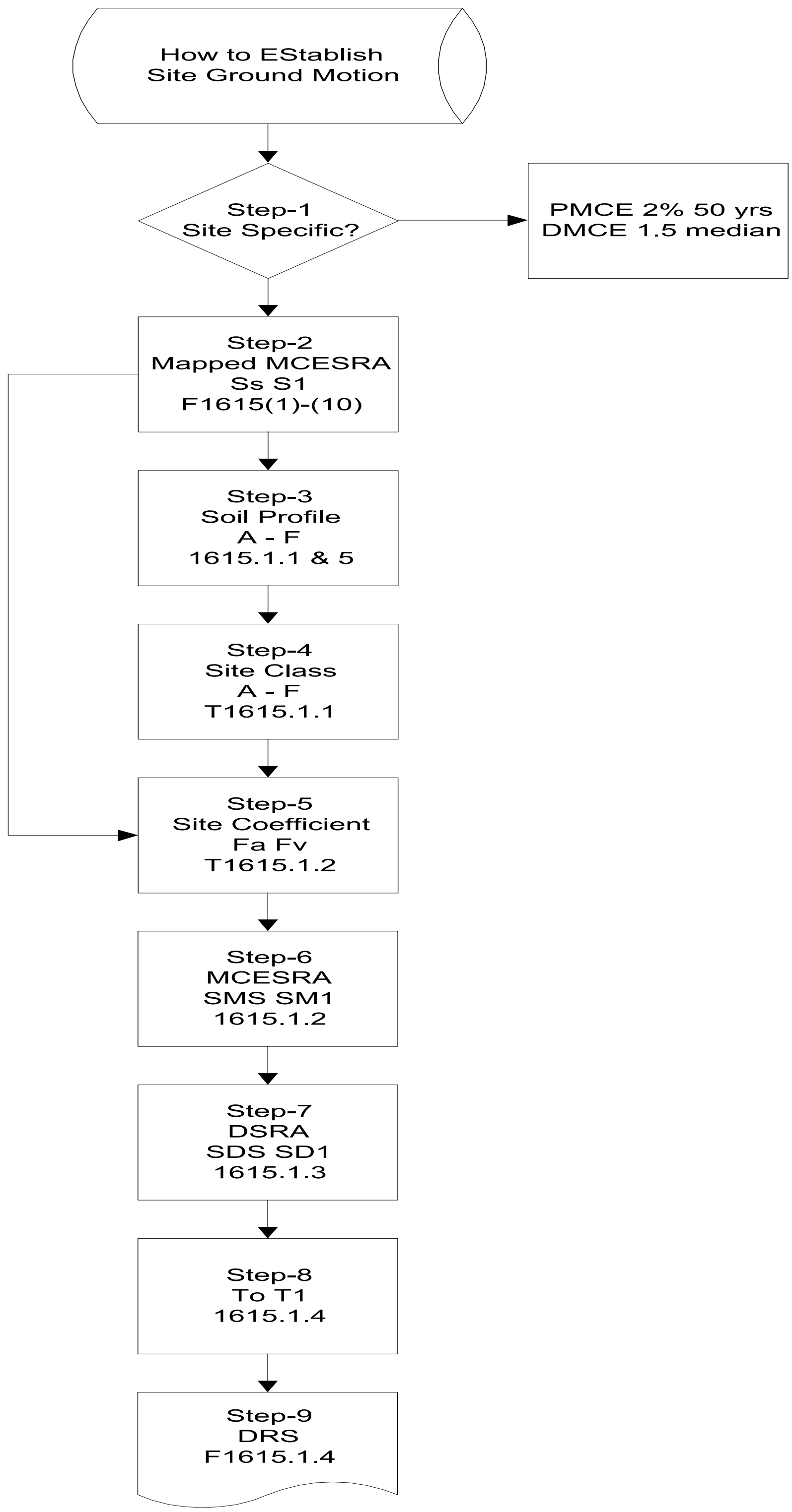

Figure 4.3.1-1 Determination of Site Ground Motion per IBC
(Numbers 1600's refer to IBC-2000 section number)

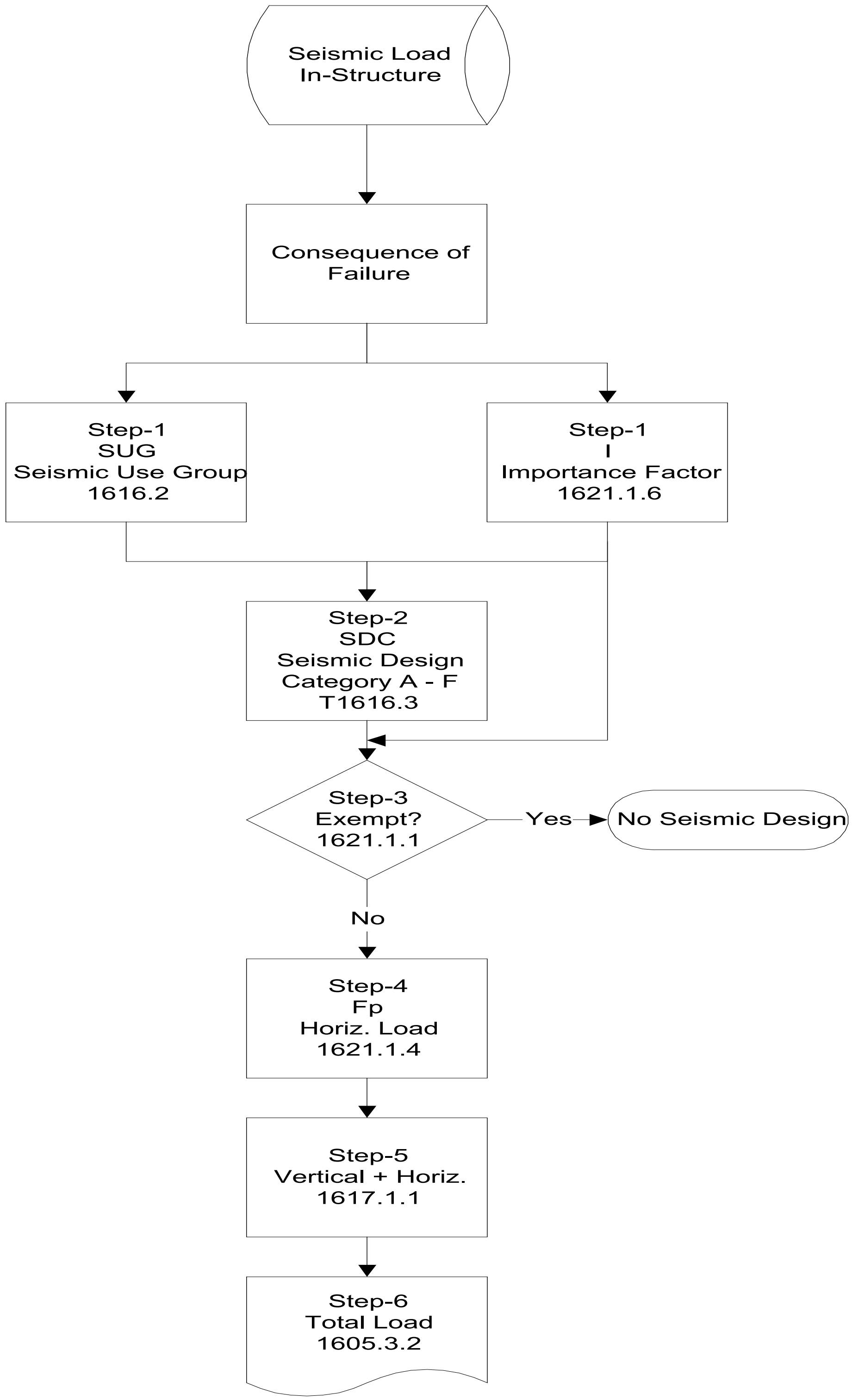

Figure 4.3.2-1 Determination of Seismic Load per IBC
(Numbers 1600's refer to IBC-2000 section number)