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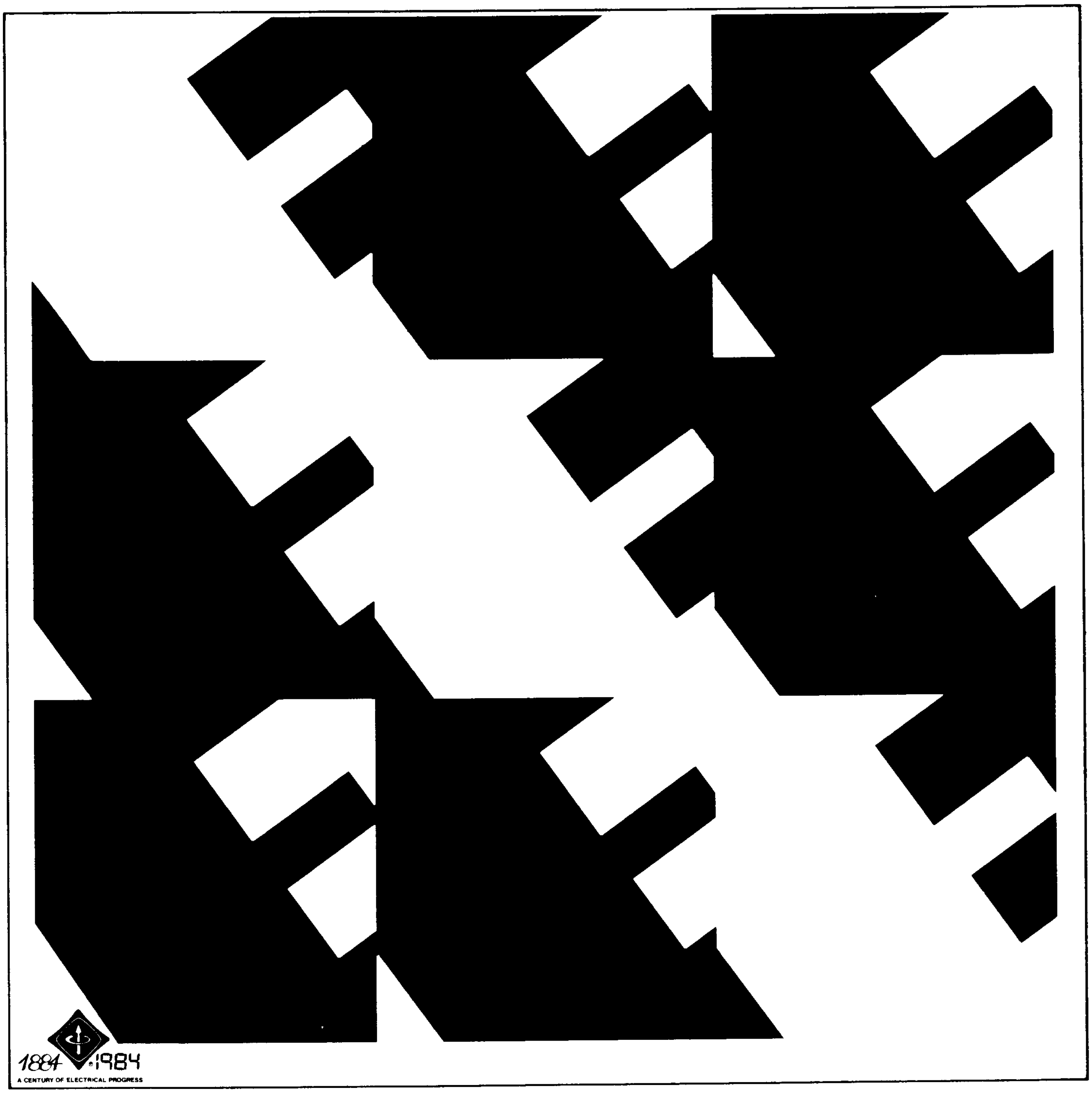
IEEE Recommended Practices for Seismic Design of Substations

IEEE Std 693-1984



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IEEE Recommended Practices for Seismic Design of Substations

1. Introduction

1.1 Scope. These recommended practices contain recommendations for the seismic design of substation facilities.

1.2 Background. The evolution of seismic design practices is related to the occurrence of major earthquakes. The 1906 San Francisco, the 1923 Kanto, Japan, the 1925 Santa Barbara, and the 1933 Long Beach earthquakes all led to design and building code changes. These changes were all improvements but were basically static load design methods. These methods did not take into account the dynamic behavior of the equipment or structure. However, starting about 1950, building codes such as the Uniform Building Code [4][1] began to incorporate dynamic behavior concepts into the static equivalent load method.

The type and amount of damage sustained by power equipment and structures during the San Fernando, California earthquake of February 9, 1971, pointed out the necessity for the Power Industry to consider the dynamic behavior of equipment and structures and to reassess anticipated ground motions for use in analysis and design.

2. References

[1] AISC Specifications for Design, Fabrication, and Erection of Structural Steel for Building, 1978.[2]

[2] ANSI/IEEE Std 344-1975, IEEE Recommended Practices for Seismic Qualification of Class 1E Equipment for Nuclear Power Generating Stations.

[3] ASME Boiler and Pressure Vessel Code, 1977.[3]

[4] ICBO Building Code, 1982.[4]

[5] NEWMARK, N. M. and ROSENBLUETH, E. *Fundamentals of Earthquake Engineering.* Englewood Cliffs, NJ: Prentice-Hall, 1971, p 422.

[6] PRITSKY, W. W. *Aluminum Construction Manual Specification for Aluminum Structures.* The Aluminum Association, 1982.[5]

2.1 Applicable Document in Preparation[6]

3. Definitions

acting stress. Maximum applied or expected stress in the material during normal operation of the apparatus of which it is a part, including the stresses caused by wind, seismic, or short-circuit loading, acting either independently or simultaneously as determined by the user.

allowable stress. The maximum stress permitted by applicable standards or codes, or both.

Class A component. Any component or system whose failure, malfunction, or need for repair prevents the proper operation of the substation during or after the design earthquake.

[1] Number in brackets correspond to those of the References listed in Section 2.

[2] AISC publications are available from the American Institute of Steel Construction, 400 North Michigan Avenue, Chicago, Illinois 60611.

[3] ASME publications are available from the American Society of Mechanical Engineers, 345 East 47th Street, New York, NY 10017.

[4] ICBO publications are available from the International Conference of Building Officials, 5360 South Workman Mill Road, Whittier, California 90601.

[5] Aluminum Association publications are available from the Aluminum Association, 818 Connecticut Avenue NW, Washington, DC 20006.

[6] When the following document is completed, approved and published, it becomes a part of this listing.

(1) IEEE Project C37.122 (in preparation) Recommended Practice for Gas-Insulated Substations.

Class B component. Any component or system whose failure, malfunction, or need for repair does not prevent the operation of the substation during or after the design earthquake.

component. The devices and equipment which are assembled at the erection site, or readily removed or accessed for maintenance, and which perform a function (for example, power circuit breakers, disconnect switches, relays, sensors).

damping. A dynamic property which indicates the ability of a structure to dissipate energy.

NOTE: The phenomenon of damping is represented by a quantity called the damping ratio which is a percent of critical damping. After being forced to deflect and allowed to vibrate freely, structures with zero damping vibrate indefinitely. Structures with critical damping return to their static or neutral position in the shortest time without oscillation.

design earthquake. The greatest earthquake postulated during the life of the substation for which the user wishes the substation to remain operational.

ductility factor. The ratio of the maximum displacement (ultimate) to the displacement which corresponds to initiation of the yielding.

maximum ground acceleration. The maximum value of acceleration input to the equipment during a given earthquake for a particular site.

natural frequency. The frequency(s) at which a body vibrates due to its own physical characteristics (mass, shape, boundary conditions, and elastic restoring forces brought into play) when the body is distorted and then released, while restrained or supported at specified points.

resonance. A dynamic condition which occurs when any input frequency of vibration coincides with one of the natural frequencies of the structure. In a plot of the response of the structure (acceleration, velocity, displacement) versus input frequency for a constant input, as the input frequency approaches one of the natural frequencies of the structure the response increases to a maximum value if damping is less than critical. The response of the structure at resonance may be much greater than the input, if the damping is low.

response spectrum. A plot of the maximum response of single-degree-of-freedom bodies of different natural frequencies, at a damping value expressed as a percent of critical damping, rigidly mounted on the surface of interest (that is, on the foundation for the foundation response spectrum or on the floor of a building for that floor's response spectrum) when that surface is subjected to a given earthquake motion as modified by intervening structures.

system. A group of components operating together to perform a function (for example, disconnect switch, support structure and foundation, relay protection system, and telemetering system).

time history. The record of acceleration, velocity or displacement as a function of time which the floor of a building or the ground experiences due to an earthquake.

zero period acceleration. The peak time history acceleration which can be determined from response spectra by the merging of response spectra, for all damping values, in the high-frequency range (usually above 30 Hz) in which no change of acceleration occurs with frequency.

4. Seismic Criteria

4.1 Seismic Information User Should Provide to Equipment Manufacturer

4.1.1 General. The user should provide information to the manufacturer that will adequately describe the seismic environment which the equipment will be expected to withstand. Any condition which may be of consequence during a seismic event should be described. However, the user should at least describe the maximum acceleration and response spectra or time history, as discussed in 4.1.2, 4.1.3, and 4.1.4.

The maximum vertical ground acceleration should be taken as 67% of the maximum horizontal design acceleration.

4.1.2 Maximum Acceleration. The maximum acceleration is the maximum value of acceleration input to the equipment during a given earthquake for a particular site. Typical design values of maximum acceleration range from 0.1 g (g is the acceleration due to gravity) to 0.5 g, with values over 0.5 g being required in some special instances. If the equipment is not mounted on the ground, the acceleration at the mounting location should be used.

4.1.3 Time History. The time history is a way of describing a particular earthquake. A particular earthquake time history may not be truly representative of the earthquake the equipment may experience during its service life. This is true because characteristics of real earthquakes can vary from one earthquake to another. The following earthquake characteristics are of major concern:

(1) Maximum horizontal acceleration
(2) Maximum vertical acceleration
(3) Frequency content
(4) Duration.

Each earthquake has different characteristics. To allow for the aforementioned variables, the worst possible earthquake ground accelerations can be incorporated into groups of ground motion earthquake time histories (ensembles) of different frequency content and duration. These individual time histories can then be used in conjunction with each other to simulate or represent the effect of the design earthquake.

To use the time history method, four of the eight ground motion acceleration time histories used to develop the response spectra of Fig 1 can be obtained from the California Institute of Technology, Pasadena, California.

The earthquake records which may be used in testing a mathematical model are the El Centro, California, 1940 NS (multiplied by a factor of 1.12), the Olympia, Washington, 1949 N86E (multiplied by a factor of 1.96); the Helena, Montana, 1935 EW (multiplied by a factor of 3.03); and the Pacoima Dam, California, 1971 S16E (multiplied by a factor of 0.46). For other than Zone 4 users (Figs 2, 3, and 4) the above acceleration time-histories should be scaled by the factors shown in 4.2, Method 3.

These earthquakes occurred in the western United States. They may not be representative of earthquakes in other parts of the United States or other regions of the world.

4.1.4 Response Spectrum. Another description of an expected earthquake environment is a response spectrum. A response spectrum (see Fig 1) is obtained utilizing a time history. The response spectra shown in Fig 1 are smoothed response spectra representing the average response spectrum shapes calculated from eight time histories.

Maximum ground acceleration of the earthquake can be obtained by reading the zero period response acceleration (typically taken as the acceleration of bodies with frequencies over 30 Hz) at any damping. Frequency content of the ground motion is indicated by the shape of the response spectrum curve. Earthquake duration and mechanism cannot be determined from a response spectrum.

4.1.5 Miscellaneous. Other conditions which may be described are:

4.1.5.1 Soil Structure Interaction. Amplification of a structure's seismic response can result from interaction between the vibrational characteristics of the structure and those of the foundation and soil.

This amplification can be dependent on:

(1) The ratio between the effective soil plus foundation mass and the equipment mass
(2) The ratio between the effective soil stiffness and effective equipment stiffness
(3) The effective soil damping

Some measures that can be taken to minimize possible deleterious effects of soil structure interaction are:

(a) Use of monlithic foundations (that is, install transformers on a monolithic foundation).

(b) Custom grade soil (selected fill) upon which the foundation will rest to increase its rigidity.

4.1.5.2 Displacement Limitations. Restrictions which impose displacement limitations on equipment (See 5.2.2 and 5.2.3):

(1) Alignment of moving parts
(2) Impact with adjacent equipment
(3) Interconnections to equipment on separate foundations.

4.1.5.3 Soil and Foundation Failures. Soil failure which can be detrimental to equipment:

(1) Fault rupture
(2) Liquefaction of soil
(3) Landslides
(4) Foundation failures
 (a) Foundation breaking
 (b) Exceeding bearing capacity of soil
(5) Differential settlement.

4.1.5.4 Drawings. Drawings of support structures and foundation(s) should be furnished as applicable.

4.2 Site Evaluation for Site Oriented Equipment. The user should consider the adoption of earthquake criteria arrived at by any one of the following three methods to determine the maximum earthquake risk.

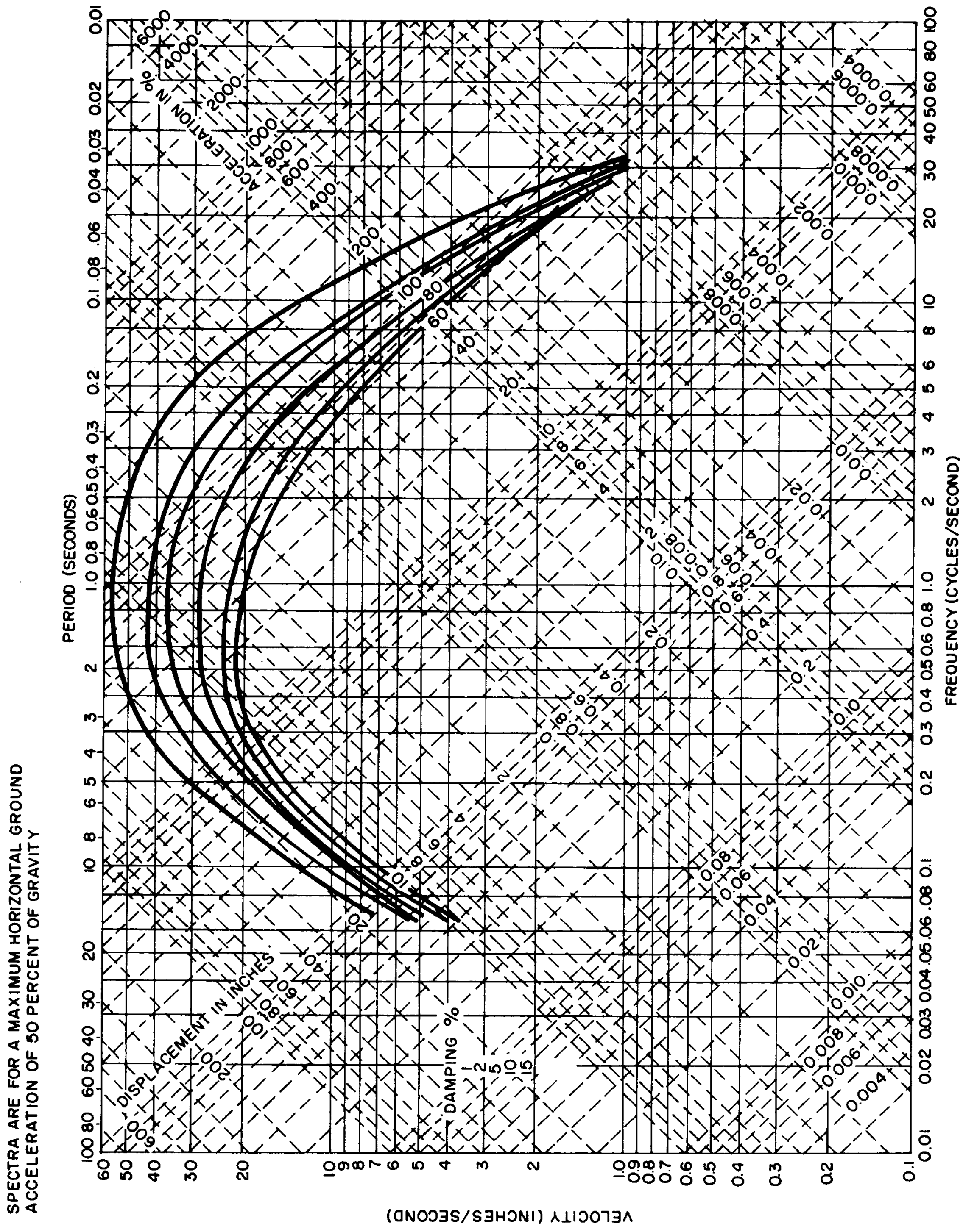
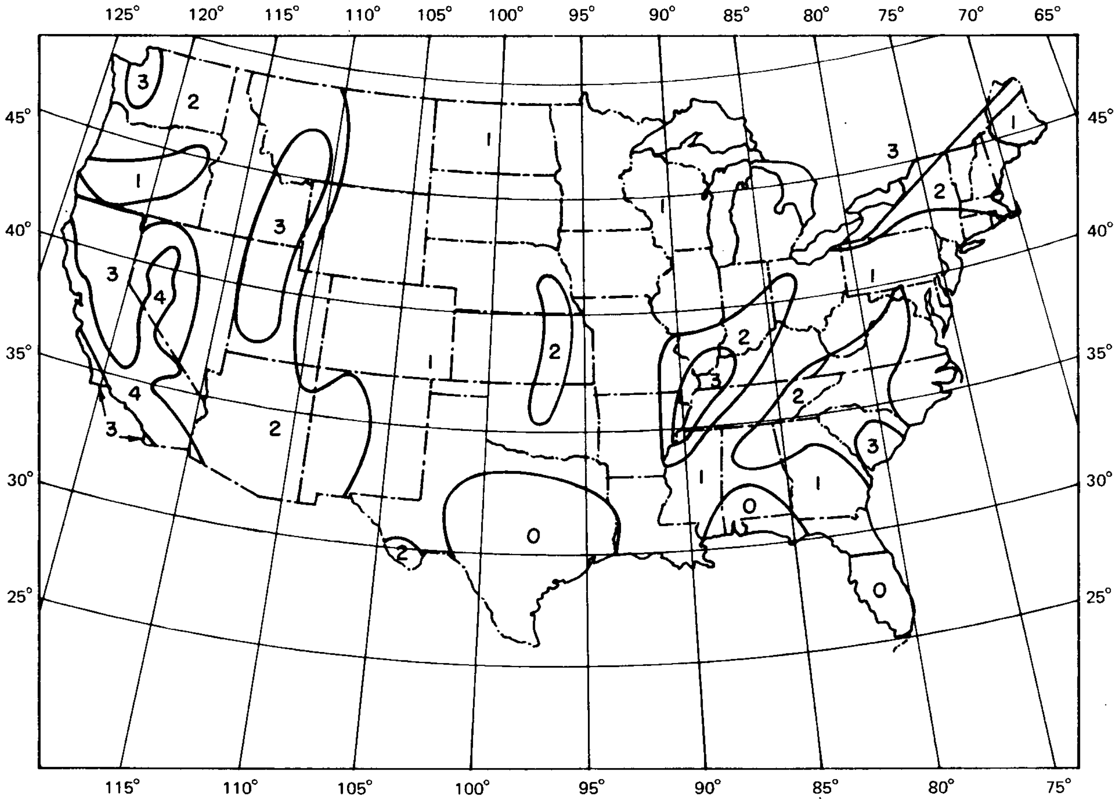


Fig 1
Seismic Response Spectra



ZONE 0	No damage.	ZONE 3	Major damage, corresponds to intensity VIII and higher of the M M* Scale
ZONE 1	Minor damage, distant earthquakes may cause damage to structures with fundamental periods greater than 1.0 second, corresponds to intensities V and VI of the M M* Scale	ZONE 4	Those areas within Zone No 3 determined by the proximity to certain major fault systems.
ZONE 2	Moderate damage, corresponds to intensity VII of the M M* Scale		

*Modified Mercalli Intensity Scale of 1931

Fig 2
Seismic Zone Map of the United States from the Uniform Building Code, 1982

The results of a site-specific analysis (Method 1) should take priority over Method 2 or 3. The results of a microzonation study (Method 2) should take priority over Method 3.

4.2.1 Method 1 — Site Specific Analysis. A special seismic study for a particular site considering the local seismic history, geology, and dynamic properties of the soil.

4.2.2 Method 2 — Microzonation. A seismic study covering a limited area (for example, the size of a utility company's service area) that produces a seismic-relief map of the area. The seismic-relief map should contain at least three to six values of known earthquake disturbances. The study should consist of a less intensive investigation of seismic history and geology than Method 1.

4.2.3 Method 3 Macrozonation. A seismic study, usually developed by a public agency covering large areas, as is typically followed in building codes. The use of macrozone maps such as those included in the ICBO Uniform Building Code 1982 [4]: (Figs 2, 3, and 4 are

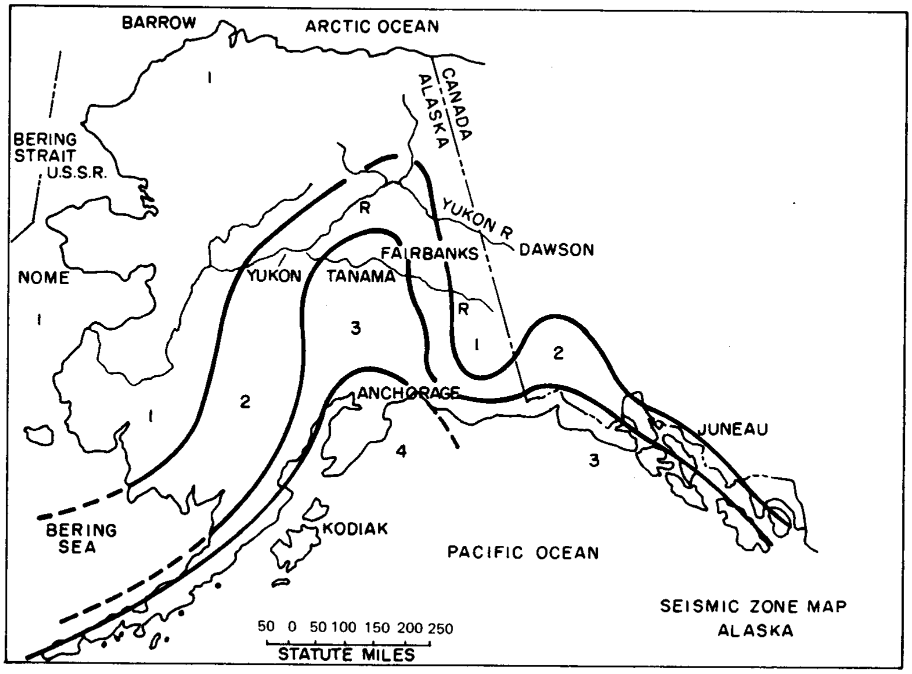


Fig 3
Seismic Zone Map of Alaska from the Uniform Building Code, 1982

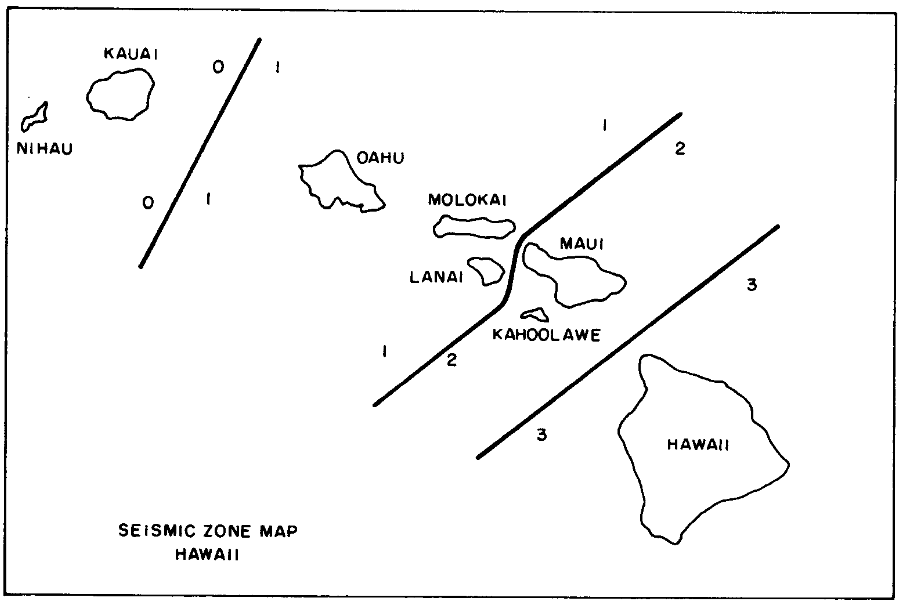


Fig 4
Seismic Zone Map of the Hawaiian Islands from the Uniform Building Code, 1982

Table 1
Acceleration Values

Zone	Acceleration (% of Gravity)
4	50
3	40
2	20
1	10
0	Local Building Code

recommended). The response spectra should be applied as in Table 1.

The response spectra in Fig 1 are from earthquakes in the western United States which may not be representative of earthquakes in other regions in the United States or in other parts of the world.

5. Performance Requirements

Equipment seismic classifications and the criteria of adequacy which the substation shall satisfy are described here. Adequacy means the capability of each critical component of the substation to perform its principal functions during and after a design earthquake.

5.1 Component Seismic Classifications. Component seismic classifications may be different depending upon application. The two seismic classes discussed below are based on functional importance of the equipment in maintaining service. The following lists are not meant to cover all equipment in either the Class A or Class B category, but are only a guide for the user who shall consider components which may be unique to the user's system.

5.1.1 Class A Components. The designs for installation of Class A components or systems whose failure, malfunction, or need for repair would prevent the proper operation of the substation during or after the design earthquake should be in accordance with these recommended practices.

Class A Listing

Arresters, Surge
Batteries, Station
Bus Systems
Bushings, Entrance and Apparatus
Circuit Breakers, Power
Capacitor Voltage Transformers
Lighting, Attended Substation
Metering, Indicating
Power-Line Carrier Equipment
Reactors, Fault Limiting
Reactors, Shunt
Regulators, Feeder Voltage
Relays, Protective
Switches, Disconnect, Grounding
Switchboards, Control
Transformers, Instrument
Transformers, Power, Station Service

5.1.2 Class B Components. Classification of substation components or systems in this category has been determined on the basis that their failure or need for repair would not prevent the proper operation of the substation. The user should evaluate the cost of adequate seismic withstand designs against the cost of possible repairs. Thus, Class B Components or systems may be designed to meet either a lower level design earthquake or national seismic standards applicable to the site. The application of further design requirements is left to the discretion of the user.

Class B Listing

Lighting, Unattended Stations
Power-Factor Correction Equipment
Shunt Capacitors
Synchronous Condensers
Service Capacitors
Switchboards, Station Service

5.2 Criteria of Adequacy. If during — and for 72 h immediately following — the design earthquake, all Class A components and systems continue to operate properly, and if the proper operation of connected systems, assemblies, subassemblies and components is not disturbed, then the substation has met the specified seismic requirement.

Failure of Class B components and systems, though not desirable, may be tolerated if such failure does not effect the proper operation of Class A components and systems.

Under maximum excitation generated by the design earthquake, substation components should be shown to satisfy the performance criteria described below:

5.2.1 Permanent Deformation. Permanent deformation of substation equipment following a design earthquake is acceptable, provided that no impairment of essential function results.

5.2.2 Motion Limitations. The ability to accommodate relative motion between adjoining equipment constitutes an especially crucial seismic requirement of the substation. In particular, special attention should be given to the following types of relative motion:

(1) Coupling between equipment components mounted on a common monolithic slab.

(2) Coupling between equipment mounted on separate adjoining foundation slabs, so that relative motion can occur at the foundation line.

(3) Connections between the substation and overhead lines. This is principally a matter of providing adequate line slack, thus decoupling the overhead line motion from substation equipment.

(4) Pothead connections to an underground cable run.

(5) Underground conduit duct runs interacting with the surrounding soil.

5.2.3 Misalignment. Misalignment should not prevent the equipment — such as grounding devices, disconnect switches, and power circuit breakers — from performing normal functions during or after an earthquake.

Table 2 of this recommended practice is applicable to substation use.[7]

Table 2
Damping Factors

Type of Construction	Percent Critical Damping[8] Below ¼ Yield	At ½ Yield	At Yield
Welded joints	0.5–1.0	2	5
Torqued bolted joints	0.5–1.0	5–7	10–15
Reinforced concrete with cracking	0.5–1.0	3–5	7–10
Pre-stressed concrete	0.1–1.0	2	5–7
Brittle components (failing at yield)	0.5–1.0	0.5–1.0	7–10

[7] IEEE Project C37.122, Recommended Practice for Gas-Insulated Substations (in preparation). Alternately, the methods and procedures of qualifications described in this project will be acceptable qualification methods to demonstrate the adequacy of design when the document is approved and published.

[8] See [5].

5.2.4 Dielectric Degradation. Degradation of dielectric strength could arise from displacement — either permanent or temporary — between components of different potential which may result in reduced clearances and increased voltage stresses. Such degradation should not impair the performance of the equipment below its specified value.

5.2.5 Other Conditions. Special attention should be given to particular conditions which could affect the behavior of the system and which could reasonably be expected to occur simultaneously as the result of seismic disturbances. For example:

(1) The maximum, transient, and relative motion should not compromise normal voltage requirements.

(2) The electromagnetic stresses due to a rated short circuit should not, when combined with seismic disturbance, lead to any intolerable system or operating abnormalities.

6. Qualification Methods

The use of methods and procedures of qualification described in ANSI/IEEE Std 344-1975 [2], Sections 4, 5, 6, 7, and 8 satisfies the recommendations of these recommended practices with the following modifications:

In ANSI/IEEE Std 344-1975 [2], Table 1 for damping is not applicable to use in substation design. Instead, Table 2 of these recommended practices is recommended.

In ANSI/IEEE Std 344-1975 [2] the term Class 1E Equipment used is not applicable to substation components. Instead of Class 1E Equipment, these recommended practices recommend the qualification of components in Class A and B of 5.1.1 and 5.1.2.

The terms *operating basis earthquake* and *safe shutdown earthquake* are not applicable to substations; instead, the term *design earthquake* is used in these recommended practices to indicate an earthquake level which should be used for substation design. Class A equipment is expected to operate during and after a design earthquake. Class B equipment may have a lower seismic withstand capability and its failure may be acceptable during a design earthquake as noted in 5.1.2.

7. Design and Construction Practices

The references to codes, standards, and information published by USA organizations, such as the American Society of Mechanical Engineers (ASME) and the American Institute of Steel Construction (AISC) are meant for use in the USA. In other areas, codes and standards should be used which are applicable to that specific location.

7.1 Allowable Stresses (for Seismic Loading)

7.1.1 General. The maximum acting stress allowed within any material under seismic loading should be in that material's allowable stress range. Allowable stresses (to be used for seismic design) for materials not listed below can be found in ASME Boiler and Pressure Vessel Code, 1977 [3]. Where two values of allowable stress are given, the smaller should always be used.

7.1.2 Structural Steel. The AISC Specification for the Design, Fabrication, and Erection of Structural Steel for Building-1978 [1] should apply to steel structural members.

7.1.3 Aluminum. Aluminum Association Publication, Aluminum Construction Manual, Section 1, Specifications for Aluminum Structures, 1982 [6] should apply to aluminum structural members.

7.1.4 Nonmetallic Materials. The acting stress of nonmetallic materials such as wood, fiberglass, porcelain, etc, should be within a range between 0.25 to 0.5 times the rated strength.

7.2 Reserve Strength. It is recommended that whenever possible, the reserve strength and reserve operational limits of the equipment be provided by one or both of the following methods:

(1) Provide elements so that the mode of structural failure due to response greater than the design response will be ductile in nature. Care should be exercised to ensure that brittle components are protected by yielding elements.

(2) Provide structural independence so that structural failure of one piece of equipment does not cause failure of any other equipment.

7.3 Damping. In the absence of test data justifying larger values, damping should be considered to be no more than that shown in Table 2. Computations may be based on these levels of damping without further justification.

7.4 Foundations. It is desirable that interconnected equipment, as much as is practical and economical, be placed on a monolithic foundation to reduce the differential movement of the supported equipment. If this is not feasible, the expected differential motions between foundations should be provided for. Foundations should be adequate to withstand compression, shear, and moment forces due to the design earthquake. Both vertical and horizontal earthquake motion should be applied simultaneously.

A soil investigation is recommended to determine if any unusual conditions exist at the site which would warrant special design considerations for the substation foundations as discussed in 4.1.5. If equipment is rigidly coupled to structural elements — such as walls or adjacent floors — the element response should be taken into account.

7.5 Methods for Anchoring Equipment to Foundations

7.5.1 Welding to Embedded Members. Large equipment and equipment with large dimensions between anchor locations should be anchored by welding the base to steel members, embedded in and firmly anchored to the concrete foundation.

7.5.2 Bolting to Foundations. If bolts are used to anchor equipment, they should be in cast concrete. Large bolts of mild, ductile steel should be chosen over smaller, less ductile, high strength bolts.

Consideration should be given to any unusual distribution of dynamic earthquake loadings on the anchor bolts (due to bolt hole tolerance, torquing, or noncontact of nut). Bolt tightening procedure, size, strength, location, and material should be shown on the construction drawings.

7.5.3 Bolt Tightening Procedure. Bolted clamping plates for anchorage should be designed to provide adequate resistance to prying action and to prevent rotation of the clamp plate into an ineffective position.

All anchor systems and supporting structures should be designed to carry the tensile, shear, moment, and axial loads applied during the design earthquake.

Application of the following recommendations will ensure that seismically-induced dynamic loads in the retaining bolts will be less than 10% of their static pretension loads:

(1) The bolt stiffness (or bolt spring constant) in tension should be 10%, or less, of the total restraining flange stiffness (or flange spring constant).

(2) The total stiffness of each bolt retaining flange (or total spring constants) should be greater than or equal to 10 times the tensile stiffness of the bolts associated with them.

(3) The tensile preload applied (by torquing or turn-of-nut tightening) to each retaining bolt should be equal to the maximum uplift force that would occur at the bolt locations due to the design earthquake.

7.6 Motion Limitation Due to Equipment Interconnections. All interconnections between equipment should be adequate to accommodate large relative, axial, lateral, moment, and torsional motions. Structures which are dynamically dissimilar may experience large relative displacements. Leads and interconnections should be long and flexible enough to allow these displacements to occur without causing damage. Particular attention should be paid to brittle, nonductile parts such as ceramic bushings and insulators. In no circumstances should electrical or structural interconnections abruptly stiffen with increasing motion or strain. Such nonlinearities develop large impact forces. Consideration should be given to the resultant change in dynamic characteristics of the equipment as a result of any conductor being used to make interconnections between equipment.

7.7 High-Voltage Underground Cable Terminals. Cable terminations should be designed for any possible cantilever loads on pothead porcelains caused by a seismic disturbance. If evaluation shows seismic load on the potheads in excess of the porcelain cantilever strength, the following modifications should be considered.

(1) Increased rigidity in the support structure to attain a natural frequency above the critical seismic frequency range will reduce amplification of accelerations at the pothead.

(2) Increased flexibility in the support structure to attain a natural frequency below the critical seismic frequency range will reduce accelerations and increase relative displacement at the pothead.

7.8 Pedestal Mounted Equipment. Pedestal mounting requires that the equipment and supporting structure and foundation be analyzed as a single system. If analysis indicates that additional damping is required so as to reduce the stresses on porcelain elements, a damping device (that is, Belleville washers) may be added between the supporting structure and the equipment. A damping device should be selected by the user and its adequacy determined by dynamic analysis.

7.9 Switchrack Structures. A rigid rack structure (that is, one having no dynamic response to excitation frequencies below 30 Hz) such as a braced frame should be used whenever possible. This will ensure minimum amplification of ground motion at the level of the equipment attachment and hence, the ground response spectra of Fig 1 can be used directly to design the equipment.

7.10 Bus Support Systems. Tension and rigid bus system construction are both widely used in substations. In high seismic risk areas, careful consideration should be given to the dynamic characteristics of each system in selecting and designing the preferred system to meet the requirements of 5.2.5.

7.11 Underground Conduits. Conduit duct bank installations should be constructed to allow vertical and horizontal movement to take place during a seismic disturbance. One construction method that can be used to accommodate these displacements utilizes slip-joints at various locations in the duct bank to hold the conduits in place and backfills the duct-bank with a *sand-slurry material.* At the manholes, the duct-bank openings are backfilled with a weak concrete mixture and a plastic sealant is used on the sides to provide a slip connection at the manhole walls.

7.12 Control, Relay and Communication House Equipment, and Building

7.12.1 Building Structure. The building structure should be designed to conform with local building codes. Special attention should be given to floor, wall, and ceiling areas where electrical equipment may be installed. These areas should be designed to withstand any additional forces which may be produced due to the installation of equipment.

7.12.2 Electrical Equipment. Equipment such as lighting fixtures, relay panels, power panels, batteries, and cabinets housing other equipment should be classified as either Class A or Class B as described in 4.1. The methods described in 7.5 should be followed for anchoring equipment.

The equipment classified as Class A by the user should be carefully selected and consideration should be given to the combined dynamic response of the equipment itself and the floor, wall, or ceiling to which it is attached.

The equipment classified as Class B by the user should be mounted so that its failure under a seismic disturbance would not interfere with the operation of adjacent Class A equipment.