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SEISMIC STRUCTURAL DESIGN/ANALYSIS GUIDELINES FOR BUILDINGS. (U)
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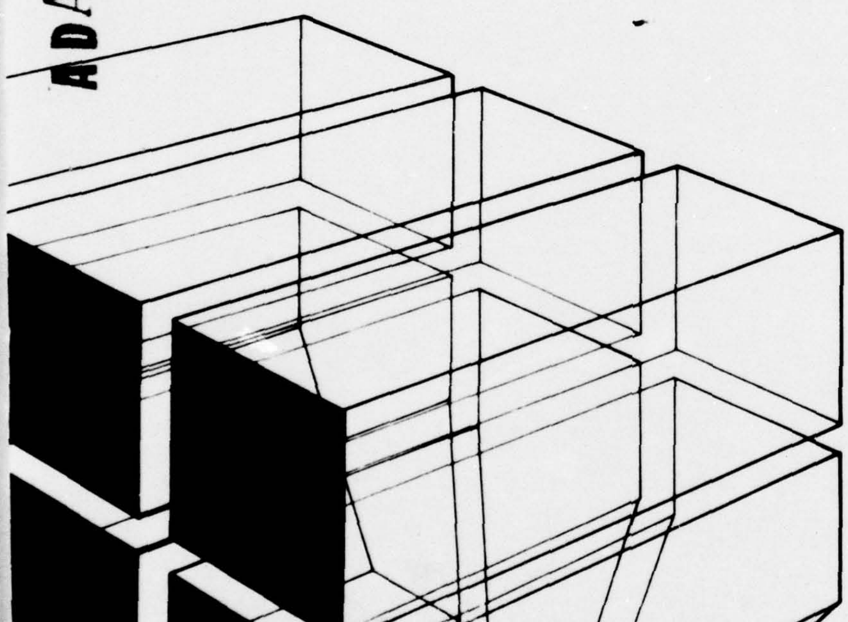
SPECIAL REPORT M-206
February 1977
Seismic Design Criteria for Critical Facilities

SEISMIC STRUCTURAL DESIGN/ANALYSIS GUIDELINES FOR BUILDINGS



by
J. D. Prendergast
W. E. Fisher

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This report presents interim guidelines for the seismic structural design/analysis of the lateral-force-resisting systems of permanent military buildings. These guidelines are intended to enable critical, high-loss- and low-loss-potential buildings to withstand their respective design earthquakes without unacceptable loss of function or structural damage. Modal analysis procedures are advocated for critical buildings and high-loss-potential buildings with irregular shapes, large

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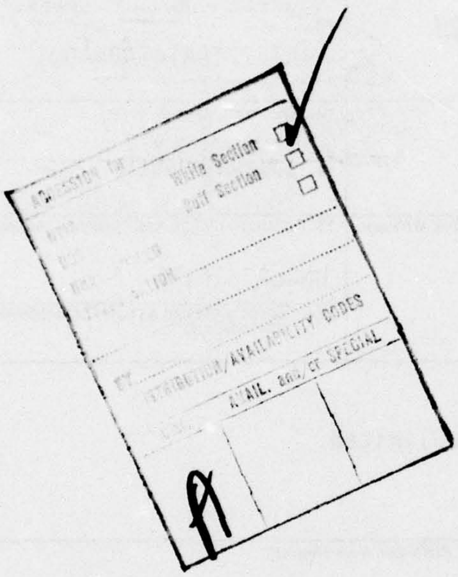
differences in lateral resistance, or other unusual structural features. The equivalent static lateral load method is advocated for high-loss- and low-loss-potential buildings which are regular in shape and have uniform mass and stiffness distributions. Both procedures employ a design spectrum for the seismic ground motion which is constructed based on the effective peak ground acceleration at the site.



FOREWORD

This project was conducted for the Directorate of Military Construction, Office of the Chief of Engineers (OCE), under RDT&E Program 6.27.12A, Project 4A762719AT41, "Design, Construction, and Operation and Maintenance Technology for Military Systems"; Task 04, "Construction Systems Technology"; Work Unit 001, "Seismic Design Criteria for Critical Facilities." The applicable QCR is 1.03.003. The OCE Technical Monitor was Mr. G. M. Matsumura.

The work was performed by the Structural Mechanics Branch (MSS) of the Materials and Science Division (MS), U.S. Army Construction Engineering Research Laboratory (CERL). Dr. W. E. Fisher is Chief of MSS and Dr. G. Williamson is Chief of MS.

COL J. E. Hays is Commander and Director of CERL, and Dr. L. R. Shaffer is Technical Director.

CONTENTS

SEISMIC STRUCTURAL DESIGN/ANALYSIS
GUIDELINES FOR BUILDINGS

1 INTRODUCTION

Background

The seismic design provisions in TM 5-809-10[1] are directly related to the 1968 *Recommended Lateral Force Requirements* developed by the Structural Engineers Association of California.[2] These requirements set forth provisions and principles which are intended to enable a structure to (1) resist minor earthquakes without damage, (2) resist moderate earthquakes without structural damage, but with some nonstructural damage, and (3) resist major earthquakes, of the severity of the strongest experienced in California, without collapse, but with both structural and nonstructural damage. The 1971 San Fernando, CA, earthquake, however, clearly demonstrated that upgrading these seismic requirements is necessary to insure continued operation of critical facilities such as hospitals, fire stations, communication centers, and other essential facilities and to prevent collapse of noncritical facilities.

Active earthquake engineering research and the lessons learned from the San Fernando earthquake have advanced the state-of-the-art and technology available in the pre-1968 period and produced more definitive data on earthquake motions, new knowledge in geotechnical fields, a clearer understanding of the performance of materials and structural elements, and new design procedures based on the design spectrum approach. These advances have provided the foundation for development of the seismic design and analysis guidelines for buildings contained in this report. These guidelines are based on the design spectrum approach with different design requirements for various classes of military building, and are structured to be compatible with the facilities' functional or occupancy conditions.

Purpose

The purpose of this report is to present seismic structural design/analysis guidelines for the lateral-force-resisting system in military buildings which will minimize damage and danger to occupants during an earthquake.

[1]*Seismic Design for Buildings*, TM 5-809-10 (Department of the Army, April 1973).

[2]*Recommended Lateral Force Requirements* (Structural Engineers Association of California, 1968).

These guidelines are intended, as far as practicable, to enable:

1. Critical buildings (see Glossary) to remain operational following the design earthquake with only minor inelastic deformations (ductility factor $\mu = 1.5$).

2. High-loss-potential buildings to deform inelastically to a moderate extent ($\mu = 3$) without unacceptable loss of function during the design earthquake.

3. Low-loss-potential buildings to deform inelastically to a great extent ($\mu = 5$) without collapsing during the design earthquake.

Scope

These guidelines are applicable to all new permanent military construction and reflect methods of analysis based on a design spectrum. The design spectrum is constructed from the effective peak ground acceleration postulated for seismic motions at the site, which is determined from a seismic regionalization map or a site investigation of the seismic ground motions, and from specific damping values and ductility factors for the particular building classes. Procedures incorporated in these guidelines enable both the modal analysis and the equivalent lateral load methods to be used with the design spectrum. These guidelines, however, are preliminary and set forth provisions for only the major factors which impact a building's seismic resistance.

Design Philosophy

In developing these guidelines, a philosophy was adopted that there should be only a single seismic threat for a site and that the desired seismic performance level for military buildings at the site (i.e., the tolerable level of loss of function or structural damage) should be dictated by the building's occupancy and functional requirements. Furthermore, the practical approach to controlling the level of loss of function or structural damage is by specifying the damping value and ductility factor for various classes of buildings--critical, high-loss-potential, and low-loss-potential.

Other design philosophies which have been proposed or implemented in seismic design provisions are based on multiple seismic threats for a given site, each with an associated probability of being exceeded, or implicit damping values and ductility factors which are hidden in empirical formulas. Multiple seismic threats, however, generally require multiple design or reanalysis efforts--refinements which are time consuming and impractical if the intent is truly that buildings withstand future earthquakes without unacceptable loss of function or structural damage. Likewise, empirical formulas do not provide the designer an appreciation and understanding of how the design objective is achieved.

Therefore, underlying these guidelines is an effort (1) to make the seismic design provision easily understood and practical to implement, (2) to provide the designer with a better understanding of the building's behavior and performance, and (3) to insure that military buildings can withstand future earthquakes without unacceptable loss of function.

2 SEISMIC DESIGN MOTIONS

Seismic Ground Motion Criteria

The maximum seismic ground motion at a particular site should be determined by a detailed assessment of the geological and seismological conditions surrounding the site and the local soil conditions. The maximum seismic ground motion so determined should be presented as an effective peak ground acceleration (see Glossary) and be reviewed and approved by the Office of the Chief of Engineers (OCE DAEN-MCE-A) in conjunction with the using service. The procedures presented in the following section should be used to construct the required design spectrum.

Design Spectrum Construction

The design spectrum for horizontal ground motion at a site should be constructed based on (1) the effective peak ground acceleration as determined above, (2) the damping values and ductility factors for various building classes specified in Table 1, (3) the spectral amplification factors for horizontal, elastic response specified in Table 2, and (4) the basic ground motion spectrum presented in Figure 1. The design spectrum should be constructed in accordance with the following steps:

Step 1. Determine the effective peak ground acceleration associated with the proposed building's location.

Step 2. Multiply the acceleration (1 g), velocity (48 in./sec [1.2 m/sec]), and displacement (36 in. [0.9 m]) bounds for the basic ground motion spectrum (Figure 1) by the effective peak ground acceleration value (Step 1) to determine the respective bounds of the site ground motion spectrum.

Step 3. Obtain the critical damping value from Table 1 for the applicable building class.

Step 4. Obtain the acceleration, velocity, and displacement amplification factors from Table 2, based on the critical damping value (Step 3).

Step 5. Multiply the acceleration, velocity, and displacement bounds for the site ground motion spectrum (Step 2) by the corresponding amplification factors (Step 4) to determine the respective bounds of the elastic response spectrum.

Step 6. Obtain the ductility factor μ from Table 1 for the applicable building class.

Table 1

Damping Values and Ductility Factors for Various Building Classes*

Building Class	Damping Value Percent Critical	Ductility Factor
Critical	3	1.5
High-loss-potential	5	3
Low-loss-potential	7	5

* Adapted from N. M. Newmark, "Seismic Design Criteria for Structures and Facilities Trans-Alaska Pipeline System," *Proceedings of the U.S. National Conference on Earthquake Engineering 1975*, by permission of the Earthquake Engineering Research Institute.

Table 2

Spectral Amplification Factors for Horizontal, Elastic Range*

Damping Value Percent Critical	Amplification Factor		
	Acceleration	Velocity	Displacement
3	2.9	2.4	2.1
5	2.5	2.1	1.8
7	2.2	1.9	1.6

* Adapted from N. M. Newmark, "Seismic Design Criteria for Structures and Facilities Trans-Alaska Pipeline System," *Proceedings of the U.S. National Conference on Earthquake Engineering 1975*, by permission of the Earthquake Engineering Research Institute.

Step 7. Divide the velocity and displacement bounds (elastic response spectrum, Step 5) by the value of μ obtained in Step 6. For frequencies below 8 Hz, divide the elastic response spectrum acceleration bound (Step 6) by $\sqrt{2\mu-1}$.

Step 8. Construct the design spectrum for frequencies below 8 Hz using the acceleration, velocity, and displacement bounds determined in Step 7. For frequencies above 33 Hz, the design spectrum acceleration equals the effective peak ground acceleration determined in Step 1. Draw a linear transition between the design spectrum accelerations at 8 and 33 Hz to complete the construction of the design spectrum.

The effects of vertical earthquake motions usually do not need to be considered in the design of military buildings. However, if investigating the effects of vertical earthquake motions is necessary, two-thirds of the horizontal design spectrum bounds should be used to draw the vertical design spectrum.

The appendix illustrates the construction of a design spectrum.

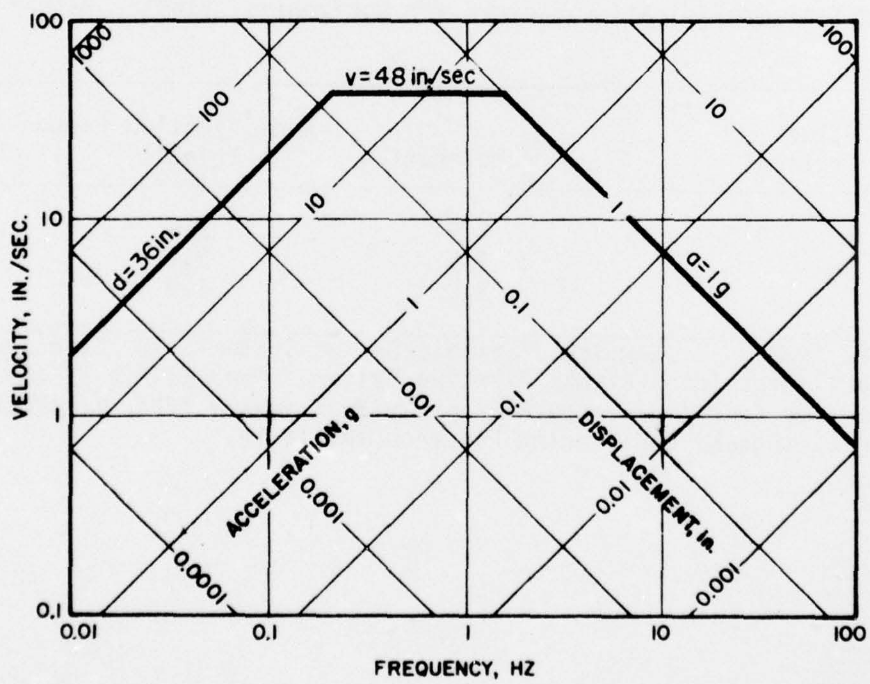


Figure 1. Basic ground motion spectrum. SI conversion factor: 1 in. = 25.4 mm.

3 SEISMIC STRUCTURAL DESIGN/ANALYSIS

Structural System

A building's structural system, particularly the lateral-force-resisting system, should accommodate the various architectural and functional requirements, but should not be solely determined by them. In planning the structural system, the designer should attempt to minimize the possibility of structural collapse and control damage by observing the following rules:

1. Preserve symmetry. Avoid irregularly (L, T, U, and +) shaped building layouts unless adequate design precautions are taken to subdivide the building into regularly shaped integral units which can respond independently and are structurally separated by sufficient distance to avoid contact under the expected maximum lateral deflections. Furthermore, avoid mixed framing systems such as a shear wall on one side of a building and a steel frame on the other.

2. Minimize building torsion. The distance between the center of mass and the center of rigidity should be minimized.

3. Provide direct vertical paths for lateral forces. Avoid transferring lateral forces over long distances through diaphragm action or through complicated structural systems that require the lateral forces to be transferred through setbacks, overhangs, and other geometrical irregularities before reaching the foundation.

4. Avoid abrupt discontinuities. Minimize abrupt changes in the lateral resistance or stiffness such as large openings in shear walls, interruption of columns and beams, diaphragm openings, or changes in structural systems between stories.

5. Provide strong joints and ductile members. Attempt to keep excessive strain outside the connections in the more ductile members in order to prevent early fracture or severe buckling in the connections. The paths of stress transfer within connections are apt to be complex, and strains may tend to concentrate in small regions.

6. Avoid interactions. Provide sufficient clearance between the structural system and all nonstructural rigid elements (e.g., curtain walls) to insure that the rigid elements do not interact with the structural system.

7. Provide proper detailing. Insure that the building behaves as an integral unit by providing proper detailing to tie the building's lateral-force-resisting elements together.

Design Load Combinations

For a building to withstand the inertial forces imposed on it by earthquake ground motions, the building's structural system (i.e., frame members, shear walls, etc.) must resist the inertial forces as well as dead and live design loads. Thus, each member individually and the building as a whole must be able to resist the effects resulting from the design load combinations shown in Eqs 1 and 2.

$$U = D + L + E \text{ or} \qquad \text{[Eq 1]}$$

$$U = D + E \qquad \text{[Eq 2]}$$

where U = strength required to resist design loads or their related load effects

D = dead loads or their related load effects

L = live loads or their related load effects

E = load effects of seismic motions.

Reinforced concrete members should be proportioned using the ultimate strength design method with the appropriate strength reduction factors. Structural steel members should be proportioned using the working stress method; however, the allowable stresses may be increased by 1.7 times the allowable stresses for dead loads.

Lateral Deflections

Under the design lateral forces, the lateral deflection for any story of the proposed building relative to the adjacent story should not exceed 0.005 times the story height. The maximum lateral deflections the building may be required to withstand should be estimated by multiplying the deflections calculated for the design lateral forces by the appropriate ductility factor in Table 1. The maximum lateral deflection for any story relative to the adjacent story should not exceed 0.010 times the story height unless it can be demonstrated that greater deflections can be tolerated. The building should be checked at these deflections for stability and secondary stresses such as P-Delta effects.

Orthogonal Effects

The vertical elements of the building's structural system and its foundation should be designed to resist the member load effects resulting from the prescribed loads acting in one axis combined with 0.4 times the load effects resulting from the prescribed loads acting in the direction perpendicular to the first axis. The combination producing the maximum member load effects should be used.

Seismic Analysis Guidelines

The total lateral design force, representing earthquake effects, and the distribution of the lateral force over the height of the building and throughout the major lateral-force-resisting elements should be determined in accordance with the following methods. These specified methods do not prohibit use of a time history analysis. However, such an analysis is usually not technically or economically justified unless it is absolutely necessary to determine a story-level time history to evaluate the response of nonstructural elements such as mechanical and electrical equipment and/or piping systems.

Modal Analysis Method

For critical buildings and for high-loss-potential buildings with irregular shapes, large differences in lateral resistance or stiffness between adjacent stories, or other unusual structural features, a response spectrum modal analysis should be performed to obtain a better understanding of how the structural system will respond when subjected to an earthquake and to obtain a more realistic distribution of the lateral forces on the structural system. U.S. Army Construction Engineering Research Laboratory (CERL) Technical Report M-132[3] presents the general procedures for performing a response spectrum modal analysis. The expected response of the structural system (bending moments, shears, axial loads, story shears and displacements, etc.) should be computed using the square root of the sum of the squares of the maximum response of those modes that significantly add to the response parameter under investigation. The minimum total lateral force should not be less than that obtained from a design spectrum constructed for an effective peak ground acceleration of 0.05 g.

Equivalent Static Lateral Load Method

For high-loss- and low-loss-potential buildings that are regular in shape and have uniform mass and stiffness distributions, the total lateral force V should be determined using Eq 3.

$$V = \alpha AW \qquad \text{[Eq 3]}$$

where α = fundamental mode shape lateral force response coefficient

A = acceleration coefficient

W = total dead load plus 25 percent of the floor live loads and, where snow load duration warrants consideration, 50 percent of the snow load.

[3] W. K. Stockdale, *Modal Analysis Methods in Seismic Design for Buildings*, Technical Report M-132/ADA012732 (U.S. Army Construction Engineering Research Laboratory, 1975).

The value of α is obtained from Figure 2, and the value of A is obtained from the applicable design spectrum, considering the period of the fundamental mode of vibration of the building in the direction under consideration. The fundamental period T should be estimated as follows:

$T = 0.12\ N$ for steel frame construction

$T = 0.08\ N$ for reinforced concrete frame construction

$T = 0.05\ N$ for buildings with 50 percent or more of the total shear carried by shear walls

where N = total number of stories above exterior grade level to uppermost level of the main portion of the structure.

The total lateral force V should be distributed laterally over the height of the building in accordance with Eq 4.

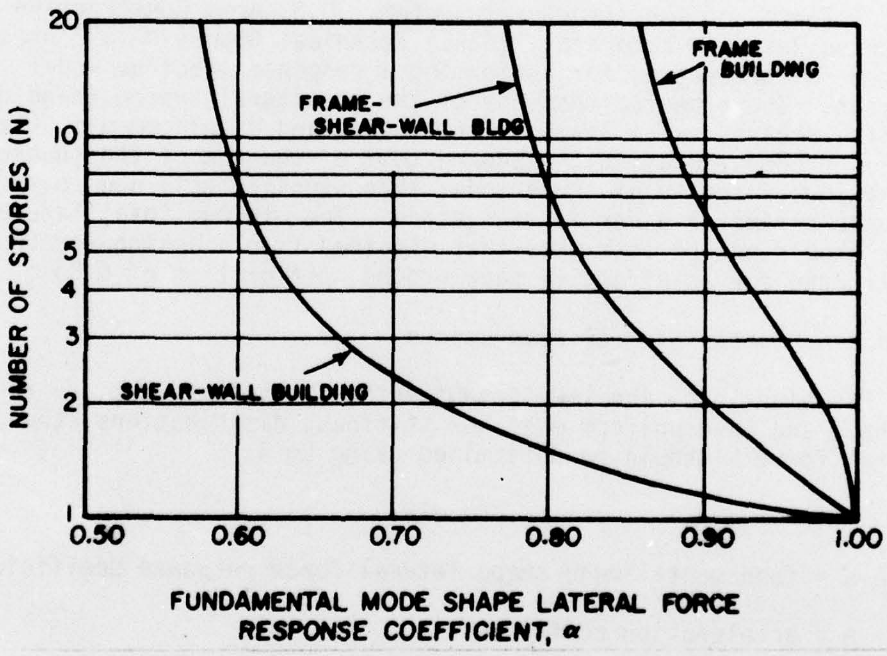


Figure 2. Fundamental mode shape lateral force response coefficient for various types of buildings with uniform mass and stiffness distributions. Constructed from *Effects Prediction Guidelines for Structures Subjected to Ground Motion*, JAB-99-115 (URS/John A. Blume & Associates, Engineers, July 1975).

$$V = F_t + \sum_{i=1}^{n} F_i \qquad \text{[Eq 4]}$$

where F_i = lateral force applied to level i

F_t = the concentrated force at the top of the building.

In Eq 4, F_t shall be determined by

$$F_t = 0.07\ TV \qquad \text{[Eq 5]}$$

The value of F_t need not exceed 0.25 V and may be considered as zero when T is 0.7 sec or less. The remaining portion of the total lateral force should be distributed over the height of the building, including the top level n, according to Eqs 6 and 7.

For frame and combination frame-shear wall buildings:

$$F_x = (V - F_t) \frac{w_x h_x}{\sum_{i=1}^{n} w_i h_i} \qquad \text{[Eq 6]}$$

For shear buildings:

$$F_x = (V - F_t) \frac{w_x h_x^2}{\sum_{i=1}^{n} w_i h_i^2} \qquad \text{[Eq 7]}$$

where F_x = lateral force applied at level x, the level under design consideration

w_x, w_i = portion of W located at or assigned to level x or i, respectively

h_x, h_i = height in feet above the base to level x or i, respectively

V and F_t are as defined in Eq 4.

At each floor level designated as x, the force F_x should be applied in accordance with the mass distribution at that floor level. This loading must be used in the design of the floor as a horizontal diaphragm as set forth in TM 5-809-10.

The total shear in any horizontal plane should be distributed to the various vertical elements of the lateral-force-resisting members in proportion to their rigidities, considering the rigidity of the horizontal diaphragm (floor).

Provisions should be made for the increase in shear resulting from the horizontal torsion due to an eccentricity between the center of mass and the center of rigidity at each floor level. Where the vertical-shear-resisting elements depend on diaphragm action for shear distribution at any level, they should be capable of resisting the larger torsional moment computed by considering the total torsional moments due to the computed eccentricity of F_i for level x and all levels above, or the torsional moment produced by the total story shear acting at an eccentricity of 5 percent of the maximum building dimension at that level. Absolute values of the torsional shear loads should be added to the horizontal shear forces applied to each vertical element.

4 CONCLUSION

Although the seismic structural design/analysis guidelines presented above are preliminary in nature, they are believed to be adequately conservative and will provide a more rational design basis for military buildings within the continental United States.

APPENDIX:

EXAMPLE OF THE CONSTRUCTION OF A DESIGN SPECTRUM

Purpose and Scope

This appendix provides an example of the construction of a design spectrum for use in the seismic design of a high-loss-potential building located on a military installation.

Solution

Step 1. The effective peak ground acceleration for the building's location was determined to be 0.22 g.

Step 2. The acceleration, velocity, and displacement bounds (a, v, and d) of the site ground motion spectrum are

$$a = 1 \times 0.22 = 0.22 \text{ g}$$

$$v = 48 \times 0.22 = 10.56 \text{ in./sec (268 mm/sec)}$$

$$d = 36 \times 0.22 = 7.92 \text{ in. (201 mm)}$$

Figure A1 presents spectra corresponding to the basic ground motion spectrum and the site ground motion spectrum as dashed and solid lines, respectively.

Step 3. From Table 1, the critical damping is 5 percent.

Step 4. From Table 2, the spectral amplification factors for acceleration, velocity, and displacement are 2.5, 2.1, and 1.8, respectively.

Step 5. The acceleration, velocity, and displacement bounds for the elastic response spectrum are:

$$a = 0.22 \times 2.5 = 0.55 \text{ g}$$

$$v = 10.56 \times 2.1 = 22.18 \text{ in./sec (563 mm/sec)}$$

$$d = 7.92 \times 1.8 = 14.26 \text{ in. (362 mm).}$$

Figure A2 presents the spectra corresponding to the site ground motion spectrum obtained in Step 2 and the bounds of the elastic response spectrum as dashed and solid lines, respectively.

Step 6. From Table 1, the ductility factor is 3.

Step 7. The acceleration, velocity, and displacement bounds of the design spectrum below 8 Hz are

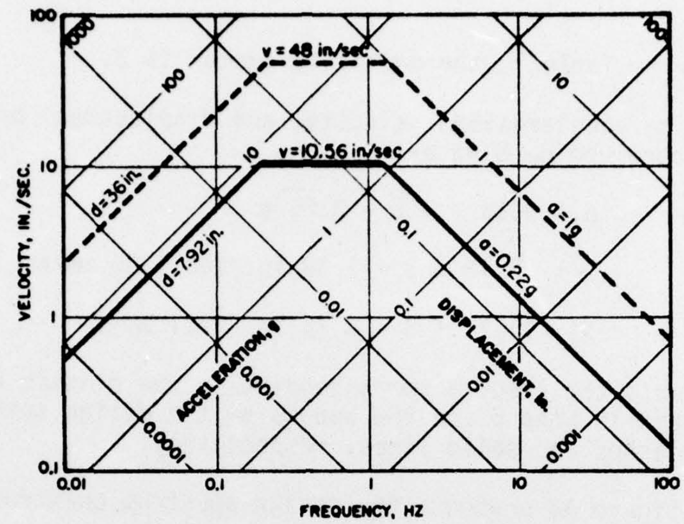
$$a = 0.55 \div \sqrt{5} = 0.25 \text{ g}$$

$$v = 22.18 \div 3 = 7.39 \text{ in./sec (188 mm/sec)}$$

$$d = 14.26 \div 3 = 4.75 \text{ in. (121 mm).}$$

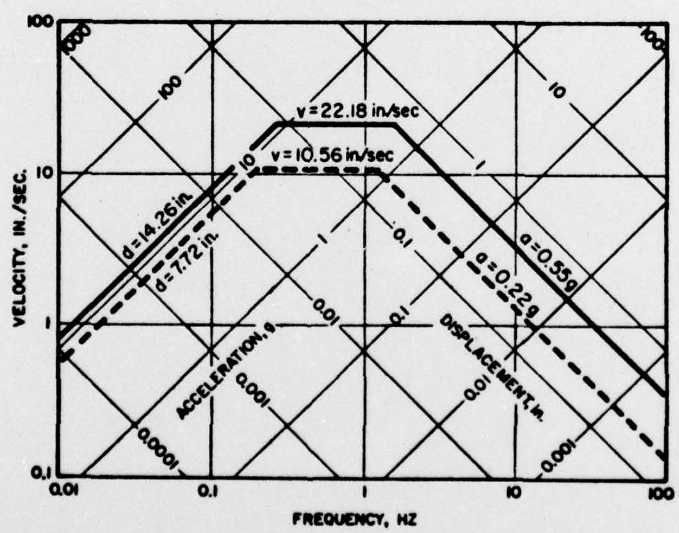
Figure A3 presents the spectra corresponding to the elastic response spectrum obtained in Step 5 and the bounds of the design spectrum below 8 Hz as dashed and solid lines, respectively.

Step 8. Figure A4 presents the design spectrum constructed using the results from Steps 1 through 7.



BASIC GROUND MOTION SPECTRUM-----
SITE GROUND MOTION SPECTRUM———

Figure A1. Basic ground motion and site ground motion spectra. SI conversion factor: 1 in. = 25.4 mm.



SITE GROUND MOTION SPECTRUM-----
ELASTIC RESPONSE SPECTRUM ———

Figure A2. Site ground motion and bounds of elastic response spectra. SI conversion factor: 1 in. = 25.4 mm.

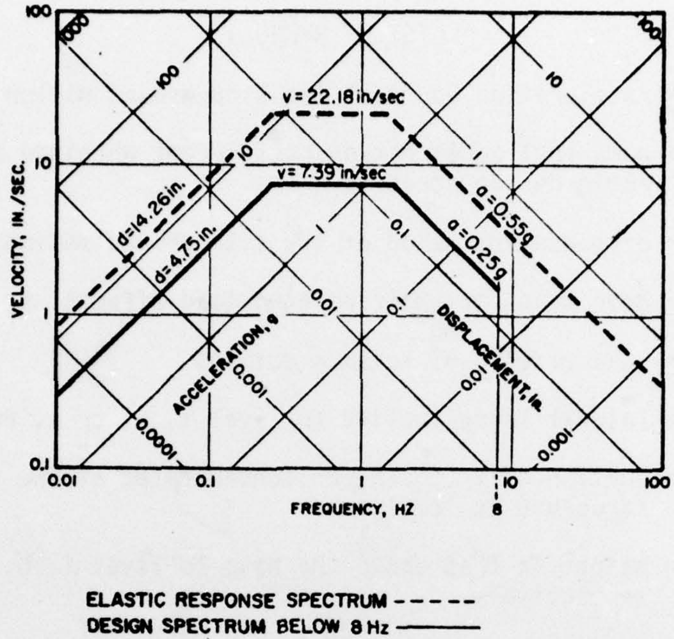


Figure A3. Elastic response spectrum and bounds of design spectrum below 8 Hz. SI conversion factor: 1 in. = 25.4 mm.

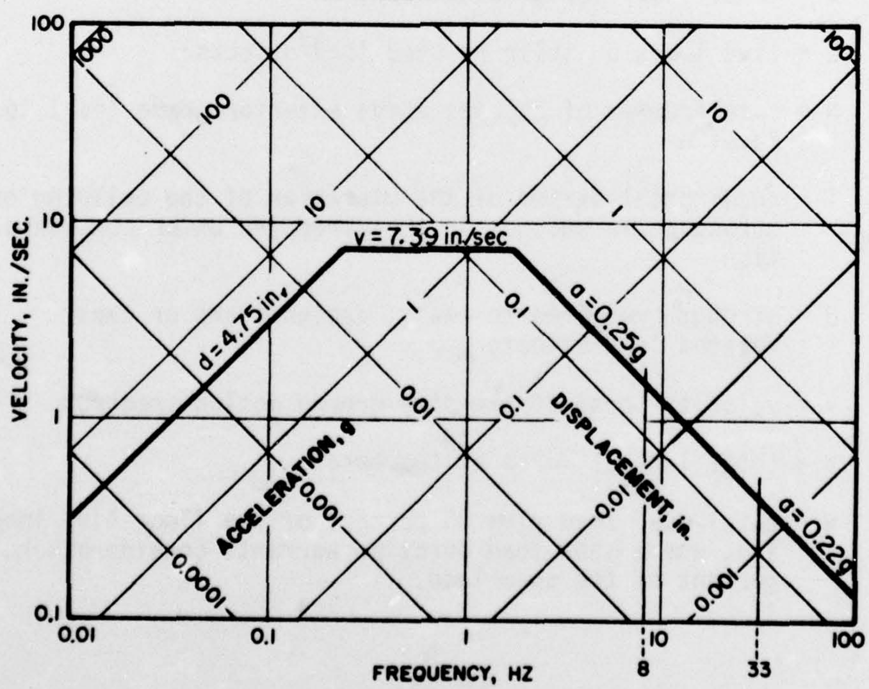


Figure A4. Design spectrum. SI conversion factor: 1 in. = 25.4 mm.

LIST OF SYMBOLS

a = acceleration bound of the site ground motion spectrum

A = numerical acceleration coefficient obtained from applicable design spectrum

d = displacement bound of the site ground motion spectrum

D = dead loads or their related load effects

E = load effects of seismic motions

F_i, F_n, F_x = lateral force applied to level i, n, or x, respectively

F_t = portion of V considered concentrated at the top of the structure at level n

h_i, h_n, h_x = height in feet above the base to level i, n, or x, respectively

Level i = level of the structure referred to by subscript i

Level n = uppermost level in the main portion of the structure

Level x = level under design consideration

L = live loads or their related load effects

N = total number of stories above exterior grade level to level n

T = fundamental period of the vibration of the building or structure in seconds in the direction under consideration

U = strength required to resist design loads or their related load effects

v = velocity bound of the site ground motion spectrum

V = total lateral force at the base

W = total dead load plus 25 percent of the floor live loads and, where snow load duration warrants consideration, 50 percent of the snow load:

$$W = \sum_{i=1}^{h} w_i$$

w_i, w_x = portion of W which is located at or assigned to level i or x, respectively

α = numerical coefficient relating the effects of the fundamental mode shape on the total lateral force (Figure 2)

μ = ductility factor

GLOSSARY

acceleration coefficient: the ratio of the acceleration obtained from the design spectrum to 1 g.

critical buildings: buildings essential to disaster and/or strategic response capability. Typical examples are:

1. Hospitals, excluding non-physically-annexed outpatient facilities such as dental clinics and dispensaries

2. Fire and rescue stations and emergency vehicle garages

3. Mission-essential, primarily communication or data-handling facilities

4. Operational missile control, launch, tracking, or other critical defense facilities

5. Handling, processing, or storage facilities for sensitive munitions, nuclear weaponry or processes, gas and petroleum fuels, and chemical or biological contaminants.

design earthquake: an earthquake which produces the maximum horizontal seismic ground motions which could believably occur at the site within the presently known tectonic framework. It is a rational event derived from a detailed analysis of all geological and seismological data for the appropriate region surrounding the site. No consideration should be given to its probability of occurrence except that its likelihood of occurrence is great enough to be of concern.

ductility factor: a measure of the extent of inelastic deformation in a building. For an elastoplastic force displacement representation of the resistance of a building, the ductility factor is defined as the ratio of the ultimate displacement to the yield point displacement.

effective peak ground acceleration: values of ground acceleration which occur several times during an earthquake, rather than an isolated peak ground acceleration.

high-loss-potential buildings: buildings whose occupancy or function is such that an earthquake may cause hardships for or danger to the occupants, severe damage to the functional operation, or large economic loss. Typical examples include:

1. Family housing, bachelor quarters, dormitories, administrative, industrial, and commercial facilities (including dining halls and commissaries) that are three or more stories high

2. Confinement facilities

3. Schools

4. Churches, theaters, gymnasiums, and other recreational facilities often occupied by a large number of people

5. Central utility (power, heat, water, sewage) plants serving large areas

6. Transportation terminal buildings.

low-loss-potential buildings: buildings which are not critical or high-loss potential. Typical examples are:

1. Family housing, bachelor quarters, dormitories, administrative offices, and industrial and commercial buildings (including commissaries and dining halls) that do not exceed two stories in height

2. Facilities subject to occupancy by only a small number of people.

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