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UNIVERSITY OF ILLINOIS
AT URBANA-CHAMPAIGN
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DEPARTMENT OF CIVIL ENGINEERING
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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

<u>Actual vs. Effective Earthquake Motions</u>. 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 located at end of paper.

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.

<u>Combining Horizontal and Vertical Seismic Motions</u>. 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.

<u>Gravity Loads</u>. 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.

<u>Unsymmetrical Structures and Torsion</u>. 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.

<u>Overturning and Moment and Shear Distribution</u>. 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

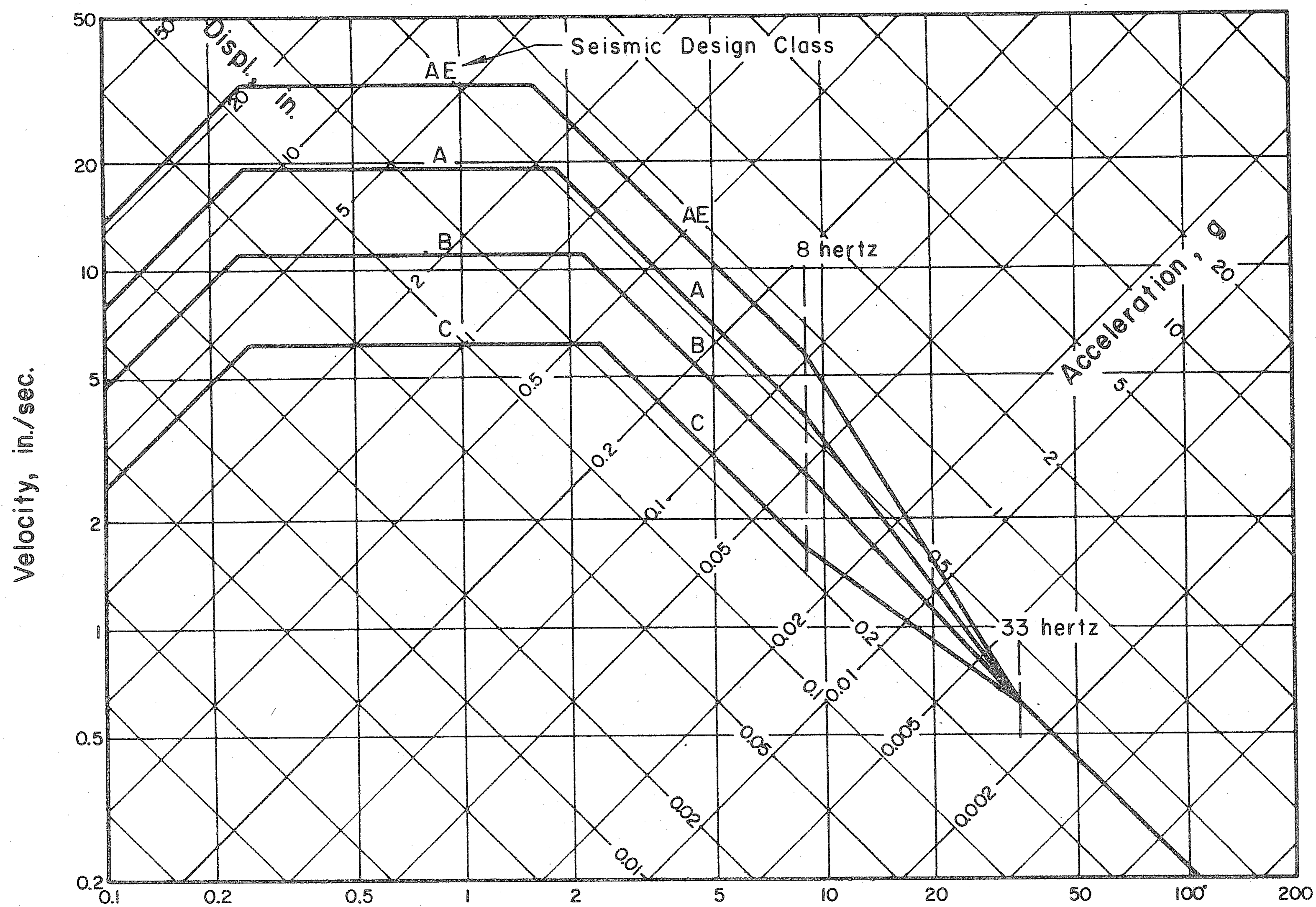

Figure 1. Design Spectra for Horizontal Motion, Magnitudes 8.5 and 8

PIPELINE DESIGN TO RESIST LARGE FAULT DISPLACEMENT

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INTRODUCTION

A buried pipe in a trench in either rock or soil will strain longitudinally and deform transversely in the vicinity of a break in the ground surface caused by motions at a fault intersecting the pipeline. If the pipe is placed in a shallow trench so that it can be displaced out of the trench along shallow sloping sides, the pipe can readily conform to the transverse components of motion of the fault break, although there may be distortions of the diameter short of rupture or failure, in general. The pipe need be displaced out of the trench only for a distance of less than about 100 ft each side of the fault break to accommodate even 20 ft transverse components of fault motion. However, the longitudinal component of fault motion can introduce compressions or tensions in the pipe and can cause damage if the fault motions are great enough. In general, if the longitudinal strain in the pipe is kept well below the strain corresponding to the ductility limit of the pipe, shortening of the pipe will be accompanied by wrinkling which can absorb a great deal of strain. However, extension of the pipe can produce tensile stresses that might cause failure unless the strains are limited. Where very large fault displacements are expected it is likely that the design will lead to laying the pipeline on the ground surface with provision for freedom of movement between anchor points.

This paper considers the capability of a pipe buried at several depths, and made of one of three possible grades of steel and two wall thicknesses, to resist fault motions corresponding to total fault displacements of 10 ft and greater. The capability of a pipe buried in soil to resist fault motions is generally greater than its capability in rock. For conservatism the values and conditions herein are taken as consistent with a pipe in a trench in rock.

General conclusions are presented herein regarding the depth of cover that might be used for different grades of pipe in order to assure capability of resisting the fault motions. In some instances, especially for the deeper depths and the higher grades of steel, it may be necessary to avoid regions where the angle of the fault plane with the pipe axis is so small that nearly all of the fault displacement is transmitted to the pipe as a longitudinal deformation in the pipe. Some typical results of calculations also are presented.

ASSUMPTIONS AND RELATIONS USED

In general, conservative assumptions are made herein regarding the various parameters. These are listed below.

Pipe Slip and Friction

The resistance of the pipe to slip in the medium in which it is buried is determined by the angle of friction between the pipe and the medium, multiplied by the average pressure exerted against the wall of the pipe, which is a function of the depth of cover and the height of the water table.

The average radial pressure on the pipe p is given by the relation:

$$p = \frac{1 + k_o}{2} \gamma H \qquad (1)$$

where H = depth of cover + radius of pipe (2 ft in these calculations)

γ = weight per unit of volume of soil (net or submerged)

k_o = coefficient of lateral earth pressure at side of pipe

If k_o is taken as 0.5, a reasonable value, and γ is taken as 135 lb/cu ft, then the average pressure against the wall of the pipe for a 3 ft depth of cover is given by:

$$p = 0.75 \times \frac{135}{144} \times 5 = 3.516 \text{ psi} \qquad (2)$$

If the material is submerged, the effective weight per unit of volume of the soil is reduced by 62.4 lb/cu ft, and the value of the average pressure is about half as much. If the depth of cover is 8 ft, and the material is dry, the pressure is twice as much that given by Eq. (2). For an angle of internal friction of the medium against the pipe of 20 degrees, as might be typical, the change in stress per foot of length in the pipe, q, is given by:

$$q = p \tan 20° \times 12/t \qquad (3)$$

where t is the thickness of the pipe wall in inches. For t = 0.462 in., q = 33.24 psi/ft, using the value of p from Eq. (2). For a 3 ft depth of cover with the water table at the surface, the value of q will be 17.87 psi/ft, and for a depth of cover of 8 ft in the dry, the value of q will be 66.47 psi/ft, for the same thickness. The value of q is assumed to be constant over the length of the pipe that slips in the calculations reported herein.

Material Properties

The properties of the pipe material were considered for three grades of steel, X-70, X-65, and X-60; the stress-strain curve for X-65 pipe is shown in Fig. 1. The stress-strain curve is approximated by a polygonal curve having an elastic initial part to an "effective" yield point somewhat greater than the actual yield point, then a second linear portion with a much shallower slope to a strain corresponding to 0.04, followed by a constant stress level to the point of failure. The maximum stress on the stress-strain curve is reached at 8 to 10 percent strain for the three grades, and failure does not occur until 10 to 17 percent strain. Consequently, the 4 percent strain limit is a reasonable one.

The parameters used in the calculations are shown in Fig. 2, and the properties for X-65 grade pipe used in the analyses are shown in parentheses following the notation given next. Here the effective yield point is denoted by the symbol σ_1 (72,000 psi) at which the strain is ε_1 (0.0024), and the stress at a strain of 0.04 is indicated by the symbol σ_2(81,800 psi). The slope of the stress-strain curve between these two points corresponds to a modulus E_2(260,638 psi). This is in contrast to the initial modulus E of 30 x 10^6 psi. If the line with slope E_2 is projected back to the axis, it intersects it at a stress of σ_o (71,374 psi).

— Figures located at end of paper. —

Figure 1. Uniaxial Stress-Strain Curve (Ref. 1)

Figure 2. Notation Used for Stress-Strain Curve

Basic Relations

In all cases the length of pipe that is subject to slip between two points where the stresses are defined is obtained by dividing the difference in stress between the two points by the quantity q applicable to the depth of cover and condition of burial.

The average strain between the two points can be computed for each region in which the modulus is constant as the average of the two strains at the ends of the region, and from this average strain, multiplied by the length of pipe that slips, the change in length of the pipe can be determined. These relations are basic to all of the cases considered in the following.

Elastic Range

For the elastic range in which slip occurs from the point of zero stress to some maximum stress σ_m in the pipe, the length L_e over which slip occurs, the average strain ε_{ave}, and the displacement or change in the length L_e of the pipe, d_e, are given by the following:

$$L_e = \sigma_m/q \tag{4}$$

$$\varepsilon_{ave} = \sigma_m/2E \tag{5}$$

$$d_e = \sigma_m L_e/2E \tag{6}$$

By substituting Eq. (4) into Eq. (6) and solving for L_e, one finds:

$$L_e = \sqrt{\frac{2Ed_e}{q}} \tag{7}$$

Equation (7) can be used directly if the amount of displacement is given, and L_e is determined thereby. However, if this is done, the value of σ_m given by the solution of Eq. (4), following this determination of L_e, must lead to a stress that is still in the elastic range for this method to be valid.

Inelastic Range

In the inelastic range, if σ_1 is the effective yield point stress, then with the notation that L_p is the slipping length in the plastic or inelastic range with modulus E_2, the following relations are applicable:

$$\sigma \geq \sigma_1 \tag{8}$$

$$\varepsilon = \frac{\sigma - \sigma_o}{E_2} \tag{9}$$

Between σ and σ_1,

$$\varepsilon_{ave} = \frac{\sigma_1 - 2\sigma_o + \sigma}{2E_2} \tag{10}$$

$$L_p = \frac{\sigma - \sigma_1}{q} \quad \frac{d_p}{\varepsilon_{ave}} \tag{11}$$

If the stress σ is known, then L_p can be obtained directly from Eq. (11), and the displacement d_p can then be obtained also, directly. However, if σ is not known, but d_p is given, the following relations are needed. Using this value in Eq. (10), one finds:

$$L_p = \frac{d_p E_2}{\sigma_1 - \sigma_o + qL_p/2} \tag{12}$$

$$\frac{qL_p^2}{2} + (\sigma_1 - \sigma_o)L_p - d_p E_2 = 0 \tag{13}$$

$$L_p = \sqrt{\frac{2E_2 d_p}{q} + \left(\frac{\sigma_1 - \sigma_o}{q}\right)^2} - \left(\frac{\sigma_1 - \sigma_o}{q}\right) \tag{14}$$

$$\sigma = qL_p + \sigma_1 \tag{15}$$

The value of L_p is obtained directly from Eq. (14), and having the value of L_p, one can obtain the stress σ from Eq. (15). If σ is greater than σ_2, however, then these relations are not applicable.

For a combined range, having parts in both the elastic and plastic regions, one can find the net length over which slip occurs by adding the elastic length to the plastic length, and the displacement is the sum of the two components of displacement.

These relations are valid if one keeps the stress σ_1 fixed and the unknown stress σ is greater than σ_1 but less than σ_2. In the alternative case where one considers the strain ε_2 and the stress σ_2 as fixed, and the unknown stress σ is less than σ_2 but greater than σ_1, modification in Eqs. (8) to (15) is necessary. This modification is simply to replace σ_1 by σ_2, and to change the sign of q. With this change, the important relations, Eqs. (11), (14) and (16) become:

$$L'_p = \frac{\sigma_2 - \sigma}{q} = \frac{d'_p}{\varepsilon_{ave}} \tag{16}$$

$$\therefore L'_p = -\sqrt{-\frac{2E_2 d'_p}{q} + \left(\frac{\sigma_2 - \sigma_o}{q}\right)^2} + \left(\frac{\sigma_2 - \sigma_o}{q}\right) \tag{17}$$

$$\sigma = \sigma_2 - qL'_p \tag{18}$$

In order to distinguish these equations from the preceding ones, the symbol L'_p is used in place of L_p and d'_p is used in place of d_p.

Relation between Pipe Deformation and Fault Motion

If the change in length of the pipe on each side of the fault is given by the symbol d, and the total fault motion is D, where the angle between the plane of the fault and the pipe axis is ϕ, the relation among these quantities is given by:

$$d = \frac{D}{2} \cos \phi \tag{19}$$

Strain Due to Transverse Component of Fault Motion

Even a purely transverse fault motion will produce gross longitudinal strains in the pipe in addition to those corresponding to flexure of the pipe. The average longitudinal strain is that associated with the change in length of the pipe between the points at which it is effectively anchored on both sides of the fault. For an anchor length L on each side, and an offset D at right angles to the pipe, the average longitudinal strain $\bar{\varepsilon}$ is, approximately:

$$\bar{\varepsilon} \cong \frac{1}{8}\left(\frac{D}{L}\right)^2 \tag{20}$$

If the fault motion makes an angle ϕ with the pipe axis, the average strain is increased by the axial component of relative motion between the anchor points. Under these conditions, the average longitudinal strain becomes, conservatively:

$$\bar{\varepsilon} \cong \frac{1}{8}\left(\frac{D}{L}\right)^2 + \frac{1}{2}\frac{D}{L} \cos \phi \tag{21}$$

The second term on the right in Eq. (21) is recognizable as Eq. (19) divided by L.

It can be seen that if L/D is 10 or greater, the part of the strain coming from Eq. (20) is less than about 3 percent of the maximum strain of 0.04 considered as applicable in the calculations herein. Hence, the transverse component of fault motion can be considered as having a negligible effect except on local flexure, if the pipe is free to move up and out of the ground between points of effective anchorage at least as far apart as 100 ft on each side of the fault, even if the total fault displacement is as much as 10 ft. The pipe should not be subject to impact or constraint in its lateral motion, however, over the major central portion of the total length of 200 ft. However, other considerations may require a longer "free" length.

The "exact" relationship for which Eqs. (20) and (21) are approximations is:

$$\bar{\varepsilon} + \frac{\bar{\varepsilon}^2}{2} = \frac{1}{2}\left(\frac{D}{2L}\right)^2 + \left(\frac{D}{2L}\right)\cos\phi \tag{22}$$

A better approximation than Eq. (22), valid at both $\phi = 0$ and $\phi = 90$ degrees, with only negligible error between those limits, is:

$$\bar{\varepsilon} \cong \left(\frac{D}{2L}\right)\cos\phi + \frac{1}{2}\left(\frac{D}{2L}\right)^2 \sin^2\phi \tag{23}$$

One can solve Eq. (22) to find the allowable values of D/2L for any fault angle ϕ to give a particular average strain $\bar{\varepsilon}$ over the length 2L.

The results of calculations made for several values of $\bar{\varepsilon}$ are given below in Table 1.

Table 1. Fault Displacement divided by Total Free Slip Length $\left(\frac{D}{2L}\right)$

Angle, deg.	$\bar{\varepsilon} = 0.04$	$\bar{\varepsilon} = 0.03$	$\bar{\varepsilon} = 0.02$
0	0.0400	0.0300	0.0200
15	0.0413	0.0310	0.0207
30	0.0459	0.0345	0.0230
45	0.0555	0.0418	0.0280
60	0.0758	0.0579	0.0389
75	0.1266	0.0988	0.0689
90	0.2857	0.2468	0.2010

The entries in the first line of Table 1 for $\phi = 0$, indicate the value of $\bar{\varepsilon}$, since D/2L is the average strain when the fault plane makes a zero angle with the pipe axis. It appears from the tabulated values that the ratios of D/2L for any value of ϕ up to about 60 degrees are approximately 1/cos ϕ times the values for $\phi = 0$. That is, if the fault plane makes an angle of 60 degrees with the axis, then the value of D/2L $\cong 2\bar{\varepsilon}$. The error is less than 5.5 percent if $\bar{\varepsilon}$ is less than 0.04; and the error is only 22 percent for $\phi = 75$ degrees.

The values in the table may be used to indicate the value of L required to assure survival for a combination of transverse and longitudinal components of fault motion. The resulting approximate relation for L/D based on the concept described above and the relations in the table leads to the relation:

$$\frac{L}{D} > \sim \frac{\cos\phi}{2\bar{\varepsilon}} \tag{24}$$

This relation indicates that the "free" length L on each side of the fault, relative to the fault displacement D, for $\phi = 0$, should be 16.7 for $\bar{\varepsilon} = 0.03$, and 25 for $\bar{\varepsilon} = 0.02$, although it can be only 12.5 for $\bar{\varepsilon} = 0.04$. The latter value implies a maximum strain over an appreciable length, and therefore a value of 20 is recommended for 48 in. diameter pipe; this requires a free length of 200 ft on each side of the fault, for a 10 ft fault motion, which can be reduced as the angle ϕ increases, but in no case should it be less than 100 ft.

RESULTS OF ANALYSES

With the relations given in the foregoing, analyses were made for a number of conditions. Typical of such calculations are those shown in Table 2. The length of slip in the pipe, the maximum and minimum stresses in the pipe, and the strain corresponding to the maximum stress, for a thickness of 0.462 in. are given therein. In these calculations the fault motion is taken as very large, to show the maximum capability, and also as either 10 ft or 5 ft. The angle that the fault line makes with the pipe axis is taken as 30°. The quantity q (denoted by Q in the tables) is given for each of three cases considered, where Case 1 corresponds to 3 ft of cover over the pipe with a submerged condition, Case 2 corresponds to 3 ft in the dry condition (or to approximately 8 ft of cover in the submerged condition), and Case 3 corresponds to 8 ft of cover in a dry condition.

In each case, for the elastic range, denoted by "EL-HL", the maximum stress is taken as the effective yield point stress, and the minimum stress as whatever it comes, provided it is greater than zero. Two conditions are considered for the plastic range. For condition "PL-LH" the stress is considered to range from the effective yield point up to a maximum value that will permit the pipe deformation to correspond to the fault motion assumed. This maximum is always less than σ_2. For the condition "PL-HL" the stress is considered to range down from the maximum stress to a lower stress, at or above the yield point, of such an amount as will permit the fault motion to be accommodated. The maximum capability in each of these cases is given first, then the values for 10 ft and for 5 ft of fault displacement.

For condition PL-HL, where the maximum strain is always taken as 0.04 with the corresponding maximum stress being used for that strain, the results, of course, correspond to smaller lengths of slip than for condition PL-LH, since the stress range corresponds to a higher upper limit, in general. In both plastic conditions the lengths of slip are smaller than for the elastic condition, EL-LH.

It is believed that the conditions assumed for the plastic condition calculations are realistic because of the fact that the pipe may have sufficient bends in it, or otherwise be effectively anchored, so that the fault motion will have to be accommodated in the region of the pipe very close to the fault break. Consequently, if the fault motion cannot be accommodated within several hundred feet of the pipe near the fault break, it should not be considered as a suitable condition.

Table 2. Effect of Fault Motions

GRADE X-65 EFF Y.P. 72,000 PSI MAX STRESS 81,800 PSI AT STRAIN 0.04
INITIAL MODULUS = 30,000,000 PSI, SECOND MODULUS = 260,638 PSI
FAULT ANGLE WITH AXIS OF PIPE = 30 DEG

CASE	COND	Q PSI/FT	THICK IN.	LENGTH FT	MAX S PSI	MAX STRAIN	MIN S PSI	DISPL FT
LATERAL PRESS COEFF = 0.5, DENSITY OF SOIL = 72.6 PCF WET								
1	EL-HL	17.87	0.462	4028	72,000	0.0024	0	11.16
1	PL-LH	17.87	0.462	548	81,800	0.04	72,000	26.84
1	PL-HL	17.87	0.462	548	81,800	0.04	72,000	26.84
1	EL-HL	17.87	0.462	2728	72,000	0.0024	23,245	10
1	PL-LH	17.87	0.462	322	77,757	0.024488	72,000	10
1	PL-HL	17.87	0.462	121	81,800	0.04	79,642	10
1	EL-HL	17.87	0.462	1035	72,000	0.0024	53,499	5
1	PL-LH	17.87	0.462	219	75,909	0.017398	72,000	5
1	PL-HL	17.87	0.462	57	81,800	0.04	80,783	5
LATERAL PRESS COEFF = 0.5, DENSITY OF SOIL - 135 PCF DRY								
2	EL-HL	33.24	0.462	2166	72,000	0.0024	0	6
2	PL-LH	33.24	0.462	295	81,800	0.04	72,000	14.44
2	PL-HL	33.24	0.462	295	81,800	0.04	72,000	14.44
2	EL-HL	33.24	0.462	2166	72,000	0.0024	0	6
2	PL-LH	33.24	0.462	242	80,058	0.033318	72,000	10
2	PL-HL	33.24	0.462	139	81,800	0.04	77,177	10
2	EL-HL	33.24	0.462	1281	72,000	0.0024	29,437	5
2	PL-LH	33.24	0.462	166	77,531	0.02362	72,000	5
2	PL-HL	33.24	0.462	60	81,800	0.04	79,811	5
LATERAL PRESS COEFF = 0.5, DENSITY OF SOIL = 135 PCF DRY								
3	EL-HL	66.47	0.462	1083	72,000	0.0024	0	3
3	PL-LH	66.47	0.462	147	81,800	0.04	72,000	7.22
3	PL-HL	66.47	0.462	147	81,800	0.04	72,000	7.22
3	EL-HL	66.47	0.462	1083	72,000	0.0024	0	3
3	PL-LH	66.47	0.462	121	80,058	0.033318	72,000	5
3	PL-HL	66.47	0.462	70	81,800	0.04	77,177	5

CONCLUSIONS

Based on the calculations and studies made, the following conclusions and recommendations are reached:

1. The smaller the frictional force on the pipe, the greater is the capability for surviving fault motion. Normally it is unrealistic to assume the medium is submerged because the water may drain off and result in a more dangerous condition owing to the greater frictional resistance.

2. The lower the grade of steel, the more yielding can take place (or the greater is the toughness) and hence the greater is the capability.

3. For a given grade of steel, if increasing the thickness does not reduce the ductility nor the weld strength, the greater the thickness of the pipe, the greater is the capability. In general, however, the motion capability increases in a smaller proportion than the thickness increases, other things being equal.

4. Most of the displacement of the pipe takes place in a short length of the pipe on each side of the fault. Because of vertical and horizontal bends in the pipe, variations in depth of cover and therefore in the frictional resistance, and other variations, it is desirable to assure survival of the pipe with deformations limited to a length of several hundred feet either side of a fault that intersects the pipe, even if the fault makes only a small angle with the pipe. The following conclusions are based on this concept, with the allowance of at most a longitudinal strain of 0.04 in the pipe in the most highly stressed region, for wall thicknesses of pipe of 0.462 in. and 0.562 in.

5. All three grades of steel, X-70, X-65, and X-60, can survive a 10 ft fault motion, with deformations extending over a length of less than about 160 ft on each side of the fault, if the cover is less than 3 ft and the material is submerged. If the material is dry, grades X-65 and X-60 can survive the 10 ft fault motion, with deformations over less than about 170 ft. However, grade X-70 can survive 9.4 ft of fault motion, with deformations over a length of 220 ft on each side of the fault, for a thickness of 0.562 in. This grade can survive a 10 ft fault displacement if the angle between the fault plane and the pipe axis is greater than 20 degrees. The thinner X-70 pipe will survive only 7.7 ft of fault motion, over a length of 180 ft, and requires an angle of 40 degrees or more to withstand 10 ft.

6. All the grades for 3 ft of cover, either submerged or dry, can withstand 5 ft of fault motion with substantially smaller lengths of deformation.

Similar conclusions can be drawn for other depths of burial.

7. If potential fault motions of 10 ft or less can be crossed nearly at right angles, subject to the restrictions stated below, all grades of pipe can be used, with depths of cover less than 8 ft. If the fault direction is uncertain, the depth of cover should be limited to 3 ft, with special precautions if Grade X-70 material is used. This restriction on depth of cover should extend for about 200 ft on either side of expected fault zones. Moderate bends, both vertically and horizontally, should be used in this length, and may even be helpful, but anchors should be avoided.

8. All of the above is based on the assumption that the pipe is placed in a trench with shallow sloping sides so that it can accommodate itself to the transverse as well as the longitudinal components of fault displacement in part by moving out of the trench. It is recommended that the lower limiting length of shallow depth of cover be maintained for about 300 ft on each side of the fault zone, where possible, to decrease the maximum strain in the pipe for large fault motions (of 10 ft or more), but only about half this length is needed if fault motions of 5 ft or less are expected. If very large fault motions are expected, the design probably will lead to placing the pipeline on the ground surface with provision for freedom of movement between anchor points.

REFERENCE

1. "Design Criteria and Stress Analysis for the Trans-Alaska Pipeline", Summary Report, Alyeska Pipeline Service Company, Fig. A-1, App. A, Dec. 18, 1972.

ACKNOWLEDGMENT

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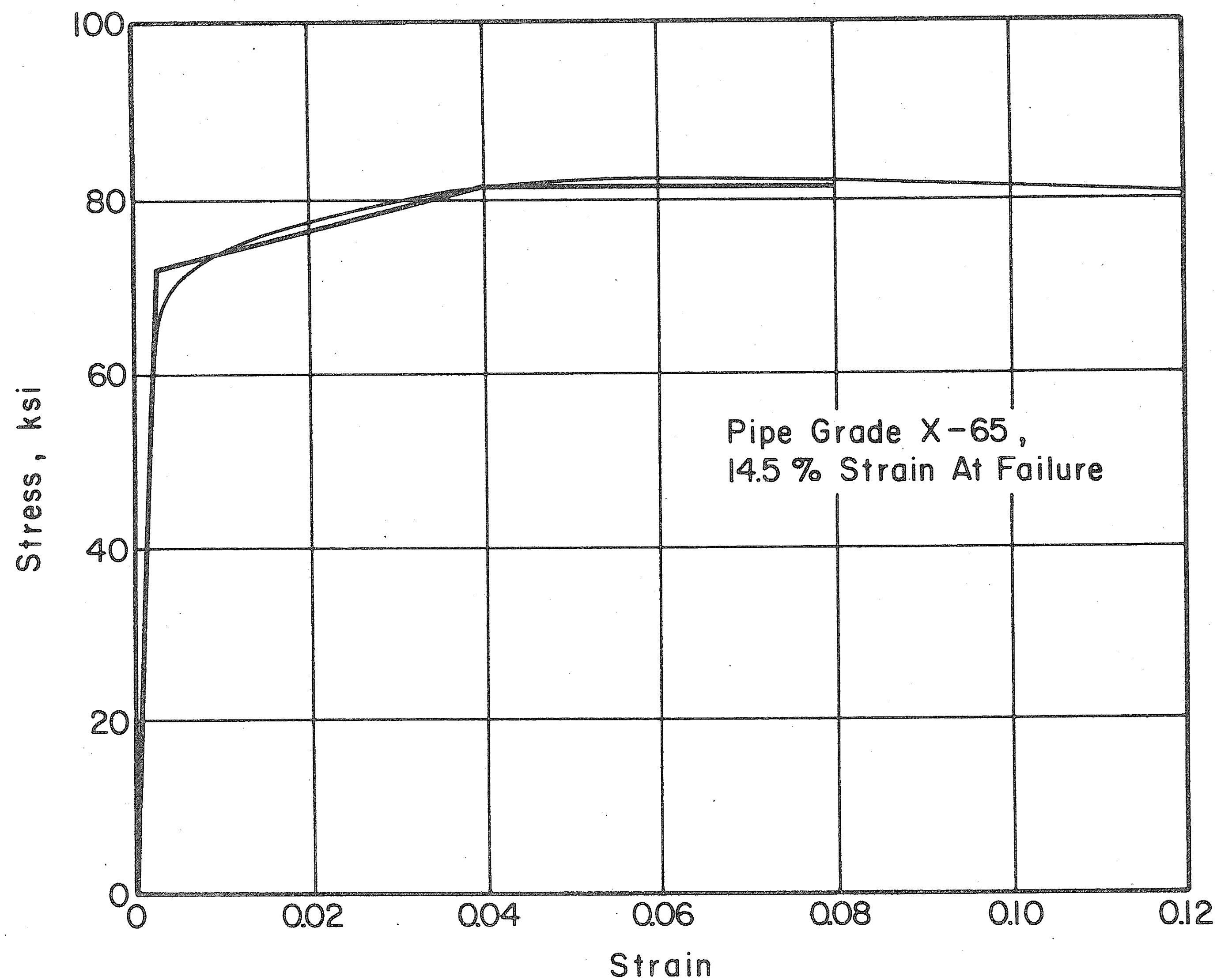

FIG. 1 UNIAXIAL STRESS-STRAIN CURVE (REF. 1)

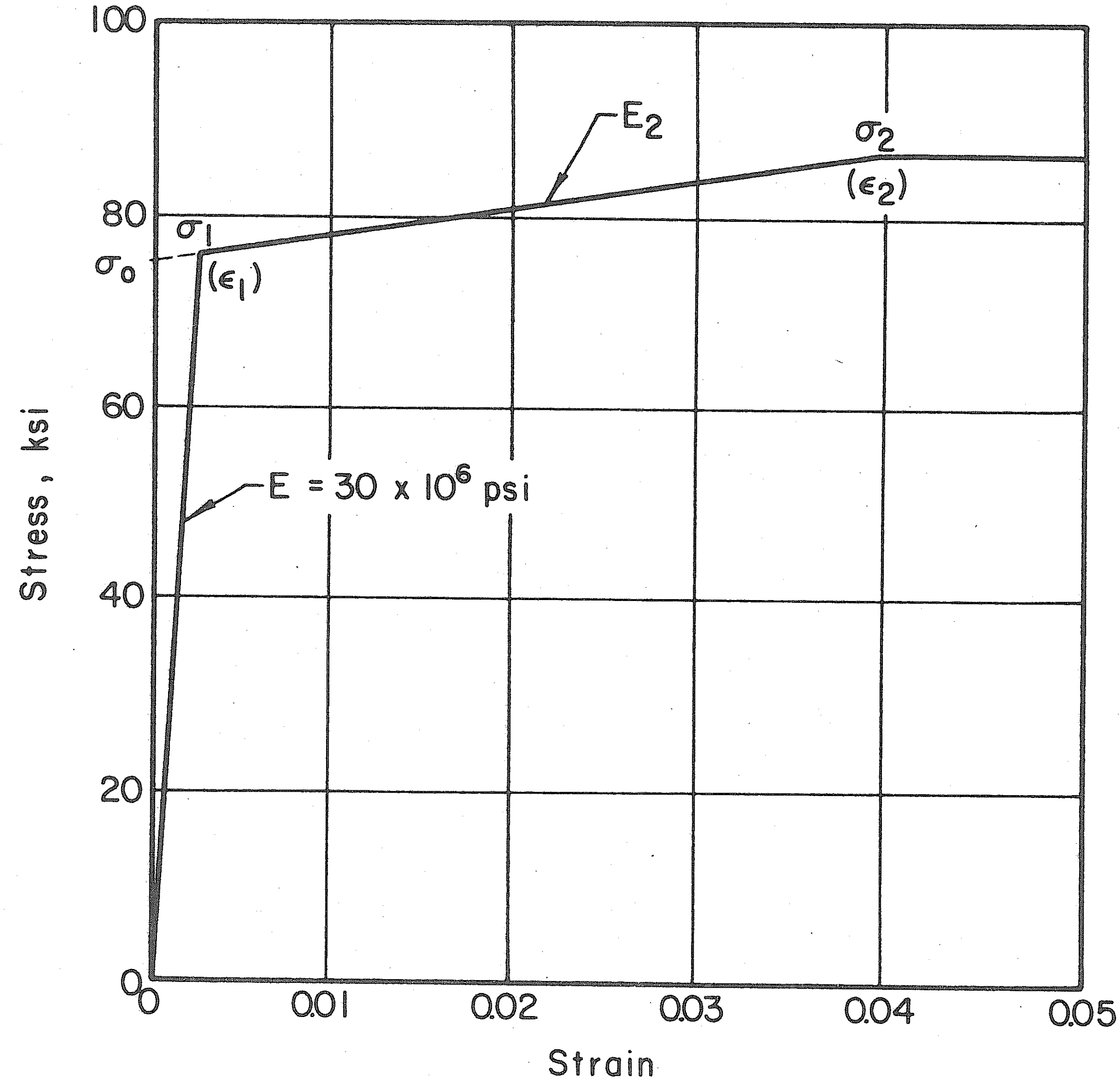

FIG. 2 NOTATION USED FOR STRESS-STRAIN CURVE

OBSERVATIONS ON THE PROCESS OF EQUIPMENT QUALIFICATION

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INTRODUCTION

The seismic qualification process has been described in numerous papers dealing with analytical and test procedures for qualifying equipment, and consideration of free-field and in-structure response spectra. A summary of most of the accepted procedures for seismic qualification of nuclear equipment is presented in a guideline standard (Ref. 1); this standard also is used as a guide in nonnuclear applications. The purpose of this paper is not to offer comments on the aforementioned standard, but to provide some observations on the overall process of equipment qualification employed in meeting seismic requirements and specifically to describe the interrelationship of three groups involved in manufacture and use of the final product or system. The three groups are designated herein as the Final User, the System Assembler, and the Component Manufacturer. Current literature on equipment qualification to meet seismic design requirements inadequately discriminates between these three groups. Despite differences in constraints and elements under their direct control, they must provide a final system capable of qualification and which meets functional requirements.

As an example of Final User considerations, the approach employed in the trans-Alaska Pipeline equipment procurement is described. Only brief mention is made of nuclear power equipment qualification requirements because these are well documented in the literature. Brief attention is given to a topic described in recent literature as Lifeline equipment. It is the hope of the authors that attention to the interrelationship problems between the Component Manufacturer, System Assembler and Final User will help clarify an area of major importance and will lead to procurement of equipment with improved functional capability at reasonable cost.

DEFINITIONS AND INTERRELATIONSHIP

Final User

The Final User category is intended to include the client (industrial concern, utility, building owner, or even city management) and the engineer-architect team responsible for the project management in both design and construction. Normally this group begins with a plant, project or system located in some geographical domain which may be subject to various types of input including seismic and wind effects. A major aspect of the design process is that of evaluating the various hazards and establishing the applicable design criteria. The latter subject is not discussed in this paper and it is assumed, in that which follows, that it has been adequately evaluated by the Final User. The goal of the Final User is to evolve an economically practical and functioning system, plant or project, yet one which meets the safety and environmental requirements.

System Assembler

The System Assembler category is intended to denote the intermediary between the Final User and the Component Manufacturer. In the usual case, the assembler must bring together components from various manufacturers, place them in cabinets or racks, and assemble a system that achieves the desired function. The System Assembler has "geographical control" within his own system in terms of where he locates components, how he structures the cabinetry and in this way can, in many respects, control the seismic performance of his product. It is appreciated that in some cases the System Assembler is not in the equipment-to-Final-User stream, but he is included herein since this aspect of design is often used and leads to special problems.

Component Manufacturer

The Component Manufacturer designation is employed for those who provide basic components to the Assembler for use in the system, or to the Final User for direct installation. In many cases the Component Manufacturer has no knowledge of the probable use to which his device may be placed. Thus, his primary problem is to describe adequately the performance of his device so that the Final User or Component Assembler may judiciously employ the device with full knowledge of its limitations.

OBSERVATIONS ON SEISMIC QUALIFICATION

The administration of seismic qualification programs for major projects commonly involves serious problems, particularly with regard to meeting procurement schedules, excessive costs for qualification and those problems which arise from a general lack of understanding of seismic design requirements by many vendors. A vital requirement in the qualification process is that of establishing and maintaining communication between all parties during the entire design and procurement process.

Each of the three groups identified have common as well as unique problems; these are discussed next.

Final User

The Final User is faced with a host of problems in developing a seismic qualification program. These range from defining explicitly the performance required of the equipment during an earthquake event (in terms of the selected hazard) to maintaining a timely and economically realistic procurement schedule. On the assumption that a realistic hazard evaluation has been established, the problem evolves into that of arriving at a plausible preliminary design in terms of project costs, functional requirements, and procurement and construction schedules.

The design of most major projects is directed by a project management group that is primarily familiar with the functioning of the various operational systems that make up the facility. Many different design engineers, each representing a particular specialty, are normally responsible for determining the equipment needed and in many respects have follow-through responsibilities for eventual selection of equipment.

Specialists in earthquake engineering who are versed in seismic qualification are relatively few in number and in most cases they are either part of, or assigned to, outside support groups. Thus, the definition of performance objectives for equipment is made difficult by the need of project engineers and design engineers to communicate with each other, and the need to find a way of communicating with seismic specialists, procurement groups, and vendors.

The vehicle that appears most promising to expedite communication between seismic qualification specialists and project design engineers is a detailed set of categories that define performance objectives for the equipment. In a sense they serve as criteria for seismic qualification and evaluation.

Some of the definitions in current use aid in establishing such performance objectives but in many cases they are broad and general. For example, in the nuclear industry, Class IE equipment is defined as "the safety classification of the electrical equipment and systems that are essential to emergency reactor shutdown, containment isolation, reactor core cooling, and containment and reactor heat removal, or otherwise are essential in preventing significant release of radioactive material to the environment" (Ref. 1). Class IE equipment is identified with the Safe Shutdown Earthquake (SSE) which is defined as that earthquake which produces the ground motion for which those features of the nuclear power plant necessary to shut down the reactor and maintain the plant in a safe condition without undue risk to the health and safety of the public are designed to remain functional. Normally, nuclear plant load combinations and resistance evaluations are such that design must be considered for both the SSE and one-half SSE earthquakes. In the nuclear industry, various techniques have been evolved to insure that these requirements are met.

In certain other industries seismic qualification already has become a consideration. It is expected that this will be increasingly the case in years to come because of public concern about the effects of earthquakes and other natural disasters and also because, as population centers grow, the risk of loss of life and damage increases by virtue of increased exposure.

A term which increasingly is being used to define seismic criteria for other than nuclear or large facility projects is "Lifeline Engineering". It is expected that this term will find increasing use in the years ahead for many applications. In the case of equipment it is interpreted to mean items necessary for survival of the population and/or emergency services during and following an earthquake. Many of the concepts discussed herein are applicable to this area as well.

An example of a major, nonnuclear project where the concept of using a detailed set of categories has been used is the trans-Alaska Pipeline System (Refs. 2 and 3). The primary objective for qualification of equipment is to prevent environmental damage and to provide a controlled shutdown, if necessary, during a Design Contingency Earthquake (analogous to the Safe Shutdown Earthquake used in the nuclear industry). During an earthquake of lesser magnitude, termed the Design Operating Earthquake, an additional objective is to maintain uninterrupted operation of the pipeline system. The seismic categories used for the trans-Alaska Pipeline System (Alyeska Pipeline Project) are described as follows:

Category 1A: Equipment that shall maintain its operating function both during and following the Design Contingency Earthquake (DCE).

Category 1B: Equipment that shall maintain its operating function both during and following the Design Operating Earthquake (DOE).

Category 2A: Equipment that shall be capable of performing its operating function following but not necessarily during the DCE.

Category 2B: Equipment that shall be capable of performing its operating function following but not necessarily during the DOE.

<u>Category 3</u>: Equipment vital for continued operation of the pipeline but whose failure is deemed unlikely and which cannot easily or effectively be qualified by testing and/or analysis, or at reasonable cost. Failure or malfunction should cause only an interruption in service but no threat of environmental damage or impairment of safe shutdown. The design requirement is that the equipment must be anchored properly and must not collapse.

<u>Category 4</u>: Equipment not vital for continued operation of the pipeline and whose performance during an earthquake is relatively unimportant, but which must be anchored properly to preclude damage to Category 1, 2, or 3 equipment.

<u>Category 5</u>: All other equipment for which seismic considerations are unnecessary.

The categories listed above represent performance objectives for equipment and do not imply any specific qualification approach or procedure. In general, testing or combined analysis and testing would be required for complex equipment in Categories 1 and 2. Analysis only may be sufficient for equipment that is primarily structural in nature even though it is assigned to Category 1 or 2.

In major projects where environmental or safety stipulations are of concern, it is important to recognize the subsystems or components which are required to operate during and/or after an earthquake for stipulation compliance. Categories 1A and 2A for the Alyeska Project include the components required to operate during and/or after the maximum credible earthquake to prevent environmental damage. Categories 1B, 2B and 3 are assigned to components that are required to operate in order to maintain uninterrupted pipeline service. Since an equipment item in Category 1B or 2B is required to maintain its function as appropriate for satisfying operational objectives only, the qualification can be less stringent than required for 1A or 2A. Category 3 is reserved for equipment that is vital for continued operation, but whose qualification is impractical. Category 4 implies the same qualification requirements as Category 3; the only rationale for making them separate is that items that are clearly required for operation can be assigned to Category 3. In certain cases an item might be given a dual classification, such as 2A/1B, which would imply that the equipment should be capable of operating after the DCE and during and after the DOE.

The most important function of the categories noted is that they serve to provide a communication link between those that are familiar with the operational system and the seismic specialists who generally are not familiar with the system. The classification of equipment according to seismic categories for large facilities requires a joint input of project engineers, operations and seismic specialists and management, and must be done in a consistent and systematic manner. The classification process must be initiated and completed early in the project design to avoid impacting procurement.

Some of the items that follow are implicitly contained in the qualification requirements listed earlier but need further elaboration and/or definition. The group responsible for operating and maintaining the system must define in qualitative terms the reliability desired during an earthquake event and there must be realistic evaluation of the feasibility of achieving that qualification status. As a part of this study the project engineering group, in conjunction with the operations group, must identify the operational systems in their entirety whether the performance of these systems during an earthquake is required for stipulation compliance or merely to meet operational objectives. The system itself should be classified and it may fall in more than one category. The project engineering group must decompose each operational system into its basic components and assign seismic categories to each subsystem or component. This is a detailed process which can involve considerable investigation. It may turn out that, because of redundancy, failure or malfunction of certain components may not compromise the function of the overall system. In such a case a lower category of seismic qualification for a particular item can be justified. In other cases the availability of replacement units or spare parts, time for repair, etc., can enter in this evaluation as well.

The seismic qualification requirements for equipment are normally given to vendors in the form of specifications. The specification for equipment that requires seismic qualification should be self-contained. It should clearly state the vendor's options in qualification approach and it should summarize acceptable analytical and test procedures. The specification should allow for as many qualification method options as possible, especially with regard to testing. If necessary, a commentary on the specifications should thoroughly explain the provisions of the specifications and provide examples of acceptable qualification procedures for representative equipment items for various categories. Most important, close communication should be maintained with the selected vendor to insure that he provides a qualification proposal which is meaningful.

If the vendor has difficulties with his qualification proposal, it behooves the Final User to provide assistance at an early stage to enable the vendor to understand better the requirements and to meet his obligations. An important aspect of the seismic qualification process is the monitoring of the entire qualification and procurement process to insure that the equipment is qualified satisfactorily, on time, with adequate documentation, and to follow through in cases where difficulties occur. The time and effort required on the part of the Final User and the vendor can be minimized by interacting early to insure that a satisfactory qualification procedure is developed.

Often there are equipment items that cannot be satisfactorily qualified in accordance with the project seismic specification without extensive redesign and with great time delays and costly overruns. In such cases the Final User should investigate the unsatisfactory behavior (e.g., malfunction, overstress, etc.) in detail to determine if and how much it compromises function. In some cases it may prove worthwhile to allow certain components to behave inelastically to an acceptable degree, or to provide for replacement units, depending upon the importance of this item in the system operation.

In many cases equipment is located in buildings on upper floors, where the free-field motion does not control but where the response of the building and the building elements will control the input environment. So-called "floor response spectra" are used to define the spectral environment of such locations. Designers often overlook the fact that they have considerable latitude in moving equipment items geographically on a given floor, or between floors, to enhance the survivability of the system. The cost effectiveness of rearranging the location of items often can be shown to be advantageous.

In some special cases it may be desirable for the Final User to consider buying standard equipment from the vendor and performing the qualification himself. In the event that modifications are required, these changes must be with the vendor's concurrence to preclude voided warranties.

System Assembler

In many respects the System Assembler should look at his problem in the same way as the Final User but on a smaller scale. Hopefully, the System Assembler has been provided with a specification which is definitive in terms of the seismic requirements. While the System Assembler has no control over the input motion, or more specifically, the selection of the hazard and development of the seismic criteria, he has on the other hand a definite responsibility to provide an assembly that satisfies the system requirements. As a result, the Assembler must have thorough understanding of the inservice seismic requirements provided by the Final User in the specification and has the responsibility of additional communication as required to be sure that all aspects of the problem are fully understood.

For a large complex assembly, the System Assembler may use an exercise similar to that described previously for the Final User; he should classify the elements of his product in much the same manner as the Final User has done for the overall system. The System Assembler, it is recognized, has considerable latitude in the design of his structure in terms of component placement, attachments and supports. He can, in this way, exercise considerable judgment in developing his assembly.

A System Assembler who receives considerable business in a given class of equipment, may find it advantageous and economical to establish a line of cabinetry and/or other mounting equipment which meets some relatively high level of seismic qualification and to carry forward such a line of "overqualified" equipment for various applications rather than undertaking a one-by-one development and assembly process.

The Assembler has additional problems; usually he must obtain components from various manufacturers who may or may not know the seismic qualifications of their components over the wide ranges required by the System Assembler. The System Assembler must require seismic qualification by the component suppliers or evaluate the seismic resistance of these devices himself. Finally, he will be required to undertake seismic qualification by analysis or testing of his entire system assembly.

Component Manufacturer

The Component Manufacturer in many cases does not know the final destination or application of his device, especially in mass-produced standard product lines. The same component, in fact, may be subjected to widely different inputs, depending upon its physical location, and may have widely different reliability requirements, depending upon its functional location. Thus the Component Manufacturer who supplies components for equipment to be used in seismically qualified systems must describe their use in general but clearly understandable terms. The behavior of his device must be described when it is subjected to input motion over a wide frequency band. This description allows the System Assembler to choose the component that satisfies his need. Because of the various uses to which a given component may be placed, the purchaser probably also will have concern about the long-term operating characteristics of the component equipment in terms of durability, resistance to fatigue, corrosion effects, etc. If there are, for example, fatigue characteristics of concern, these need to be noted, not in the sense of fatigue arising from earthquake motions but from a realization that the equipment may be mounted in a structural subsystem (cabinet for example) which, because of its flexibility or effects of nearby operating equipment, could lead to repeated motions of the mounting system of the component during normal operation.

Another item of importance in component behavior is its impact sensitivity since impact can and will possibly occur during seismic disturbances due to jostling, racking, failure of possibly noncritical elements, and handling during shipment.

The normal rule-of-thumb should be borne in mind by those supplying and procuring components that the greater the mechanical, electrical, or pneumatic complexity, the less reliable the seismic resistance. In many cases accurate analysis is impossible and the results of approximate analyses are dubious in value; but testing is expensive and judicious choice is required in arriving at a basis for qualification. In many cases equipment can be qualified on the basis of previous tests for military, aerospace or nuclear application. It may be also that an entire line of equipment can be qualified by testing representative models. However, it is often impossible to find a representative model; in some cases a representative unit from a string of identical units may be obtained. It is fully appreciated that the Manufacturer may be faced with the dilemma of having to qualify equipment that he has sold across the shelf for years as standard equipment.

Concluding Remarks

It is apparent that the subject of equipment qualification to meet seismic effects will be of increasing concern in the years ahead. This is true not only for large projects such as nuclear facilities, pipelines, and other types of industrial facilities, but also in the standard Lifeline Engineering area for office buildings, city emergency facilities, etc. It is necessary in all of these situations to develop a seismic qualification program in the preliminary design phase regardless of the complexities of the facility. When such a program is established it is vital that the procurement specification, monitoring and follow-through be adequately handled. The same considerations are involved in equipment assembly, and to a lesser degree by the Component Manufacturer who provides the product elements that must be adaptable to meeting a variety of different requirements. It is hoped that future design guides and standards in this area will provide guidance for the groups involved and will help develop techniques to expedite the qualification process. In this way, not only will a more reliable functioning product be achieved but it also will be achieved at a savings in cost.

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