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SEISMIC DESIGN CRITERIA FOR STRUCTURES AND FACILITIES
TRANS-ALASKA PIPELINE SYSTEM

by

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INTRODUCTION

Summary and Acknowledgment. The basis for the original seismic design for elevated and buried pipeline and some of the appurtenant structures of the Trans-Alaska Pipeline System was described in a report by N. M. Newmark to the Alyeska Pipeline Service Company under the original date of October 1972, and summarized in Ref. 1. Additional studies made in the course of the analysis and design have indicated the desirability of developing criteria more directly applicable to the wide variety of structures, facilities, components, equipment, and instruments associated with the pipeline system. This paper describes the author's recommendations for the seismic design criteria for structures and facilities for the system.

There are some differences between the present treatment and that used in Ref. 1, the most notable of which is the adoption of the concept of a seismic design classification into which the various special structures or components can be placed, depending on their function and importance as well as on their need for continued operation.

Included herein are a discussion of earthquake motions, description of the design seismic motions used, the elastic response spectrum considered applicable, and the recommended design spectra which take into account appropriate amounts of inelastic behavior. The seismic design classification used is described together with the damping and ductility factors pertinent to the various classes adopted.

The recommendations made herein were developed by the author and are not to be construed as representing an official position of ALYESKA. Acknowledgment is made of suggestions and comments from Dr. William J. Hall, Professor of Civil Engineering at the University of Illinois at Urbana-Champaign.

Seismic Design Philosophy. The design criteria and recommendations described herein take into account the seismic motions and seismic generated forces having a reasonable degree of probability of occurrence along the route of the pipeline. The basis for the selection of these criteria and recommendations involves the selection of the acceptable risk of exceeding the design levels for the several different classes of structures, equipment and/or facilities involved in the pipeline system. For the most critical classes, where failure, defined as exceeding the allowable levels recommended, would have a bearing on life and safety of the population or might adversely affect the environment, or where because of economic reasons interruption of the service provided by the pipeline is not tolerable, the margins of safety implicit in these criteria are considerably greater than those now used in the seismic design of major buildings, including school buildings and hospitals, on the West Coast of the United States. For the least critical class, the margins of safety are at least as great as those provided by current building codes such as the Uniform Building Code or the SEAOC code. (See Ref. 2.)

Hence it is considered that the procedures recommended herein will result in a design having appropriate factors of safety against seismic disturbances combined with other operating and environmental conditions.

In accordance with principles developed for use in the design of nuclear reactor power plants, the design criteria encompass two levels of earthquake hazard. The lower level is that associated with a return period for the design earthquake of approximately 50 years and is designated herein as the "Operating Earthquake". The higher level is that associated with a longer return period, of the order of about 100 to 200 years or more, and is designated as the "Contingency Plan Earthquake".

The earthquake history in the entire region of the pipeline is too sparse to justify accurate estimates of the intensities of either of these earthquakes or of their return periods. For this reason the relationship between the intensities of the two earthquakes has been taken as a factor of 2, arbitrarily.

The earthquake intensity by itself has little significance in terms of design to resist seismic motions. Of equal importance are the structural parameters governing its response, such as stress or strain and deflection, that the designer intends to use for the particular earthquake hazard selected. These criteria were selected to make the Contingency Plan Earthquake govern the design in general. However, the criteria are such that, in the event of the smaller earthquake, the structure, if properly designed in accordance with the recommendations, will generally be able to continue operation.

SEISMIC DESIGN MOTIONS AND RESPONSE

Actual vs. Effective Earthquake Motions. Peak values of ground motion may be assigned to the various magnitudes of earthquake, especially in the near vicinity of the surface expression of the fault or at the epicenter. However, these motions are in general considerably greater than smaller motions which occur many more times in an earthquake. Design Earthquake response spectra are based on "effective" values of the earthquake intensities of accelerations, velocities and displacements, which occur several times during the earthquake, rather than isolated peak values of instrumental reading. The earthquake hazards selected for design are about 1/2 to 1/3 the expected isolated peak instrument readings.

In assessing the importance of the accelerations and velocities for which the design is to be made, it must be remembered that maximum ground accelerations, in themselves, are of less significance than the accumulated effects of the larger number of somewhat smaller accelerations that contribute to the principal structural or element response. In general, the significant effects of an earthquake are measured more directly by the maximum ground velocity than by the maximum ground accelerations. A single spike of high acceleration that is consistent with the maximum velocity of the ground may have much less significance on response than would be computed by straightforward applications of linear elastic analysis for dynamic systems.

The response spectra computed for purely elastic elements are not a good measure of design requirements. For this reason, emphasis must be placed on what one may call "design" earthquake motions, for which design spectra may be drawn, corresponding more directly to accelerations that are repeated in a pattern that might produce larger responses, and to the maximum ground velocities rather than the actual maximum ground accelerations. Design spectra determined from these parameters can take into account the various energy mechanisms, both in the ground and in the element, and other energy absorptions including radiation of energy into the ground from the responding system.

The relation between magnitude of energy release in an earthquake and the maximum ground motion is very complex. There are some reasons for inferring that the absolute maximum accelerations and velocities are, for example, very nearly the same for all magnitudes of relatively shallow earthquakes for points very near to the focus or epicenter. However, for larger magnitudes, the values do not drop off so rapidly with

distance from the epicenter, and the duration of shaking is longer. Consequently, the statistical mean or expected values of ground motions show a relationship increasing with magnitude, although not in a linear manner.

Design Seismic Motion. In selecting the earthquake hazards for use in design, the general concept has been used that the earthquake magnitude selected should be at least as large as those that have occurred in the past, and these earthquakes are generally considered to have equal probabilities of occurring at any point within regions of similar or closely related geologic character. In particular, the estimates of motion considered are appropriate for competent materials at or near the ground surface, including rock and permafrost, or competent consolidated sediments at or near the surface. The values selected are nearly independent of the properties of the surface materials. It is considered that the predominant part of strong earthquake ground motion, generated by a near shallow earthquake energy release, is represented by surface waves. In general, these are propagated in a manner consistent with the properties of the material at a depth considerably beneath the surface and are not affected to a large extent by the surface properties themselves. The design values of motion are based on the assumption that the same values are applicable in a particular zone for all competent soils.

The design seismic motions adopted are given for four seismic zones in Table 1. These zones are characterized by the magnitude of earthquake considered as the Contingency Plan Earthquake. Table 1 gives for each of the zones two sets of ground motion values. The first set, entitled "Ground Motion", lists those values which may affect the stability of slopes or the liquefaction of cohesionless materials, and are also the values which should be used to infer the strains in underground piping. The second set of values, entitled "Structural Design", lists those values that are to be used for the design of structures or other facilities. These values take into account implicitly soil-structure interaction, and are generally less than those used for defining soil instabilities. In both cases, values are given of the maximum effective design ground acceleration, in percent of the acceleration of gravity, the maximum effective design ground velocity, in in/sec, and the maximum effective design ground displacement, in inches. Of course, the actual values are transient values at variable times, but only the effective design values are listed in the table.

The maximum ground motion values given in Table 1 are considerably less than the isolated peak values of motion that correspond to the magnitudes of earthquakes that might be assigned to these various zones. The values have been selected to be consistent with response levels, using conservatively computed soil responses and/or structural responses.

The design motions given in Table 1 are for the horizontal direction and may occur with equal probability in either of two orthogonal horizontal directions more or less simultaneously. The design motions to be used in the vertical direction are to be taken as 2/3 of the values given in Table 1. This relationship is consistent with the observations noted in Ref. 4.

Elastic Spectral Amplification. The elastic response of a simple dynamic system subjected to motion of its supports is affected to a very large extent by the damping in the structure. This damping is usually expressed in terms of the percentage of the "critical value" of damping. Values of damping for particular structures or structural types are discussed in Refs. 5 and 6. The importance of damping is indicated by the large effect of damping on the elastic spectral amplification. This matter is discussed in more detail later.

The ductility factor of a structure or element is defined as the value of deformation or strain x_m which the structure or element can sustain before failure relative to that value x_y for which it departs appreciably from elastic conditions. It is

defined precisely only for an "Elasto-Plastic" relation. However, where the load deformation or stress-strain curve is one which does not have the characteristics of an initial elastic, followed by a perfectly plastic relationship, then the ductility factor must be defined in the fashion given in Refs. 5 or 6 by use of an equivalent elasto-plastic relation drawn to make the energy or area under the original curve up to x_y and x_m the same as that under the elasto-plastic curve.

The amount of inelastic deformation that a structure can undergo without suffering undue damage also affects its response, in terms of the stresses in it and the corresponding deformations and deflections. The allowable values of ductility depend on the material of which the structure is made and on its manner of construction, principally the way in which joints are made. In general, welded steel structures of high-quality steel, made with good welding techniques, have high ductility. However, under certain circumstances, the ductility is impaired by a tendency to fracture in a brittle manner. For these reasons, the ductility levels that are used in a design must be verified to determine that the materials themselves and their fabrication processes, and especially for reinforced concrete the details of construction, are controlled in such a way that the value of ductility used can actually be achieved; it is recommended that the design and details be made capable of developing a ductility factor of at least 1.5 times that used in the design spectrum. Possible ductility levels under ordinary conditions are discussed in Ref. 5.

Where the permissible level of structural response does not involve yielding at all, then the ductility factor that can be used is limited to a value of unity.

Response and Design Spectra. The response spectrum, as explained in Refs. 5 and 6 is a plot of the maximum transient response to dynamic motion of a simple dynamic system having viscous damping. An elastic response spectrum has peaks and valleys, but in general has a roughly trapezoidal shape, similar to the upper part of Fig. 1. The design spectra developed for use in the pipeline are based on an elastic spectrum which has the general relations described in Ref. 4. Spectral amplification factors for horizontal motion, in the elastic range, for damping values of 2, 3, 5 and 7 percent critical, taken from Ref. 4, are shown in Table 1.

To draw the elastic response spectrum for any contingency plan earthquake motion, one takes the values of ground motion for any one of the zones from Table 1, using the "structural design" values only, and applies the appropriate amplification factors from Table 2 for the particular percentage of damping to the accelerations, velocities, and displacements, respectively. One obtains in this way a roughly trapezoidal form of response spectrum similar to the curves in Fig. 1. The intersections of the upper two knees of the elastic response spectrum are determined by the amplified motion lines. The two lower knees, at the higher frequencies, are taken as 8 hertz and 33 hertz, respectively. The value of the spectral acceleration at 33 hertz and beyond is taken as the maximum ground acceleration for the elastic response spectra.

Spectra may also be drawn for the operating earthquake for any zone, where the ground motion values are taken as half of those that correspond to the larger earthquake. In general, the amplification values, because of the different values of damping that might be used for the lower intensity earthquake, will not be the same as for the larger earthquake.

To determine the design spectra for acceleration or seismic coefficient, one takes the appropriate value of ductility factor from Table 3 for the seismic design class defined in the next section and divides the values of elastic displacement and velocity bounds by the value of ductility factor selected. The values of the elastic acceleration bound, however, are divided by the quantity $\sqrt{2\mu - 1}$, where μ is the ductility factor. For frequencies higher than 33 hertz, the design acceleration level is the same as the elastic acceleration.

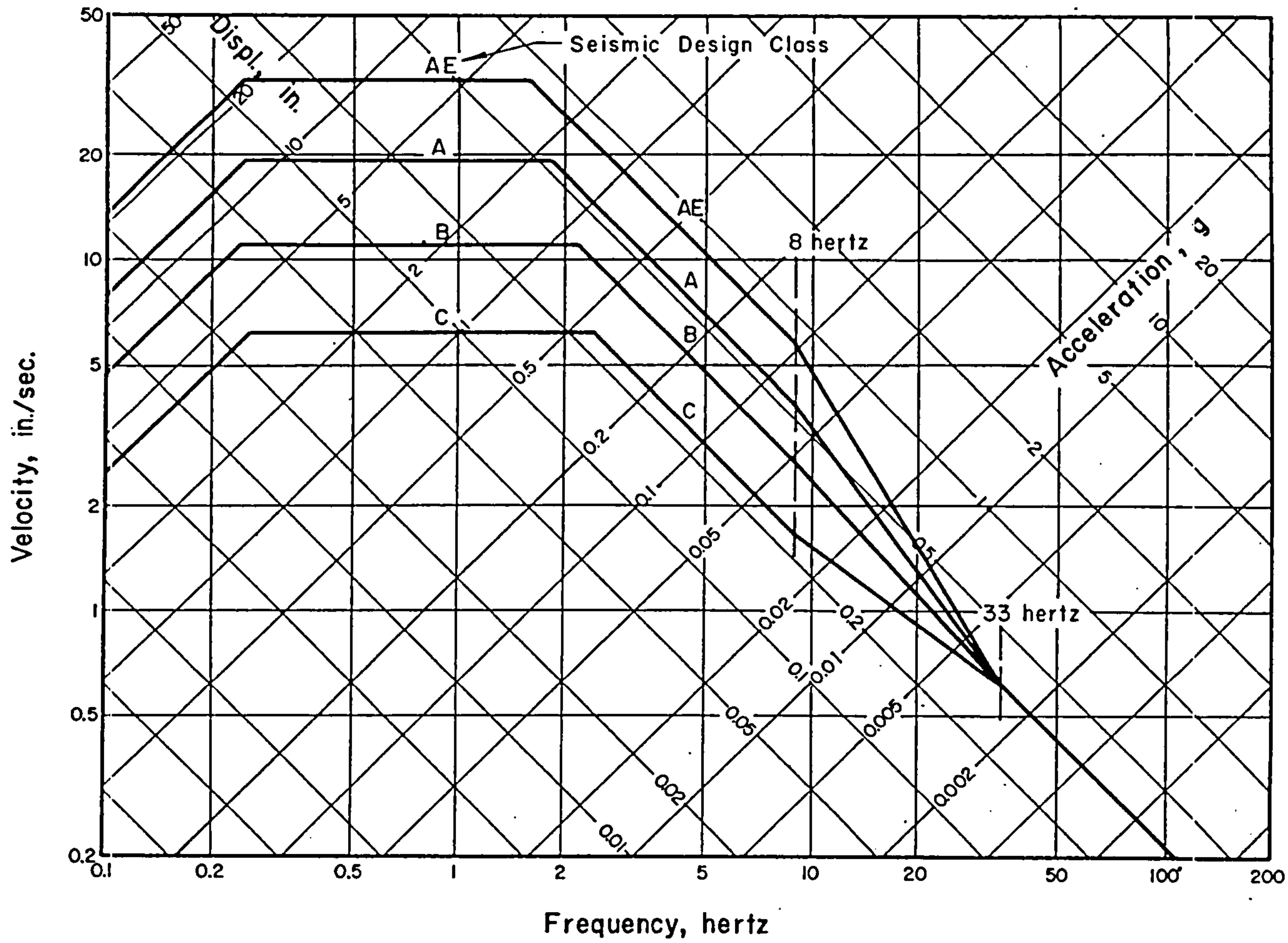

Figure 1. Design Spectra for Horizontal Motion, Magnitudes 8.5 and 8

The design spectra for all seismic design classes are shown in Fig. 1 for the zone with magnitude 8 and 8.5 earthquakes.

From the procedure described, it is clear that the intensity of earthquake motion must be considered in the light of the way in which that earthquake motion is used in design. In other words, one would prescribe a lower value of acceleration to be used with a procedure that involves the use of working stresses, than would be the case when one uses a procedure that involves yield point strengths. One cannot compare the earthquake accelerations prescribed by various codes without taking into account the design criteria used for those earthquake accelerations. The Uniform Building Code of the United States, which generally is based on the Code of the Structural Engineers Association of California, has up to the present time used working stress design criteria, and the seismic coefficients described in the SEAOC code (Ref. 2) are consistent with those values. One would have to increase the seismic coefficients prescribed in the code to arrive at values comparable with those developed herein, which are to be used at yield point levels.

Seismic Design Classification. Because of the importance of the amount of deformation or stress that can be permitted in buildings of various types subjected to

earthquakes, some guidance is necessary in arriving at an appropriate means of selecting the design requirements. For this purpose, a seismic classification system is recommended, as outlined below. Four classes for seismic design are considered. The assignment of particular structures or items to a Seismic Design class involves judgment, applied in accordance with the basic criteria described below.

Class AE includes those instruments and equipment performing vital functions that must remain nearly elastic. Obviously, items that are essential for the safe operation of the pipeline or any facility thereof, if damage to the particular unit would cause extensive loss of life or major impairment of the environment would be in Class AE. Other items might be included in Class AE if failure of such items would entail large costs in repair or replacement, should an earthquake occur which could cause the item to function improperly and thereby cause a major degree of damage that would require lengthy shutdown of the pipeline.

Class A includes items for which the requirements are slightly less stringent than Class AE. This includes items that must remain operative after an earthquake but need not operate during the event, and structures that can deform slightly in the inelastic range. It also includes facilities that are vital but whose service can be interrupted until minor repairs are made.

Class B includes buildings, facilities and equipment that can deform inelastically to a moderate extent without unacceptable loss of function. This class also includes any items for which the allowable probability of exceeding design limits can be somewhat larger than in Class A. This also includes structures housing items of Classes AE or A that must not be permitted to cause damage to such items by excessive deformation of the structure.

Class C includes, in general, buildings or equipment that can be permitted to deform a great deal, or any items for which ordinary seismic design codes are applicable. However, buildings that contain Class AE or Class A items and which might damage or put out of action those items if the building should deform excessively, should be moved to a higher class, i.e. Class B or in extreme cases, Class A. Class C includes all of those items for which the allowable probability of exceeding design limits can be moderately high.

The damping and ductility factors used in defining the design spectra for the various seismic design classes are given in Table 3. These were selected to give results that are consistent with the Class definitions above, and to satisfy the criterion that the Contingency Plan Earthquake, with its higher intensity, should in general give more stringent requirements than the Operating Earthquake.

DESIGN CRITERIA AND PROCEDURES

Design Considerations. For the design classifications used, Class C is considered as falling under the provisions of extant codes for ordinary buildings. Hence, the concept is implicit in the recommendations made herein that Class C items should not have design levels lower than those for the applicable codes such as Ref. 2.

It is believed that the recommendations made here are adequately conservative. This statement is based on the concept that the codes themselves are possibly often of less importance in guaranteeing successful resistance against earthquake motions than is careful attention to detail in design, construction, and quality control of materials. The design provisions made herein are based on the concept that there will be this careful attention throughout the design and construction procedures. Without it, even more conservative design procedures and design criteria would probably not be adequate.

Attention is called to the fact that the design spectra in Fig. 1 for Class AE, Class A, Class B, and Class C can be used only to obtain acceleration levels or seismic coefficients but not deflections or deformations.

In order to obtain displacements or deflections, one must multiply the design spectra by the appropriate value of ductility factor from Table 3. In general, this will lead to displacements that are equal to or greater than the elastic spectral displacements in all cases. For frequencies higher than about 2 hertz, the total displacements are slightly to considerably greater than the corresponding elastic displacements, but for lower frequencies, they are precisely the same.

Combining Horizontal and Vertical Seismic Motions. For those parts of structures or components that are affected by motions in various directions, in general, the net response may be computed by either one of two methods.

The first method involves computing the responses for each of the directions independently and then taking the square root of the sums of the squares of the resulting stresses in a particular direction at a particular point as the combined response. Alternatively, one can use the procedure of taking the seismic forces corresponding to 100 percent of the motion in one direction, combined with 40 percent of the motions in the other two orthogonal directions, then adding the absolute values of these, to obtain the maximum resultant forces in a member or at a point in a particular direction, and computing the stresses corresponding to the combined effect. In general, this alternative method is slightly conservative for most cases and is quite adequate since its degree of conservatism is relatively small.

Gravity Loads. The effects of gravity loads, when structures deform laterally by a considerable amount, can be of importance. In accordance with the general recommendations of most extant codes, the effects of gravity loads are to be added directly to the primary and earthquake effects. In general, in computing the effect of gravity loads, one must take into account the actual deflection and not that corresponding to the reduced seismic coefficient. In other words, if one designs for 1/5 of the actual acceleration, as one does when using seismic Class C, the actual total lateral deflections of the structure are obtained by multiplying the elastically computed deflections for the design accelerations by 5.

Unsymmetrical Structures and Torsion. Consideration should be given to the effects of torsion on unsymmetrical structures, and even on symmetrical structures where torsion may arise accidentally, because of various reasons, including lack of homogeneity of the structures, or the wave motions developed in earthquakes. The accidental eccentricities of the horizontal forces prescribed by current codes require that 5 percent of the width of the structure in the direction of the earthquake motion considered be used as an accidental eccentricity. If the actual eccentricity does not exceed this value, then the accidental value should be used, but it need not be used if the actual eccentricity is greater than the value specified as an accidental eccentricity. The effect of eccentricity is to produce a greater stress on one side of the structure than on the other, and the outer walls and columns will in general be subjected to larger deformations and forces than would be the case if the structure were considered to deform uniformly.

Overturning and Moment and Shear Distribution. In general when modal analysis techniques are not used, in a complex structure or in one having several degrees of freedom, it is necessary to have a method of defining the seismic design forces at each mass point of the structure in order to be able to compute the shears and moments to be used for design throughout the structure. The method described in the SEAOC Code (Ref. 2) is preferable for this purpose. It is essentially the following:

(1) Assume a linear variation of acceleration in the structure from zero at the

base to a maximum at the top.

(2) Multiply the accelerations assumed in (1) by the masses at each elevation to find an inertial force acting at each level.

(3) Find the total base shear corresponding to the seismic coefficient for the structure multiplied by the total weight.

(4) Assign a proportion of the total base shear not exceeding 15 percent to the top of the structure, in accordance with equation (13-4) of Ref. 2, which may be stated as:

$$0.004 \text{ times total base shear times } (h_n/D_s)^2$$

where h_n = height of building above exterior grade and D_s = plan dimension of vertical lateral-force resisting system.

(5) Adjust the assumed value of acceleration at the top of the structure in (1) so that the total distributed lateral forces add up to the total base shear.

(6) Use the resulting seismic forces, assigned to the various masses at each elevation in proportion to their value, to compute shears and moments throughout the structure.

(7) The "overturning" moment at each elevation and at the base, so computed, may give rise to tensions and compressions in the columns and walls of the structure.

(8) The "overturning" moment at the base should be considered as causing a tilting of the base consistent with the foundation compliance, and may also case a partial uplift at one edge of the base.

(9) The increased compression due to such tilting should be considered in the foundation design.

GENERAL COMMENTS AND RECOMMENDATIONS

Recommended design values of ground acceleration, velocity, and displacement are given in Table 1 for the various seismic zones of the pipeline route. These are to be used with the inelastic spectral amplification factors for the Operating and the Contingency Plan Earthquakes for the several seismic design classes. It is concluded that these are adequate to account for the behavior of special structures and facilities with an appropriate degree of conservatism, which is in general higher than values used in current design codes for buildings in high seismic regions in the United States.

The design spectra recommended herein differ somewhat from those given in Ref. 1. They are based on studies and methods that have been widely adopted and that are being used in revisions of building codes. The design values are consistent among themselves and take into account recent studies of all available strong-motion earthquake records. They also consider realistically the actual relations between force and deformation for real structures, rather than depending entirely on linear, elastic relationships. Finally, the design criteria are stated in such a way that the highest intensity of earthquake hazard, the Contingency Plan Earthquake, controls the design throughout the entire range of frequencies, in contrast to the previous criteria of Ref. 1 where sometimes, for some ranges of frequencies, the Operating Earthquake controlled the design.

The spectral amplifications used in Table 2 are based on more recent studies of a much larger number of earthquakes than were those in Ref. 1. Somewhat lower values of

amplification are found for low damping, and somewhat higher values for high damping than in the studies on which Ref. 1 was based. The new data are more reliable, and with only slight modification have been adopted for seismic design of nuclear power plants. The concept of seismic design classification is new and permits the design for various parts of a system to be made for the same earthquake hazard with adjustment in the design spectra to account for the energy absorption capability before the limiting value of deformation is reached.

The proper use of these new criteria involves the following steps, which must be handled in accordance with the methods discussed in the body of this report.

(1) Assignment of the item to a seismic design classification.

(2) Design in accordance with allowable stress or strain limits and the appropriate combination of all sources of stress and deformation.

(3) Consideration of the effect of lateral deflection on the eccentricity of gravity loads, using deflections computed from the ductility factors of Table 3 for the Seismic Design Class.

(4) Insuring the capability of developing the requisite inelastic deformation by appropriate quality control of materials, details, fabrication, and construction supervision.

(5) Consideration of overturning, uplift, etc., and of accidental torsion or of torsion due to actual eccentricity of masses and stiffnesses.

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Table 1. Design Seismic Motions

Magnitude	Ground Motion			Structural Design		
	Accel % g	Veloc in/sec	Displ in	Accel % g	Veloc in/sec	Displ in
8.5 and 8	60	29	22	33	16	12
7.5	45	22	16	22	11	8
7.0	30	14	11	15	7	5.5
5.5	12	6	4.5	10	5	4

Table 2. Spectral Amplification Factors, Horizontal, Elastic Range

Damping % Critical	Amplification Factor		
	Accel	Veloc	Displ
2	3.4	2.7	2.2
3	2.9	2.4	2.1
5	2.5	2.1	1.8
7	2.2	1.9	1.6

Table 3. Damping and Ductility Factors for Various Design Classes and Earthquakes

Earthquake	Seismic Design Class	Damping % Critical	Ductility Factor
Operating	AE	2	1
	A	2	1.5
	B	3	2
	C	5	3
Contingency Plan	AE	3	1.2
	A	3	2
	B	5	3
	C	7	5