Procedures for Estimating Earthquake Ground Motions

GEOLOGICAL SURVEY PROFESSIONAL PAPER 1114

PROCEDURES FOR ESTIMATING EARTHQUAKE GROUND MOTIONS

High-altitude view of the San Francisco Bay region showing surface traces of the Hayward and Calaveras faults. The Hayward fault was the source of two large earthquakes in 1836 and 1868 that caused surface rupture along as much as 64 km of its trace. The Calaveras fault, with a length of approximately 160 km, is one of the largest in northern California. The San Andreas fault passes offshore near Mussel Rock (arrow at bottom of photograph). Fault systems such as these must be critically studied when evaluating the seismic hazards and risk in an urban area.

Procedures for Estimating Earthquake Ground Motions

By WALTER W. HAYS

GEOLOGICAL SURVEY PROFESSIONAL PAPER 1114

UNITED STATES GOVERNMENT PRINTING OFFICE, WASHINGTON : 1980

UNITED STATES DEPARTMENT OF THE INTERIOR

CECIL D. ANDRUS, *Secretary*

GEOLOGICAL SURVEY

H. William Menard, *Director*

Library of Congress Cataloging in Publication Data

Hays, Walter W.
Procedures for estimating earthquake ground motions.

(Geological Survey professional paper ; 1114)
Bibliography: p. 69-77.
Supt. of Docs. no.: I 19.16:1114
1. Earthquakes–United States. 2. Seismology–United States. 3. Earthquake resistant design. I. Title. II. Series: United States. Geological Survey. Professional paper ; 1114.
QE539.H39 363.3'495 79-607183

For sale by the Superintendent of Documents, U.S. Government Printing Office
Washington, D.C. 20402

Stock Number 024-001-03276-7

CONTENTS

ILLUSTRATIONS

TABLES

GLOSSARY

Absorption. A process whereby the energy of a seismic wave is converted into heating of the medium through which the wave passes.

Accelerogram. The record from an accelerometer showing acceleration as a function of time.

Accelerometer. An instrument for measuring acceleration.

Acceptable risk. A specification of the acceptable number of fatalities due to earthquake hazards, or an equivalent statement in terms of loss in buildings.

Acoustic impedance. Seismic wave velocity multiplied by density of the medium.

Active fault. A fault is active if, because of its present tectonic setting, it can undergo movement from time to time in the immediate geologic future.

Aftershocks. Minor seismic tremors that may follow an underground nuclear detonation or the secondary tremors after the main shock of an earthquake.

Alluvium. A general term for loosely compacted particles of rock, sand, clay and so forth deposited by streams in relatively recent geologic times.

Amplification. Modification of the input bedrock ground motion by the overlying unconsolidated materials. Amplification causes the amplitude of the surface ground motion to be increased in some range of frequencies and decreased in others. Amplification is a function of the shear-wave velocity and damping of the unconsolidated materials, its thickness and geometry, and the strain level of the input rock motion.

Amplitude. Maximum deviation from mean or center line of wave.

Amplitude spectrum. Amplitude versus frequency relation such as is computed in a Fourier analysis. See **Fourier transform.**

Anisotrophic mass. A material having different properties in different directions at any given point.

Anisotropy. Variation of a physical property depending on the orientation along which it is measured.

Anomaly. A deviation from uniformity or normality.

Asthenosphere. The layer or shell of the earth below the lithosphere; roughly equivalent to the upper **mantle.**

Attenuation. (1) a decrease of signal amplitude during transmission, (2) a reduction in amplitude or energy with or without change of waveform, or (3) the decrease in seismic signal strength with distance which depends not only on geometrical spreading but also may be related to physical characteristics of the transmitting medium causing absorption and scattering.

Bandpass. Describing a range of frequencies (bandwidth) in which transmission is nearly complete while signals at frequencies outside these limits are attenuated substantially.

Bar. Equals 1 atmosphere: A unit of pressure, 0.01 kilopascal.

Basement. The igneous, metamorphic, or highly folded rock underlying sedimentary units.

Bedrock. An solid rock exposed at the surface or underlying soil; has shear-wave velocity greater than 765 m/s at small (0.0001 percent) strains. See **Firm soil** and **Soft soil.**

Body wave. Waves propagated in the interior of a body, that is, compression and shear waves, the P- and S-waves of seismology.

Body-wave magnitude. m_b. See **Magnitude.**

Bulk modulus. The ratio of the change in average stress to the change in unit volume.

Capable fault. A fault that has the potential to undergo future surface displacement. A fault is capable if: (1) it has had late

Quaternary or more recent movement, or (2) macroseimic activity has been associated with it, or (3) it has a demonstrated structural relation to a known capable fault such that movement of the one may cause movement of the other, especially during the lifetime of the project under consideration.

Compression wave. A wave in which an element of the medium changes volume without rotation.

Converted wave. A wave which is converted from longitudinal to transverse, or vice versa, upon reflection or refraction at oblique incidence from an interface.

Convolution. The change of wave shape as a result of passing a signal through a linear filter.

Corner frequency. A spectrum's corner frequency is that frequency where the high- and low-frequency trends intersect. The location of the corner frequency, f_o, is related to the radius, r, of the equivalent circular fault through the relation $r = \frac{-2.34\beta}{2\pi f_o}$ where β is the shear-wave velocity at the source.

Covariance. A statistical regression analysis technique that allows one to analyze subsets of data having a common characteristic property.

Critical angle. Angle of incidence, θ_c, for which the refracted ray grazes the surface of contact between two media in which the seismic velocities are v_1 and v_2.

Crust. The outermost portion of the earth, averaging about 30 km, that overlies the Mohorovičič discontinuity.

Design earthquake. The largest earthquake that has such a high probability of occurrence based on studies of historic seismicity and structural geology that it is appropriate to design a structure to withstand it. Ground shaking of the design earthquake might be exceeded, but the probability of this happening is considered to be small.

Design spectra. Spectra appropriate for earthquake-resistant design purposes. Design spectra are typically smooth curves that have been modified from a family of spectra of historic earthquakes to take account of features peculiar to a geographic region and a particular site. Design spectra do not include the effect of soil-structure interaction.

Design time history. One of a family of time histories which produces a response spectrum that envelopes the smooth design spectrum, for a selected value of damping, at all periods.

Earthquake hazards. The probability that natural events accompanying an earthquake such as ground shaking, ground failure, surface faulting, tectonic deformation, and inundation, which may cause damage and loss of life, will occur at a site during a specified exposure time. See **Earthquake risk.**

Earthquake risk. The probability that social or economic consequences of earthquakes, expressed in dollars or casualties, will equal or exceed specified values at a site during a specified exposure time.

Earthquake waves. Elastic waves propagating in the earth, set in motion by a sudden change such as faulting of a portion of the earth.

Effective peak acceleration. The peak ground acceleration after the ground-motion record has been filtered to remove the very high frequencies that have little influence upon structural response.

Effective peak velocity. The peak ground velocity after the ground motion record has been filtered to remove high frequencies.

Epicenter. The point on the Earth's surface vertically above the point where the first rupture and the first earthquake motion occur.

Exceedance probability. The probability (for example, 10 percent) over some period of time that an earthquake will generate a level of ground shaking greater than some specified level.

Exposure time. The period of time (for example, 50 years) that a structure is exposed to the earthquake threat. The exposure time is sometimes chosen to be equal to the design lifetime of the structure.

Failure. A condition in which movement caused by shearing stresses in a structure or soil mass is of sufficient magnitude to destroy or seriously damage it.

Fault. A fracture or fracture zone along which displacement of the two sides relative to one another has occurred parallel to the fracture. See **Active, Capable, Normal, Thrust** and **Strike-slip** faults.

Filter. That part of a system which discriminates against some of ths information entering it. The discrimination is usually on the basis of frequency, although other bases such as wavelength may be used. Linear filtering is called **convolution.**

Finite element analysis. An analysis which uses an assembly of finite elements which are connected at a finite number of nodal points to represent a structure or a soil continum.

Firm soil. A general term for soil characterized by a shear wave velocity of 600 to 765 m/s. See **Soft soil, Bedrock.**

Focal depth. The vertical distance between the hypocenter and the epicenter in an earthquake.

Focus. The point within the earth which marks the origin of the elastic waves of an earthquake.

Forced vibration. Vibration that occurs if the response is imposed by the excitation. If the excitation is periodic and continuing, the oscillation is steady-state.

Fourier spectrum. See **Amplitude spectrum, Phase response,** and **Fourier transform.**

Fourier transform. The mathematical formulas that convert a time function (waveform, seismogram, etc.) $G(t)$ into a function of frequency $S(f)$ and vice versa.

Free field. The regions of the medium that are not influenced by manmade structures, or a medium that contains no such structures. It also refers to that region in which boundary effects do not significantly influence the behavior of the medium.

Free vibration. Vibration that occurs in the absence of forced vibration.

Frequency. Number of cycles occurring in unit time. **Hertz** (hz) is the unit of frequency.

Gaussian distribution. Equals normal distribution (bell-shaped curve): A quantity or set of values so distributed about a mean value, m, that the probability, $\epsilon(\Delta a)$, of a value lying within an interval, Δa, centered at the point, a, is:

$$\epsilon(\Delta a) = \frac{1}{2\pi\sigma} \; e \; \frac{-(a-m)^2}{2\sigma^2} \Delta a$$

where σ is the standard error of estimate.

Geometrical damping. That component of damping due to the radial spreading of energy with distance from a given source.

Geophone. Sensing device used to measure electronically the rate of travel of sound or force waves transmitted through the earth from a known source.

Geophysics. The study of the physical characteristics and properties of the earth.

Geotechnical. Related to soil mechanics.

Grain size. A term relating to the size of mineral particles that make up a soil deposit.

Ground response, ground motion, seismic response. A general term, includes all aspects of ground motion, namely, particle acceleration, velocity, or displacement; stress and strain from a nuclear explosion, an earthquake, or another energy source.

Group velocity. The velocity with which most of the energy in a wave train travels. In dispersive media where velocity varies with frequency, the wave train changes shape as it progresses so that individual wave crests appear to travel at a different velocity (the phase velocity) than the overall energy as approximately enclosed by the envelope of the wave train.

Half-space. A mathematical model bounded only by one plane surface; that is, the model is so large in other dimensions that only the one boundary affects the results. Properties within the model are assumed to be homogeneous and usually isotropic.

Hertz. A unit of **frequency;** cycles per second (cps).

Holocene. The past 10,000 years of geologic time.

Hydrostatic pressure. The pressure in a liquid under static conditions; the product of the unit weight of the liquid (water=1 kg/L) and the difference in elevation between the given point and the ground water elevation.

Hypocenter. The location in space where the slip responsible for an earthquake occurs; the focus of an earthquake.

Hysteresis loop. (1) the stress-strain path of a material under cyclic loading conditions, or (2) a trace of the lag in the return of an elastically deformed specimen to its original shape after the load has been released.

Incident angle. The angle which a ray path makes with a perpendicular to an interface.

In situ strength. The in-place strength of a soil deposit.

Intensity. A numerical index describing the effects of an earthquake on the earth's surface, on man, and on structures built by him. The scale in common use in the United States today is the Modified Mercalli scale of 1931 with intensity values indicated by Roman numerals from I to XII. The narrative descriptions of each intensity value are:

I. Not felt or, except rarely under especially favorable circumstances. Under certain conditions, at and outside the boundary of the area in which a great shock is felt: sometimes, birds, animals, reported uneasy or disturbed; sometimes dizziness or nausea experienced; sometimes trees, structures, liquids, bodies of water, may sway; doors may swing, very slowly.

II. Felt indoors by few, especially on upper floors, or by sensitive, or nervous persons. Also, as in grade I, but often more noticeably: sometimes hanging objects may swing, especially when delicately suspended; sometimes trees, structures, liquids, bodies of water, may sway, doors may swing, very slowly; sometimes birds, animals, reported uneasy or disturbed; sometimes dizziness or nausea experienced.

III. Felt indoors by several, motion usually rapid vibration. Sometimes not recognized to be an earthquake at first. Duration estimated in some cases. Vibration like that due to passing of light, or lightly loaded trucks, or heavy trucks some distance away. Hanging objects may swing slightly. Movements may be appreciable on upper levels of tall structures. Rocked standing motor cars slightly.

IV. Felt indoors by many, outdoors by few. Awakened few, especially light sleepers. Frightened no one, unless apprehensive from previous experience. Vibration like that due to passing of heavy or heavily loaded trucks. Sensation like heavy body striking building or falling of heavy objects inside. Rattling of dishes, windows, doors; glassware and crockery clink and clash. Creaking of walls, frame, especially in the upper range of this grade. Hanging objects swung, in numerous instances. Disturbed liquids in open vessels slightly. Rocked standing motor cars noticeably.

V. Felt indoors by practically all, outdoors by many or most; outdoors direction estimated. Awakened many, or most. Frightened few—slight excitement, a few ran outdoors. Buildings trembled throughout. Broke dishes, glassware, to some extent. Cracked windows—in some cases, but not generally. Overturned vases, small or unstable objects, in many instances, with occasional fall. Hanging objects, doors, swing generally or considerably. Knocked pictures against wall, or swung them out of place. Opened, or closed, doors, shutters, abruptly. Pendulum clocks stopped, started or ran fast, or slow. Moved small objects, furnishings, the later to slight extent. Spilled liquids in small amounts from well-filled open containers. Trees, bushes, shaken slightly.

VI. Felt by all, indoors and outdoors. Frightened many, excitement general, some alarm, many ran outdoors. Awakened all. Persons made to move unsteadily. Trees, bushes, shaken slightly to moderately. Liquid set in strong motion. Small bells rang—church, chapel, school, etc. Damage slight in poorly built buildings. Fall of plaster in small amount. Cracked plaster somewhat, especially fine cracks in chimneys in some instances. Broke dishes, glassware, in considerable quantity, also some windows. Fall of knick-knacks, books, pictures. Overturned furniture in many instances. Moved furnishings of moderately heavy kind.

VII. Frightened all; general alarm, all ran outdoors. Some, or many, found it difficult to stand. Noticed by persons driving motor cars. Trees and bushes shaken moderately to strongly. Waves on ponds, lakes, and running water. Water turbid from mud stirred up. Incaving to some extent of sand or gravel stream banks. Rang large church bells, etc. Suspended objects made to quiver. Damage negligible in buildings of good design and construction, slight to moderate in well-built ordinary buildings, considerable in poorly built or badly designed buildings, adobe houses, old walls (especially where laid up without mortar), spires, etc. Cracked chimneys to considerable extent, walls to some extent. Fall of plaster in considerable to large amount, also some stucco. Broke numerous windows, furniture to some extent. Shook down loosened brickwork and tiles. Broke weak chimneys at the roof-line (sometimes damaging roofs). Fall of cornices from towers and high buildings. Dislodged bricks and stones. Overturned heavy furniture, with damage from breaking. Damage considerable to concrete irrigation ditches.

VIII. Fright general; alarm approaches panic. Disturbed persons driving motor cars. Trees shaken strongly—branches, trunks, broken off, especially palm trees. Ejected sand and mud in small amounts. Changes: temporary, permanent; in flow of springs and wells; dry wells renewed flow; in temperature of spring and well waters. Damage slight in structures (brick) built especially to withstand earthquakes. Considerable in ordinary substantial buildings, partial collapse: racked, tumbled down, wooden houses in some cases; threw out panel walls in frame structures, broke off decayed piling. Fall of walls. Cracked, broke, solid stone walls seriously. Wet ground to some extent, also ground on steep slopes. Twisting, fall, of chimneys, columns, monuments, also factory stacks, towers. Moved conspicuously, overturned, very heavy furniture.

IX. Panic general. Cracked ground conspicuously. Damage considerable in (masonry) structures built especially to withstand earthquakes: Threw out of plumb some wood-frame houses built especially to withstand earthquakes; great in substantial (masonry) buildings, some collapse in large part; or wholly shifted frame buildings off foundations, racked frames; serious to reservoirs; underground pipes sometimes broken.

X. Cracked ground, especially when loose and wet, up to widths of several inches; fissures up to a yard in width ran parallel to canal and stream banks. Landslides considerable from river banks and steep coasts. Shifted sand and mud horizontally on beaches and flat land. Changed level of water in wells. Threw water on banks of canals, lakes, rivers, etc. Damage serious to dams, dikes, embankments. Severe to well-built wooden structures and bridges, some destroyed. Developed dangerous cracks in excellent brick walls. Destroyed most masonry and frame structures, also their foundations. Bent railroad rails slightly. Tore apart, or crushed endwise, pipe lines buried in earth. Open cracks and broad wavy folds in cement pavements and asphalt road surfaces.

XI. Disturbances in ground many and widespread, varying with ground material. Broad fissures, earth slumps, and land slips in soft, wet ground. Ejected water in large amounts charged with sand and mud. Caused sea-waves ("tidal" waves) of significant magnitude. Damage severe to wood-frame structures, especially near shock centers. Great to dams, dikes, embankments often for long distances. Few, if any (masonry) structures remained standing. Destroyed large well-built bridges by the wrecking of supporting piers, or pillars. Affected yielding wooden bridges less. Bent railroad rails greatly, and thrust them endwise. Put pipe lines buried in earth completely out of service.

XII. Damage total—practically all works of construction damaged greatly or destroyed. Disturbances in ground great and varied, numerous shearing cracks. Landslides, falls of rock of significant character, slumping of river banks, etc., numerous and extensive. Wrenched loose, tore off, large rock masses. Fault slips in firm rock, with notable horizontal and vertical offset displacements. Water channels, surface and underground, disturbed and modified greatly. Dammed lakes, produced waterfalls, deflected rivers, etc. Waves seen on ground surfaces. Distorted lines of sight and level. Threw objects upward into the air.

Interface. The common surface separating two different geologic media in contact.

Internal friction. The resisting shear strength considered to be due to the interlocking of the soil grains and the resistance to sliding between the grains.

Isotropic. Having the same physical properties regardless of the direction in which they are measured. Strictly applies only to an arbitrarily small neighborhood surrounding a point and to single properties.

Lame's constants. See **Modulus.**

Least squares fit. An analytic function which approximates a set of data with a curve such that the sum of the squares of the distances from the observed points to the curve is a minimum.

Linear system. A system whose output is linearly related to its input. If a linear system is excited by a an input sine wave of frequency f_1, the output will contain only the frequency f_1; the amplitude and phase may be changed.

Linear viscoelastic medium. A medium for which the functional relation between stress and strain can be expressed as a linear relation between stress, strain and their nth order temporal derivatives.

Liquefaction Temporary transformation of unconsolidated materials into a fluid mass during an earthquake.

Lithology. The description of rock composition and texture.

Lithosphere. The **crust** and upper **mantle** of the earth.

Loading. The force on an object or structure or element of a structure.

Longitudinal wave. Equals **compression wave;** equals **P-wave.**

Love wave. A seismic surface wave which propagates in a surface layer. The vibration is transverse to the direction of propagation with no vertical motion.

Low-cut filter. Equals high pass filter: A **filter** that transmits frequencies above a given cutoff frequency and substantially attenuates lower frequencies.

Low-pass filter. Equals high-cut filter: A **filter** that transmits frequencies below a given cutoff frequency and substantially attenuates all others. The earth acts like a low-pass filter.

Magnitude. A quantity that is characteristic of the total energy released by an earthquake, as contrasted to **intensity,** which subjectively describes earthquake effects at a particular place. Professor C. F. Richter devised the logarithmic magnitude scale in current use to define local magnitude (M_L) in terms of the motion that would be measured by a standard type of seismograph located 100 km from the epicenter of an earthquake. Several other magnitude scales are in use, for example, body-wave magnitude (m_b) and surface-wave magnitude (M_s) which utilize body waves and surface waves. The scale is open ended, but the largest known earthquake magnitudes (M_s) are near 8.9.

Major principal stress. (See **Principal stress**) The largest (with regard to sign) principal stress.

Mantle. The part of the earth's interior between the core and the **crust.** The upper surface of the mantle is the **Mohorovičić discontinuity.**

Meizoseismal zone. Zone of intense shaking in the near field of an earthquake. The radial width of this zone increases with magnitude.

Mesosphere. The lower **mantle.** It is not involved in the earth's tectonic processes.

Microtremor. A weak tremor.

Minor principal stress. (See **Principal stress**). The smallest (with regard to sign) principal stress.

Model. A concept from which one can deduce effects that can then be compared to observations; this concept assists in understanding the significance of the observations. The model may be conceptual, physical , or mathematical.

Modulus. A measure of the elastic properties of a material. Moduli for isotropic bodies include:

1. **Bulk modulus, k.** The stress-strain ratio under simple hydrostatic pressure: the bulk modulus can be expressed in terms of other moduli as:

$$k=E/3(1-2\sigma)\ .$$

2. **Shear modulus.** Equals rigidity modulus, equals Lame's constant, μ: The stress-strain ratio for simple shear. The shear modulus can also be expressed in terms of other moduli and Poisson's ratio σ as:

$$\mu=\frac{E}{2(1+\sigma)}.$$

3. **Young's modulus,** E. The stress-strain ration when a rod is pulled or compressed.
4. **Lame's constant** λ. If a cube is stretched in the up-direction by a tensile stress, S, is giving an upward strain, s, and S' is the lateral tensile stress needed to prevent lateral contraction, then:

$$\lambda=S'/s\ .$$

This constant can also be expressed in terms of Young's modulus, E, and Poisson's ratio, σ:

$$\lambda=\frac{E\ \sigma}{(1+\sigma)\ (1-2\sigma)}.$$

The velocities of P- and S-waves, V_p and V_S, can be expressed in terms of the moduli and the density, ρ:

$$V_p=\sqrt{(\lambda+2\mu)/\rho}$$

$$V_S=\sqrt{\mu/\rho}\ .$$

Modulus of elasticity. The ratio of stress to strain for a material under given loading conditions; numerically equal to the slope of the tangent of a stress-strain curve.

Mohorovičić (M) discontinuity. Seismic discontinuity which separates the earth's **crust** and **mantle.**

Moment. The seismic moment $M_o = \mu \bar{u} A$ contains information on the rigidity (μ) in the source region, average dislocation ($\bar{u}$), and area (A) of faulting. It determines the amplitude of the long-period level of the spectrum of ground motion.

Monotonic loading. Continuously increasing load in one direction.

Natural frequency. Property of the elastic system in free vibration. Free vibration occurs naturally at a discrete frequency when an elastic system vibrates under the action of forces inherent in the system itself and in the absence of external impressed forces.

Normal fault. Vertical movement along a sloping fault surface in which the block above the fault has moved downward relative to the block below. The Wasatch fault in Utah is an example.

Normal stress. That stress component normal to a given plane.

Operating basis earthquake (OBE). A design earthquake used by the U.S. Nuclear Regulatory Commission in nuclear power plant siting: the largest earthquake that reasonably could be expected to affect the plant site during the operating life of the plant. The powerplant is designed to withstand the OBE and still operate without undue risk to the health and safety of the public. See **Safe shutdown earthquake.**

Oscillation. The variation, usually with time, of the magnitude of a quantity with respect to a specified reference when the magnitude is alternately greater and smaller than the reference.

Overburden. The generic term applied to uppermost layers of the geologic structure, usually unconsolidated materials having low seismic velocity overlying rock.

P-wave. (See also **Compression** or **Body wave**). Body wave in which the direction of the particle motion is the same as the direction of wave propagation. P-wave velocity is commonly measured in geophysical refraction surveys to define the contact between the competent rock layers (high-velocity materials) and the overlying unconsolidated materials (low-velocity materials).

Particle acceleration. The time rate of change of particle velocity.

Particle displacement. The difference between the initial position of a soil particle and any later position.

Particle velocity. The time rate of change of particle displacement.

Period. The time interval occupied by one cycle.

Permeability. A measure of the ease with which a fluid can pass through the pore spaces of a formation.

Phase. The angle of lag or lead (or the displacement) of a sine wave with respect to a reference; the stage in the course of a rotation or oscillation to which it has advanced, considered in relation to a reference or assumed instant of starting.

Phase response. A graph of phase shift versus frequency illustrates the phase response characteristics of a system. The amplitude-frequency response of a filter to the shape of pulses put through it will be different for different phase characteristics; this response leads to phase distortion.

Phase velocity. The velocity with which any given phase (such as a wave of single frequency) travels; it may differ from **group velocity** because of dispersion.

Plane strain (biaxial). A measure of strain that takes place in two directions while remaining zero in the third dimension.

Plastic range. The stress range in which a material will not fail when subjected to the action of a force, but will not recover completely, so that a permanent deformation results when the force is removed.

Plate tectonics. A theory introduced in 1967 and subsequently refined that considers the earth's crust and upper mantle to be made up of more than 15 relatively undistorted plates about 60 km thick which move relative to one another. The plates spread from the mid-oceanic ridges where, by means of the upflow of magma, new lithospheric material is continually added. On the opposite margins of the plates, there are usually deep submarine trenches. At these trenches, the plates converge from opposite directions (for example, the Nazca and South American plates along the Andes Mountains), and one plate is consumed or subducted beneath the other into the deeper parts of the earth. Earthquake belts or zones mark plate boundaries, the zones along which the lithospheric plates collide, diverge, and slide past one another. The San Andreas fault zone is an example of a boundary between the North American and Pacific plates.

Poisson's ratio. The ratio of the transverse contraction to the longitudinal extension when a rod is stretched. The ratio of the velocities of P- and S-waves, V_p and V_S, can be expressed in terms of Poisson's ratio, σ:

$$\frac{V_p}{V_S} = \frac{2(1-\sigma)}{(1-2\sigma)}.$$

Pore water pressure. Pressure or stress transmitted through the pore water filling the voids of the soil.

Power spectrum. A graph of power spectral density versus frequency. The power spectrum is the square of the amplitude-frequency response.

Principal stress. Stresses acting normal to three mutually perpendicular planes intersecting at a point in a body, on each of which the shearing stresses are zero.

Probability of occurrence. The annual rate of occurrence of a hazard.

Pulse. A waveform whose duration is short compared to the time scale of interest and whose initial and final values are the same (usually zero).

Q. Q, the reciprocal of the specific dissipation function, is an index of the dissipative nature of the earth's transmission path on propagating seismic waves. Q is essentially independent of frequency or wavelength for a wide range of frequencies. Empirically determined values of Q range from 50 to 500 for crustal materials in various regions of the United States. Also called quality factor.

Rayleigh wave. A type of seismic surface wave which propagates along the surface. Particle motion is elliptical and retrograde in the vertical plane containing the direction of propagation, and its amplitude decreases exponentially with depth.

Raypath. A line everywhere perpendicular to wavefronts in isotropic media. The path which a seismic body wave takes.

Reflection. The energy or wave from a seismic source which has been reflected (returned) from an acoustic impedance contrast or series of contrasts within the earth.

Reflection coefficient. The ratio of the amplitude of a reflected wave to that of the incident wave. For normal incidence on an interface which separates media of densities ρ_1 and ρ_2 and velocities V_1 and V_2, the reflection coefficient for a plane wave is:

$$\frac{\rho_2 V_2 - \rho_1 V_1}{\rho_2 V_2 + \rho_1 V_1}.$$

Region. A geographical area surrounding and including the site sufficiently large to contain all the features related to a physical phenomenon or to a particular earthquake hazard.

Relative density. The ratio of (1) the difference between the void ratio of a cohesionless soil in the loosest state and any given void ratio, to (2) the difference between its void ratios in the loosest and in the densest state.

Resonance. The reinforced response of one of the natural modes of vibration of a body when excited at a frequency close to the natural frequency of vibration.

Resonant frequency. A frequency at which resonance occurs.

Response. The motion in a system resulting from an excitation under specified conditions.

Response spectrum. The peak response of a series of simple harmonic oscillators of different natural period when subjected mathematically to a particular earthquake ground motion. The response spectrum may be plotted as a curve on tripartite logarithmic graph paper showing the variation of the peak spectral acceleration, displacement, and velocity of the oscillators as a function of vibration period and damping.

Return period. The average period of time or recurrence interval between events causing ground shaking exceeding a particular level at a site; the reciprocal of annual probability of exceedance. A return period of 475 years means that, on the average, a particular level of ground motion will be exceeded once in 475 years.

Risk. See **Earthquake risk.**

Rock. See **Bedrock.**

Rupture velocity. The velocity at which the fault rupture propagates along its length. The rupture velocity is usually some fraction of the shear wave velocity and in the range 1.5 to 4.5 km/s for most earthquakes. It affects the effective **stress.**

S-wave (Shear wave). Body wave in which the particle motion is at right angles to the direction of wave propagation. **SH** and **SV** denotes planes of polarization of wave. S-wave velocity may be measured by in-hole geophysical procedures to determine the dynamic shear moduli of the materials through which the wave passes.

Safe shutdown earthquake (SSE). A design earthquake used by the U.S. Nuclear Regulatory Commission in nuclear powerplant siting: the largest possible earthquake at the site, considering the regional and local geology and seismology and specified characteristics of local and subsurface material. Important nuclear power plant structures, systems, and components are designed to remain intact during the SSE. See **Operating basis earthquake.**

Saturated soil. Soil with zero air voids. A soil which has its interstices or void space filled with water to the point where runoff occurs.

Seismic source zones. Areas of spatially homogeneous earthquake activity.

Seismic wave. An elastic wave generated by an earthquake or explosion which causes only a temporary displacement of the medium, the recovery of which is accompanied by ground vibrations.

Seismogram. A record of ground motion or of the vibrations of a structure caused by a disturbance, such as an underground nuclear detonation or an earthquake. See **Accelerogram.**

Seismograph. A system for amplifying and recording the signals from seismometers.

Seismometer. The instrument used to transform seismic wave energy into an electrical voltage. Most seismometers are velocity detectors their outputs being proportional to the velocity of the inertial mass with respect to the seismometer's case (which is proportional to the velocity of the earth motion.) Below the natural frequency, the response of most geophones decreases linearly with frequency so that they operate as accelerometers.

Seismotectonic province. A geographic area characterized by similarity of geologic structure and earthquake characteristics.

Sensitivity. The smallest change in a quantity that a detector can detect.

Shear modulus (Rigidity). The ratio between shear stress and shear strain in simple shear.

Shear wave. Equals S-wave equals transverse wave: A body wave in which the particle motion is perpendicular to the direction of propagation.

Shear wave velocity. See **Modulus.**

Simple shear. The state of stress at the point where only shearing stresses act on any two perpendicular planes.

Site vicinity. The geographical region within about 10-km radius of the center of the site.

Snell's law. When a wave crosses a boundary, the wave changes direction such that the sine of the angle of incidence divided by the velocity in the first medium equals the sine of the angle of refraction divided by the velocity in the second medium.

Soft soil. A general description for soil which has a shear wave velocity less than 600 m/s. See **Firm soil, Bedrock.**

Sonic log. A record of the seismic velocity (or of interval time) as a function of depth.

Specific dissipation. See **Q.**

Standard deviation. The standard deviation, σ, of n measurements of a quantity x_i, with respect to the mean, $\bar{X}$, is:

$$\sigma = \left(\frac{1}{N-1} \sum_{i=1}^{N} (X_i - \bar{X})^2 \right)^{1/2}$$

Standing wave. A wave produced by simultaneous transmission in opposite directions of two similar waves. It may result in fixed points of zero amplitudes called nodes.

Station. A ground position at which a geophysical instrument or seismograph is set up for an observation.

Steady-state vibration. Vibration in a system where the velocity of each particle is a continuing periodic quantity.

Stochastic. Random; value determined entirely by chance.

Strain. The change in length per unit of length in a given direction which a body subjected to deformation undergoes.

Strain dependent property. A property exhibited by soil wherein the magnitude of a physical property depends on the magnitude of the induced strain.

Stratigraphy. The order of succession of the different sedimentary rock formations in a region.

Strength of earthquake. In current usage, it is often expressed in terms of the peak ground acceleration recorded or predicted for a particular earthquake, expressed usually in g units, where 1 g is an acceleration equal to that of gravity, or 980 cm/s^2.

Stress drop. $\Delta\sigma = \sigma_0 - \sigma_1$ where σ_0 is the initial stress before the earthquake and σ_1 is the stress after the earthquake. For the 1971 San Fernando, Calif. earthquake, the average initial stress is estimated to have been about 100 bars and the stress drop to have been about 60 bars. Stress drop controls the high-frequency spectral content of earthquake ground motions.

Stress (effective). In modeling an earthquake, the effective stress is defined as $\sigma = \sigma_0 - \sigma_f$ where σ_0 is the stress before the earthquake and σ_f is the frictional stress acting to resist the fault slip.

Strike-slip fault. A fault in which movement is principally horizontal. The San Andreas fault is strike-slip.

Strong motion. Ground motion of sufficient amplitude to be of engineering interest in the evaluation of damage due to earthquakes or nuclear explosions.

Structural features. Features such as faults and folds which are produced in rock by movements after deposition, and commonly after consolidation, of the constituent sediment.

Surface waves. Seismic energy which travels along or near the surface. **Rayleigh** and **Love** waves.

Surface wave magnitude. M_S. See **Magnitude.**

Tectonic province. As defined by the U.S. Nuclear Regulatory Commission, it is a region of the North American continent characterized by the uniformity of the geologic structures contained therein.

Tectonic structure. As defined by the U.S. Nuclear Regulatory Commission, it is a large dislocation or distortion within the earth's crust whose extent is greater than several kilometers.

Tectonics. A branch of geology dealing with the broad architecture of the upper part of the earth's crust in terms of the origin and historical evolution of regional structural or deformational features.

Thrust fault. An inclined fracture along which the rocks above the fracture have apparently moved up with respect to those beneath. The 1964 Alaska and 1971 San Fernando earthquakes occurred on thrust faults.

Time-distance curve. Equals $T-X$ curve: A plot of the arrival time of refracted events against the source-receiver distance.

Time dependent. Describing an operation in which the physical parameters vary with time.

Transfer function. Filter characteristics in the frequency domain as represented by the amplitude-versus-frequency and phase angle-versus-frequency curves. Contains the same information as the impulse response in the time domain and is convertible into the impulse response through the **Fourier transform.**

Transform. To convert information from one form into another, as with the **Fourier transform.**

Transverse wave. See **Shear wave.**

Upper-bound earthquake. The hypothetical earthquake that is considered to be the most severe reasonably possible on the basis of comprehensive studies of historic seismicity and structural geology.

Vibration. An oscillation. The motion of a mechanical system.

Viscoelastic. Having a stress-strain relation that includes terms proportional to both the strain and the rate of strain. Leads to frequency-dependent attenuation for seismic waves. Materials with this property are also called **Voigt solids.**

Viscoelastic medium. A stress-strain relation in which the stress is a function of both strain and strain rate, although not necessarily proportional to both.

Viscosity. The cohesive force between particles of a fluid that causes the fluid to offer resistance to a relative sliding motion between particles; internal fluid friction.

Viscous damping. The dissipation of energy that occurs when a particle in a vibrating system is resisted by a force that has a magnitude proportional to the speed of the particle and a direction opposite to the direction of the particle.

Void ratio. The proportion of void space in a given soil mass.

Voigt solid. See **Viscoelastic.**

Waveform. A plot of voltage, current, seismic displacement, etc., as a function of time.

Wave guide. A geologic situation which permits surface waves.

Wave length. Normal distance between two wave fronts with periodic characteristics and a phase difference of one complete cycle.

Wavelet. A seismic pulse usually consisting of 1½ to 2 cycles.

Wavenumber. The number of wave cycles per unit distance; reciprocal of wavelength.

White noise. Random energy containing all frequency components in equal proportions.

Young's modulus. E. The ratio of unit stress to unit strain within the elastic range of a material under a given loading condition, numerically equal to the slope of the tangent of a stress-strain curve.

PROCEDURES FOR ESTIMATING EARTHQUAKE GROUND MOTIONS

By Walter W. Hays

ABSTRACT

This paper is a comprehensive review of the current procedures used for specifying earthquake ground motion for many applications in the United States. These applications include: siting and design of nuclear powerplants, hospitals, dams, schools, oil pipeline systems, waste storage facilities and military facilities; city and land-use planning; disaster planning; building codes; and evaluation of insurance needs for indemnification of losses from natural hazards. The seismic design problem varies considerably in the United States because of the markedly different seismicity in the east and west. In the Western United States, particularly in California and Nevada, the seismicity is very high. More large- and moderate-sized earthquakes have occurred in these two states than in any other part of the conterminous United States. Tectonic surface ruptures related to historic (0–200 years before present) and Holocene (0–10,000 years before present) earthquakes are common. In addition, the active plate boundary represented by the 1,000-km-long San Andreas fault system makes part of the Western United States very different from other seismically active parts of the country. By contrast, the Central and Southeastern United States have almost none of the characteristics exhibited in the Western United States. Seismicity is low, large- to moderate-sized earthquakes occurred only in 1811, 1812, and 1886, and no evidence of tectonic surface ruptures related to historic or Holocene earthquakes has been found. Also, no currently active plate boundaries of any kind are known there.

Setting the seismic design parameters for a site requires consideration of a large body of geologic, geophysical, seismological, and geotechnical information. For the region surrounding the site, statistical and deterministic models are developed from this information to characterize the geologic province where the earthquake occurs, the earthquake source and wave propagation path, and the local ground response.

Knowledge of the physical parameters that affect the characteristics of ground motion and their range of values has been gained from: observational and instrumental data from earthquakes, nuclear explosions and aftershock sequences, regional seismicity networks, geologic mapping, trenching of fault zones, analytical models, geophysical measurements, and laboratory measurements. Although each source of data has contributed to the knowledge about ground motion, all these data have not been incorporated into earthquake-resistant design procedures. For example, current procedures do not use stress drop or seismic moment. Also, conservatism is introduced in the current procedures because the various physical processes that occur during an earthquake are not completely understood, and statistical distributions for many empirical relations used to estimate earthquake ground motions are not well defined.

Seven basic steps are followed in specifying the characteristics of the ground motion needed for earthquake-resistant design. They are:

1. to determine the seismicity of the geographic region where the application is planned,
2. to identify the seismotectonic features,
3. to estimate the regional seismic attenuation,
4. to estimate the ground shaking parameters (for example, peak acceleration or Modified Mercalli intensity) at the site,
5. to define the ground-motion response spectra for the site,
6. to determine the local amplification effects and to modify the design response spectra for the site as necessary, and
7. to estimate the uncertainty in the ground-motion design values.

Each step requires careful evaluation of the best available data. For some applications, the available data may be inadequate for precise specification of the earthquake ground motion. In these cases, an effort is generally made to use ground motion values that, based on experience and the uncertainty in the data, are considered to be conservative. Examples of conservatism include: using a rare event as the maximum possible earthquake because the location and magnitude of potential earthquakes are uncertain, using upper-bound values for the peak ground acceleration expected at a site because of uncertainties in the regional seismic attenuation function and the local ground response, and using upper-bound values for the design response spectrum because the details of ground-motion spectra can vary widely for a given value of peak ground acceleration or Modified Mercalli intensity. The controversy that exists today in earthquake-resistant design is largely a debate over whether the geologic, geophysical, seismological, and geotechnical data are adequate for the specific design application under consideration and whether the judgments about conservative ground-motion estimates are reasonable.

The ideal data base, which is not yet available for all geographic regions of the United States, should contain the following information for the region surrounding the site:

1. *Seismicity*
   - A complete historical record and location map of all reported earthquakes in the region;
   - Information about the source parameters such as epicenter, focal depth, source mechanism and dimensions, magnitude, stress drop, effective stress, seismic moment, and rupture velocity) of each historic earthquake;
   - Earthquake-recurrence relations for the region and for specific seismic source zones in the region.
2. *Seismotectonic features*
   - Maps showing the seismotectonic provinces and capable faults;
   - Information about the earthquake potential of each seismotectonic province including information about the geometry, amount, sense of movement, and temporal history of each fault and the correlation with historical and instrumental earthquake epicenters;
   - Correlation of historic earthquakes with tectonic models to estimate the upper-bound magnitude (or seismic moment) that should be associated with specific tectonic features.

3. *Seismic attenuation*
   Isoseismal maps of significant historic earthquakes that occurred in the region;
   Strong ground-motion records of historic earthquakes;
   Scaling relations and their statistical distribution for ground-motion parameters as a function of distance.
4. *Characteristics of historic ground shaking*
   Isoseismal maps of all significant historic earthquakes that have affected the site;
   Ensembles of strong ground-motion records of earthquakes that occurred either in the region of interest or in other regions that have similar source-path-site characteristics adequate for "calibrating" the near-field, the regional seismic wave attenuation characteristics, and the local ground response.
5. *Earthquake spectra*
   Ensembles of spectra (Fourier, power spectral density, and response) adequate for "calibrating" the near-field, the transmission path, and the local ground response.
6. *Local amplification effects*
   Seismic-wave transmission characteristics (amplification or damping) of the unconsolidated materials overlying bedrock and their correlation with physical properties, including seismic shear wave velocities, bulk densities, shear moduli, strain levels, water content, and geometry;
   Strong ground motion records at surface and subsurface locations for a wide range of strain levels.

Very limited empirical data exist for the near field of earthquakes. Also, analytical models are presently considered to be inadequate for specifying the details of the ground motion in a manner that is acceptable in current earthquake-resistant design. In the near field, ground-motion parameters are strongly influenced by the dynamics of the fault rupture, a physical process that is not well understood at the present time.

The strong-motion accelerograph network is the source of ground-motion date used in earthquake-resistant design. About 200 of the approximately 500 digitized records currently available are basement or free-field records, principally from the 1971 San Fernando, California earthquake. Only a few records have been obtained in the near field distance range in which earthquakes have caused significant damage. Relatively few records have been obtained at surface and subsurface sites underlain by rock and unconsolidated materials having varied physical characteristics. Also, only accelerograms from small earthquakes have been recorded in the Eastern United States.

Better estimates of earthquake ground motion will require improved data. Regional seismicity and strong-motion accelerograph networks must be expanded in order to obtain adequate data for "calibrating" large regions of the United States in terms of their earthquake source mechanisms, regional seismic attenuation, and local ground response. Better geologic and geophysical data and analyses are needed to define the earthquake potential and upper-bound magnitude in different geographic regions and to establish the dynamics of faulting and recurrence intervals for specific faults. Knowledge about the origin of intraplate earthquakes, which seem to have different causes than the earthquakes that occur along plate boundaries, is needed to assess more accurately the earthquake potential of low-seismicity regions such as the Eastern United States.

INTRODUCTION

This paper is a part of ongoing investigations by the U.S. Geological Survey to better understand the causative mechanisms and physical effects of earthquakes in order to contribute to the reduction of earthquake hazards in the United States. This paper provides a comprehensive summary of current procedures that use geologic, geophysical, seismological, and geotechnical data for estimating ground-motion characteristics of earthquakes for sites of interest in the United States. These procedures are used in many applications, including siting of nuclear power plants (U.S. Atomic Energy Commission, 1971 and 1973 a, b; American Society of Civil Engineers, 1976); construction of hospitals (Veterans Administration, 1973); construction of dams (Peak, 1973); seismic design of oil pipeline systems (Page and others, 1972; Newmark and Hall, 1973); construction of schools (State of California, 1933); construction of military facilities (Department of Army, Navy and Air Force, 1973); city and land-use planning (California Council on Intergovernmental Relations, 1972 and 1973; Woodward-NcNeill and Associates, 1973; Nichols and Buchanan-Banks, 1974); city lifeline engineering (American Society of Civil Engineers, 1974); regional earthquake zonation (Borcherdt, 1975; Espinosa, 1977); earthquake ground shaking hazard maps (Algermissen, 1969; Algermissen and Perkins, 1976); disaster planning (Office of Emergency Preparedness, 1972, Algermissen and others, 1972, 1973; Hopper and others, 1975, Rogers and others, 1976); insurance against natural hazards (Baker, 1971); building codes (Wiggins and Moran, 1971; Applied Technology Council, 1976), and management of hazardous wastes (Healy and others, 1968;Wyss and Molnar, 1972).

A great deal of important research is being performed through the earthquake research programs of the U.S. Geological Survey (USGS) and the National Science Foundation (National Science Foundation and U.S. Geological Survey, 1976; Hamilton, 1978). These programs are complementary and represent a balanced study of six elements: (1) fundamental earthquake studies, (2) earthquake prediction, (3) induced seismicity, (4) earthquake hazards assessment, (5) engineering, and (6) research for utilization. Academic and private-sector workers are involved in these studies along with USGS personnel.

The information contained in this paper is developed for the geologist or engineer who needs to know how to estimate the earthquake ground motion for a site. It represents several scientific disciplines and is a subset of the comprehensive body of knowledge now available. This subset of information provides a framework for a technical understanding of the empirical procedures currently used to estimate ground motion.

Simplifications and generalizations are made to some degree in the paper to enable the geologist or engineer to have a broad understanding of the technical concepts without having to know all of the details.

Extensive references are provided to give additional information when needed. Also, a glossary of of standard nomenclature, terminology, and definitions is provided to aid understanding. Some subjects, such as the causative mechanisms of U.S. earthquakes, are obviously too complex to be covered completely; therefore, only the most important facts related to the problem of estimating earthquake ground-motion are emphasized. Earthquake-resistant design is a dynamic field; therefore, the procedures discussed in this paper should be expected to change as progress in fundamental research is made.[1]

A number of investigators (for example, Barosh, 1969; Lomenick, 1970; Werner, 1970; Shannon and Wilson, Inc., and Agbabian Associates, 1972, 1975; Algermissen, 1973; Hoffman, 1974; Trifunac, 1973b; Hays and others, 1975b; Krinitzsky and Chang, 1975; Werner, 1975, Gates, 1976; Guzman and Jennings, 1976; American Society of Civil Engineers, 1976; and McGuire, 1977a) have published procedures for estimating earthquake ground motions. On the basis of accumulated knowledge and experience in geology, geophysics, seismology, and geotechnical engineering, a general procedure, such as shown in figure 1, provides a reasonable basis for specifying the ground-motion parameters needed for earthquake-resistant design.

Empirical correlations are widely used today in earthquake resistant design. These correlations are frequently based on statistical analysis of the best available data, but, in many cases, they are based on interpreted trends or projected upper bounds in the data. Thus, all the empirical correlations do not have well-defined statistical distributions. The relations most frequently used are:

1. Earthquake recurrence relations (Algermissen, 1969; Algermissen and Perkins, 1976);
2. Magnitude and Modified Mercalli intensity (Gutenberg and Richter, 1942);
3. Peak ground acceleration and Modified Mercalli intensity (Neumann, 1954; Gutenberg and Richter, 1956; Trifunac and Brady, 1975c; O'Brien and others, 1977);
4. Magnitude and length of fault rupture (Bonilla, 1970; Wallace, 1970; Housner, 1970; Mark, 1977);
5. Peak acceleration, distance, and magnitude (Housner, 1965; Schnabel and Seed, 1973; Donovan, 1973; Boore and others, 1978);
6. Modified Mercalli intensity and distance (Nuttli, 1972; Brazee, 1976; Young, 1976);
7. Duration of shaking and magnitude (Housner, 1965; Page and others, 1972; Bolt, 1973; Trifunac and Westermo, 1977);
8. Peak velocity and distance (Esteva and Rosenblueth, 1964; Seed, Murarka, Lysmer, and Idriss, 1976);
9. Site-independent response spectra (Housner, 1959; Newmark and Hall, 1969; U.S. Atomic Energy Commission, 1973; N. M. Newmark Consulting Engineering Services, 1973; and J. A. Blume and Associates, Engineers, 1973);
10. Site-dependent response spectra (Seed, Ugas, and Lysmer, 1976).

Deterministic models have been developed by a number of investigators (for example, Brune, 1970; Schnabel, Lysmer and Seed, 1972) to simulate numerically the various physical processes that occur in an earthquake. With the exception of the local ground-response models, deterministic models generally have not been adopted in current earthquake-resistant design.

Probabilistic methods have recently emerged as a useful way to estimate ground motion. It will take a number of years, however, to evaluate their full range of usefulness and to incorporate them into earthquake-resistant design.

The steps in a general procedure for estimating earthquake ground motion for earthquake-resistant design are discussed below.

DETERMINE SEISMICITY

The objective of this step is to use the historic seismicity record to define earthquake recurrence relations applicable for the region of interest, to provide a basis for correlating earthquake epicenters and tectonic structure, and to define seismic source zones. From the seismicity record, one attempts to establish:

1. The date of occurrence of each past event;
2. Epicentral intensity and, for post-1933 events, magnitude;
3. Epicenter and hypocenter locations;
4. Epicentral maps showing the epicenters of all reported earthquakes centered within an 80-km radius of the site and all earthquakes with Modified Mercalli intensity greater than or equal to V within a 320-km radius;
5. The aftershock zone of historic earthquakes;
6. Correlation of epicenter locations and tectonic structure;
7. The frequency of occurrence for earthquakes of various magnitudes or epicentral intensities.

Evaluation of the seismicity of a region requires the

[1]Note added in press. The October 15, 1979, Imperial Valley, Calif., earthquake is an example of a significant opportunity to increase our knowledge. This M_L 6.6 earthquake was well recorded, especially near the fault, and will provide a basis for improving present procedures used in earthquake-resistant design.

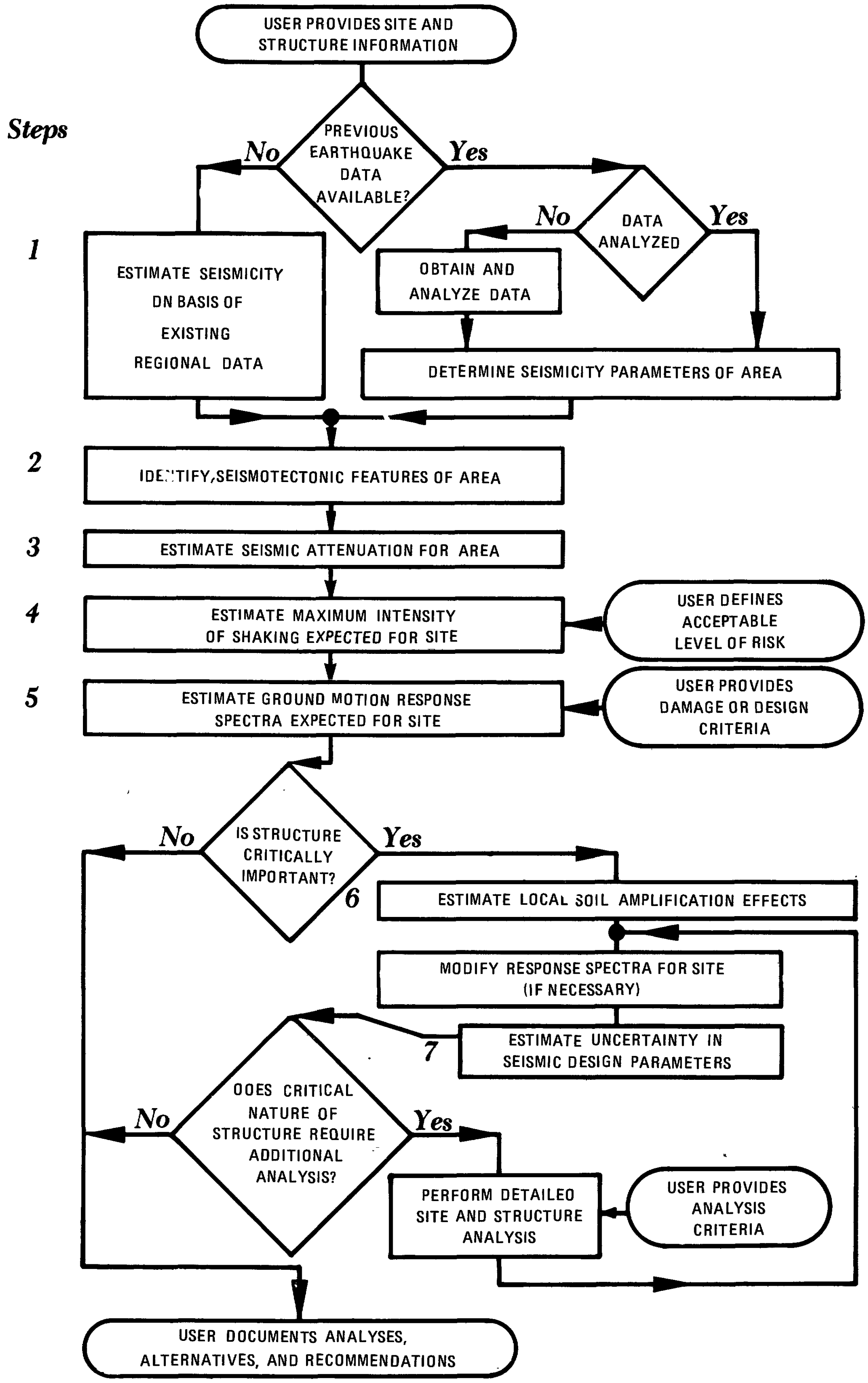


FIGURE 1.—Steps in estimating ground motion for design of earthquake-resistant structures.

compilation and evaluation of an earthquake catalog (Stepp, 1972; Gardner and Knopoff, 1974; Kagen and Knopoff, 1976). This task is complex because the design application (for example, a dam, hospital, or nuclear power plant) under consideration may require a fairly precise specification of the frequency of occurrence of large earthquakes on a local scale whereas the catalogs of instrumentally recorded earthquakes and felt earthquakes generally do not cover a time interval long enough to allow valid extrapolations of future earthquake activity except on a broad regional scale.

It has been clearly demonstrated by Evernden (1970) and others that the earthquake recurrence law follows the empirical linear relation

$$\log N(M) = a - bM ,$$

where $N(M)$ is the number of earthquakes occurring within a region in a given time period with a magnitude greater than or equal to M. The constants a and b are determined from least squares analysis. The seismicity index a is dependent upon the size of the geographic area, the level of activity, and the length of the time period considered. The seismic severity index b is usually in the range -0.8 to -1.0 for most parts of the world and appears to be related to the nature of the tectonic activity causing the earthquakes. A similar empirical linear relation holds for Modified Mercalli intensity.

SOURCES OF INFORMATION

There are numerous sources of seismicity data. The most complete single source of seismicity data is *Earthquake History of the United States* (Coffman and Von Hake, 1973) which is published by NOAA (National Oceanic and Atmospheric Administration). In addition, detailed information is given in the annual publication, *U.S. Earthquakes,* formerly published by U.S. Department of Commerce but now published jointly by NOAA and USGS. This publication contains reproductions of important accelerograms, isoseismal maps, and other important data.

A catalog of some 6,000 U.S. earthquakes is contained in Hays and others (1975b). This catalog includes earthquakes through 1970 that have been assigned Modified Mercalli intensities of IV or greater. Information about the seismicity in individual states is usually available through the State Survey or a state university. For example, information on the seismicity of Nevada can be obtained from the University of Nevada, Reno, and from publications such as Rogers, Perkins, and McKeown (1976) and Ryall (1977). Information on the seismicity of Utah is available from the University of Utah at Salt Lake City. Townley and Allen (1939) cataloged preinstrumental data in California, whereas information on the instrumental seismicity of California can be obtained from California Institute of Technology's Seismological Laboratory, University of California, Berkeley's Seismic Station, and the California Division of Mines and Geology. Information on Alaska's seismicity is contained in the publication by Meyers (1976). Recently, an earthquake information center was established at Memphis State University, Tennessee.

The seismicity of the Eastern United States has been discussed by several investigators (for example, McClain and Meyers, 1970; Bollinger, 1972, 1973; Chinnery and Rogers, 1973; Sbar and Sykes, 1973; Hadley and Devine, 1974; Nuttli, 1974; Long, 1974; Young, 1976, and McGuire, 1977b).

The *Bulletin of the Seismological Society of America* contains data about recent earthquakes in the "Seismological Notes" of each issue.

Current data are frequently available through the National Earthquake Information Service, USGS, Golden, Colo. (for example, Stover and others, 1976).

The earthquake history of the United States will be discussed below to illustrate the problem of seismicity on a national scale. Regional earthquake recurrence relations, "b values," upper-bound magnitudes, and seismic source zones can be readily compared on this scale.

SUMMARY OF UNITED STATES EARTHQUAKE HISTORY

Although the zone of greatest seismicity in the United States is along the Pacific Coast in Alaska and in California, the central and eastern parts of the United States have also experienced seismic activity (fig. 2). Earthquakes have occurred in the St. Lawrence River region on many occasions from 1650 to 1928, in the Boston vicinity in 1755, in the central Mississippi Valley at New Madrid, Mo., in 1811–1812, in Charleston, S.C., in 1886, and at Hebgen Lake, Mont., in 1959.

Historical earthquakes that have caused notable damage and loss of life are listed in table 1. Property damage in the United States due to earthquakes occurring since 1865 approaches $2 billion. The loss of life in the United States has been relatively light, considering the number of destructive earthquakes that have occurred. Since 1964, the United States has experienced one great earthquake (the 1964 Alaska earthquake). The Alaska earthquake had a magnitude of 8.4 and caused $500 million in property damage, 131 deaths, and hundreds of injuries. The San Fernando earthquake had a magnitude of 6.6. It released about one-thousandth as much energy as the Alaska earthquake, but it caused the same amount of property

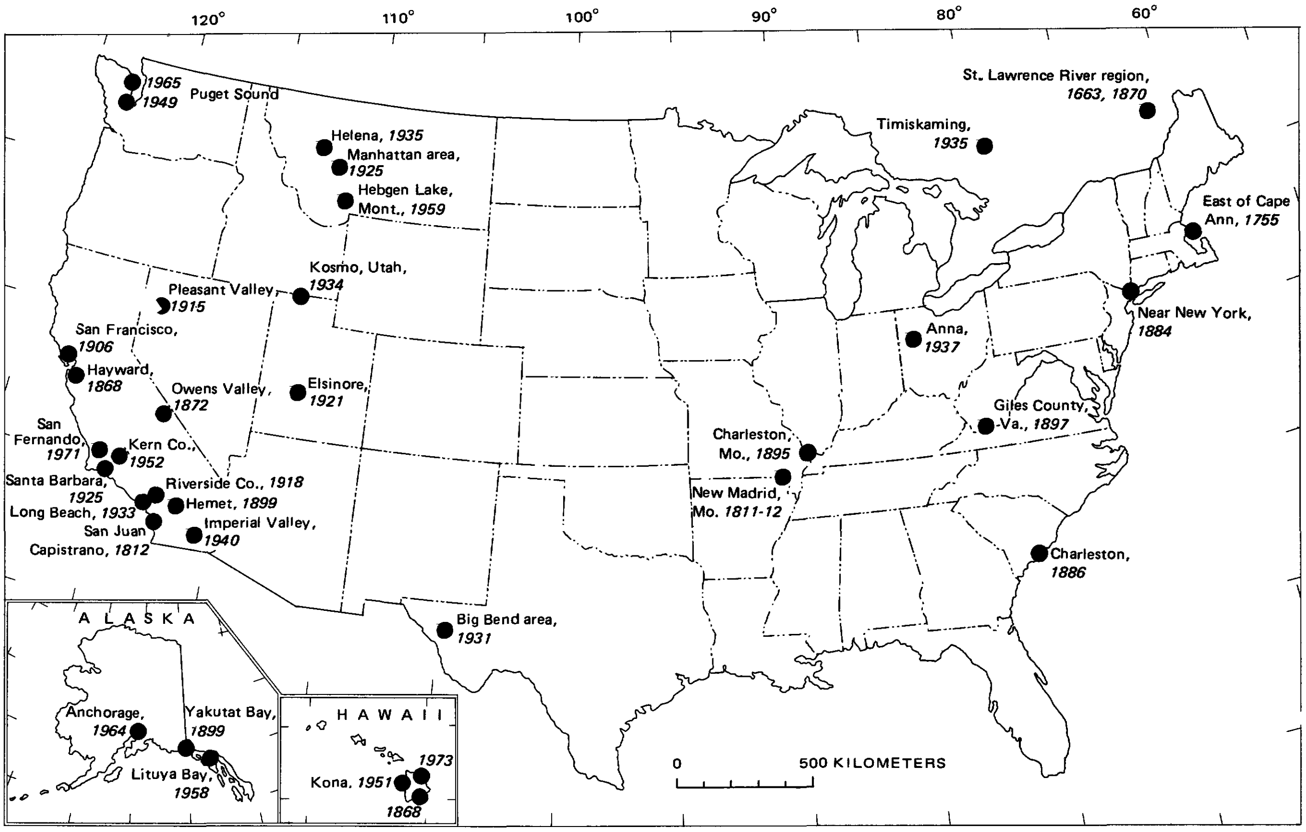


FIGURE 2.—Location of past destructive earthquakes in the United States.

TABLE 1.—*Property damage and lives lost in notable United States earthquakes*

[From Office of Emergency Preparedness, v. 3 (1972), p. 80–82]

Year	Locality	Magnitude	Damage (million dollars)	Lives lost
1811–12	New Madrid, Mo.	7.5 (est.)	----	----
1865	San Francisco, Calif.	8.3 (est.)	0.4	----
1868	Hayward, Calif.	----	.4	30
1872	Owens Valley, Calif.	8.3 (est.)	.3	27
1886	Charleston, S.C.	----	23.0	60
1892	Vacaville, Calif.	----	.2	----
1898	Mare Island, Calif.	----	1.4	----
1906	San Francisco, Calif.	8.3 (est.)	500.0	700
1915	Imperial Valley, Calif.	----	6.0	6
1925	Santa Barbara, Calif.	----	8.0	13
1933	Long Beach, Calif.	6.3	40.0	115
1935	Helena, Mont.	6.0	4.0	4
1940	Imperial Valley, Calif.	7.0	6.0	9
1946	Hawaii (tsunami)	----	25.0	173
1949	Puget Sound, Wash.	7.1	25.0	8
1952	Kern County, Calif.	7.7	60.0	8
1954	Eureka, Calif.	----	2.1	1
1954	Wilkes-Barre, Pa.	----	1.0	----
1955	Oakland, Calif.	----	1.0	1
1957	Hawaii (tsunami)	----	3.0	----
1957	San Francisco, Calif.	5.3	1.0	----
1958	Khantaak Island and Lituya Bay, Alaska	----	----	5
1959	Hebgen Lake, Mont.	----	11.0	28
1960	Hilo, Hawaii (tsunami)	----	25.0	61
1964	Prince William Sound, Alaska	8.4	500.0	131
1965	Puget Sound, Wash.	----	12.5	7
1971	San Fernando, Calif.	6.6	553.0	65

damage and half as many deaths because the San Fernando earthquake occurred on the edge of a large metropolitan area, whereas the Alaska earthquake occurred in a sparsely populated region.

One indication of the seriousness of the earthquake problem in the United States is the fact that earthquakes were felt in 34 states in 1973. All or parts of 39 states lie in regions classified as having major and moderate seismic risk. Within these 39 states, more than 70 million people are exposed to earthquake hazards.

The focal depths of earthquakes vary widely throughout the United States. Earthquakes in California occur at relatively shallow depths, ($\leq$16 km), whereas large earthquakes in the Puget Sound, Washington, area occur primarily at depths of 50–60 km. Earlier, scientists thought that earthquakes in the central United States (for example, New Madrid area) occurred at depths of 50–60 km, but recent studies have shown that they occur at depths of 5–20 km. A shallow depth of 5–10 km is also indicated for earthquakes in the Charleston, S.C. area.

The historical seismicity record in the United States is not more than 400 years long and quite variable regionally. Earthquake recurrence relations have been derived from this relatively short record. (Algermissen, 1969). Figure 3 shows the regions studied by Algermissen in 1969 to determine earthquake recurrence relations, expressing the number of earthquakes, N, occurring in a given region in a given time period with intensity greater than or equal to Modified Mercalli intensity I. These recurrence relations are summarized in table 2. These data, integrated with Alaska seismicity data, provide the relative ranking of regional seismicity shown in table 3.

In 1976, Algermissen and Perkins defined 71 regions (fig. 4) within the conterminus United States as seismic source zones. Each zone was defined on the basis of the historic seismicity and the distribution and activity of faults. Table 4 lists the seismicity parameters de-

TABLE 2.—*Summary of earthquake recurrence relations in the United States*
[From Algermissen (1969), fig. 3. N, number of earthquakes of intensity I]

Area: Nos. from fig. 3	Area: States	Recurrence relation	Earthquakes/100 yrs/100,000 km² for Modified Mercalli intensity: V	VI	VII	VIII
1	California	$\log N=3.92-0.54\,I$	300	84.6	23.8	6.72
2	Nevada	$\log N=3.98-0.56\,I$	------	------	------	------
3	Puget Sound, Wash	$\log N=3.45-0.62\,I$	68.0	16.3	3.92	.94
4	Montana, Idaho, Utah, Arizona (Intermountain Seismic Belt)	$\log N=3.41-0.56\,I$	64.4	17.7	4.99	1.35
5	Wyoming, Colorado, New Mexico	$\log N=3.66-0.68\,I$	32.8	6.85	1.42	.31
6	Oklahoma, North Texas	$\log N=2.10-0.55\,I$	13.3	3.73	1.07	.30
7	Nebraska, Kansas, Oklahoma	$\log N=1.99-0.49\,I$	13.0	4.20	1.35	.45
8A, B	Mississippi and St. Lawrence Valleys	$\log N=2.71-0.5\,I$	24.2	7.65	2.42	.76
9	East Coast	$\log N=3.02-0.58\,I$	12.8	3.39	.88	.23

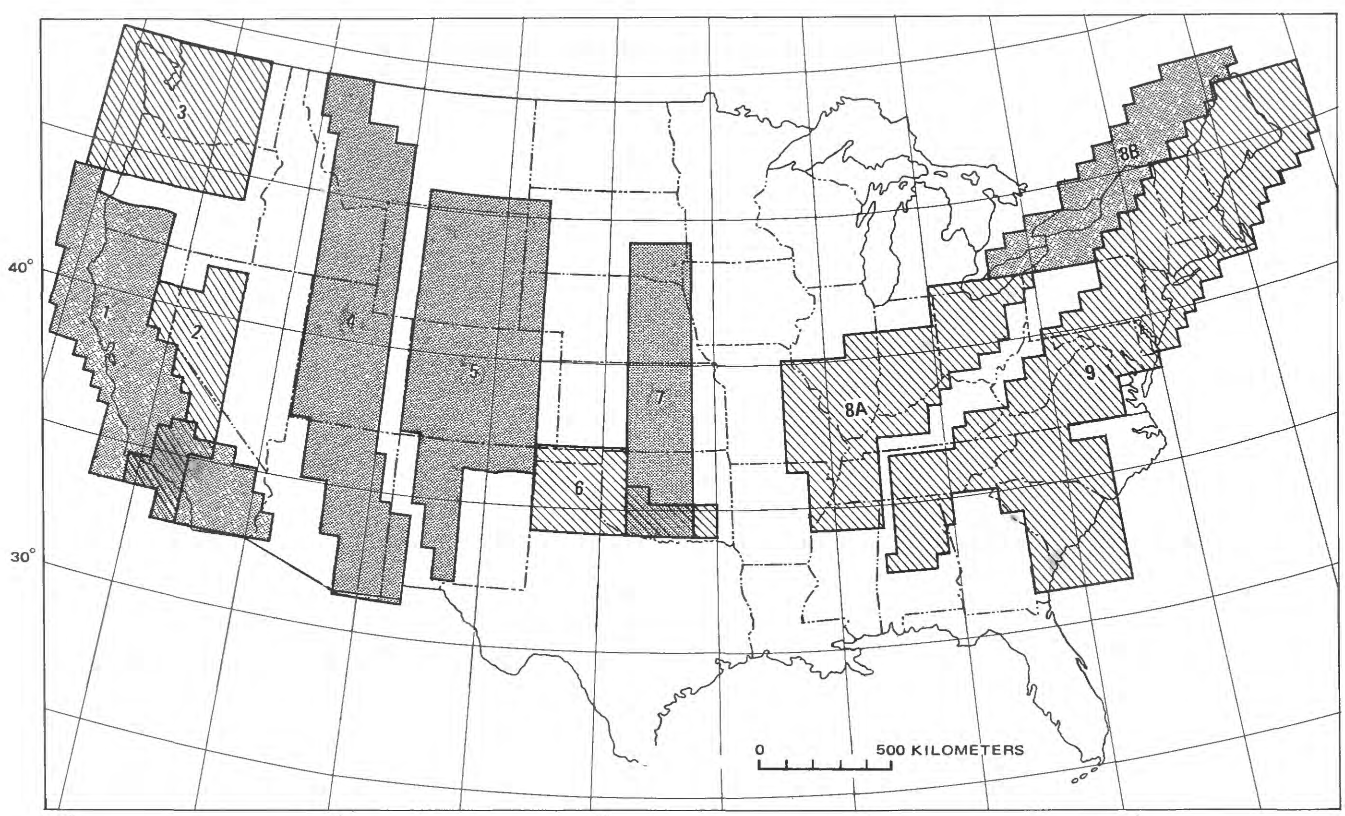


FIGURE 3.—Geographic areas of the conterminous United States where regional seismicity studies have been made (modified from Algermissen, 1969). Numbered areas are described in table 2. Shading depicts boundaries of regions.

TABLE 3.—*Relative seismicity of regions of the United States*

Area	Equivalent magnitude-4 earthquakes/year/ 1,000 km^2	Normalized to Pacific West
S.E. Alaska (lat 54°–63° N.) (long 144°–156° W.)	15	75
Pacific West (west of long 114° W.)	.20	1.0
Rocky Mountains (long 106°–114° W.)	.04	.20
Central Plains (long 92°–106° W.)	.006	.03
Eastern United States (east of long 92° W.)	.017	.08

termined for each source zone. On the basis of current knowledge, future earthquakes are considered equally likely to occur anywhere in a source zone.

Estimating the upper-bound magnitude for various geographic regions of the United States is a difficult problem (Smith, 1976). The nature of the problem varies for different areas, as discussed below, and its solution depends upon comprehensive studies of the available geologic and seismological data:

1. *Area of high seismicity, several major shocks, and a fairly long (>100 years) historical record of earthquakes.*—The number of major (M>8) shocks may be insufficient to obtain a reliable average rate of occurrence, but the average rate of occurrence can probably be estimated reasonably well from a plot of log $N=a-bM$. California and Alaska are examples of such an area.
2. *Area of high seismicity, some moderate shocks, no known major shocks, fairly long (>100 years) historical record of earthquakes.*—The crustal rocks may not be able to support high levels of strain and thus strain accumulation is relieved through moderate magnitude (6–7) shocks. The rate of occurence of moderate and small shocks can probably be estimated accurately from the historic record. Unless geologic evidence indicates the possibility of large shocks, it is probably justified to assume that no large shocks will occur. The Puget Sound area and the Intermountain

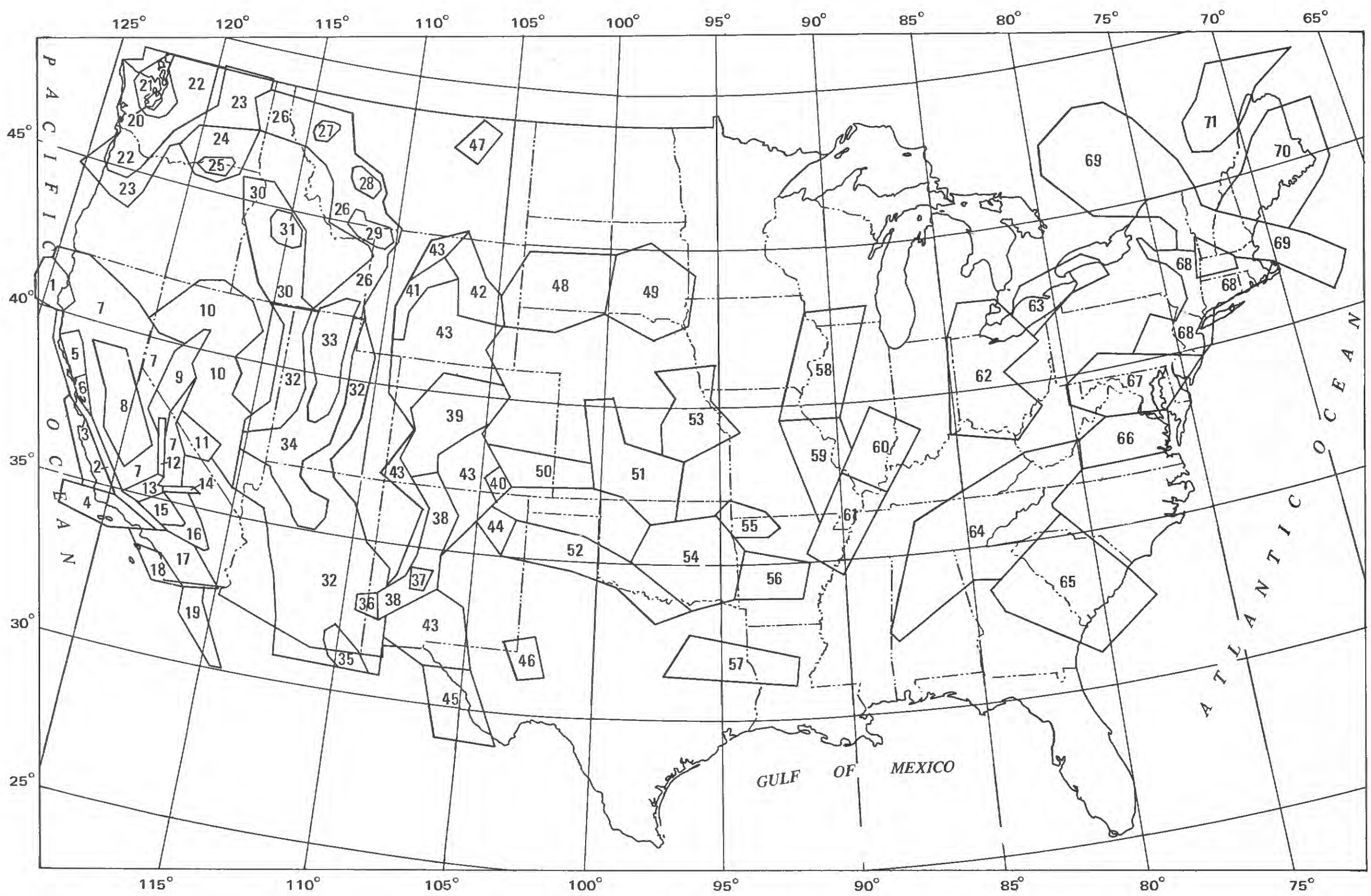


FIGURE 4.—Seismic source zones within the conterminous United States (from Algermissen and Perkins, 1976). Zone numbers correspond to those in table 4.

TABLE 4.—*Seismicity parameters for seismic source zones*

[Zone numbers shown in fig. 4]

Zone No.	Number of Modified Mercalli maximum intensity V's/100 yrs	Seismic severity index b	Maximum intensity	Corresponding maximum magnitude
1	245.2	−0.50	X	7.3
2	110.0	−.40 up to IX then zero	XII	8.5
3	27.2	−.45	XI	7.9
4	75.1	−.45	XI	7.9
5	14.9	−.50	X	7.3
6	44.4	−.45	XI	7.9
7	299.6	−.53	VIII	6.1
8	7.3	−.49	VI	4.9
9	208.0	−.40	XI	7.9
10	125.0	−.51	VIII	6.1
11	80.1	−.53	VIII	6.1
12	43.0	−.43 up to XI then zero	XII	8.5
13	99.4	−.45	XI	7.9
14	34.9	−.45	XI	7.9
15	0.0	−.53	VIII	6.1
16	33.9	−.50	X	7.3
17	223.0	−.45	XI	7.9
18	2.8	−.50	X	7.3
19	613.6	−.52	X	7.3
20	14.8	−.29	VIII	7.1
21	79.8	−.59	VII	5.5
22	80.1	−.76	VI	4.9
23	12.7	Not applicable	V	4.3
24	6.0	do	V	4.3
25	8.5	−.59	VII	5.5
26	137.1	−.72	VI	4.9
27	99.9	−.67	VII	5.5
28	35.3	−.32	IX	6.7
29	90.4	−.36	X	7.3
30	10.5	−.26	VII	5.5
31	84.6	−.63	VII	5.5
32	17.0	−.56	VI	4.9
33	126.8	−.56	IX	6.7
34	71.0	−.56	VII	5.5
35	23.0	−.56	VIII	6.1
36	15.3	−.54	VII	5.5
37	15.6	−.31	VIII	6.1
38	31.1	−.54	VII	5.5
39	21.5	−.54	VII	5.5
40	2.7	−.40	VI	4.9
41	27.6	Not applicable	V	4.9
42	11.1	−.40	VI	4.9
43	23.0	Not applicable	V	4.3
44	13.8	do	V	4.3
45	6.7	−.31	VIII	6.1
46	2.7	−.40	VI	4.9
47	2.7	−.40	VI	4.9
48	14.7	−.54	VII	5.5
49	10.3	Not applicable	V	4.3
50	4.6	do	V	4.3
51	7.4	−.53	VI	4.9
52	13.0	−.40	VI	4.9
53	9.3	−.24	VIII	6.1
54	21.2	−.55	VII	5.5
55	1.7	Not applicable	V	4.3
56	5.7	−.53	VI	4.9
57	7.8	−.55	VII	5.5
58	.6	−.50	VII	5.5
59	16.0	−.50	VIII	6.1
60	16.0	−.50	VIII	6.1
61	84.5	−.50	X	7.3
62	22.0	−.50	VIII	6.1
63	22.1	−.64	VIII	6.1
64	54.4	−.59	VIII	6.1
65	19.9	−.33	X	7.3
66	13.0	−.59	VIII	6.1
67	7.8	−.59	VII	5.5
68	69.1	−.67	VIII	6.1
69	117.6	−.59	IX	6.7
70	33.5	−.65	VIII	6.1
71	21.7	−.49	X	7.3

Seismic Belt are examples of this type of area.

3. *Area of moderate seismicity and occasional or single occurrence of a moderate or large shock.*—Unless the seismic history is long, it is difficult to estimate the rate of occurrence of moderate or major shocks in such an area with high reliability. The lower Mississippi Valley is an example of this type of area.
4. *Area of low seismicity with no known moderate shocks.*—Unless geologic information is available, no reliable method for estimating future seismicity is presently available for these areas. Special studies utilizing temporary seismograph stations to investigate the occurrence of microearthquakes may provide important research information, but the relation between the level of microearthquake activity and the occurrence of large (or even intermediate) earthquakes is not clear. The Atlantic and Gulf Coastal Plains geologic provinces are examples of this type of area.

Probably the most useful data for estimating the upper-bound magnitude in a region and recurrence rates of moderate to large earthquakes are the lengths of rupture in recent and prehistoric faulting. Length of rupture seems to be closely related to the magnitude of the earthquake (Wallace, 1970; Bonilla, 1970; Mark, 1977). Also, dating of the times of occurrence and the time intervals between fault ruptures is useful for establishing recurrence rates. Present data are inadequate to resolve all the questions that have now arisen about the upper-bound magnitude for most regions of the United States.

IDENTIFY SEISMOTECTONIC FEATURES

The location and characteristics of faults and other tectonic structures in the region surrounding the site are essential information along with the historical seismicity for estimating the upper-bound magnitude and the locations of potential earthquakes. An analysis of faulting and tectonic activity in a region can be complex and time consuming, requiring data from three sources: (1) geologic data on faults and the ages of rock formations they displace, (2) seismological data on the areal distribution of seismicity in relation to known faults and tectonic structures, and (3) historical accounts which provide evidence that a fault has ruptured at the surface or that earthquakes might reasonably be associated with a particular fault.

Faults that are active, such as the San Andreas and Hayward faults in California, usually exhibit clear geologic, seismological, and historical evidence of recent and recurrent fault movement. In many cases, however, the information is not definitive and the fault tends to fall in the borderline category between active and inactive. Specific criteria (Cluff and others, 1972) for recognizing an active fault are given in table 5.

One rationale for classifying fault activity (table 6) uses the available geologic, seismological, and historical data to specify four fault-activity classifications: active, potentially active, activity uncertain, and inactive. To quantify fault activity requires researching the scientific literature concerning specific faults, the instrumentally recorded seismicity of the region, and historical accounts of past earthquakes and their aftershock sequence. The dimensions of fault rupture can often be estimated from the distribution of aftershocks. Trenching may also be required. Data and maps may be obtained from many sources, including the United States Geological survey, state geological surveys, local universities, and private consulting firms.

Faults are considered to be significant if they fall into one of the following categories: (1) faults crossing the site that are capable of rupturing during the life of the engineered structure, and (2) faults located either near the site or some distance from the site that are capable of generating large damaging earthquakes.

Specification of faulting potential in the vicinity of the site is of particular importance, but subject to controversy. The fault is defined as a fracture along which differential slippage of adjacent earth materials has occurred. Surface faulting is differential ground displacement at or near the surface caused directly by

TABLE 5.—*Criteria for recognizing an active fault*

[from Cluff and others (1972)]

Data source	Specific criteria
Geologic	Active fault indicated by young geomorphic features such as: fault scarps, triangular facets, fault rifts, fault slice ridges, shutter ridges, offset streams, enclosed depressions, fault valleys, fault troughs, sidehill ridges, fault saddles; ground features such as: open fissures, mole tracks and furrows, rejuvenated streams, folding or warping of young deposits, ramps, ground-water barriers in recent alluvium, echelon faults in alluvium, and fault paths on young surfaces. Usually a combination of these features is generated by fault movements at the surface. Erosional features are not indicative of active faults, but they may be associated with some active faults. Stratigraphic offset of Quaternary deposits by faulting is indicative of an active fault.
Seismological	Earthquakes and microearthquakes, when well located instrumentally, may indicate an active fault. Absence of known earthquakes, however, does not ensure that a fault is inactive.
Historical	Historical manuscripts, news accounts, personal diaries, and books may describe past earthquakes, surface faulting, landsliding, fissuring or other related phenomena. Usually for a large earthquake, there will be several accounts in the historical record. Evidence of fault creep or geodetic movements may be indicated.

fault movement. Current criteria suggest that a fault should be considered capable of permanent surface displacement if it is characterized by one or more of the following:

1. Movement at or near the ground surface occurred at least once during the past 35,000 years or more than once during the past 500,000 years.
2. Instrumentally determined seismicity is directly related to the fault.
3. A relation to another active fault exists such that movement on one active fault can be reasonably expected to be accompanied by movement on the other active fault.

The controversy arises from the current lack of understanding of the geologic processes that lead to the accumulation of strain and the sudden fracture of rocks in the earth's crust. Also, in seismically quiet regions like the Eastern United States, no seismic source zones can be identified with historic surface faulting.

Cluff and others (1972), Krinitzsky (1975), American Nuclear Society (1975), and Slemmons and McKinney (1977) have published information and guidelines to aid in the evaluation of faults. The key factors in the assessment of a fault's potential for producing an earthquake are:

1. fault length,
2. magnitude and nature of displacement,
3. geologic history of displacements, especially the age of latest movements, and
4. the relation of the fault to regional tectonic features.

An example will illustrate the procedure for evaluating fault activity. Figure 5 depicts the principal faults in the San Francisco Bay region in the vicinity of the city of Fremont, Calif. Because of their location, the Hayward, Mission, Silver Creek, and Chabot faults have the potential for producing significant ground motions at the Fremont site. The San Andreas fault, despite being a greater distance away, is also important because it is capable of producing very large earthquakes. Table 7 illustrates the evaluation.

Housner (1970) developed an empirical relation for correlating fault rupture length and earthquake magnitude (fig. 6). The rupture lengths for the San Andreas, Hayward, and Calaveras faults are plotted on the figure as a guide. The relation shows that (1) faults with rupture lengths of 32–40 km generally produce magnitude 5 to 7 earthquakes, (2) faults with rupture lengths of 40–113 km generally produce magnitude 7 to 7.5 earthquakes, and (3) faults with rupture lengths of 300 km or more generally produce earthquakes of magnitude 8 or greater. Exceptions to the general trend occur, for example, some magnitude-8 earth-

TABLE 6.—*Classification of fault activity*

[From Cluff and others (1972)]

	Active	Potentially active	Uncertain activity	Inactive
Historical	Surface faulting and associated strong earthquakes. Tectonic fault creep or geodetic indications of movement.	No reliable report of historic surface faulting.		No historic activity.
Geologic	Generally young deposits have been displaced or cut by faulting. Fresh geomorphic features characteristic of active fault zones present along fault trace. Physical ground-water barriers in geologically young deposits.	Geomorphic features characteristic of active fault zones subdued, eroded, and discontinuous. Faults are not known to cut or displace the most recent alluvial deposits, but may be found in older alluvial deposits. Water barrier may be found in older materials. Geologic setting in which the geomorphic relation to active or potentially active faults suggests similar levels of activity.	Available information does not satisfy enough criteria to establish fault activity. If the fault is near the site, additional studies are necessary.	Geomorphic features characteristic of active fault zones are not present, and geologic evidence is available to indicate that the fault has not moved in the recent past.
Seismological	Earthquake epicenters are assigned to individual faults with a high degree of confidence.	Alinement of some earthquake epicenters along fault trace, but locations have a low degree of confidence.		Not recognized as a source of earthquakes.

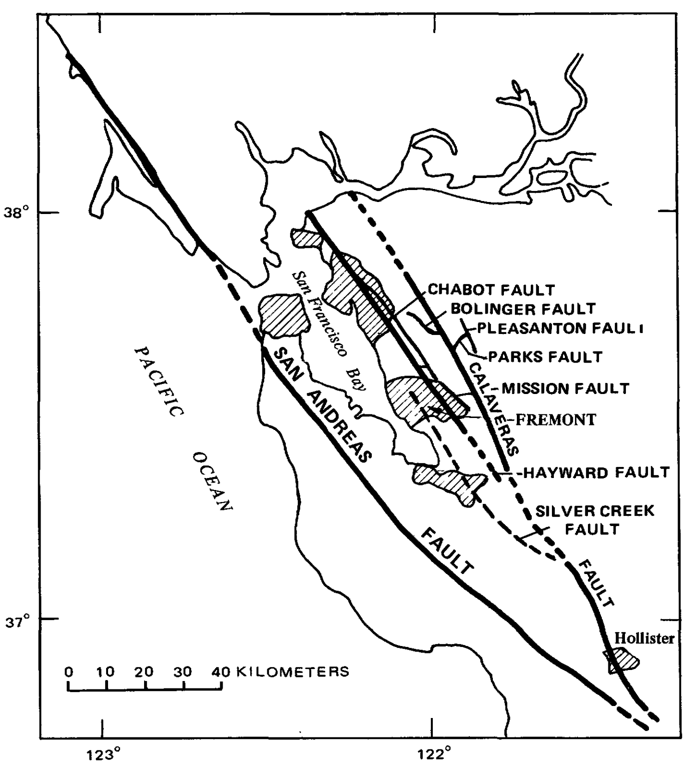


FIGURE 5.—Principal faults in the vicinity of Fremont, Calif. (modified from Cluff and others, 1972).

TABLE 7.—*Classification of selected faults relative to Fremont, Calif.*

[From Cluff and others, (1972)]

Fault	Classification of activity	Criteria
Hayward	Active	Historical faulting.
Mission	Potentially active	Geologic setting and microearthquake epicenters.
Silver Creek	Tentatively active	No geomorphic features, no ground water barrier, no earthquake epicenters.
Chabot	Potentially active	Geologic setting.
Calaveras	Active	Geomorphic features, historical faulting, and strong earthquakes.
Pleasanton	Active	Documented tectonic fault creep.
Bolinger	Potentially active near junction with Calaveras. Tentatively inactive away from Calaveras junction.	Geologic setting, no characteristic geomorphic features.
Parks	Potentially active	Ground-water barrier in Tertiary-Quaternary gravels.
San Andreas	Active	Geomorphic features, historic faulting, and strong earthquakes.

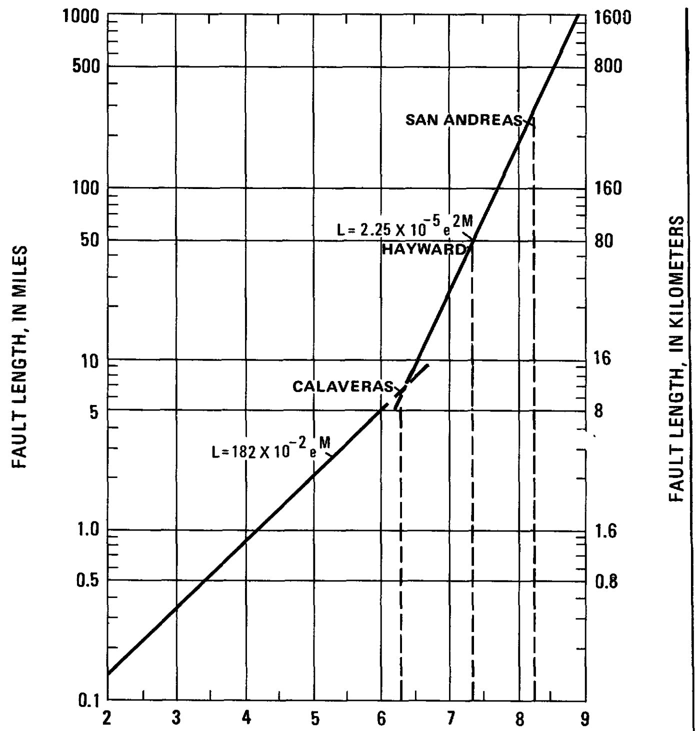


FIGURE 6.—Empirical relationship of fault rupture length and earthquake magnitude (modified from Housner, 1970).

quakes have had fault rupture lengths that are less than 300 km long. Housner did not specify the statistical distribution for his empirical relation. Mark (1977), however, showed that σ = 0.93 for the least squares fit to the magnitude and fault rupture length relation, and he argued that this relation is more physically meaningful than fault rupture length as a function of magnitude.

SUMMARY OF UNITED STATES EARTHQUAKES

The exact mechanisms that produce tectonic earthquakes in various parts of the United States are still in doubt. The most extensively favored theory is that tectonic earthquakes are caused by slip along geologic faults. The correlation of earthquakes with fault slip is clear in the Western United States, but it is not very clear in the Central and Eastern United States. The seismicity patterns of the Western and Eastern United States are quite different, and the causative mechanisms are not well understood at the present time.

A number of physical factors are different in the Eastern and Western United States and may be the cause, in part at least, of the difference in seismicity. The area east of the Rocky Mountains is generally characterized by low heat flow, a thick crust in which east-northeast compressive stress is typical, and Cenozoic epeirogenic uplift. The area west of the Rockies is characterized by high heat flow, a thin crust, and extensive late Cenozoic volcanism. The attenuation of seismic waves is also appreciably lower east of the Rocky Mountains than it is to the west (Nuttli, 1973a, b; Nuttli and Zollweg, 1974), suggesting a distinctly different crustal structure. The basic premise is that basement structures and crustal blocks are adjusting to epeirogenic forces and continued movements along old fracture lines developed at different times in the geologic past to produce the present seismicity.

WESTERN UNITED STATES

The complex tectonic pattern of eastern and south-central Alaska is created by the interaction of the Pacific and North American plates (Packer and others, 1975). Interaction between two crustal plates either creates, destroys, or preserves crustal material. Crust is created at oceanic ridges, destroyed at trenches and collision-type mountain belts, and preserved along transform and strike-slip faults. Because of the present plate interaction in Alaska, two types of boundaries occur (fig. 7). An active subduction zone, which extends

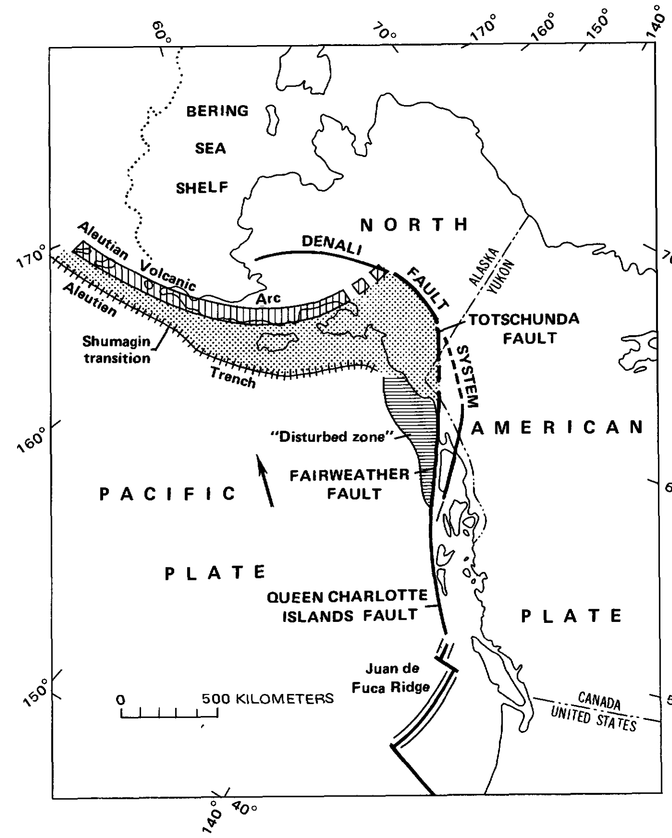


FIGURE 7.—Major tectonic features along the Pacific-North American plate boundary in Alaska (modified from Packer and others, 1975).

from the Aleutian Islands to the vicinity of Mount McKinley, is defined by a line of volcanoes and a Benioff zone (Davies and Berg, 1973). In the east, a topographic trench is defined in the Gulf of Alaska.

The eastern boundary of the subduction zone is a series of faults that roughly define a transform fault system. This system is believed to be a westward extension of the Queen Charlotte Islands fault (Tobin and Sykes, 1968). The exact characteristics of the faults that connect the Alaska subduction zone with the Queen Charlotte Islands transform fault are poorly defined and are still a major unsolved problem.

The geology and seismicity of Alaska are complex and still not well known in many areas. For this reason, many hypotheses (for example, Plafker, 1965, 1967; Grantz, 1966; Gedney, 1970; Page, 1972; Van Wormer and others, 1974; Brogan and others, 1975) have been proposed to explain the origin of Alaska and its tectonic development and seismicity (fig. 8). At least 24 active faults have been identified in Alaska (Brogan and others, 1975). The dominant fault in the southen area is the Denali fault system (fig. 9). This system consists of relatively straight, right-slip segments that combine to create a 2,200-km-long arcuate fault that curves 30° and extends from Chatham Strait to Bristol Bay. The fault system is generally considered to be an extension of the Queen Charlotte Islands transform fault. Estimates of total right-lateral displacement on the Denali fault range from 80 to 250 km.

Evaluation of the seismicity of California and Nevada shows that fault slips are the causative mechanism (Allen and others, 1965; Albee and Smith, 1966; Ryall and others, 1966; Bonilla, 1967, 1970; Wallace, 1970; Allen, 1975). Seismicity data show that the earthquakes occur primarily at relatively shallow depths (≤16 km) in the crust. Tectonic surface ruptures related to historic (0–300 years before the present) and Holocene (0–10,000 years before the present) earthquakes are common.

The well-known San Andreas fault (fig. 10) is a transform fault zone, or system; it is the boundary between the Pacific and North American plates. The Pacific plate carries a small piece of North America with it as it moves northward at a rate of about 3.2 cm/year along the right-lateral strike-slip San Andreas fault.

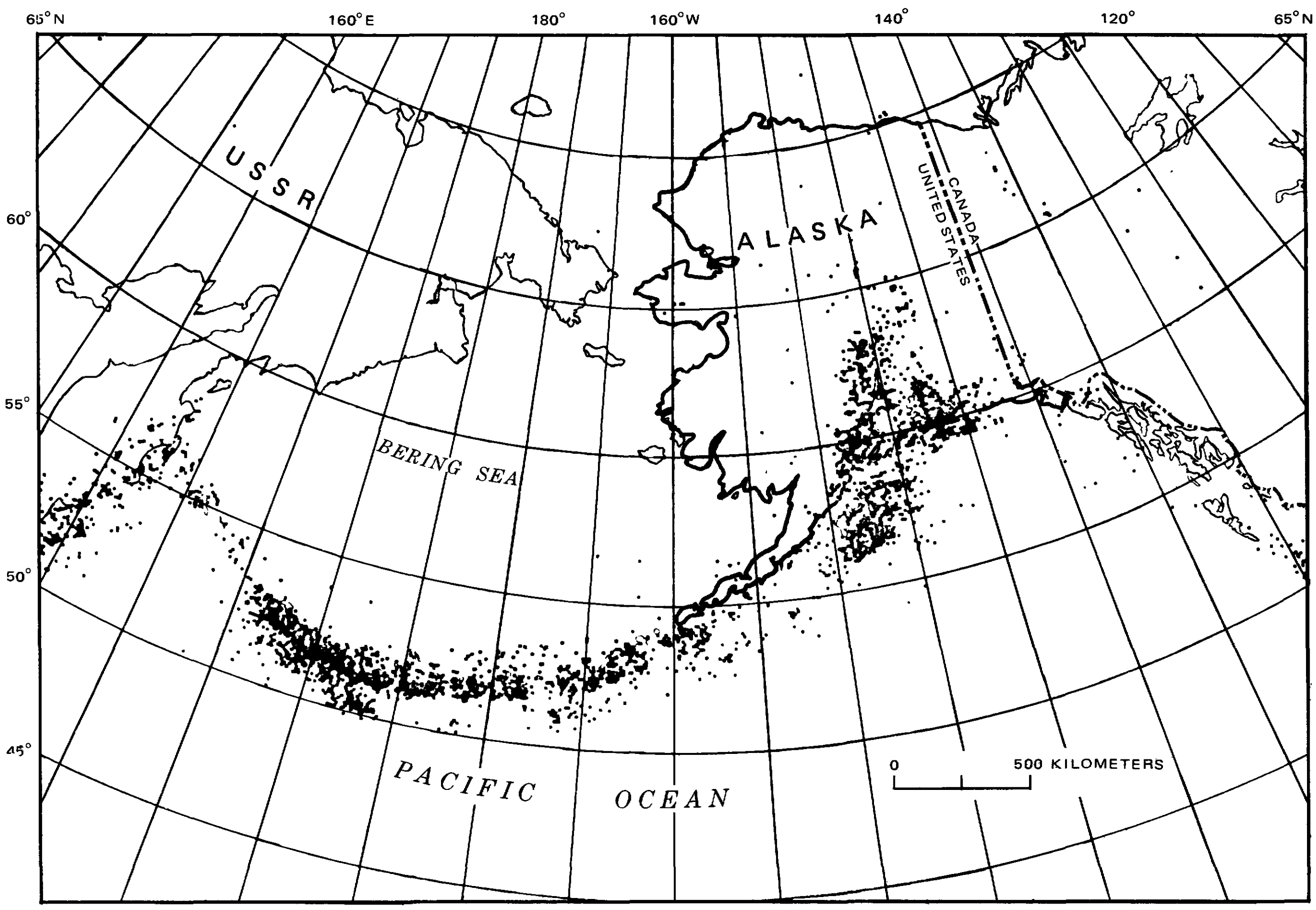


FIGURE 8.—Epicenters of earthquakes in Alaska between 1962 and 1969 (U.S. Dept. Commerce, 1970).

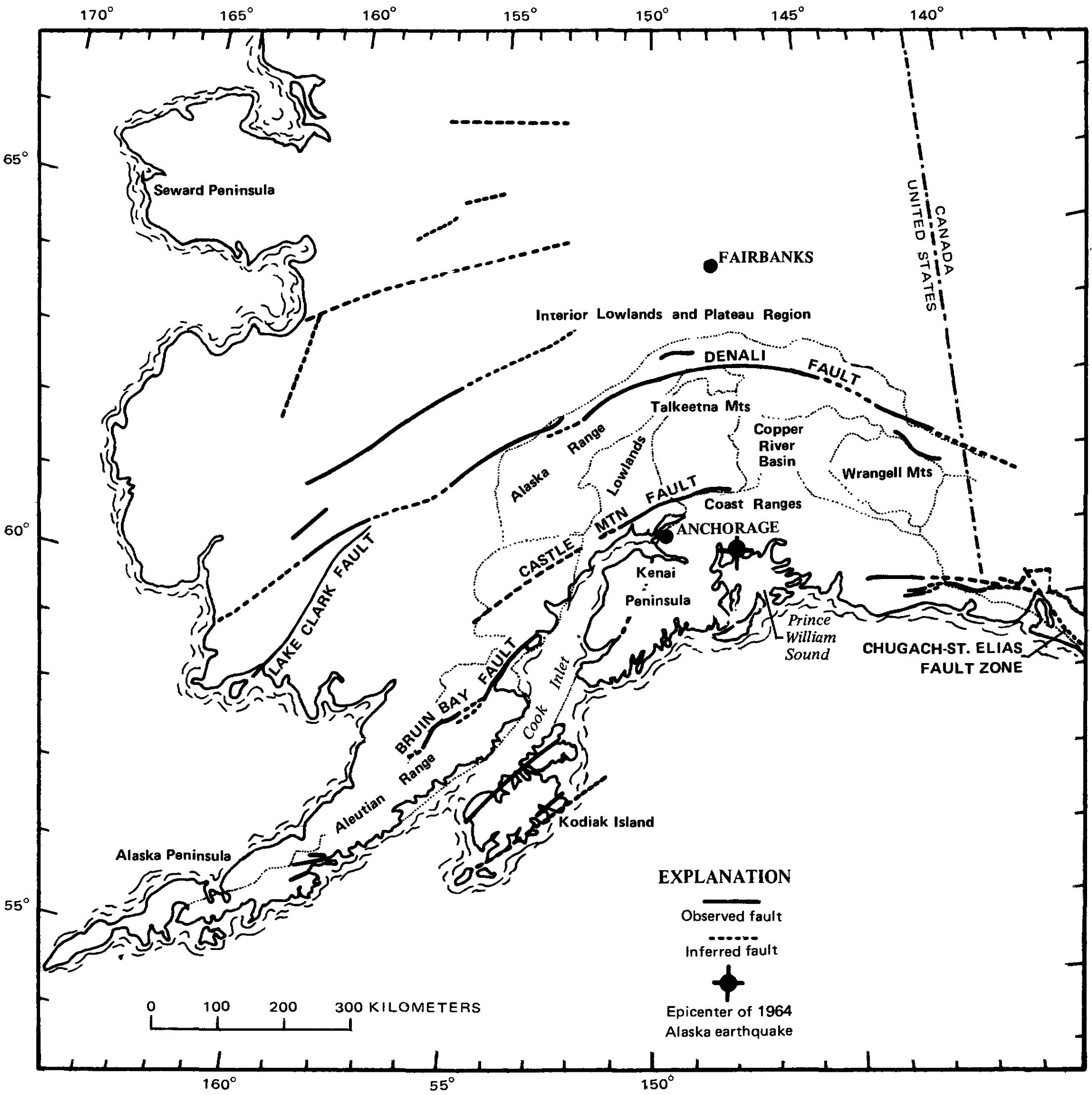


FIGURE 9.—Major faults in southern Alaska.

A distinctive alinement of seismic activity occurs in southern California. This zone of activity branches from the main trend of the San Andreas fault zone in the vicinity of the Garlock fault (fig. 10) and trends northward into western Nevada, marking the eastern flank of the Sierrra Nevada. Garfunkel (1974) suggested that right-slip motion between the Pacific and North American plates on the San Andreas fault has produced a region of crustal extension in the Gulf of California and the Salton trough. When the Pacific plate encountered the Mojave block, rotation and internal deformation of the block and bending of the San Andreas system occurred. This resistance and bending was accommodated by distortion of the block and by left-slip on the Garlock fault and other west-trending faults as well as thrusting in the Transverse Ranges.

The characteristics of some of the California and Nevada fault systems are summarized below:

1. The San Andreas fault zone is the largest fault system in California. The right-lateral strike-slip system is approximately 1,000 km long and up to 80 km wide. Several destructive earthquakes have occurred along the fault, for example, near San Francisco in 1836 and 1838 and near Fort Tejon in central California in 1857. The magnitude-8.3 San Francisco earthquake of April 18, 1906 caused a surface rupture of about 432 km. Creep occurs along sections of the fault (Nason, 1973), but some sections of the fault in both northern and southern California appear to be locked at the present time and may be the zones of future earthquakes.

2. The Hayward fault was the source of two large earthquakes in 1836 and 1868. The 1836 earthquake caused a surface rupture of 64

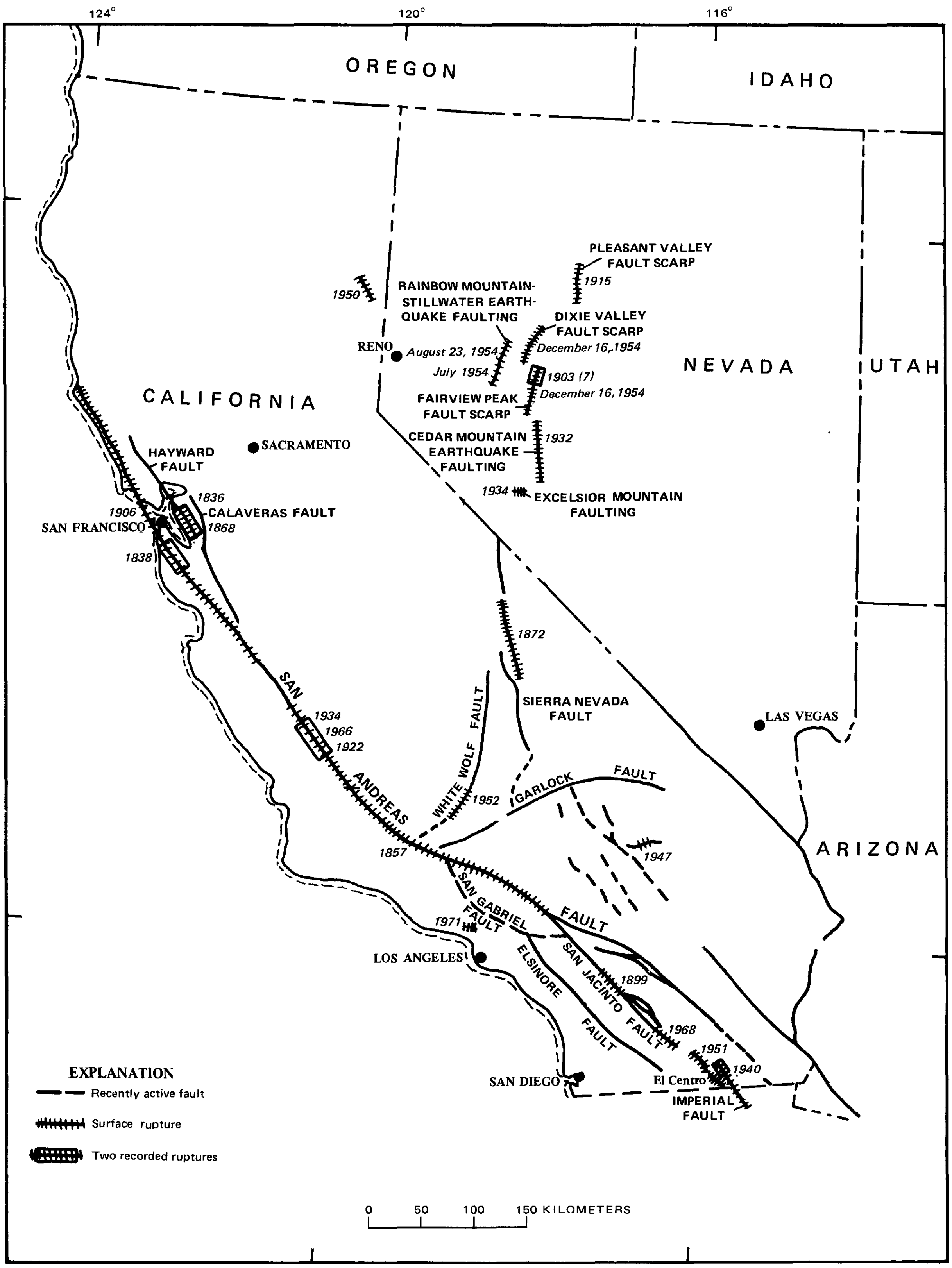


FIGURE 10.—Major faults in California and Nevada and locations of past surface ruptures.

km, and the 1868 earthquake caused a rupture of 32 km.

3. The Calaveras fault system, with a length of approximately 160 km, is one of the largest in northern California. It is primarily a right-lateral strike-slip fault with a vertical

component responsible for upward movement on the west side. The vertical component is estimated to be about 90.4 m. Creep presently occurrs along the fault near Hollister (Rogers and Nason, 1971; Mayer-Rosa, 1973).

4. The 240-km-long Garlock fault in southern California has a left-lateral movement and separates the Mojave Desert province from the Sierra Nevada and Basin and Range provinces. Only small historic earthquakes have been attributed to this fault system.
5. The Sierra Nevada fault zone was the source of the 1872 Owens Valley earthquake which had an estimated magnitude of 8.3. Many people consider this earthquake to be the largest in California.
6. The White Wolf fault zone was the source of the 1952 magnitude-7.7 Kern County earthquake. The fault motion was mainly dip-slip and produced a surface rupture of about 52 km.
7. The Imperial fault, a southern extension of the San Andreas fault system, was the source of the magnitude-7.0 1940 Imperial Valley earthquake. The surface rupture was about 64 km.
8. The 1971 San Fernando earthquake caused a 19-km surface rupture on a segment of the Sierra Madre fault system. The epicenter was about 4.8 km north of the San Gabriel fault system. Faulting was associated with the Transverse Ranges structural province, a region noted for its relatively young tectonic deformation, and it is the first example of surface faulting within that province.
9. The San Jacinto fault zone is one of the most seismically active in California (Thatcher and others, 1975). Thirteen large earthquakes have occurred since 1890 along the 240-km-long fault. The 1899 earthquake south of Hemet, Calif., ruptured the ground surface for 19 km.
10. The Pleasant Valley fault scarp in Nevada was associated with a magnitude-7.6 earthquake in 1915. The surface rupture along the normal fault system was 32–64 km.
11. The Dixie Valley fault scarp in Nevada is an example of a normal fault system. It was associated with the 1954 magnitude-6.8 earthquake which produced 61 km of surface rupture.
12. The magnitude-7.3 Cedar Mountain, Nevada, earthquake of 1932 produced surface rupture of approximately 61 km along the normal fault system.
13. The magnitude-6.5 Excelsior Mountain, Nevada, earthquake of 1934 produced 1.5 km of surface rupture.

Ryall (1977) pointed out that active faulting in California is confined fairly well to single belts such as the San Andreas fault zone, but it is fairly evenly distributed over the entire western Basin and Range province in Nevada. He argued that neither the historic seismicity nor the distribution of active faults is by itself sufficient to determine the earthquake potential in Nevada and that the seismic cycle in Nevada corresponding to the rerupture time of major faults is of the order of several thousands of years.

The Puget Sound area of Washington is another zone of seismic activity along the Pacific Coast. The earthquake-related fault breaks have not been clearly identified in the area and the exact cause of seismicity has not been determined (Crossen, 1972; Rasmussen and others, 1975). According to Walper (1976), the seismicity may be related to a triple junction at the north end of the Juan de Fuca Ridge (fig. 7). Spreading motion is transmitted there to the Explorer Ridge which joins with another segment of the transform boundary regime represented by the Queen Charlotte Islands-Fairweather fault zone. The Puget Sound area has an anomalously thick crust compared to the rest of the Western United States (Warren and Healy, 1973) and may be an extension of Vancouver Island, which also has an anomalously thick crust (Berry, 1973). Thus, one hypothesis to explain the seismicity of the area is that the block of thick crust is a continental fragment caught up in a plate-boundary regime, moving independently to cause seismicity.

The Intermountain Seismic Belt (Smith and Sbar 1974) is a zone of earthquake activity 1,300 km long and 100 km wide that extends southward from the south end of the Rocky Mountain front in western Montana, through Yellowstone, Wyoming, and eastern Idaho and then south-southwest through Utah into Arizona (see fig. 3, zone number 4). This seismic belt encompasses the Yellowstone mantle plume (Wilson, 1973) and is also coincident with the Cenozoic fault zones of the northern Rocky Mountains. Smith and Sbar (1974) interpreted the belt as a boundary between the northern rocky Mountain and the Great Basin subplates of the North American plate because it closely follows the boundary between major physiographic and structural provinces.

The Wasatch fault (fig. 11) is the dominant fault in a system of generally north-south-trending active faults in the Intermountain Seismic Belt. It is a normal fault, down to the west, that extends for 370 km from Gunni-

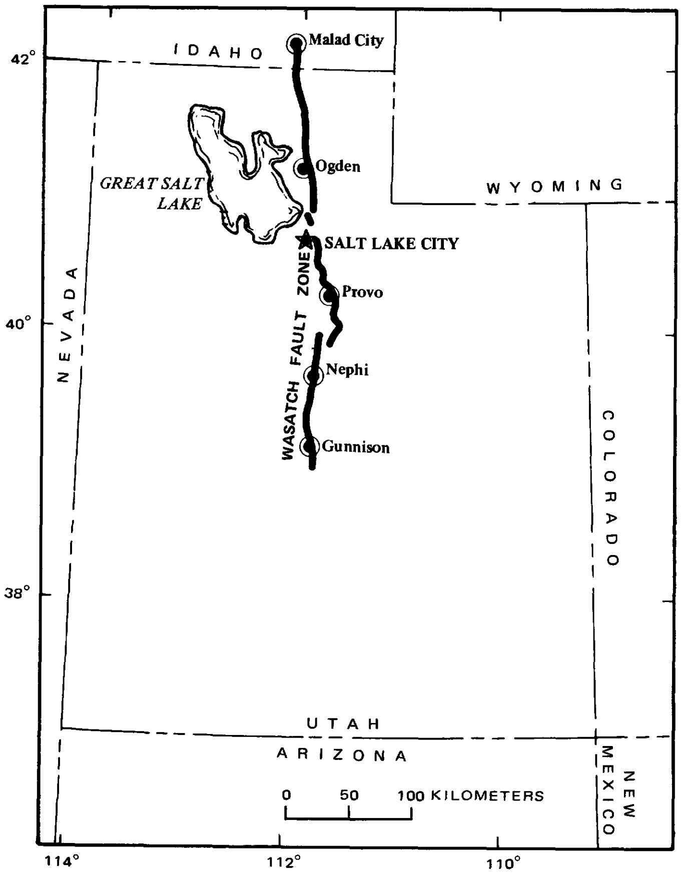


FIGURE 11.—Wasatch fault zone.

son, Utah, to Malad City, Idaho. More than 30 m of vertical displacement of late Pleistocene and Holocene materials has occurred in places along the Wasatch fault zone (Cluff and others, 1975). Only minor seismicity has been associated with the fault during the last 140 years. A 50- to 105-m-wide zone of damaged streets, curbs, houses, and buildings occurs in Salt Lake City along the fault trend. Approximately 85 percent of Utah's population lives within 8 km of the Wasatch fault zone. The only historical earthquake in Utah that produced ground displacement was the 1934 magnitude-6.6 Hansel Valley earthquake. It occurred north of the Great Salt Lake.

EASTERN UNITED STATES

The earthquakes of the Mississippi Valley are associated with continuing tectonic activity at the upper end of the Mississippi embayment (fig. 12), a part of the Gulf Coastal Plain. The embayment is a structural trough that was formed in Paleozoic basement rock and subsequently filled with marine deposits. It is generally thought that downwarping of the underlying Paleozoic basement rock is continuing today. Faults are thought to be present in the basement rocks in the embayment area but have not been conclusively identified.

With the possible exception of the 1811–12 New Madrid earthquake, surface rupture has not been associated with historic or Holocene earthquakes in the Mississippi Valley area or any other area in the Eastern United States.

Several fault systems have been identified in the Mississippi Valley area. The best-known faults include: the New Madrid fault zone, the Kentucky River fault zone, the Mount Carmel fault, the Rough Creek fault zone, the Wabash fault zone, the Cottage Grove fault zone, the Saint Genevieve-Rattlesnake Ferry fault zone, and the Bowling Green fault zone. Some of these faults are shown in figure 10. None of these faults has exhibited either displacement or concentrated seismic activity in historical time.

The New Madrid fault zone, source of the 1811–1812 earthquakes and several thousand aftershocks, is postulated to be a combination of normal fault zones trending northeastward from the northernmost extent of the Mississippi embayment to the east-west-trending Rough Creek fault zone. This zone has been inferred to exist beneath Cretaceous deposits in the embayment area. Fuller (1912) established his "epicentral line" on the basis of evidence of maximum ground surface disturbance from the 1811–1812 earthquakes. Some investigators have suggested that the New Madrid fault zone can be traced across the Mississippi river flood plain in the vicinity of New Madrid, Mo.; others believe that the fault zone may extend as far north as Vincennes, Ind., or include the Wabash fault zone. The critical fact is that the causative faults in the region of the Central United States where the largest historic earthquakes occurred are still not well identified today.

The present seismicity in the New Madrid region has been determined by a regional seismic network (Stauder and others, 1976). The most significant finding is the identification of linear trends of seismic activity. These trends are 30–100 km long and are offset from or parallel to one another. The greatest number of earthquake foci lie very close to the surface of the Precambrian rocks. Seismic activity is episodic, occurring in turn along some trends, then along others. When a particular linear segment is active, hypocenters are usually distributed along the whole segment. These phenomena suggest that the linear trends act as continuous seismic features and are not dependent on forces acting at distant plate boundaries. Since 1963, one earthquake having body-wave magnitude (m_b) greater than or equal to 4.75 has occurred about every 2 years.

Kane and Hildenbrand (1977) reported on the good

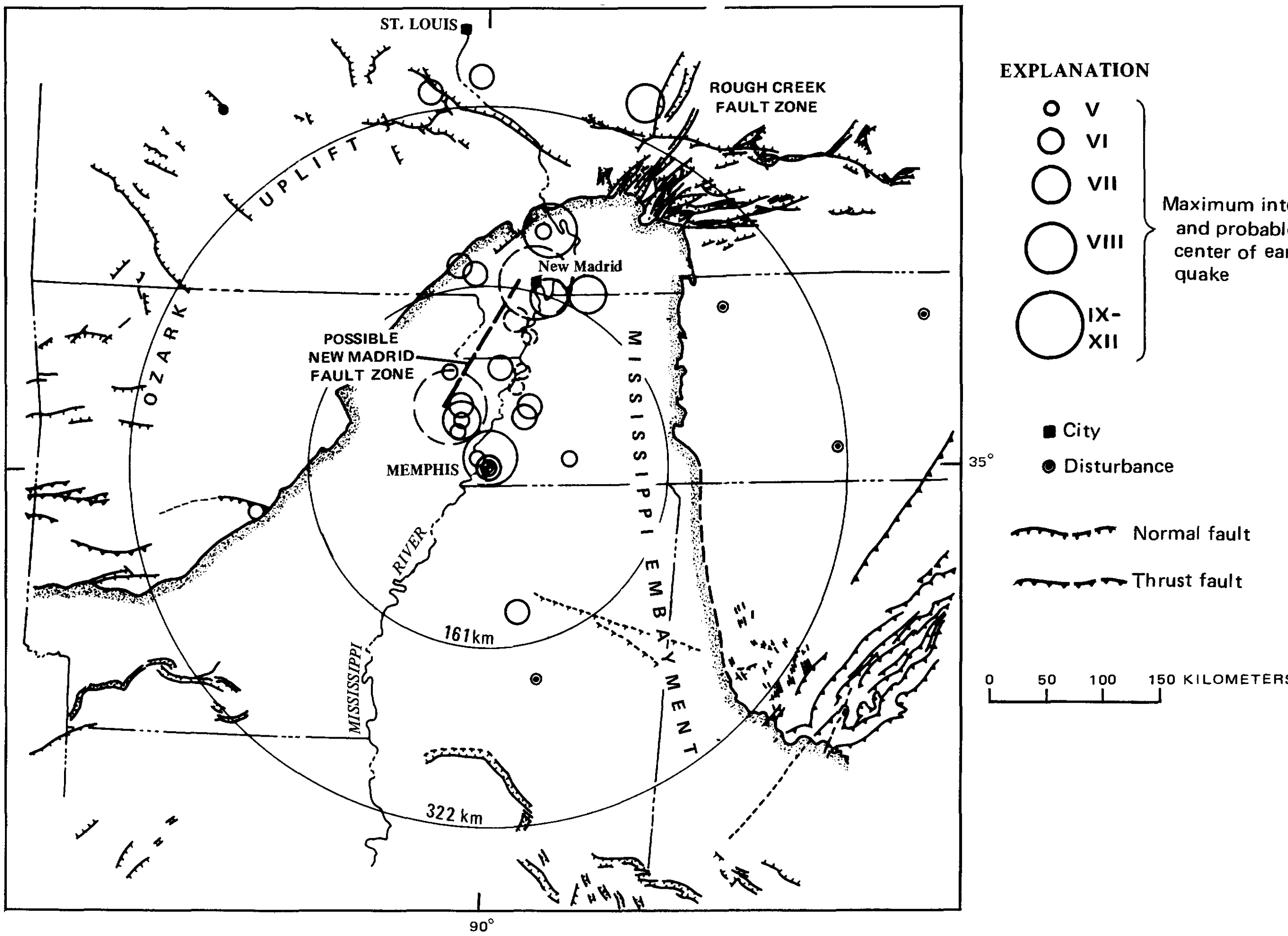


FIGURE 12.—Major tectonic features and historic earthquake activity in the Mississippi Valley area.

correlation of the Mississippi embayment seismicity with a zone of subdued magnetic field having sharply defined parallel boundaries striking N. 45° E. The zone is about 100 km wide. The principal seismicity of the Mississippi embayment, including the 1811–1812 earthquake sequence, is located along the axis of the zone in a configuration similar to spreading ridges. The magnetic field data suggest that the zone is caused by a structural depression of 1–2 km relief below the Precambrian basement, which lies at an average depth of 2–4 km.

The general alinement of earthquakes and the axis of high seismic transmissibility extending from southern Illinois to the St. Lawrence Valley in Ontario and Quebec was noted by Woolard in 1958. He suggested that the alinement might be related to unloading of the Pleistocene ice cap. Sykes (1972) pointed out that surface faulting had not been observed for any of the earthquakes in the St. Lawrence Valley and that understanding of the tectonic mechanism was limited. In addition, Sbar and Sykes (1973) noted that large seismic gaps occur in the postulated seismicity trend and argued against the continuity of the southern Illinois-St. Lawrence trend. These questions are still unresolved.

The earthquakes of the Appalachian region are associated with the Piedmont and the Appalachian Mountains, particularly the belt of thrust faults and folds. The seismicity pattern has been suggested to correlate with areas of high stress along preexisting fault zones that formed during continental collision (Rankin, 1975).

Colton (1970) suggested that the 1886 Charleston, S.C., earthquake was caused by movement on a late Precambrian or early Paleozoic aulacogen (a fault-bounded trough or graben) in the Carolina area of the Appalachians. The trends of historic epicenters (fig. 13) in this area (Bollinger, 1972, 1973) are not conclusive as to the mechanism. The seismic network in the Charleston area (Tarr and King, 1974) is providing evidence that the current seismicity is concentrated in discrete source zones, with the largest shocks being 7–14 km deep. The fault-plane solutions suggest northeast-southwest compression.

The mechanism for the New England earthquakes is controversial. No clear evidence of Holocene faulting is

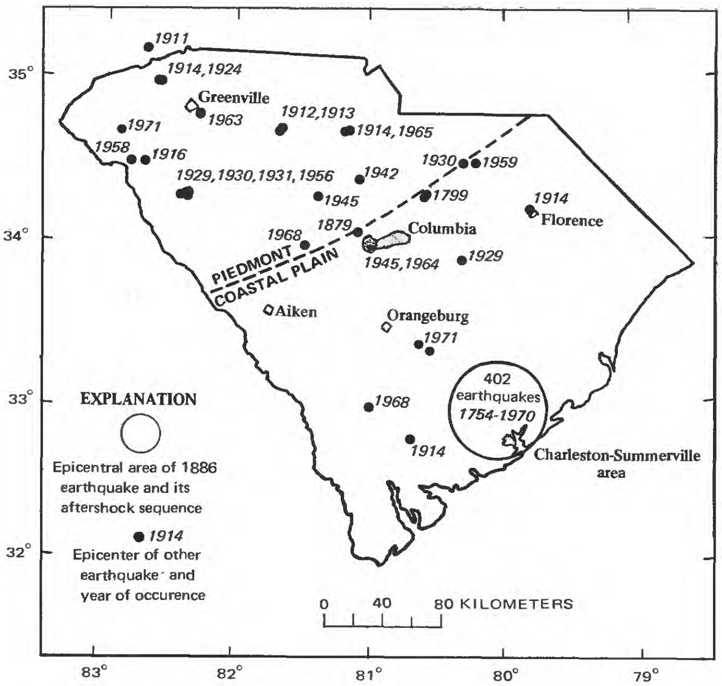


FIGURE 13.—Historic seismicity in South Carolina area (from Bollinger, 1972).

associated with the seismicity. Coney (1972) and Morgan (1973) suggested that the present seismicity is in response to the continuing adjustment of the crust to the horizontal drift of the North American plate and epeirogenic warping. They suggested that North America was over the Azores hot spot or plume before rifting took place to open the Atlantic Ocean. Sbar and Sykes (1973) suggested that the locations of earthquakes in Eastern North America are controlled by unhealed faults or fault zones in the presence of a high deviatoric stress and that the orientation of these faults with respect to the stress field may be a major factor in determining when an earthquake occurs in this area.

There are presently many gaps in knowledge about the causative mechanisms for earthquakes in various regions of the United States. Progress in understanding has been slow. Expanded regional seismicity networks and greatly improved knowledge of the 3-dimensional geologic structure over broad geographic areas are needed before the earthquake potential in various regions throughout the United States can be specified precisely.

DETERMINE REGIONAL SEISMIC ATTENUATION

One of the most important factors in specifying earthquake ground-motion precisely is knowledge of how seismic waves attenuate from the source in various geographic regions of the United States. Research on seismic attenuation has proceeded slowly because the physical parameters of the crust and upper mantle causing attenuation are difficult to quantify. Also, the present strong-ground-motion data are geographically limited, and few empirical data exist to define the effects of path parameters, such as: (1) the natural anisotropy and inhomogeneity of the earth; (2) loss mechanisms (geometrical spreading, absorption and scattering); (3) reflection, refraction, diffraction, and wave-mode conversion; and (4) wave interference.

It will be a long time before adequate strong-ground-motion data are available for all parts of the United States; therefore, attenuation functions for areas outside California will have to be based on Modified Mercalli intensity data, which have deficiencies. One significant deficiency of these relations is the lack of knowledge about the statistical distribution. A number of investigators (for example, Dutton, 1887; Lawson, 1908; Fuller, 1912; Gordon and others, 1970; Coulter and others, 1973; Evernden, 1975; Howell and Schultz, 1975; Trifunac and Brady, 1975c; Gupta and Nuttli, 1976; Brazee, 1976; Borcherdt and Gibbs, 1976; O'Brien and others, 1977; and Espinosa, 1977) have evaluated the intensity data of individual earthquakes or a set of earthquakes. These investigations have produced results, some of which are now being applied in earthquake-resistant design.

A detailed isoseismal map from a past earthquake is the best basis for deriving an intensity attenuation function for a region when ground-motion data are unavailable. The critical data contained on an isoseismal map are the values of maximum Modified Mercalli intensity reported at various locations. These values are transformed into an iso-intensity contour map. The contours can be deceiving, however, because isoseismal maps typically represent intensity values reported at sites underlain by alluvium or unconsolidated materials. Because these sites generally undergo more intense ground motion than sites underlain by rock, attenuation functions derived from an isoseismal map, without regard for the local site geology, may overestimate the ground motion level at the site of interest. Data showing the effect of site geology in central California on intensity increments are listed in table 8

TABLE 8.—*Relative intensity values and ground character, central California*

[From Evernden and others (1973)]

Ground character	Relative intensity increments
Granite	−3
Jurassic to Eocene sedimentary rocks	−2¼
Oligocene, Miocene, and Pliocene sedimentary rocks	−1½
Late Pliocene sedimentary rocks	−1
Quaternary sediments (not saturated)	−½
Saturated or near-saturated alluvium or bay fill	≥½

(Evernden and others, 1973). The reports by Hopper and others (1975) and Rogers and others (1976) also contain information about the effects of the surficial geology on intensity for the Puget Sound, Wash. and Salt Lake City, Utah areas.

Figure 14 shows the Modified Mercalli intensity isoseismal map for the 1971 San Fernando, Calif. earthquake. The area of very heavy ground shaking was 768 km^2. The total Los Angeles metropolitan area affected was about 1,536 km^2 and a total populaton of about 7 million was exposed to the shaking.

Isoseismal maps for the 1906 San Francisco and the 1811 New Madrid earthquakes are compared in figure 15. The very large difference in felt areas for these two earthquakes is characteristic of the difference in seismic wave attenuation in the Eastern and Western United States (Nuttli, 1971; 1973b).

Evernden (1975) used the difference in seismic attenuation rates in the Eastern and Western United States as a basis for assessing the size of earthquakes. Using a predictive model for intensity that incorporated regional variation in seismic attenuation, Evernden concluded that the 1906 San Francisco earthquake was more than 100 times larger than the 1811–1812 New Madrid and 1886 Charleston earthquakes. He suggested that the lengths of the fault breaks for the New Madrid and Charleston earthquakes were on the order of 10–20 km, considerably smaller than had been assumed in the past. He also suggested that the 1872 Owens Valley, Calif. earthquake was not so large as originally thought.

Gupta and Nuttli (1976) derived the relation:

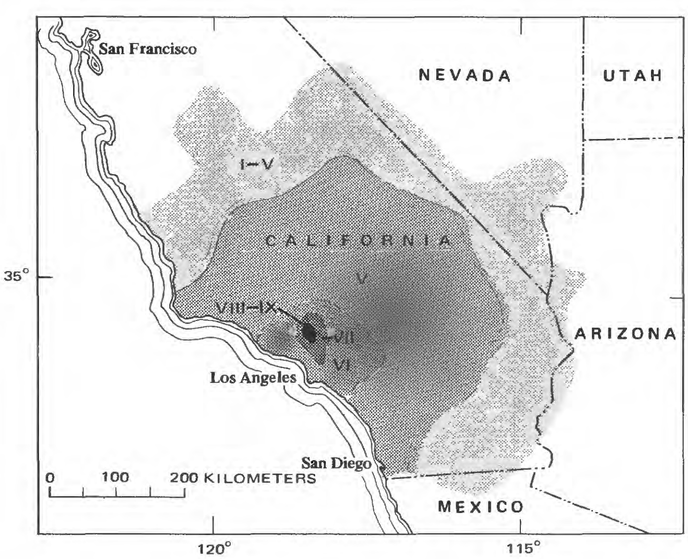


FIGURE 14.—Isoseismal contours for 1971 San Fernando, Calif., earthquake.

$$I(R)=I_o+3.7-0.001R-2.7 \log R \text{ for } R>20 \text{ km}$$

where $I(R)$ is MM intensity at R, epicentral distance in kilometers. This relation is applicable for the Central United States in the area between the Rocky Mountains and the Appalachians. This empirical attenuation law is consistent with intensity data from past earthquakes in the Mississippi Valley and model studies (Herrmann and Nuttli, 1975a, b).

A number of intensity attenuation relations have been proposed for use in the Eastern United States (for example, see Cornell and Merz, 1974; M&H Engineering and Memphis State University, 1974; and Young, 1976). Two attenuation relations proposed for use respectively in the southern Appalachian seismic zone and in the central Mississippi Valley are shown in figure 16. Both sets of curves are for firm ground conditions.

The most accurate procedure for defining the seismic attenuation function of an area is to use observed strong-motion accelerogram data to derive a family of empirical acceleration-attenuation curves. Such a family of mean acceleration attenuation curves (Schnabel and Seed, 1973) applicable for sites in the Western United States is shown in figure 17. Each site is assumed to be located on rock, material having a shear-wave velocity of at least 760 m/s at low (0.0001 percent) strain levels. These curves are somewhat controversial in terms of whether or not they underestimate the peak acceleration inside 20 km, but they are still used at the present time in many applications. The statistical distribution for the Schnabel and Seed acceleration attenuation curves is unknown. Another set of peak acceleration attenuation curves proposed by Davenport (1972) is also shown in figure 17. These curves are based on regression analysis of the available strong-motion data sample and indicate substantially higher values of peak ground acceleration than the corresponding Schnabel and Seed attenuation curves. These empirical curves have not received wide use in the United States.

Algermissen and Perkins (1976) proposed that acceleration attenuation in the Eastern United States can be estimated by modifying the Schnabel and Seed curves as shown in figure 18. These empirical curves are identical with the Schnabel and Seed curves in the distance range 45–50 km and conform to the Nuttli (1973a) curves at greater distances. The statistical distribution is unknown for these proposed attenuation curves.

Donovan (1973) used two sets of data to derive acceleration-attenuation relations. He used data from 515 worldwide earthquakes encompassing a wide range of magnitudes to derive a general relation (fig. 19). The geometrical standard deviation for the mean

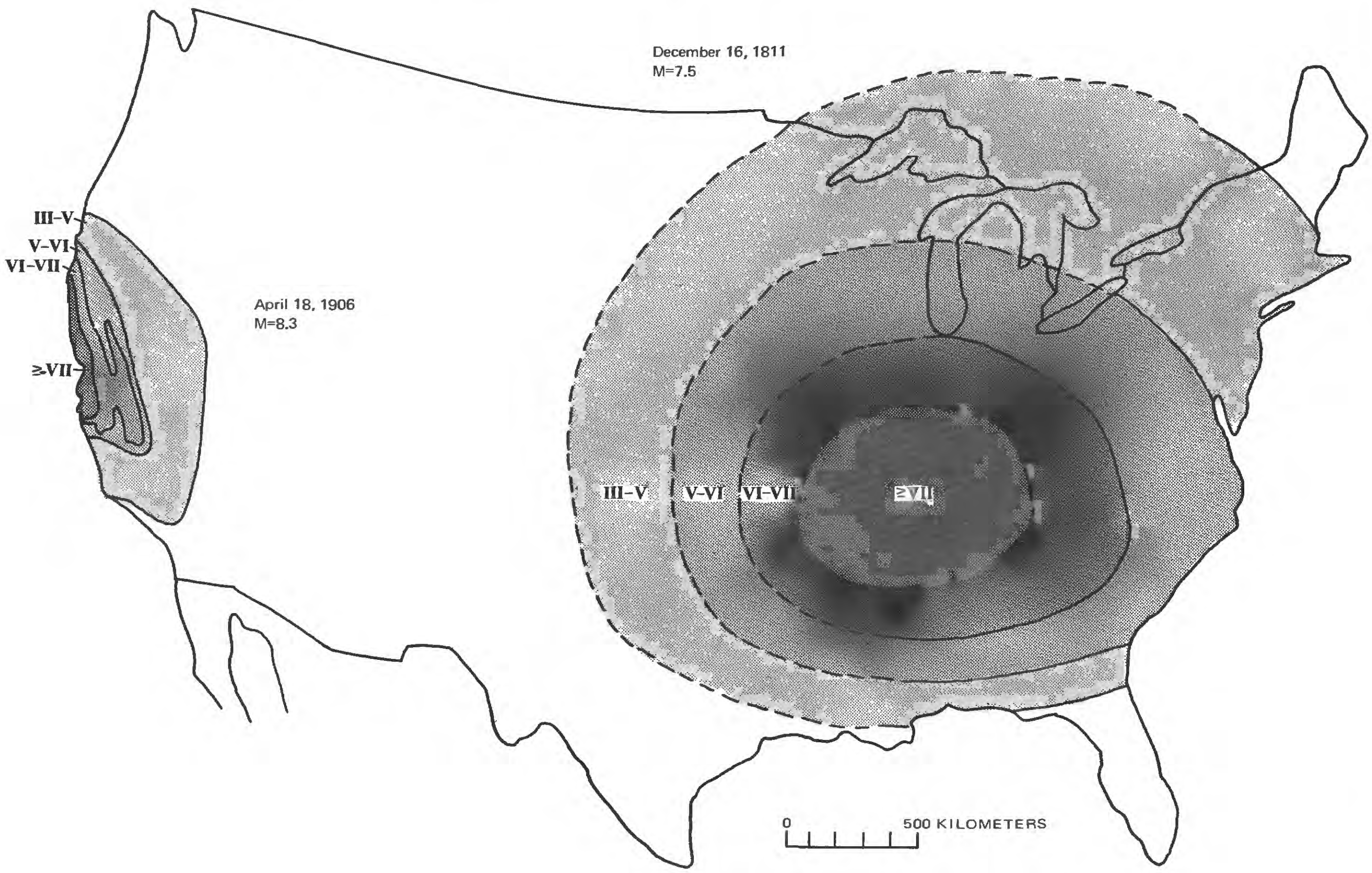


FIGURE 15.—Isoseismal contours for 1906 San Francisco and 1811 New Madrid earthquakes (modified from Nuttli, 1973b).

curve was 2.01. When he analyzed the peak acceleration data obtained from the 1971 San Fernando earthquake, he obtained a standard deviation of 1.62 (fig. 19). The distribution of data relative to the mean regression line was shown to be log-normal.

Ground-motion data from California earthquakes, from nuclear explosions in Nevada, Colorada, and New Mexico, and from the aftershock sequence of the March 1975 Pocatello Valley, Idaho earthquake have been analyzed to define preliminary frequency-dependent seismic attenuation relations (Johnson, 1973; McGuire, 1977a; and King and Hays, 1977). Values of the distance attenuation exponent, β, were derived from pseudo relative velocity (*PSRV*) response spectra by least squares analysis (that is, $PSRV = AR^{\beta}$ where R is the epicentral distance and A and β are constants derived in the least-squares analysis) and are listed in tables 9–13 along with values of σ. These data indicate that seismic attenuation rates are about the same in southern Nevada and California, and that high-frequency (5–20 Hz) seismic energy attenuates more rapidly in Colorado and northern Utah than in California and southern Nevada (fig. 20.) Values of the geometrical standard error of estimate range from 1.58 to 1.78 for the highly "calibrated" transmission path of southern Nevada (Lynch, 1973) and from 1.61 to 2.22 for the less well "calibrated" transmission path of Colorado (Foote and others, 1970). They range from 2.26 to 2.73 when both distance and magnitude are considered.

DEFINE THE CHARACTERISTICS OF GROUND SHAKING EXPECTED AT THE SITE

After specifying the location and magnitude (or epicentral intensity) of each potential earthquake and an appropriate regional attenuation relation, the characteristics of ground shaking expected at the site can be determined. To implement this step requires consideration of the earthquake mechanism and basic wave propagation theory although current design procedures are primarily based on empirical procedures.

It is well known that the amplitude, temporal, and spectral characteristics of ground motion produced at a site by an earthquake are functions of the earthquake source mechanism, the epicentral distance, and the geometry and physical properties of the geologic structures traversed by the body waves and surface waves as they propagate from the source to the site (fig. 21). Seismograms recorded at all distances are complex, but

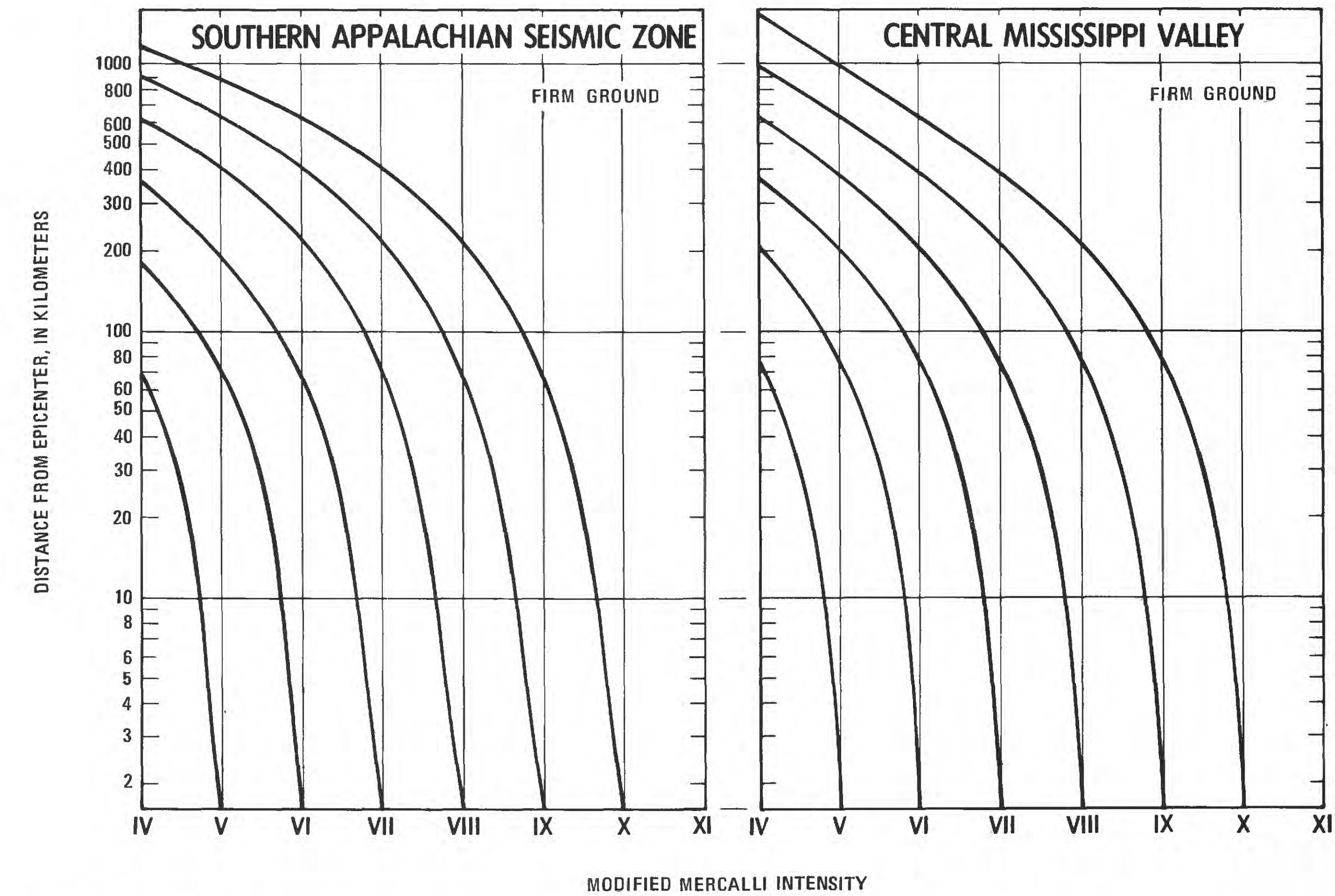


FIGURE 16.—Empirical intensity attenuation curves proposed for the Southern Appalachian seismic zone and the central Mississippi Valley (after Young, 1976).

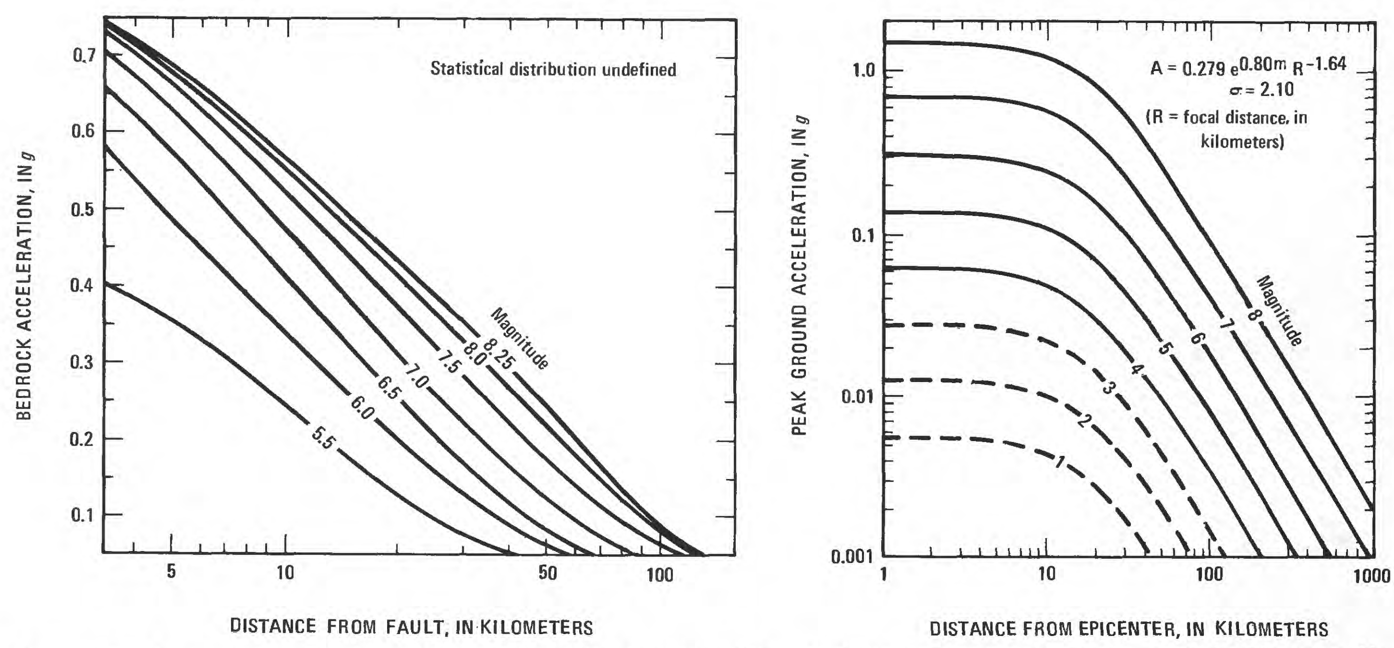


FIGURE 17.—Average value of peak acceleration A in relation to distance R from fault for earthquakes of various magnitudes M (proposed by Schnabel and Seed, 1973 (left) and Davenport, 1972 (right)). Dashed lines represent extrapolated values.

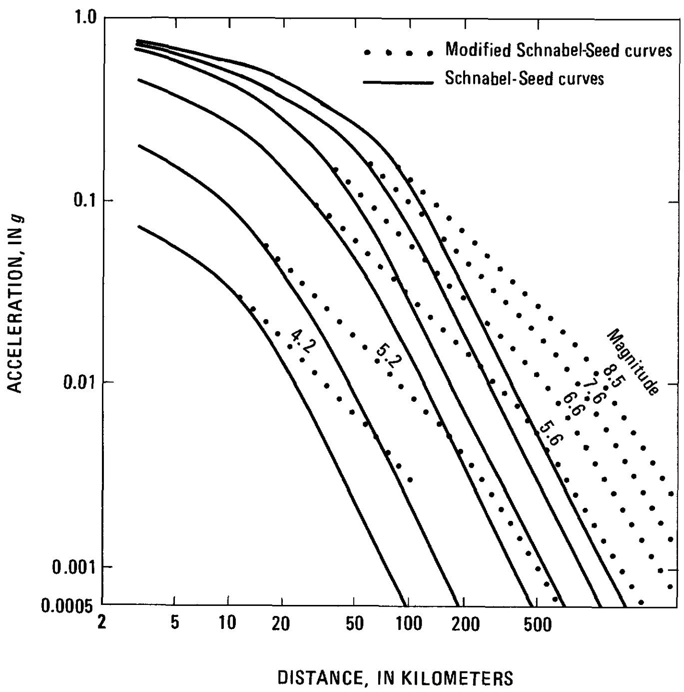


FIGURE 18.—Schnabel and Seed acceleration-attenuation curves modified for use in the Eastern United States (from Algermissen and Perkins, 1976).

they are especially complex in the near field (that is, source-to-source distances of a few fault rupture widths) where the seismic spectrum tends to be rather broad. In the near field, the ground motions are strongly influenced by the dynamics of the fault rupture, and site properties are less important than source properties in defining the characteristic features of the ground shaking.

The source of an earthquake is believed to involve a fracturing process in which rock in an environment of shear stress fails. This process may be idealized in terms of an elasto-dynamic crack in an elastic region. The failed region extends rapidly at its periphery to become the "fault surface." The loss of cohesion across the region of failure translates into a boundary condition in which the faces of the crack are free of shear stress. Assuming that the faces of the crack do not move apart, the rupture grows in a shear mode. A key to a physical understanding of the earthquake source problem, therefore, lies in understanding the physical processes that take place at the tip of the propagating crack.

Body (P, SH, and SV) and surface (Love and Rayleigh) seismic waves are generated by the complex physical processes which occur during and after the rupture along the fault surface. The body waves are characterized by high frequencies (2–10 Hz) and commonly produce the peak ground acceleration on the accelerogram. Rayleigh and Love waves travel and attenuate more slowly than body waves and have lower fundamental frequencies of vibration (for example, <1 Hz).

The physics of the earthquake source is still not completely understood although a great deal of research is being concentrated on this problem. Brune (1970) and other scientists have shown on the basis of earthquake fault models that the earthquake source parameters, rupture velocity, effective stress, seismic moment, fault length, and stress drop, appear to have a predictable effect on the radiated seismic signal. In the far field (that is, source-to-station distances greater than about ten fault rupture widths), the high-frequency characteristics of the broad-band spectrum of the seismic signal are determined primarily by the dynamic stress drop. The low-frequency characteristics are determined by the seismic moment. The character of the radiated seismic signal is strongly dependent on the rupture velocity, which in turn is directly related to the effective stress available to accelerate the fault motion. In the near field, the effective stress primarily determines the high-frequency wave characteristics, and the permanent static displacement determines the low-frequency wave characteristics although wave scattering and attenuation can affect the spectral composition of the seismic signal at any distance. None of the source parameters, stress drop, seismic moment, and rupture velocity are used in current earthquake-resistant design.

The source parameters, focal depth, rupture velocity, elastic constants of the source medium, stress drop, the fault configuration at depth, and source multiplicity, are probably the ones whose influence on ground shaking is least understood at present. The effect of focal depth may be of practical importance for nuclear power plant siting and other applications because the spectral composition of strong ground motion is strongly influenced by energy partition between body and surface waves, which is in turn influenced by focal depth. The effects of the differences in focal depth in California (≤16 km) and in the Puget Sound area (50–60 km) on ground motion are not clear.

Ground motion can be described in a wide variety of ways (for example: as a time history, as spectra, and as peak ground-motion parameters). Almost all these descriptive formats are used in at least one of the various applications that require characterization of earthquake ground motions. These formats will be described below.

THE SEISMOGRAM

The seismogram, whether written by a broad-band strong motion accelerograph system or on the short- and long-period seismographs of WWSSN (World-Wide

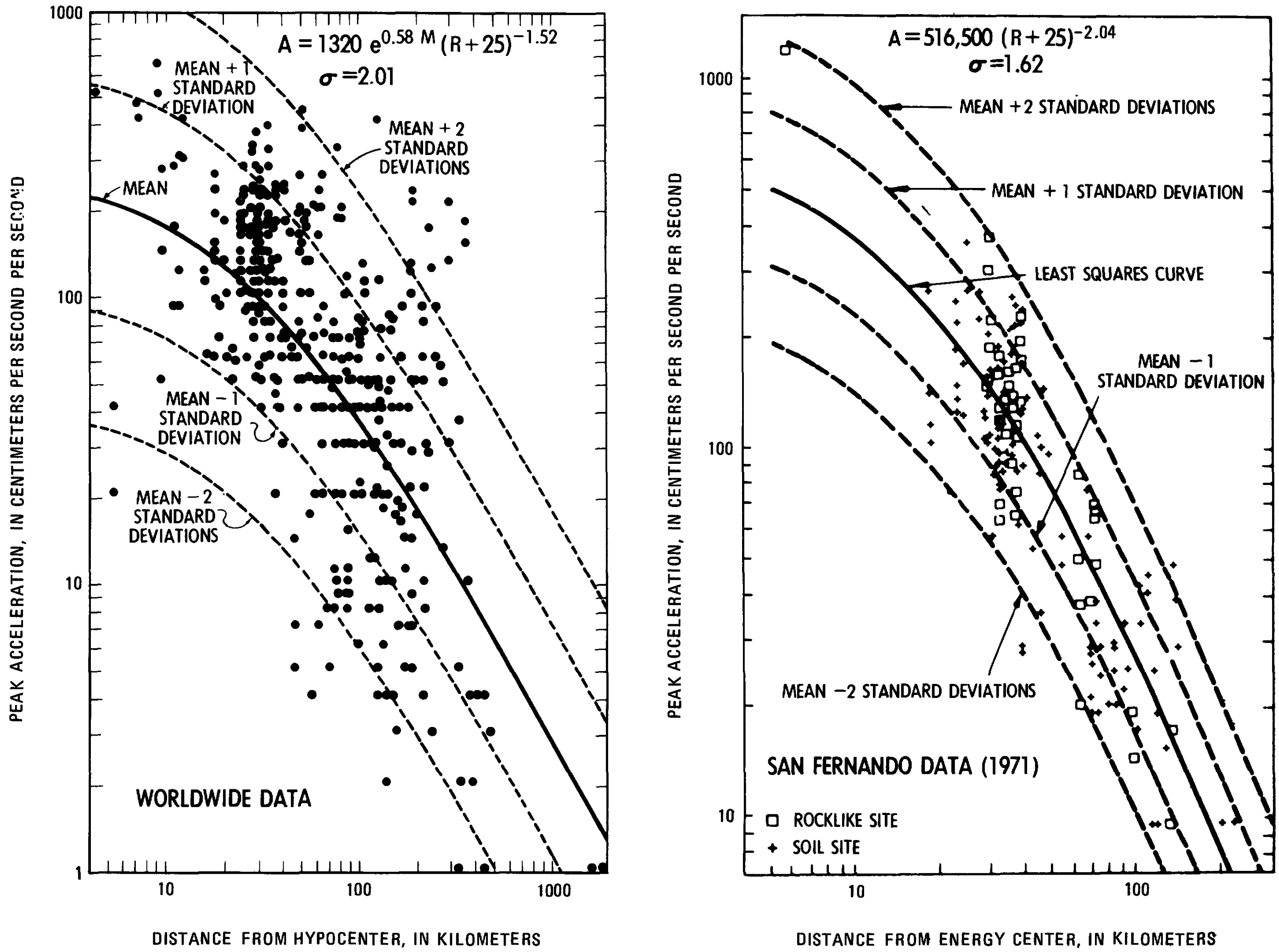


FIGURE 19.—Acceleration-attenuation relations derived from worldwide earthquakes and from the San Fernando earthquake, 1971 (from Donovan, 1973).

TABLE 9.—*Distance attenuation exponents derived from horizontal component* PSRV *spectra, northern Utah area*

[The form of the equation is $PSRV=AR^{\beta}$. Data sample-48 *PSRV* spectra (5-percent damped) from four Pocatello, Idaho, aftershocks; magnitude (m_b) range from 2.9 to 4.15, distance (R) range from 12 to 150 km. The six recording stations were located on alluvium. Data sample was inadequate to derive a reliable standard error of estimate]

Period (s)	Mean Distance exponent (β)	Period (s)	Mean distance exponent (β)
0.061	−1.74	0.499	−1.62
.075	−1.77	.609	−1.57
.082	−1.79	.744	−1.56
.101	−1.84	.822	−1.54
.123	−1.90	1.004	−1.43
.150	−1.92	1.498	− .99
.203	−1.87	2.022	− .94
.248	−1.89	2.469	− .96
.302	−1.78	3.333	−1.00
.369	−1.72	4.070	−1.06
.408	−1.66	4.972	−1.11
.451	−1.65	6.072	−1.12

Standard Seismograph Network), is a key element in seismological research. An ensemble of seismograms contains the basic information needed to characterize an earthquake and the ground motion that it produces.

Figure 22 illustrates an accelerogram of the 1940 Imperial Valley, Calif. earthquake recorded in El Centro, Calif. about 8 km from the surface trace of the fault. The peak horizontal ground acceleration was 0.33 *g*. This accelerogram has been used as a basis for seismic design throughout the world. It was recorded at a site underlain by a thick soil column, containing from the surface down (1) about 30 m of stiff clay, with a shear-wave velocity of 198 m/s, (2) 274 m of shale with a shear-wave velocity of 852 m/s, (3) 610 m of shale with a shear-wave velocity of 1,040 m/s, and (4) rock with a shear-wave velocity of 2,432 m/s. Schnabel, Seed, and Lysmer (1972) showed that the peak ground acceleration would have been in the range of 0.5 *g* in-

TABLE 10.—*Distance attenuation exponents derived from horizontal component* PSRV *spectra, southern Nevada area*

[The form of the equation is $PSRV = AR^{\beta}$. Data sample—796 *PSRV* spectra (5-percent damped) from 36 Pahute Mesa and Yucca Flat nuclear detonations; yield range less than 20 to 1,200 kilotons; distance (*R*) range from 10 to 200 km. The 103 recording sites were located on rock and alluvium of various thickness with alluvium sites predominating. From Lynch (1973)]

Period (s)	Mean distance exponent (β)	Standard error of estimate (σ)	Period (s)	Mean distance exponent (β)	Standard error of estimate (σ)
0.050	-1.33	1.75	0.369	-1.38	1.60
.055	-1.36	1.74	.408	-1.36	1.59
.061	-1.38	1.73	.451	-1.34	1.59
.067	-1.39	1.70	.499	-1.31	1.58
.075	-1.43	1.69	.551	-1.30	1.59
.082	-1.47	1.69	.609	-1.26	1.61
.091	-1.51	1.68	.673	-1.24	1.63
.101	-1.54	1.67	.744	-1.24	1.64
.111	-1.57	1.67	.822	-1.23	1.63
.123	-1.57	1.68	.908	-1.20	1.63
.136	-1.56	1.71	1.004	-1.17	1.64
.150	-1.56	1.71	1.110	-1.15	1.66
.166	-1.54	1.69	1.226	-1.14	1.67
.183	-1.53	1.68	1.355	-1.13	1.69
.203	-1.51	1.67	1.498	-1.13	1.68
.224	-1.49	1.66	1.655	-1.13	1.69
.248	-1.49	1.66	1.829	-1.13	1.72
.274	-1.47	1.64	2.022	-1.12	1.74
.302	-1.44	1.63	2.234	-1.12	1.75
.334	-1.41	1.60	2.469	-1.08	1.78

TABLE 11.—*Distance attenuation exponents derived from horizontal component* PSRV *spectra, California*

[(From Johnson, (1973) The form of the equation is $PSRV = AR^{\beta}10^{\alpha m_b}$. Data sample—41 *PSRV* spectra (5-percent damped); 37 California and 4 non-California earthquake records; magnitude range from 5.3 to 7.7; distance (*R*) range 6.3 to 149.8 km. California earthquakes in sample: Long Beach (1933), Southern California (1933), Lower California (1934), Northwest California (1938, 1941, 1951), Imperial Valley (1940), Northern California (1952, 1967), Kern County (1952), Humboldt County (1954), Santa Clara County (1954), Wheeler Ridge (1954), El Centro (1956), San Francisco (1957), Hollister (1961), Parkfield (1966), Borrego Mountain (1968), San Fernando (1971). Other earthquakes in sample: Helena, Mont. (1935), Western Washington (1949), Puget Sound, Wash. (1965). All the recording stations except four were located on alluvium. Values of the standard error of estimate are a function of distance and magnitude (m_b)]

Period (s)	Mean distance exponent (β)	Standard error of estimate (σ)	Period (s)	Mean distance exponent (β)	Standard error of estimate (β)
0.055	-1.40	2.36	0.451	-1.26	2.45
.075	-1.52	2.51	.609	-1.14	2.44
.101	-1.56	2.48	.822	-1.06	2.27
.136	-1.59	2.45	1.004	-1.13	2.41
.183	-1.53	2.43	1.355	-1.16	2.51
.248	-1.40	2.26	1.829	-1.17	2.73
.334	-1.30	2.26	2.469	-1.14	2.63

stead of 0.33*g* if the stiff clay layer had been about 9 m thick instead of 30 m.

The accelerogram recorded at El Centro, Calif., in 1940 has proved to be very valuable in earthquake resistant design. The value would be many times greater if an array of instruments underlain by various types of geologic materials had recorded the Imperial Valley earthquake.

Velocity and displacement seismograms are derived form the strong-motion accelerogram (Trifunac, 1970; Trifunac and others, 1971). These time histories, although subject to some small error because of the integration process, give useful information about the

TABLE 12.—*Distance attenuation exponents derived from horizontal component* PSRV *spectra, Piceance Creek Basin, Colo.*

[The form of the equation is $PSRV = AR^{\beta}$. Data sample 59 *PSRV* spectra (5-percent damped) from the Rulison event; yield 40 kilotons; distance (*R*) range from 6.2 to 296 km. The recording stations were located on rock or thin (1–10 m) alluvium and were primarily in the Piceance Creek Basin. From Foote and others (1970)]

Period (s)	Mean distance exponent (β)	Standard error of estimate (σ)	Period (s)	Mean distance exponent (β)	Standard error of estimate (σ)
0.050	-2.09	1.85	0.369	-1.68	2.17
.055	-2.08	1.80	.408	-1.67	2.17
.061	-2.08	1.83	.451	-1.66	2.22
.067	-2.05	1.84	.499	-1.63	2.17
.075	-2.05	1.82	.551	-1.63	2.12
.082	-2.03	1.93	.609	-1.63	2.02
.091	-2.02	2.02	.673	-1.64	1.86
.101	-2.04	2.03	.744	-1.58	1.80
.111	-2.04	2.09	.822	-1.55	1.71
.123	-1.98	2.13	.908	-1.54	1.68
.136	-1.94	2.08	1.004	-1.56	1.68
.150	-1.99	2.01	1.110	-1.54	1.64
.166	-2.01	1.98	1.226	-1.60	1.61
.183	-1.96	1.97	1.355	-1.54	1.70
0.203	-1.90	2.00	1.498	-1.49	1.71
.224	-1.86	2.13	1.655	-1.54	1.74
.248	-1.81	2.07	1.829	-1.48	1.81
.274	-1.81	2.04	2.022	-1.56	1.73
.302	-1.74	2.08	2.234	-1.51	1.76
.334	-1.72	2.11	2.469	-1.51	1.79

TABLE 13.—*Distance attenuation exponents derived from horizontal components* PSRV *spectra, San Juan Basin, N. Mex.*

[The form of the equation is $PSRV = AR^{\beta}$. Data sample-46 *PSRV* spectra (50-percent damping) from the Gasbuggy event; yield 26 kilotons; distance (*R*) range from 5 to 90 km. The recording stations were located on rock or thin (1–30 m) alluvium within the San Juan Basin. From Foote, Hays, and Klepinger (1969)]

Period (s)	Mean distance exponent (β)	Standard error of estimate (σ)	Period (s)	Mean distance exponent (β)	Standard error of estimate (σ)
0.09	-1.48	2.04	0.54	-1.63	2.35
.12	-1.66	2.00	.74	-1.70	1.70
.16	-1.73	1.82	1.00	-1.54	1.70
.22	-1.83	2.04	1.33	-1.42	1.55
.29	-1.84	2.09	1.82	-1.32	1.55
.40	-1.76	2.04	2.44	-1.27	1.66

lower frequency spectral components. Figure 23 shows the S. 16° E. horizontal component accelerogram recorded at Pacoima Dam from the 1971 San Fernando, Calif. earthquake and the corresponding velocity and displacement seismograms derived from it. The peak horizontal acceleration was estimated to be 1.2 *g*, the largest value obtained to date. The corresponding peak velocity and the peak displacement were, respectively, 115 cm/s and 43 cm.

TYPES OF INFORMATION DERIVED FROM THE SEISMOGRAM

Information about the seismic source parameters of an earthquake can be derived from the seismograph records. Examples in the literature include: Savage,

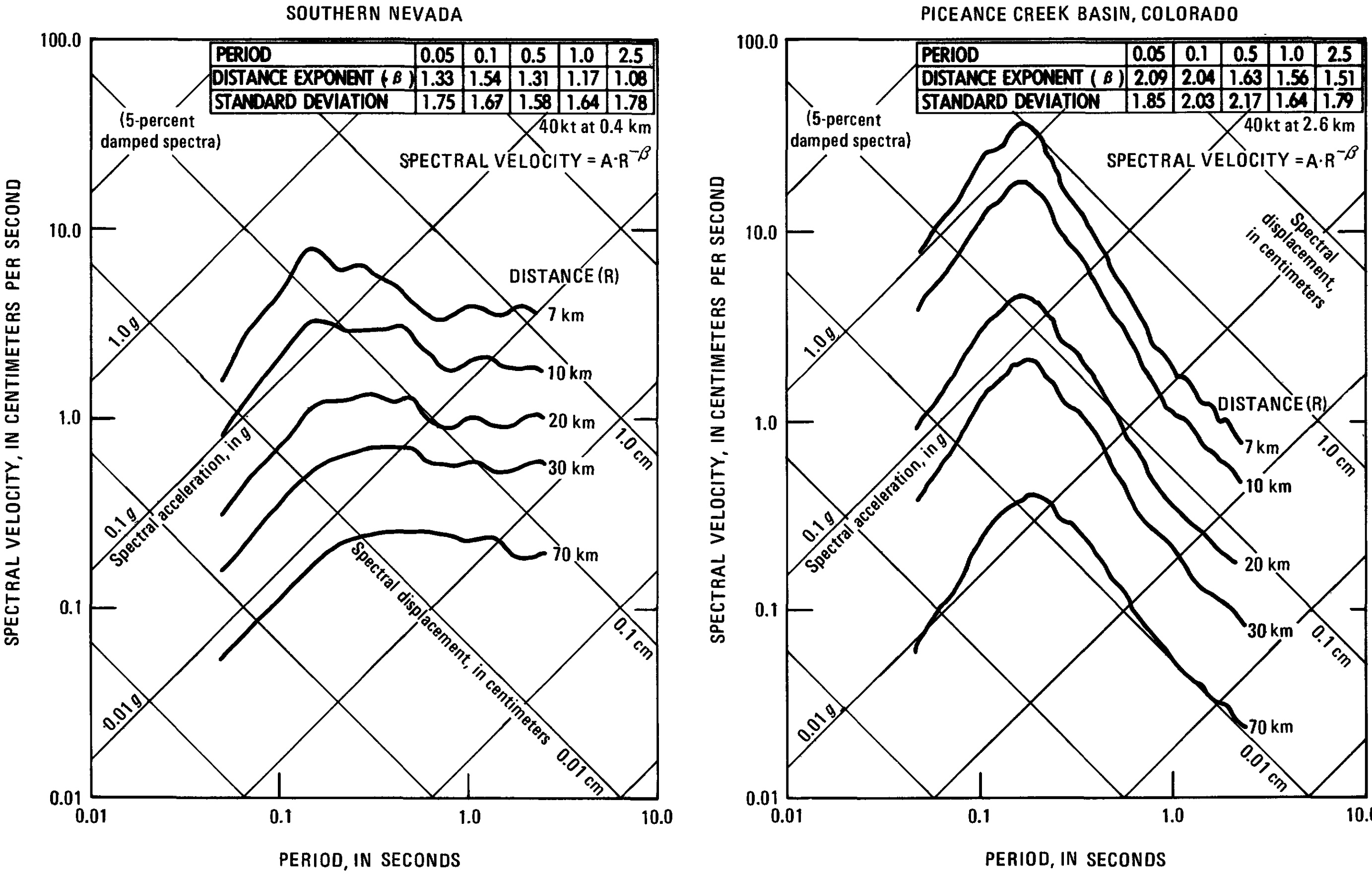


FIGURE 20.—Frequency-dependent attenuation of horizontal ground motions, southern Nevada and Colorado.

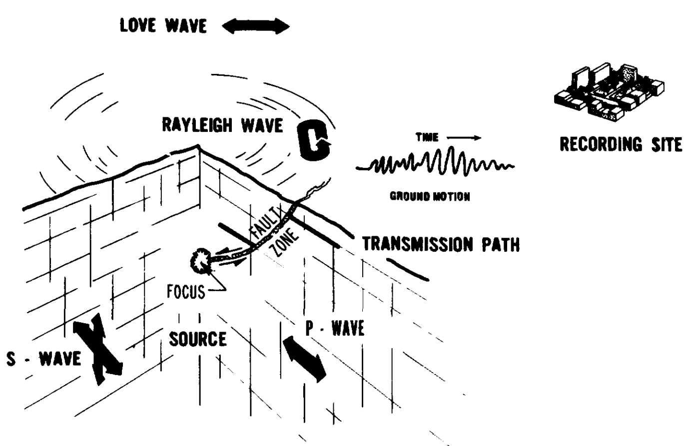


FIGURE 21.—Schematic diagram of elements that affect ground motion.

1966; Kanamori, 1970; Brune, 1970; Aki, 1972; Bolt, 1972; Savage, 1972; Hanks and Wyss, 1972; Trifunac, 1972a, b; Molnar, Tucker, and Brune, 1973; Randall, 1973; Gibowicz, 1973, Thatcher and Hamilton, 1973; Thatcher and Hanks, 1973; Savage, 1974; Boore and Zoback, 1974; Johnson and McEvilly, 1974; Archambeau, 1975; Kelleher and Savino, 1975; Hanks, Hileman, and Thatcher, 1975; Knopoff and Mouton, 1975; Anderson and Fletcher, 1976; Herrmann, 1976; Bollinger, Langer, and Harding, 1976; Helmberger and Johnson, 1977; and Kanamori, 1977. These examples demonstrate that the following parameters, considered to be important in constructing a model of faulting and in estimating ground motion effects, can be obtained:

1. magnitude (M_s, m_b, M_L) of the earthquake;
2. the spatial dimensions of the fault which ruptured;
3. seismic energy released by the earthquake;
4. moment of the earthquake;
5. average displacement across the fault;
6. orientation of the fault;
7. sense of slip across the fault;
8. depth of the fault;
9. velocity with which rupture propagates on the fault;
10. the elastic constants of the medium in which the fault is located;
11. the stress drop across the fault;
12. the configuration of the fault plane at depth (that is, whether planar or warped); and

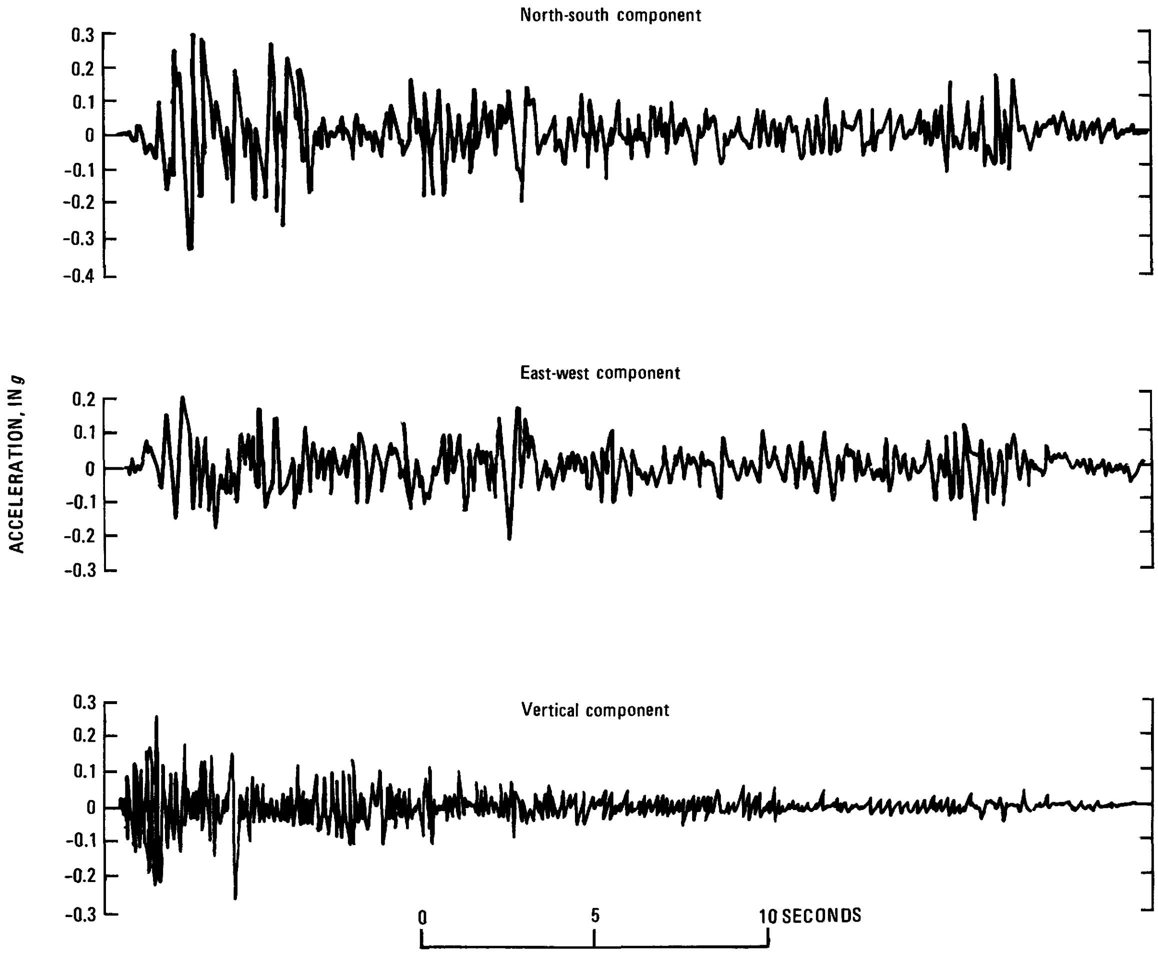


FIGURE 22.—Accelerogram of the 1940 Imperial Valley, Calif. earthquake recorded at El Centro, Calif.

13. complexity of energy release (that is, multiple sources).

Information about the characteristics of the transmission path and the site can also be extracted from the seismogram or the spectra derived from it. The types of information available include:

1. values of Q (Knopoff, 1964; Berg and others, 1971; Joyner and others, 1976; Bakun and others, 1976);
2. frequency-dependent filtering effects (Murphy, Weaver, and Davis, 1971; Hays and Murphy, 1971; Hanks, 1976; King and Hays, 1977);
3. site transfer functions (Lastrico and others, 1972; Hays, 1977a, b, 1978; Rogers and Hays, 1978).

The magnitude of an earthquake is the most familiar number computed from a seismogram (Duda and Nuttli, 1974). It is based on a measure of seismic-trace amplitude in or near a particular frequency band, and it is independent of the observation point. M_L, the original magnitude introduced in 1935 by Richter, is defined as the logarithm of the maximum recorded (trace) amplitude written by a Wood-Anderson seismograph with specified constants (free period: 0.8 sec; maximum magnification: 2,800; damping factor: 0.8) when the seismograph is on firm ground at an epicentral distance of 100 km. Observations at distances other than 100 km are corrected to the standard distance by using empirical curves, Figure 24 illustrates how the Richter magnitude is determined from a seismogram.

The body-wave (m_b) and surface-wave (M_s) magnitude scales, which are defined, respectively, in terms of 1- and 20-second-period seismic waves, are widely used. These three magnitude scales (M_L, m_b, and M_S) are interrelated by empirical formulas (see Duda and Nuttli, 1974).

Seismic moment, which characterizes the overall deformation at the source, is an interpretive quantity that some investigators (for example, Hanks and others, 1975; Geller, 1976, and Kanamori, 1977) consider to be better than magnitude for characterizing the earthquake's source strength. This is especially true for great earthquakes (M>8) because the rupture dimensions of the earthquake exceed the wavelengths

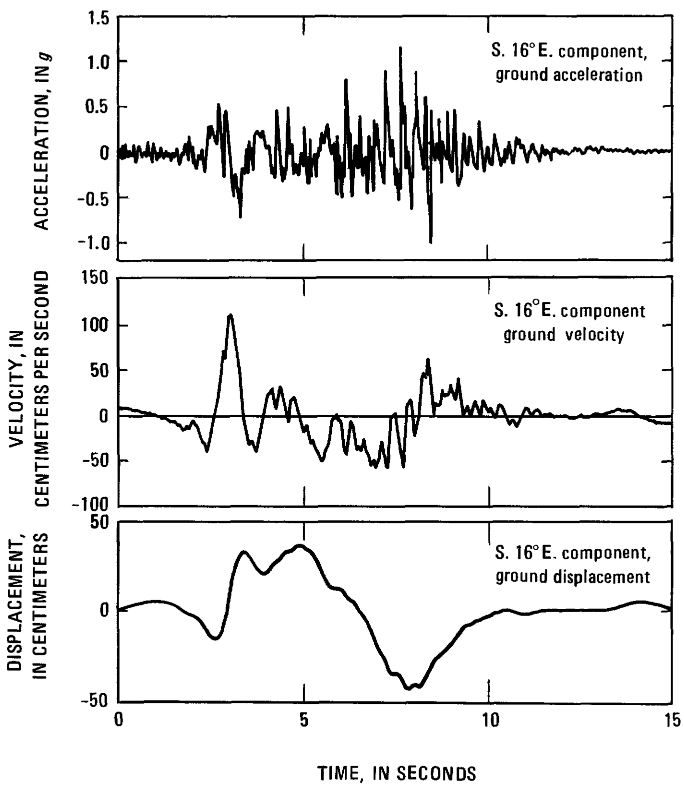


FIGURE 23.—S. 16° E. accelerogram recorded at Pacoima Dam and the velocity and displacement seismograms derived from it; 1971 San Fernando, Calif. earthquake.

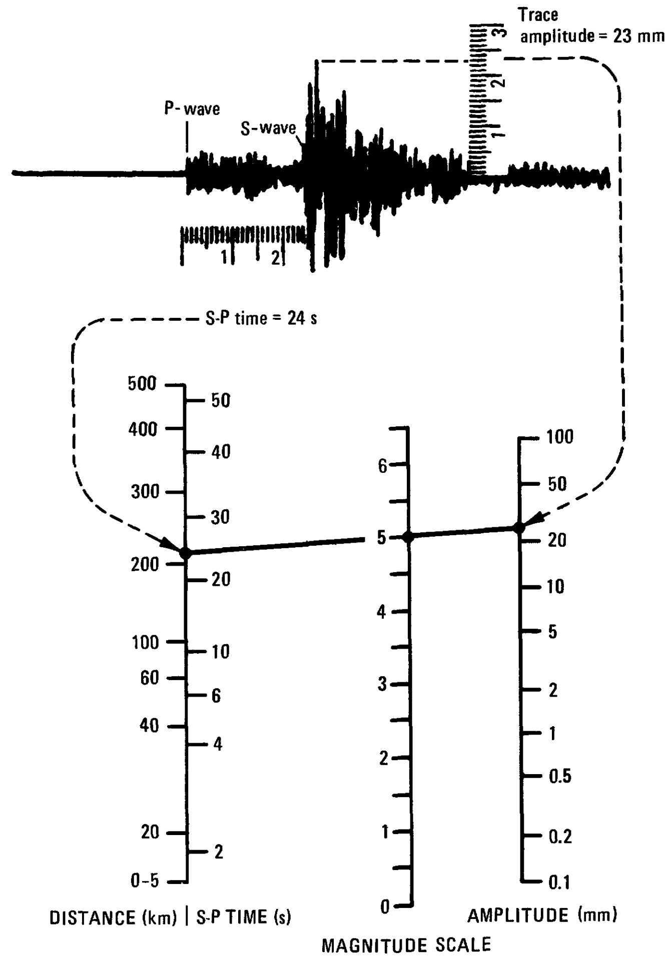


FIGURE 24.—Determination of Richter magnitude. Using the maximum amplitude of the seismogram and the difference in arrival times of the P and S waves, the value of magnitude can be read from the nomogram.

of the seismic waves used in the magnitude determination. Although seismic moment is an interpretative quantity, its greatest advantage is that it can be interpreted simply in terms of the source mechanism; that is, the moment is proportional to the product of the fault area and the displacement across the fault.

The magnitudes and seismic moments derived for a number of southern California earthquakes are listed in table 14. Although additional research is needed to establish all the physical facts about seismic moment and its applicability in earthquake-resistant design, one of the most interesting results obtained to date is the remarkable linearity that exists between the logarithm of the seismic moment and the logarithm of the fault area (Thatcher and Hanks, 1973). This linearity suggests a constant average stress drop of about 10 bars in earthquakes.

PEAK GROUND ACCELERATION

Current practice in design of earthquake-resistant structures is to use peak ground acceleration as a measure of the severity of ground motion even though peak acceleration may not be the best parameter to represent this characteristic of ground motion. Peak acceleration is used because of its familiarity and wide acceptance in the engineering community as a measure of the lateral forces on high-frequency structural systems. For intermediate- and low-frequency systems, ground velocity and displacement data are more applicable.

Values of peak horizontal ground acceleration, tabulated in table 15, have been used by various investigators to develop empirical relations for estimating horizontal ground motions.

TABLE 14.—*Magnitude and seismic moments of southern California earthquakes*

[From Hanks (1976)]

Date	Geographic locality	Magnitude	Seismic moment (10^{25} dyne-cm)
Jan. 9, 1857[1]	Fort Tejon	8 +	900
March 26, 1872[1]	Owens Valley	8 +	500
July 22, 1899[1]	San Jacinto	7 ±	15
March 11, 1933	Long Beach	6.3	2
May 19, 1940	Imperial Valley	7.1	30
July 21, 1952	Kern County	7.7	200
April 9, 1968	Borrego Mountain	6.4	6
Sept. 12, 1970	Lytle Creek	5.4	.1
Feb. 9, 1971	San Fernando	6.4	10

[1]Noninstrumental magnitude assignment.

TABLE 15.—*Values of peak horizontal ground acceleration recorded in past earthquakes and used for estimating horizontal ground motions in earthquake-resistant design*

[From Seed, Murarka, Lysmer, and Idriss 1976]

Earthquake	Date	Magnitude	Approximate source distance (km)	Component of motion	Maximum Accleration (g)	Soil depth (m)	Recording site
Rock sites							
Helena, Mont	10/31/35	6.0	8	North—South East—West	0.146 .145	rock	Carrol College, Helena.
Kern County, Calif	7/21/52	7.7	43	North 21 East South 69 East	.156 .179	do	Taft, Calif.
San Francisco, Calif	3/22/57	5.25	11	North 10 East South 80 East	.083 .105	do	Golden Gate Park, San Francisco.
Lytle Creek, Calif	9/12/70	5.4	13	South 25 West South 69 East	.197 .142	do	Wrightwood, Calif.
Do.			19	North—South East—West	.164 .177	do	Devils Canyon, San Bernardino, Calif.
Parkfield, Calif	6/27/66	5.6	7	North 65 West South 25 West	.269 .347	do	Temblor, Calif.
Borrego Mtn., Calif	4/8/68	6.5	134	North 33 East North 57 West	.041 .046	do	SCE Power Plant, San Onofre, Calif.
San Fernando, Calif	2/9/71	6.6	3–5	South 16 East North 76 West	1.24 1.075	do	Pacoima Dam.
Do.			21	North 21 East North 69 West	.367 .287	do	Lake Hughes, Sta. 12.
Do.			24	North—South East—West	.164 .147	do	3838 Lankershim Blvd., Los Angeles.
Do.			26	South 69 East South 21 West	.188 .394	do	Lake Hughes, Sta. 4.
Do.			30	South 08 East South 82 West	.217 .202	do	Santa Felicia Dam (outlet)
Do.			31	North—South East—West	.180 .171	do	Griffith Park Observatory.
Do.			30	North—South East—West	.089 .192	do	Cal. Tech. Seismol. Lab., Pasadena.
Do.			40	North 03 West North 87 East	.176 .213	do	Santa Anita Dam.
Stiff soil sites							
Lower California	12/30/34	6.5	58	North—South East—West	0.160 .182	32	El Centro, Calif.
Imperial Valley, Calif	5/18/40	7.0	8	North—South East—West	.33 .21	32	Do.
San Francisco, Calif	3/22/57	5.25	16	North 09 West North 81 East	.043 .046	45	Alexander Bldg., San Francisco.
Do.			17	South 09 East South 81 West	.085 .056	64	State Bldg., San Francisco.
Parkfield, Calif	6/27/66	5.6	.1	North 65 East	.489	48	Cholame-Shandon 2.
Do.			5	North 05 West	.354	32	Cholame-Shandon 5.
San Fernando, Calif	2/9/71	6.6	21	North 21 East North 69 West	.315 .270	19	Castaic, Old Ridge Route.
Do.			35	North—South East—West	.170 .211	64	Hollywood Storage, P.E. Lot, Los Angeles.
Do.			39	North—South	.136	14	3470 Wilshire Blvd. Los Angeles.
Do.			39	North 9 West	.153	32	3550 Wilshire Blvd., Los Angeles.
Do.			28	North 11 East North 79 West	.225 .149	22	15250 Ventura Blvd., Los Angeles.
Do.			28	South 12 West	.243	22	14724 Ventura Blvd., Los Angeles.
Do.			39	North—South East—West	.161 .165	13	3407 W. Sixth St., Los Angeles.

TABLE 15.—*Values of peak horizontal ground acceleration recorded in past earthquakes and used for estimating horizontal ground motion in earthquake-resistant design*—Continued

Earthquake	Date	Magnitude	Approximate source distance (km)	Component of motion	Maximum Accleration (g)	Soil depth (m)	Recording site
Deep cohesionless soil sites							
Western Washington	4/13/49	7.1	20	South 04 East South 86 West	0.165 .280	132	Highway Test Lab., Olympia, Wash.
Kern County, Calif	7/21/52	7.7	127	North—South East—West	.047 .053	112	Cal. Tech., Athenaeum, Pasadena.
Eureka, Calif	12/21/54	6.5	25	North 11 West North 79 East	.168 .257	80	Federal Bldg., Eureka.
Do.			30	North 44 East North 46 West	.159 .201	160	City Hall, Ferndale.
Puget Sound, Wash	4/29/65	6.5	58	South 04 East South 86 West	.137 .198	134	Highway Test Lab., Olympia, Wash.
Ferndale, Calif	12/10/67	5.6	25	North 46 West South 44 West	.105 .237	160	City Hall, Ferndale.
San Fernando, Calif	2/9/71	6.6	16	North—South East—West	.255 .134	176	8244 Orion Blvd., Los Angeles.
Do.			19	North—South East—West	.117 .110	176	15107 Vanowen St., Los Angeles.
Do.			37	North—South East—West	.095 .109	112	Cal. Tech., Athenaeum, Pasadena.
Do.			37	North—South East—West	.202 .185	112	Cal. Tech., Millikan Library, Pasadena.
Do.			30	North—South East—West	.141 .212	148	Cal. Tech., Jet Propulsion Lab., Pasadena.
Sites with soft-to-medium clay and sand							
San Francisco, Calif	3/22/57	5.25	18	North 45 East North 45 West	0.047 .046	91	So. Pacific Bldg., San Francisco.
Alaska	4/3/64	6.0	131	North 13 East North 77 West	.044 .051	110	Elmendorf AFB, Anchorage.

In current design practice, it is common to assume that the maximum ground accelerations in the two horizontal directions are equal and that the maximum vertical acceleration is two-thirds or more of the maximum horizontal acceleration. The assumption of equality for the two horizontal components of ground motion is not always correct, so alternate approaches such as the spectrally maximized record (Shoja-Taheri and Bolt, 1977) may be needed in some design applications. The assumed ratio of ⅔ for peak vertical to peak horizontal ground acceleration has a probability of exceedance of 23 percent (Werner and Ts'ao, 1975).

A number of investigators, (for example, Housner, 1965; Davenport, 1972; Boore and Page, 1972; Page and others, 1972; Schnabel and Seed, 1973; Dietrich, 1973; Orphal and Lahoud, 1974; Trifunac and Brady, 1975a; Seed, Murarka, Lysmer, and Idriss, 1976; Trifunac, 1976a; Hanks and Johnson, 1976; and Boore and others, 1978) have studied various aspects of peak ground acceleration. Some of these studies and their conclusions are summarized below:

1. Hanks and Johnson (1976) studied a set of strong-motion accelerograms and showed that the causative processes that generate peak ground accelerations within approximately 10 km of the source are independent of magnitude (M) for $4.5 \leq M \leq 7.1$. This result is important because current design practice assumes that peak acceleration is strongly dependent on magnitude.
2. Trifunac and Brady (1975a), on the basis of regression analysis of the strong-motion data recorded in the Western United States from 1933 to 1971, suggested that peak accelerations at the fault, for the frequency band 0.07–25 Hz, probably do not exceed about 3–5 *g*. They proposed that the maximum acceleration may be reached at a magnitude of 6.5–7.0. Both conclusions are controversial, mainly because of limited data and overemphasis of data from the San Fernando earthquake.
3. Seed, Murarka, Lysmer, and Idriss (1976) noted that peak amplitudes of ground acceleration measured at sites on rock in the Western

United States exhibit very little difference statistically from peak amplitudes measured at sites underlain by less than 48 m of stiff clay, sand, or gravel. At sites where rock is overlain by at least 80 m of cohensionless soil, the mean recorded peak acceleration is greater by factors of 3.5–4.0 than at rock sites for weak ground motions on the order of 0.003 *g*. The effect is reversed for peak accelerations at rock sites between 0.1 and 0.7 *g*, and these peak accelerations tend to exceed those recorded at deep cohesionless soil sites by as much as 80 percent.

4. Dietrich (1973), using finite element techniques to model various earthquake sources, showed that peak ground acceleration is proportional to stress drop. Hence, the variability in peak ground acceleration is a function of the variability in stress drop. Data to quantify the variability of stress drop are scarce. Rogers, Perkins, and McKeown (1976) estimated on the basis of the available data that stress drop has a log-normal distribution with a mean stress drop of about 20 bars and a geometrical standard deviation of 3.7.

The range of horizontal peak acceleration for sites on rock in the Western United States is shown in figure 25. These curves are based on limited data, especially for source-to-site distances of less than 20 km, which causes disagreement about whether the "probable upper bound" is correct. For example, the 1975 Oroville, California earthquake (M_L=4.7) produced a peak ground acceleration of 0.7 *g* at a distance of 11.2 km from the fault. The 1972 Stone Canyon, California earthquake (M_L=4.7) produced peak ground accelerations of 0.19, 0.63, and 0.16 *g* at distances of 3, 6, and 7 km, respectively. The 1971 San Fernando, California earthquake produced a peak acceleration of 1.2 *g* at Pacoima dam and also exceeded the bounds proposed by Schnabel and Seed (1973). The explanation for these observations is that they are "rare" points lying at the extremes of the distribution of the acceleration data sample or that the curves proposed by Schnabel and Seed depict peak ground accelerations that are too low, especially those close to the fault.

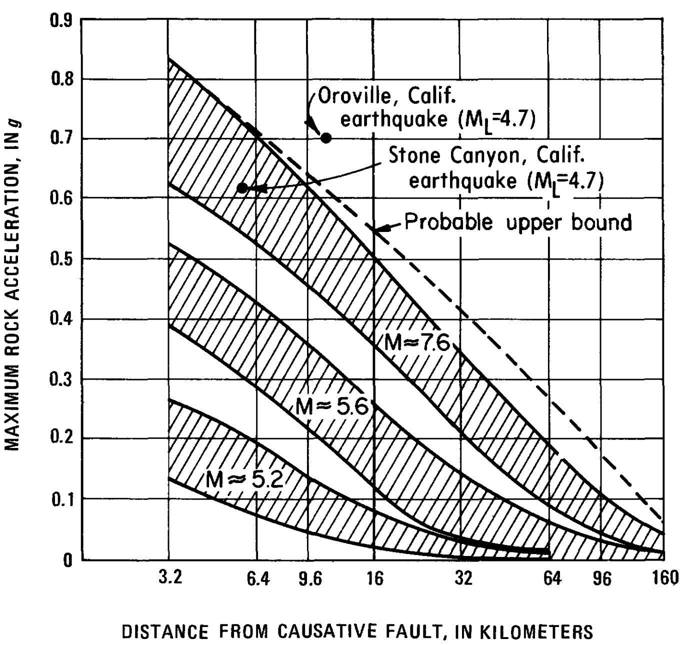


FIGURE 25.—Range of horizontal peak acceleration as a function of distance and magnitude for rock sites in the Western United States (from Schnabel and Seed, 1973).

PEAK GROUND VELOCITY AND DISPLACEMENT

Ground motion can also be characterized by velocity and displacement time histories derived from an accelerogram and their peak values. Ground velocity and displacement values (table 16) seem to have a more determinant upper bound than ground acceleration. Displacement time histories and spectra are used in defining seismic moment, stress drop, and source dimensions and are also used in wave propagation studies. The amplitudes of ground displacement are propagated more coherently than amplitudes of ground velocity and acceleration because their low-frequency spectral composition is not very sensitive to scattering by small geologic inhomogeneities. Velocity and displacement time histories are needed, respectively, for modeling earthquake effects on intermediate- and low-frequency structural systems. Velocity time histories can be used in conjunction with the shear-wave velocity of the surficial materials to estimate the level of shear strain induced in the soil and rock through the relation

$$\frac{\partial u}{\partial x} = \frac{1}{\beta}\frac{\partial u}{\partial t}$$

where $\frac{\partial u}{\partial x}$ is the shear strain level, $\frac{\partial u}{\partial x}$ is the peak ground velocity, and β is the shear-wave velocity of the material.

Various investigators (for example, Newmark and Rosenbleuth, 1971; Page and others, 1972; Ambraseys, 1973; Trifunac and Brady, 1975a; Trifunac, 1976a; Seed, Murarka, Lysmer, and Idriss, 1976; and Boore and others, 1978) have evaluated peak velocity and displacement in terms of distance and magnitude. Some of the important conclusions of these studies are:

1. Trifunac and Brady (1975a) suggested that, at the 90-percent confidence level, the peak ground velocities and displacements at the

TABLE 16.—*Values of peak horizontal ground velocity and displacement derived from accelerograms of past earthquakes and used for estimating horizontal ground motions in earthquake-resistant design*

[From Seed, Ugas, and Lysmer (1976)]

Earthquake	Date	Magnitude	Approximate source distance (km)	Component of motion	Maximum velocity (cm/s)	Maximum displacement (cm)	Recording site
			Rock sites				
Helena, Mont	10/31/35	6.0	8	North—South	7.3	1.4	Carroll College,
				East—West	13.3	3.7	Helena.
Kern County, Calif	7/21/52	7.7	43	North 21 East	15.7	6.7	Taft, Calif.
				South 69 East	17.7	9.2	
San Francisco, Calif	3/22/57	5.25	11	North 10 East	4.9	2.3	Golden Gate Park,
				South 80 East	4.6	.8	San Francisco.
Lytle Creek, Calif	9/12/70	5.4	13	South 25 West	9.6	1.03	Wrightwood,
				South 69 East	8.9	2.21	Calif.
Do.			19	North—South	------	------	Devils Canyon,
				East—West	------	------	San Bernardino, Calif.
Parkfield, Calif	6/27/66	5.6	7	North 65 West	14.5	4.7	Temblor, Calif.
				South 25 West	22.5	5.5	
Borrego Mountain, Calif	4/8/68	6.5	134	North 33 East	3.7	1.6	SCE Power Plant,
				North 57 West	4.2	2.9	San Onofre, Calif.
San Fernando, Calif	2/9/71	6.6	3–5	South 16 East	115.5	37.7	Pacoima Dam.
				North 76 West	57.7	10.8	
Do.			21	North 21 East	14.7	1.8	Lake Hughes,
				North 69 West	12.4	8.9	Sta. 12.
Do.			24	North—South	12.3	4.9	3838 Lankershim Blvd.,
				East—West	15.0	5.4	Los Angeles.
Do.			26	South 69 East	9.9	7.0	Lake Hughes,
				South 21 West	6.2	4.6	Sta. 4.
Do.			30	South 08 East	9.9	7.0	Santa Felicia Dam,
				South 82 West	6.2	4.6	(outlet).
Do.			31	North—South	20.5	7.3	Griffith Park
				East—West	14.5	5.5	Observatory
Do.			30	North—South	5.8	1.6	Cal. Tech. Seismol.
				East—West	11.6	5.0	Lab., Pasadena.
Do.			40	North 03 West	5.3	3.2	Santa Anita Dam.
				North 87 East	6.7	5.9	
			Stiff soil sites				
San Fernando, Calif	2/9/71	6.6	21	North 21 East	16.5	4.2	Castaic, Old
				North 69 West	27.2	9.3	Ridge Route.
Do.			28	North 11 East	28.2	13.4	15250 Ventura Blvd.,
				North 79 West	23.5	10.3	Los Angeles.
Do.			28	South 12 West	31.5	18.3	14724 Ventura Blvd.
				North 78 West	17.8	9.5	Los Angeles.
Do.			35	North—South	16.5	8.0	Hollywood Storage,
				East-West	21.1	14.7	P.E. Lot, Los Angeles.
Do.			39	North—South	22.3	11.4	3470 Wilshire Blvd.,
				East—West	18.5	11.6	Los Angeles.
Do.			39	North—South	18.0	10.3	3710 Wilshire Blvd.,
				East—West	22.1	12.9	Los Angeles.
Do.			39	North—South	18.3	9.0	3407 W. Sixth St.,
				East—West	16.5	10.3	Los Angeles.
Do.			39	North—South	14.7	9.9	3345 Wilshire Blvd.,
				East—West	16.1	9.1	Los Angeles.
Do.			67	North 65 East	4.1	2.6	2516 Via Tejon.
				South 25 East	5.0	3.4	
			Sites underlain by deep cohesionless soil				
Puget Sound, Wash	4/29/65	6.5	58	South 04 East	8.0	2.7	Highway Test Lab.,
				South 86 West	12.7	3.8	Olympia, Wash.
San Fernando, Calif	2/9/71	6.6	16	North—South	30.0	14.9	8244 Orion Blvd.,
				East—West	23.9	13.8	Los Angeles.
Do.			19	North—South	31.5	17.5	15107 Vanowen St.,
				East—West	28.8	15.3	Los Angeles.

TABLE 16.—*Values of peak horizontal ground velocity and displacement derived from accelerograms of past earthquakes and used for estimating horizontal ground motions in earthquake-resistant design*—Continued

Earthquake	Date	Magnitude	Approximate source distance (km)	Component of motion	Maximum velocity (cm/s)	Maximum displacement (cm)	Recording site
------ Do. ------			39	North—South East—West	7.9 14.3	3.0 7.3	Cal. Tech., Athenaeum, Pasadena.
------ Do. ------			37	North—South East—West	9.8 16.3	2.7 6.9	Cal. Tech., Millikan Library, Pasadena.
------ Do. ------			30	North—South East—West	9.0 13.4	2.9 5.0	Cal. Tech. Jet Propulsion Lab., Pasadena.

fault for the frequency band 0.07–25 Hz probably do not exceed 400–700 cm/s and 200–400 cm.

2. Seed, Murarka, Lysmer, and Idriss (1976) proposed that the average maxima of strong motion velocity and displacement may be reached for magnitude 6.5–7.0 earthquakes; however, the validity of their suggestion has yet to be proved. They proposed the attenuation relation shown in figure 26 for moderate earthquakes.

DURATION

Duration of shaking has been shown to be one of the most important parameters of ground motion for causing damage. Some earthquakes (For example, Parkfield, Calif., 1966, and Stone Canyon, Calif., 1972) have produced short, high-frequency accelerograms, but they have not caused structural damage, even though the peak ground accelerations were on the order of 0.5 *g*. In other earthquakes that produced damage, the peak ground acceleration level was less, but the duration of shaking for a wide range of frequencies was greater. The 1966 Parkfield, Calif., and 1967 Koyna Dam, India, earthquakes both produced peak ground-accelerations and velocities as large or larger than those produced by the 1940 Imperial Valley, Calif. earthquake. The Imperial Valley earthquake caused more damage than either of the other two earthquakes although towns were about the same distance from each earthquake's epicenter, mainly because the duration of ground shaking was several times greater in the Imperial Valley earthquake.

Duration of shaking also plays an important causative role in liquefaction, a physical process that can also lead to damage. In the 1964 Alaska earthquake, for example, soil liquefaction developed about 90 seconds after the ground shaking began, but it has been postulated that it would not have occurred if the ground shaking had lasted only 45 seconds (Seed and Idriss, 1971).

Since 1964, a number of investigators (for example, Esteva and Rosenblueth, 1964; Housner, 1965; Husid, 1967; Rogers, 1972; Page and others, 1972; Bolt, 1973; Hays and others, 1973; Perez, 1973; Housner, 1975; Hays, 1975a; Trifunac and Brady, 1975b; Dobry and others, 1977; Trifunac and Westermo, high-frequency accelerograms, but they have not caused structural damage, even though the peak ground accelerations were on the order of 0.5 *g*. In other earthquakes that produced damage, the peak ground 1977; and Hays and others, 1978) have studied duration of ground shaking. The studies by Trifunac and Brady (1975b) and Trifunac and Westermo (1977) were the most comprehensive in scope, but all the studies have provided evidence that three interrelated parameters (1) the amplitude, (2) the length of time that the ground shakes, and (3) the dominant frequency at which it shakes, are the parameters that cause structural damage.

Bracketed duration, a measure used frequently in the engineering community, is the time during which the acceleration level equals or exceeds some amplitude threshold such as 5 percent *g*. This parameter is illustrated in figure 27 for the accelerogram recorded at Pacoima Dam during the 1971 San Fernando, Calif. earthquake. The general trend of increasing bracketed duration with increase in magnitude is also shown in figure 27.

Trifunac and Brady (1975b) used a definition proposed by Husid (1967) to calculate the duration of strong earthquake ground motion. Their definition was based on 90 pecent of the integral of the squared time history, for example:

$$\int_0^T a\ (t)dt, \quad \int_0^T v\ (t)dt, \quad \int_0^T d\ (t)dt.$$

They correlated the integral (fig. 28) of the squared acceleration (a), velocity (v), and displacement (d) time histories with recording site conditions, magnitude, and epicentral distance and concluded:

1. The average duration for a "soft" alluvium site is 5–6 seconds longer than for an intermediate site and 10–12 seconds longer than for rock sites.

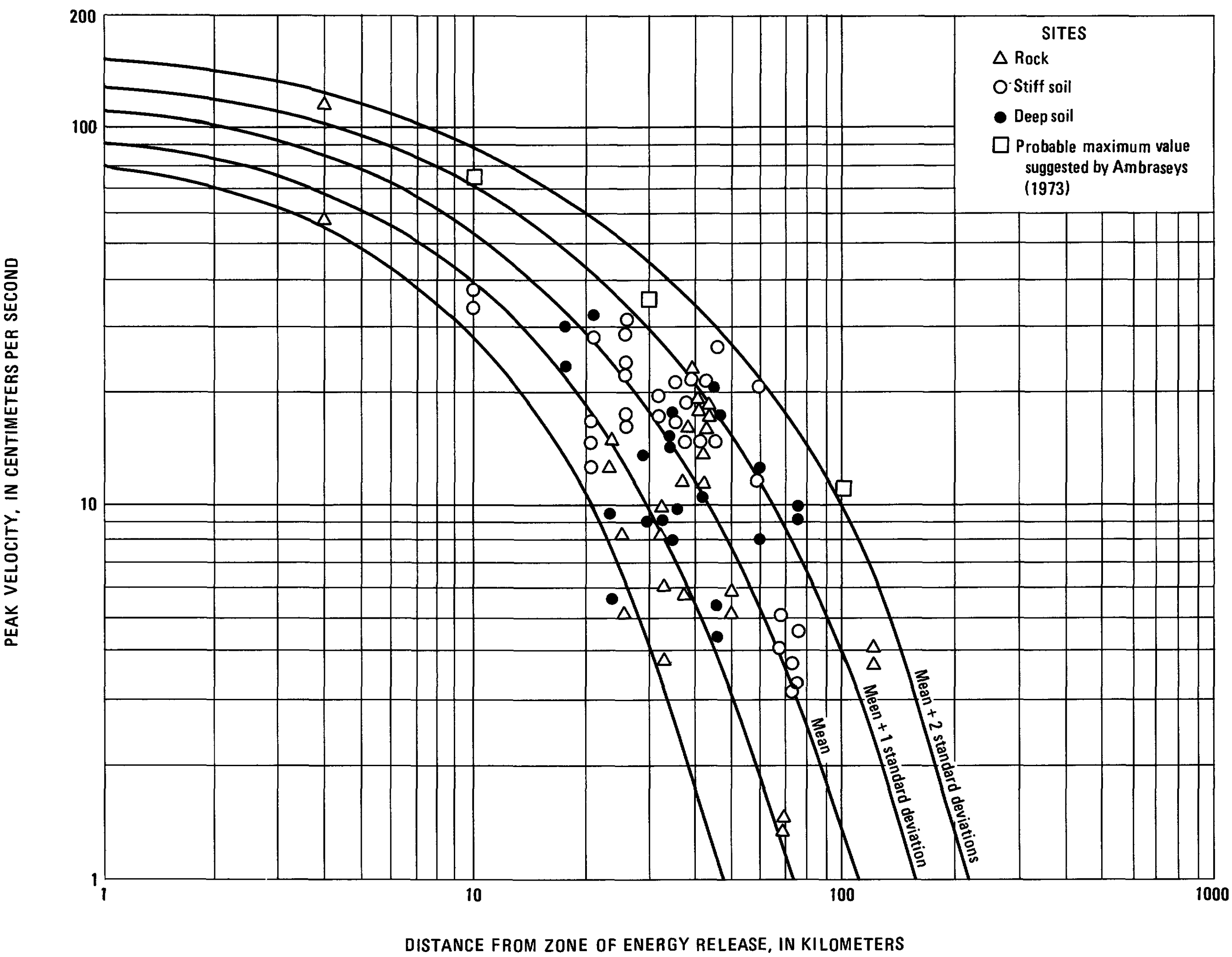


FIGURE 26.—Relation between peak horizontal ground velocity and distance from source of energy release for magnitude 6.5 earthquakes (from Seed, Murarka, Lysmer, and Idriss, 1976).

2. The average duration increases by 2 seconds for acceleration and about 5 seconds for displacement for each unit increase in earthquake magnitude.
3. The average duration increases about 1–1.5 seconds for every 10 km increase in epicentral distance.

Trifunac and Westermo (1977) extended the procedure for defining duration. Instead of deriving the integral of the squared seismogram, they calculated the integrals for 10–15 squared band-pass filtered time histories of the original seismogram. Duration derived in terms of filtered time histories exhibits the same trends as stated above, but the variability is less. Frequency-dependent characteristics of ground motion (For example, amplification) can be identified in the band-pass filtering process and eliminated from consideration in the analysis.

SPECTRA

Fourier techniques are the standard for spectral analysis of ground motion data. A Fourier spectrum resolves the ground-motion time history into an infinite series of simple harmonic functions in the frequency domain. The resulting transformation provides both an amplitude and a phase spectrum that are uniquely related to the seismogram.

Four amplitude spectra (fig. 29) are used frequently in engineering seismology. Examples of uses include: (1) analysis of ground-motion data (Hudson, 1962; Hays and others, 1975a); (2) source-mechanism studies (Savage, 1966; Brune, 1970; Trifunac, 1972b); (3) seismic attenuation studies (Hays, 1969; Trifunac, 1967b); (4) site amplification studies (Duke and Hradilek, 1973; Rorcherdt and Gibbs, 1976); and (5) soil-structure interaction (Liu and Fagel, 1973; Crouse and Jennings, 1975). The application proposed by Brune in

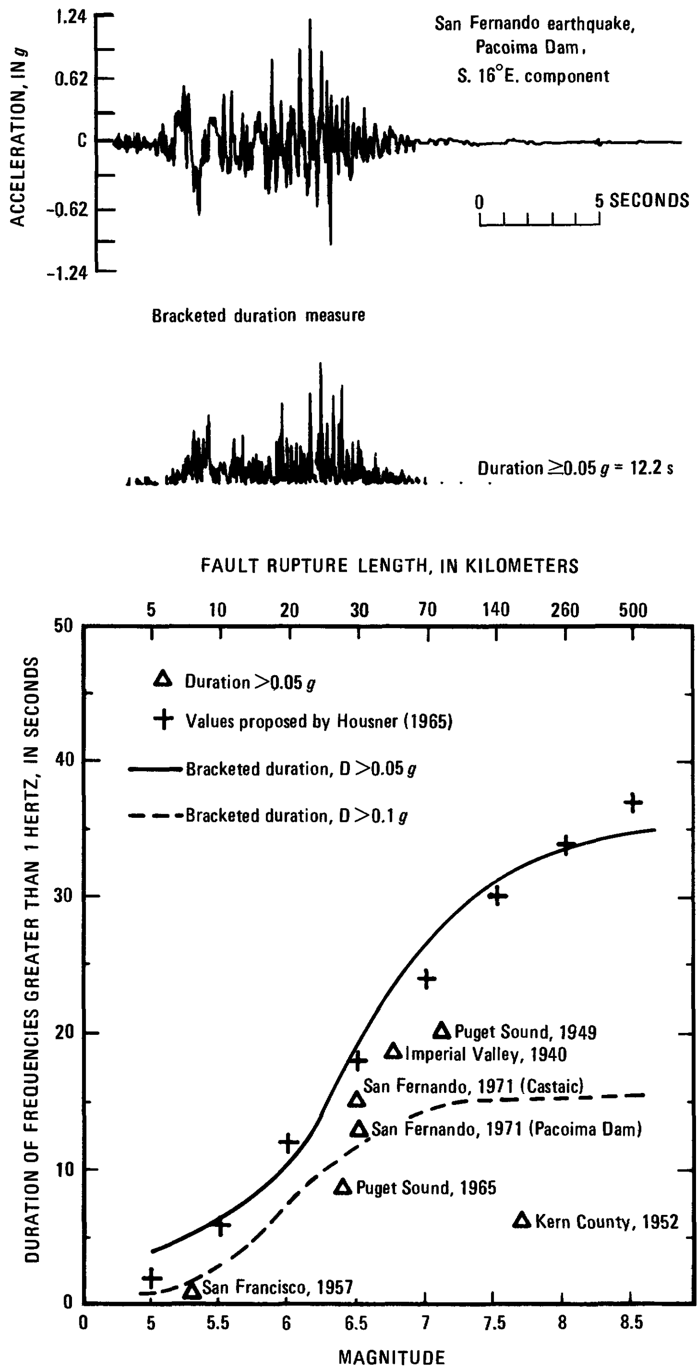


FIGURE 27.—Bracketed duration values for the S. 16° E. accelerogram recorded at Pacoima Dam from the 1971 San Fernando earthquake (top; from Hays, 1975a), and bracketed duration as a function of magnitude and fault rupture length (bottom; modified from Bolt 1973).

1970 to deduce source parameters from the far-field displacement spectrum has stimulated much important research in seismology. The displacement spectrum, after being corrected for instrument response and path propagation, has a flat low-frequency level (fig. 30), which is used to define the stress drop and seismic moment. It is also has a corner frequency (the frequency where the high- and low-frequency trends interact) that is related to the radius r of the equivalent circular fault causing the earthquake.

In engineering seismology the spectral characteristics of ground motion are normally displayed as response spectra, a form preferred by structural engineers for the study of building response. Structures respond as oscillating systems with fairly well defined periods of vibration, and their response to ground motion is strongly dependent on its spectral composition and duration. Simple systems such as viscous-damped pendulum or mass-spring systems have been successfully used to model structural elements (Blume and others, 1961). When such a model is excited by ground motion from an earthquake, it will respond by vibrating. The vibratory motion is described by the well known differential equation

$$\ddot{x}+2\omega_n hx+\omega_n{}^2x=-a(t)$$

where x is the relative displacement between the mass and ground, $\dot{x}$ and $\ddot{x}$ are the velocity and acceleration of the mass relative to the ground, h is the fraction of critical viscous damping, ω_n is the undamped natural frequency of vibration of the system, and $a(t)$ is the ground acceleration.

The Fourier amplitude spectrum has a close relation to the undamped velocity response spectrum (Hudson, 1962). These two spectral respresentations, although fundamentally different, are essentially interchangeable in seismic data analyses.

The response spectrum technique, proposed by Benioff (1934) and Biot (1943), is a method for determining the maximum amplitudes of response of an ensemble of simple damped, harmonic oscillators (a narrowband filter) when excited by a given ground-motion time history (fig. 31). The various response spectra are: (1) pseudo absolute acceleration (PSAA), (2) pseudo relative velocity (PSRV), (3) absolute acceleration (AA), (4) relative velocity (RV), and (5) relative displacement (RD). Each response characterization has a physical meaning. PSAA is a measure of the maximum elastic spring force per unit of mass. RD represents the maximum value of the relative displacement of the simple system during vibratory motion. PSRV gives an approximate index of the greatest velocity, relative to its base, of the center of mass of the resonant simple structure. PSRV can also be related to the maximum energy absorbed in the spring. For low damping, the PSRV spectrum provides an upper bound to the Fourier amplitude spectrum (Jenschke,1970).

Response spectra for four values of damping (0, 2, 5, and 10 percent of critical) derived from the horizontal component accelerogram recorded at El Centro from

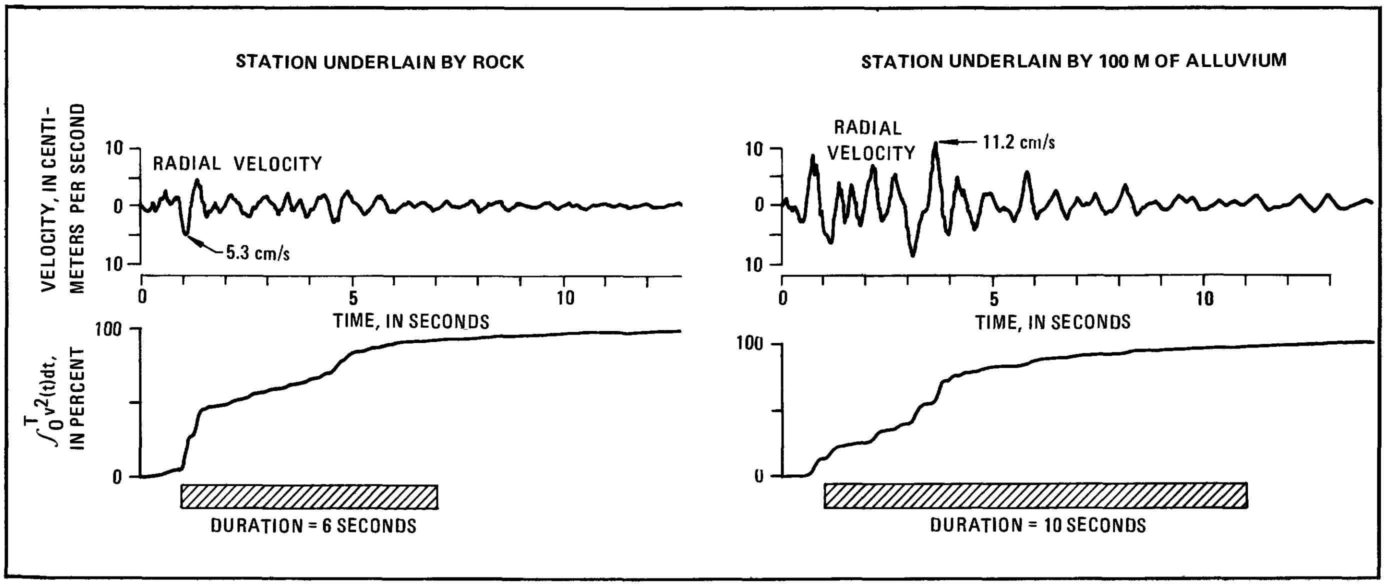


FIGURE 28.—Example of integral definition of duration of shaking for a site on rock and a site underlain by alluvium (from Hays and others, 1978).

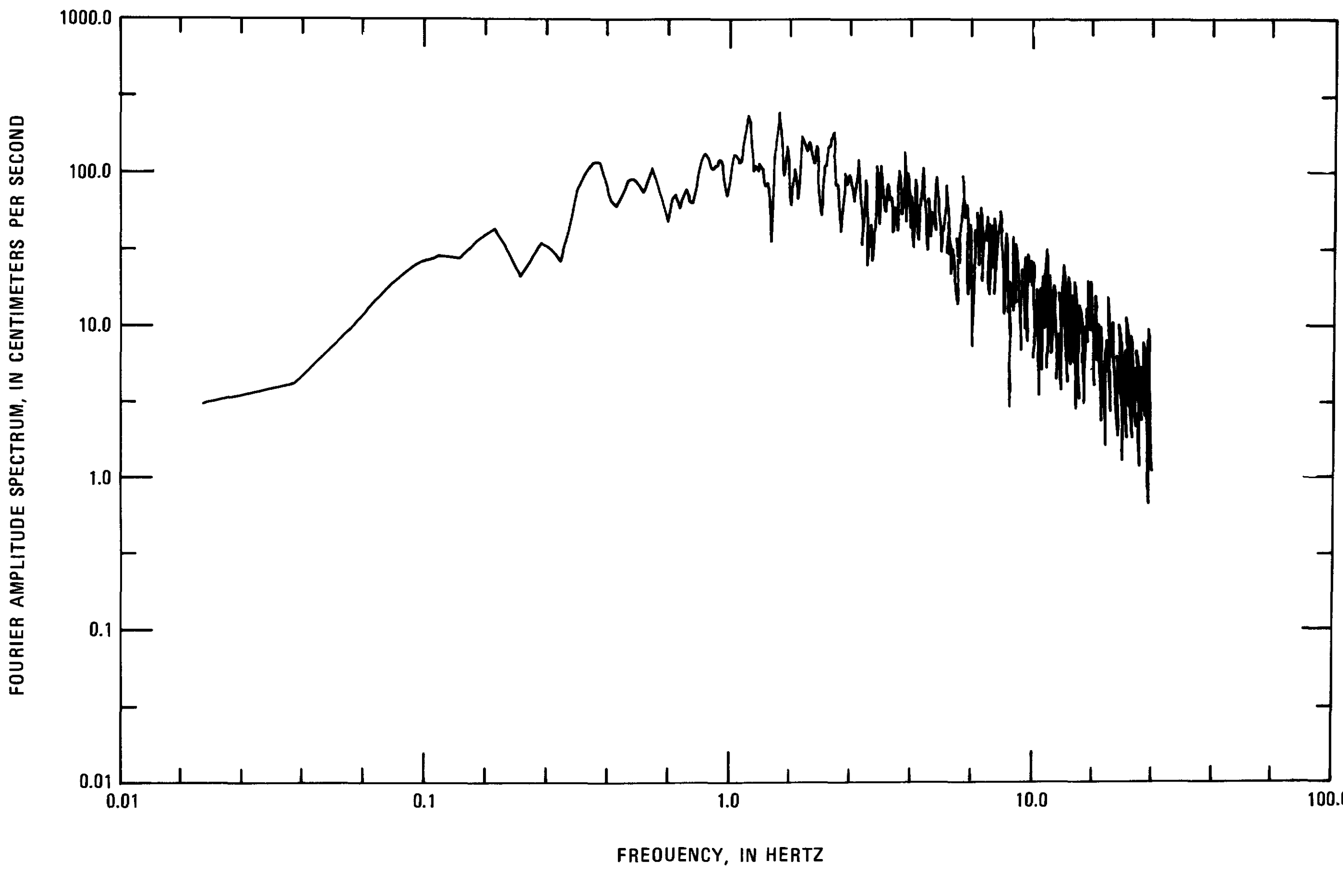


FIGURE 29.—Example of a Fourier amplitude spectrum derived from the accelerogram recorded at El Centro from the 1940 Imperial Valley, Calif., earthquake.

the 1940 Imperial Valley, Calif., earthquake are shown in figure 32. Response spectra are typically plotted on tripartite log-log paper. From such a plot, the spectral velocity, acceleration, and displacement can be determined simultaneously along with estimates of the peak ground acceleration and ground displacement. For

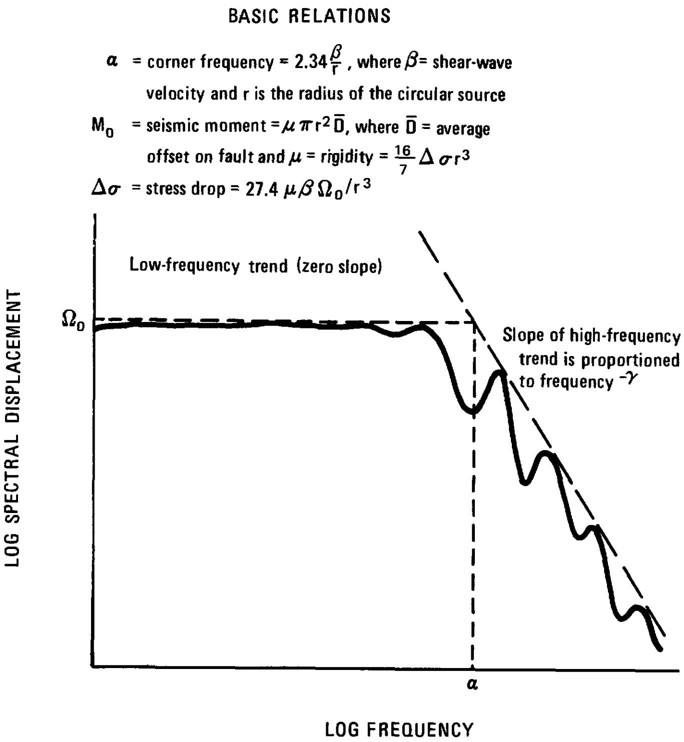


FIGURE 30.—Schematic illustration of far-field displacement spectrum and some of the information about the source that can be derived from it.

example, the peak value of horizontal ground acceleration is approximately equal to the value that the spectral acceleration approaches at very high frequencies (zero period), and the peak value of horizontal ground displacement is approximately the value which the spectral displacement approaches at very low frequencies (infinite period).

Another spectral representation, the time-dependent response envelope (Trifunac, 1971; Perez, 1973; Hays and others, 1973), is shown in figure 33. The example shown is for the 1940 Imperial Valley earthquake accelerogram recorded at El Centro, Calif. It demonstrates the increased information content over the standard response spectrum. This spectral representation is not widely used in earthquake-resistant design at the present time.

Response spectra are widely used in engineering seismology research to define the frequency-dependent effects caused by parameters of the earthquake source and the transmission path. It is well known, for example, that the dominant spectral composition of ground motion shifts to the long-period end of the spectrum with an increase in earthquake energy release. Figure 34 illustrates the shift of corner frequency for two PSRV spectra representing, respectively, the San Fernando earthquake (M=6.6) and an aftershock (M=3.2). Both events were recorded at the same recording site (Glendale Municipal Building, Glendale, Calif.) and had essentially identical travel paths. The difference in spectral composition, therefore, primarily correlates with the difference in source parameters for the two events. It is also well known that the earth tends to act like a low-pass filter on propagating seismic waves. That is, the high-frequency spectral components are attenuated more rapidly than low-frequency components. This effect is shown schematically in figure 35 for response spectra derived from accelerograms recorded during the 1971 San Fernando earthquake.

Frequency-dependent seismic-source scaling laws could be used in many design applications if they were available. Although the current practice of scaling ground-motion characteristics (for example, peak acceleration or response spectra values) in a linear manner to provide design ground-motion estimates is not satisfactory physically, the procedure has not been modified at the present time.

Frequency-dependent distance-scaling laws that characterize the low-pass filtering effect of the earth in various geographic regions of the United States could also be used if they were available. Very few frequency-dependent attenuation relations have been developed because of the lack of ground-motion data. The few relations that are available (King and Hays, 1977) are preliminary estimates. Peak ground acceleration is attenuated to the site then used as the high frequency anchor for the site-independent response spectrum. For sites in the Eastern United States where only Modified Mercalli intensity data are available, intensity is attenuated to the site, converted to peak acceleration, and used to define the response spectrum. (Intensity and the design response spectra will be discussed in a later section.)

A more accurate procedure for a scaling ground-motion data with distance could be used if data were available. Given a ground-motion response spectrum M_2 derived from a recorded accelerogram at epicentral distance R_2, the predicted spectrum M_1 of ground motion at distance R_1 is give by

$$M_1 = \left(\frac{R_1}{R_2}\right)^{\beta} M_2$$

where β is the distance scaling exponent (see tables 9–13) for a particular period. A procedure such as this would accurately account for the known differences in regional attenuation.

KNOWLEDGE GAINED FROM NUCLEAR EXPLOSION GROUND-MOTION STUDIES

During the past decade, more than 300 underground nuclear detonations have been conducted at the Nevada Test Site mainly on Yucca Flat or Pahute

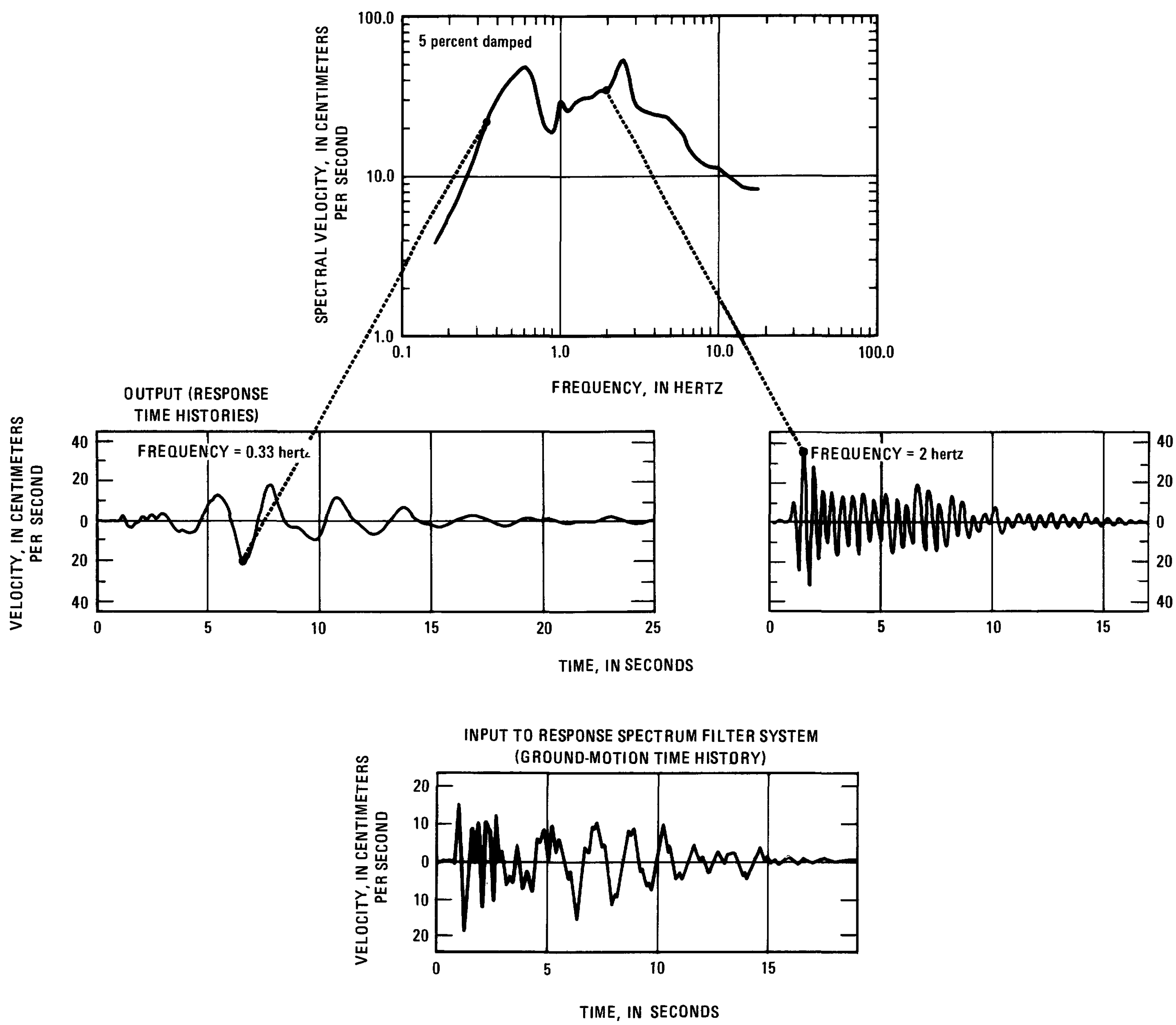


FIGURE 31.—The narrow-band-pass filtering involved in deriving a response spectrum.

Mesa (fig. 36), located northwest of Las Vegas, Nev. These detonations ranged in yield from about 1 to 1,200 kilotons (Springer and Kinneman, 1971, 1975). More than 4,000 velocity and acceleration seismograms were recorded on paper and tape. These seismograms were recorded at 600 different recording sites, which were selected for either research purposes or safety documentation. The source-to-station distances ranged from 0.4 to 600 km. The stations are underlain by rock of various types and unconsolidated materials of various thicknesses.

Eleven nuclear detonations have been conducted outside the Nevada Test Site. These detonations were as follows: Faultless and Shoal in central Nevada; Longshot, Milrow, and Cannikin on Amchitka Island, Alaska; Rulison and Rio Blanco in Colorado; Gnome and Gasbuggy in New Mexico; and Salmon and Sterling in Mississippi.

Ground-motion data recorded from some of the important nuclear detonations have been published (for example, Environmental Research Corporation, 1968, 1969, 1970a, b, c, 1974a; Hays and others, 1969; West, 1971; West and Christie, 1971). Comprehensive studies of the ground motion and structural response data have been performed and are summarized in reports by Environmental Research Corporation (1974b) and URS/John A. Blume, Engineers (1975). Research on nuclear explosion ground-motion data has established:

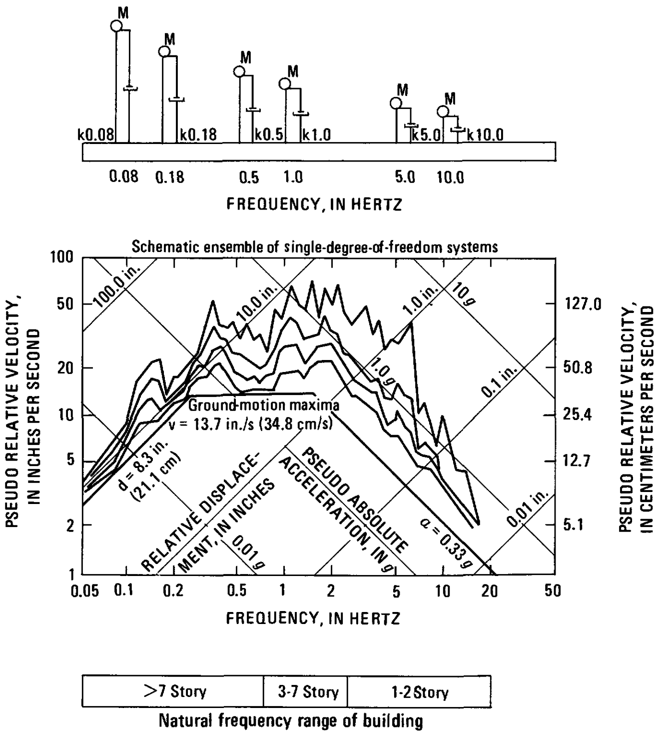


FIGURE 32.—Example of response spectra derived from the 1940 Imperial Valley, Calif., earthquake accelerogram. M and k represent the mass and spring constant of the equivalent mechanical system. Damping factor 0, 2, 5, and 10%.

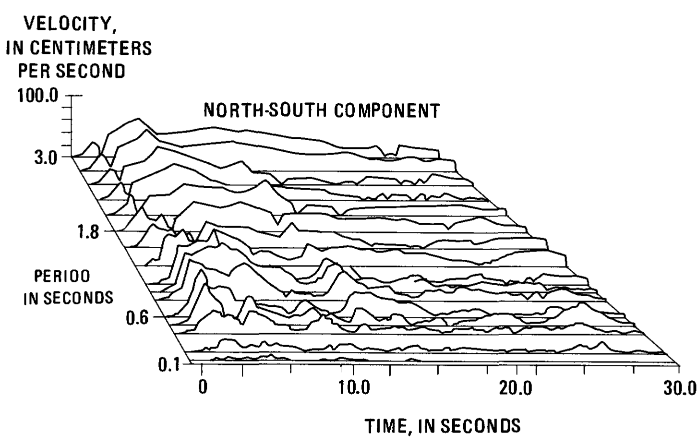


FIGURE 33.—Diagram showing time-dependent response envelope derived from the 1940 Imperial Valley, Calif., earthquake accelerogram.

1. The similarity of ground-motion response spectra of explosions and earthquakes (fig. 37) over the period range from 0.01 to 5 seconds.
2. The approximate log-normal distribution of nuclear explosion ground-motion spectral values at a fixed period (Lynch, 1969, 1973).
3. The wide range (up to a factor of 10) in levels of ground motion that can occur because of dif-

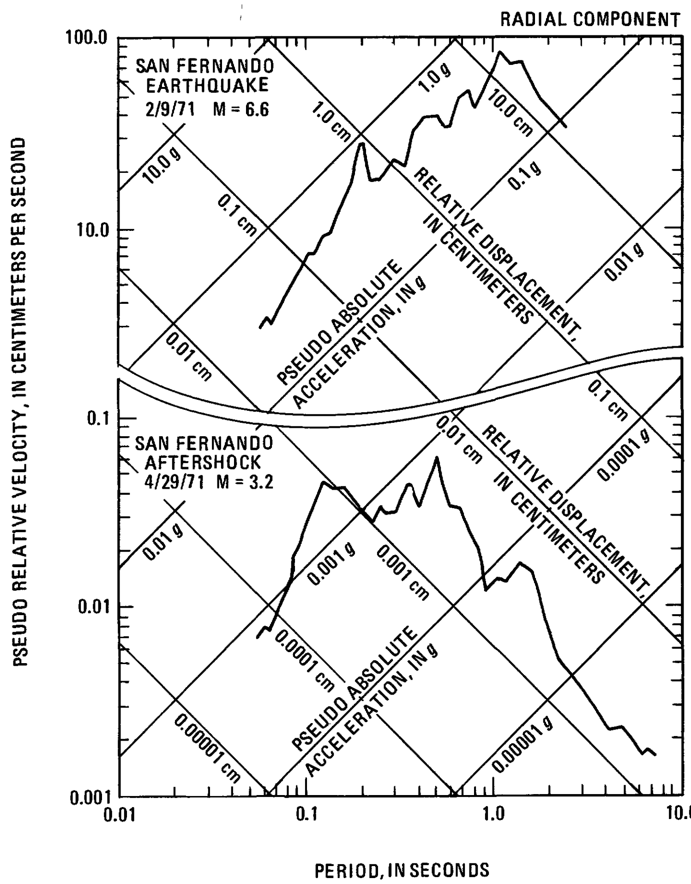


FIGURE 34.—Example of earthquake source effects on the spectral composition of ground motion.

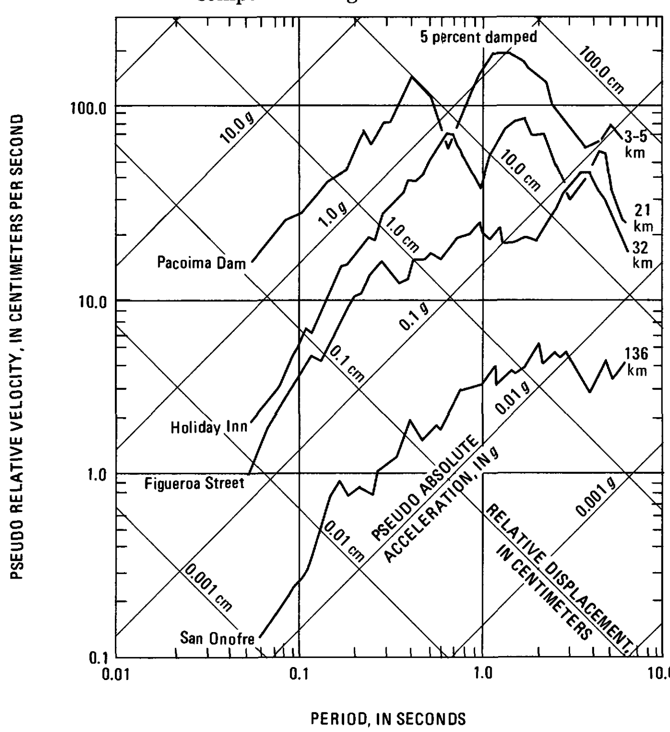


FIGURE 35.—Example of transmission path effects on the spectral composition of ground motion, 1971 San Fernando earthquake.

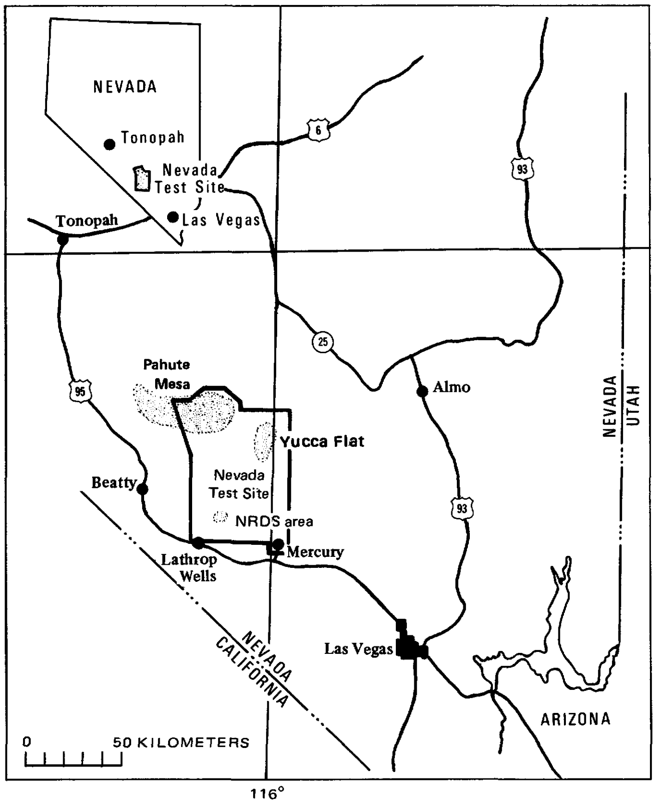


FIGURE 36.—Nevada Test Site and vicinity.

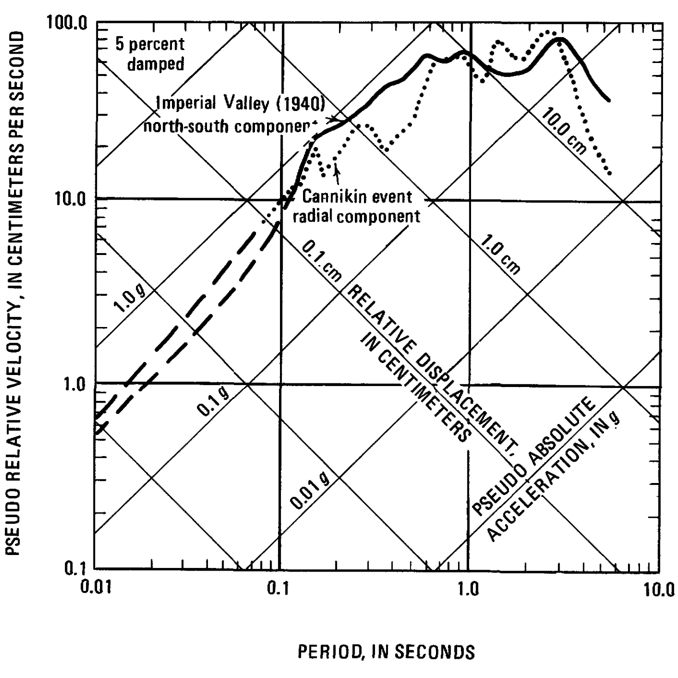


FIGURE 37.—Response spectra obtained from 1940 Imperial Valley, Calif., earthquake and Cannikin nuclear explosion. Recording stations were located within 10 km of source.

ferences in the transmission paths to two sites (fig. 38) (Weetman and others, 1970) or because of variations in the physical properties of the local geology (fig. 39) within a

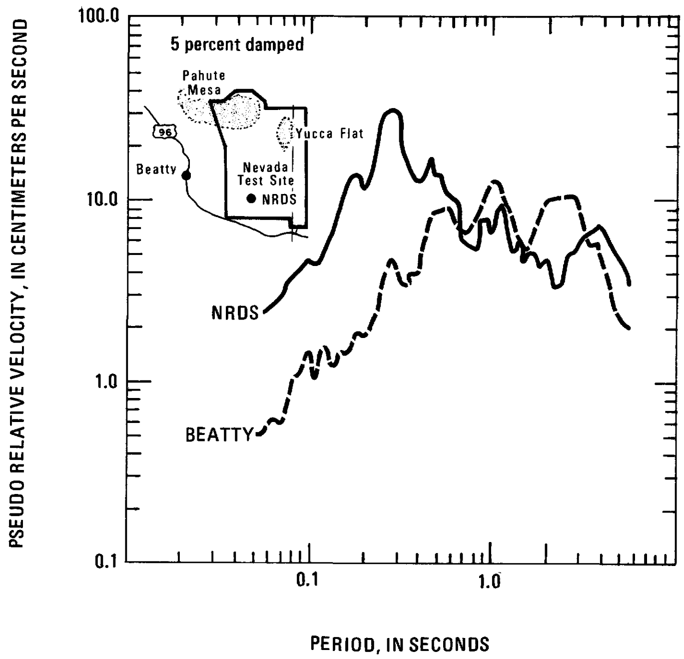


FIGURE 38.—Response spectra for two sites equidistant from energy source but on different travel paths.

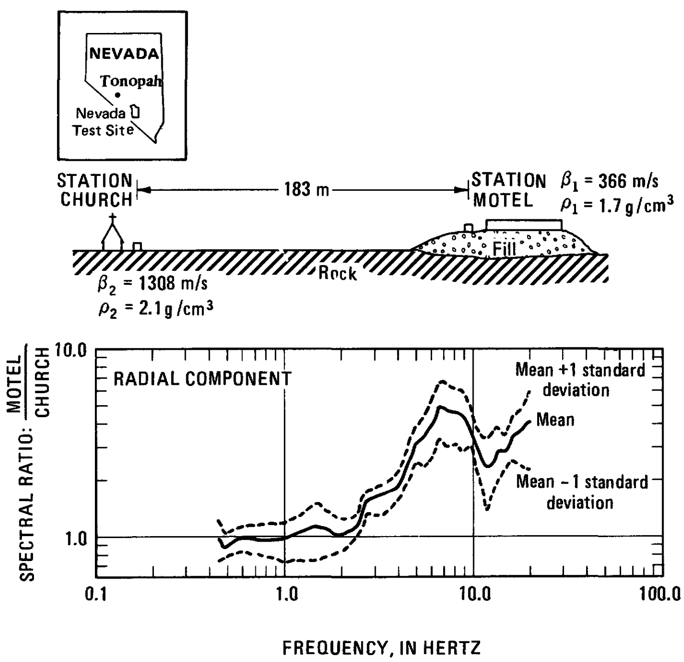


FIGURE 39.—Variability of ground motion recorded at two sites in Tonopah, Nev.

small geographic ara (Murphy, Lynch and O'Brien, 1971; Hays, 1972a, 1978).

4. The high degree of repeatability of site transfer functions for strain levels varying from 10^{-5} to 10^{-3} (Rogers and Hays, 1978; Hays and others, 1979).
5. The high degree of confidence with which a nuclear explosion can be used to "calibrate" the seismic attenuation and local ground response for a region where ground-motion data are limited (Foote and others, 1970; Hays, 1975b).

Newmark (1974) has reported on two little-known facts about nuclear explosion ground motions. The quantity $ad\text{-}v^2$ (where a is peak acceleration, v is peak velocity, and d is peak displacement) has a median value of 5 to 6, and the ratio of the peak ground velocity to the peak ground acceleration is 122 cm for 1 g acceleration (except for very close distances to a nuclear explosion). Both of these values are essentially the same as those for earthquake ground motions.

INTENSITY

In earthquake-resistant design, the accepted practice is to express the Modified Mercalli intensity at the site in terms of peak ground acceleration in order to scale the design response spectra. This step, which must be performed with care, is needed because no procedure exists for scaling spectra directly in terms of intensity. To perform the conversion, one of the empirical intensity-to-acceleration relations shown in table 17 is used. Figure 40 shows two of the empirical relations (Neumann, 1954; Gutenberg and Richter, 1956)

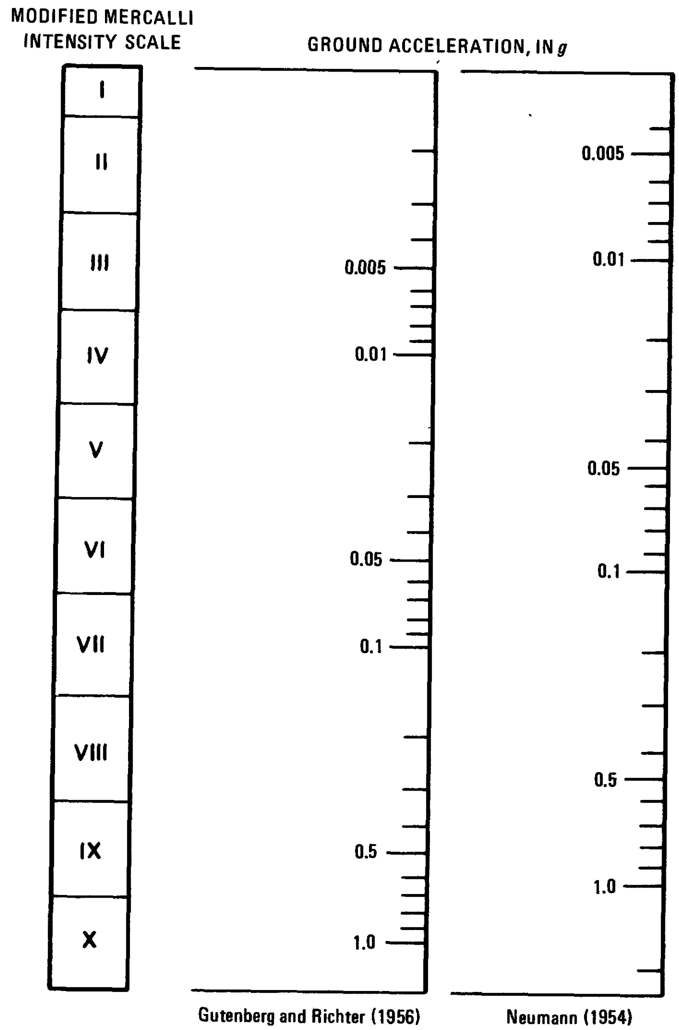


FIGURE 40.—Intensity and acceleration relations proposed by Neumann (1954) and Gutenberg and Richter (1956).

TABLE 17.—*Characteristics of the data samples used in selected studies of the correlation of Modified Mercalli intensity and peak ground acceleration*

[Modified from O'Brien, Murphy, Lahoud (1977)]

Study	Number and location location of earthquakes	Number of recordings	Range of Modified Mercalli intensity	Distance range (km)	Acceleration range (cm/s²)
Gutenberg and Richter, 1942, 1956	61, Western United States.	167	III–VIII	3–450	1–300
Neumann, 1954	10, do.	10	V–VIII	Averages of 25 and 160 (distance dependent)	40–300
Hershberger, 1956	60, do.	108	II–VIII	------	1–300
Coulter, Waldron and Devine 1973	, do. (Not based entirely on observed data)	------	IV–X	Short distance	6–3000 (Dependent on site geology and local amplification)
Trifunac and Brady, 1975c	57, do.	187	IV–X	3–250	7–1150

that have been used to convert intensity values into ground acceleration values. This conversion, depending on the empirical relation used, can lead to a range of answers that differ by more than an order of magnitude and significantly affect the seismic design. The reason for the variability is that Modified Mercalli intensity values are a function of other variables besides peak ground acceleration.

Using data from the Western United States, Trifunac and Brady (1975c) proposed empirical relations between Modified Mercalli intensity I_{MM} and: (1) peak horizontal (A_h) and vertical (A_v) ground acceleration; (2) peak horizontal (V_h) and vertical (V_u) ground velocity; and (3) peak horizontal (D_h) and vertical (D_v) ground displacement. These relations are:

$$\log A_h = -0.014 + 0.30\, I_{MM}$$
$$\log A_v = -0.18 + 0.30\, I_{MM}$$
$$\log V_h = -0.63 + 0.25\, I_{MM}$$
$$\log V_v = -1.10 + 0.28\, I_{MM}$$
$$\log D_h = -0.53 + 0.19\, I_{MM}$$
$$\log D_v = -1.13 + 0.24\, I_{MM}$$

The units of acceleration, velocity, and displacement are, respectively, centimeters per second per second, centimeters per second, and centimeters. The range of I_{MM} is from IV to X. The average trends and the standard-deviation error bars for these relations are shown in figure 41.

Murphy and O'Brien (1977) derived statistical correlations between horizontal and vertical ground acceleration and Modified Mercalli intensity using a worldwide data sample. The basic relations and the geometrical standard deviation (σ) are:

$$\log A_h = 0.24\, I_{mm} + 0.26 \qquad \sigma = 2.19$$
$$\log A_v = 0.28\, I_{mm} - 0.40 \qquad \sigma = 2.53$$

PROBABILISTIC ESTIMATES OF PEAK GROUND ACCELERATION

The ground shaking hazard map of the United States (fig. 42) published in 1976 by Algermissen and Perkins provides a basis for estimating peak ground acceleration for a site. Unlike past maps (for example, Algermissen, 1969) that were based on a mapping of Modified Mercalli intensity, the new map depicts the 90-percent probable peak horizontal ground acceleration expected at a site located on rock within a 50-year period of time. Their map was based on knowledge of: (1) the regional geology, (2) the earthquake history, and (3) the Schnabel and Seed (1973) and the "modified Schnabel and Seed" acceleration attenuation functions (see preceding section).

A 90-percent probability of not being exceeded in a 50-year time interval is equivalent to a mean return period (recurrence interval) of 475 years, or an annual risk of 0.002 events per year. It should be emphasized that the earthquake causing the extreme level of ground motion may occur once or twice, or may not occur at all in 475 years; on the average, a particular level of ground motion will be exceeded once in 475 years.

The Algermissen and Perkins map has only limited value for some design applications. For example, the nuclear power plant has a design requirement for peak rock accelerations with a 1,000,000 year return period. Such a map has not been constructed because of the short seismicity record and the lack of precise knowl-

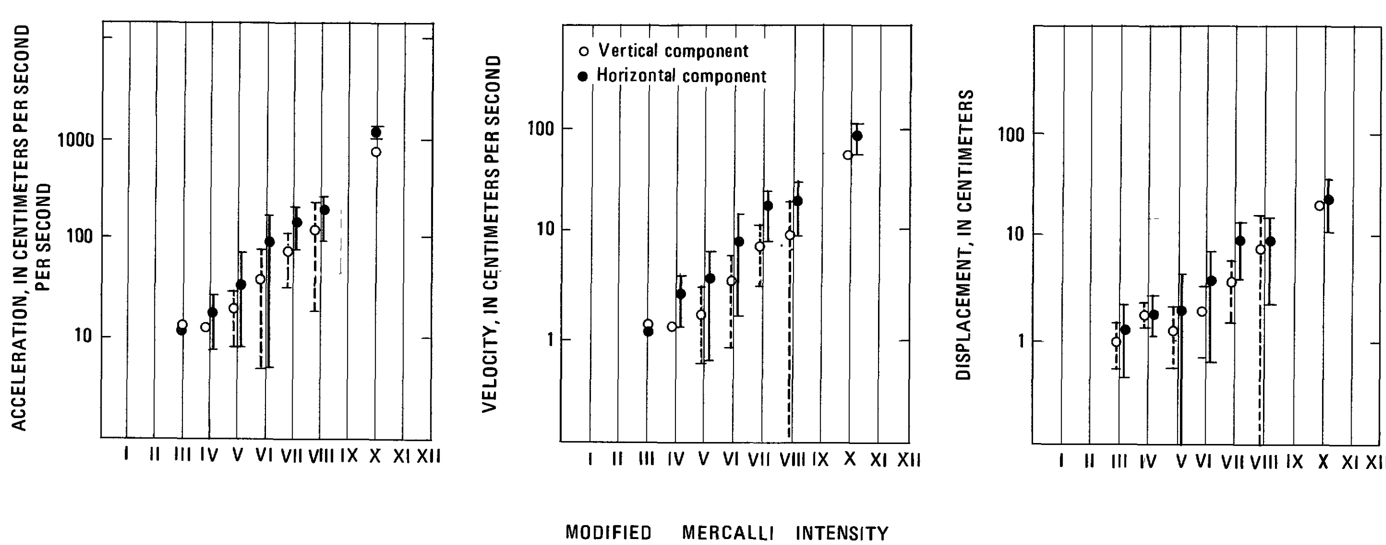


FIGURE 41.—Mean values and standard-deviation error bars of peak ground acceleration, peak ground velocity, and peak ground displacement as a function of Modified Mercalli intensity, Western United States (modified from Trifunac and Brady, 1975c).

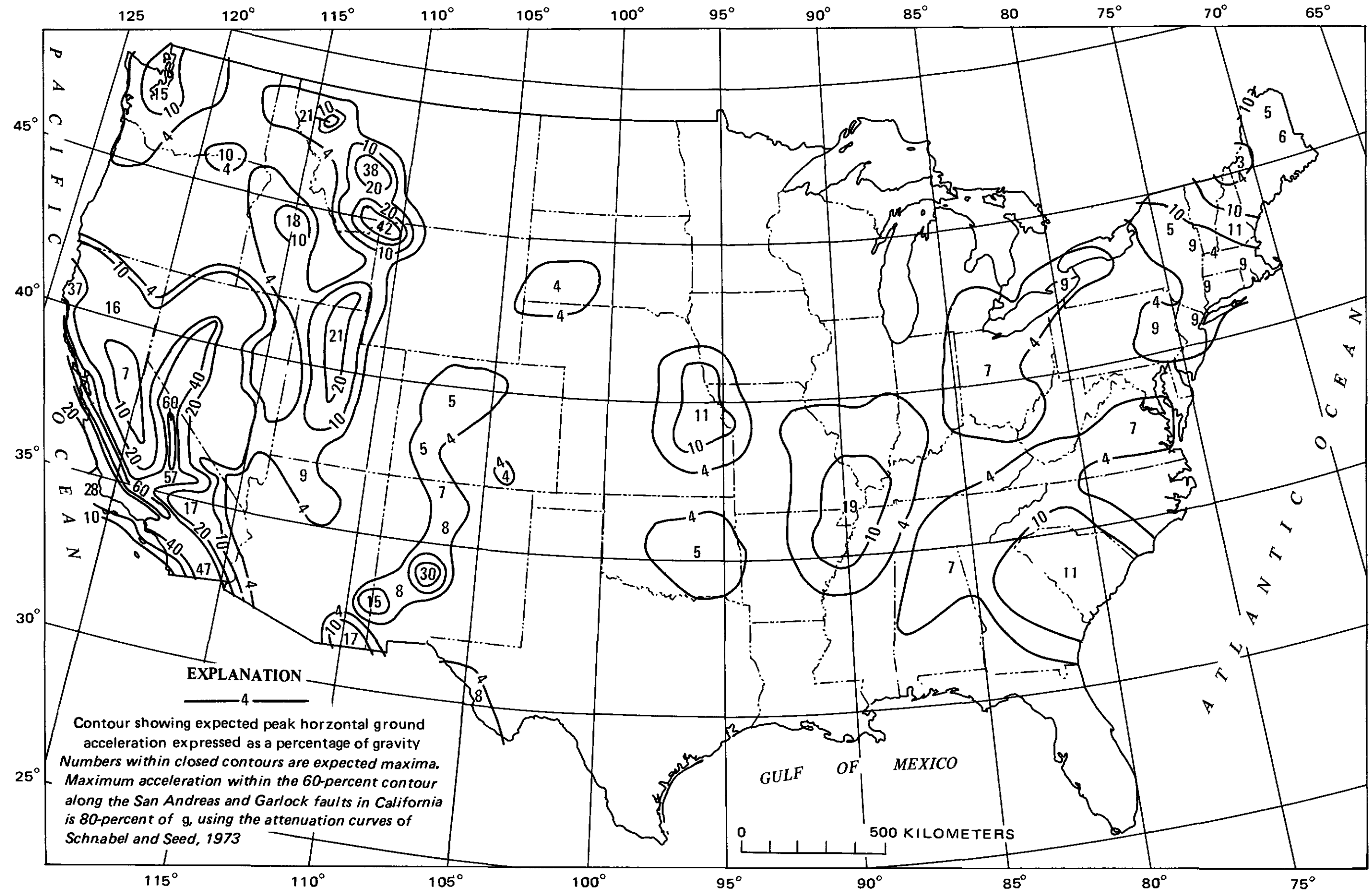


FIGURE 42.—Levels of peak horizontal ground acceleration expected at rock sites in the United States (from Algermissen and Perkins, 1976). The contoured acceleration values represent the 90-percent probability level; in other words, there is a 10-percent chance that these values will be exceeded within a 50-year period.

edge about regional seismic attenuation in various geographic provinces of the United States.

EFFECTIVE PEAK GROUND ACCELERATION

An effective peak ground acceleration value (Pfossel and Slosson, 1974) is sometimes selected for earthquake-resistant design instead of the actual value of peak acceleration. The effective peak acceleration can be thought of as the peak ground acceleration after the accelerogram has been filtered to remove the very high frequencies that have little influence on structural response. This choice is made when the peak ground acceleration is associated with one or more high-frequency spikes of short duration or when the total duration of the accelerogram is short. The accelerogram produced by the 1966 Parkfield, Calif., earthquake is one example (fig. 43) where the peak ground acceleration of about 0.5 g was caused by a single high-frequency spike. In this case, the effective peak acceleration was about 0.1 g. The accelerogram recorded at Pacoima Dam (fig. 27) from the 1971 San Fernando earthquake has been assigned an effective peak acceleration of 0.7–0.8 g by some investigators (for example, Bolt, 1972) because the peak ground acceleration of 1.2 g was caused by a high frequency spike. At the present time, the use of effective peak acceleration in seismic design is controversial owing to inconsistent practice and vagueness in the definition of the characteristics of the filter used to obtain the effective peak acceleration value from an accelerogram. A similar concept holds for effective peak velocity, but it is not yet well established.

DEFINE DESIGN RESPONSE SPECTRA FOR SITE

Once the characteristics of ground shaking at the site have been established, elastic response spectra can be defined. Response spectra are defined by using site-independent or site-dependent procedures. These procedures were developed primarily for the siting of nuclear powerplants and will be discussed in some detail below after a summary of siting procedures for nuclear powerplants.

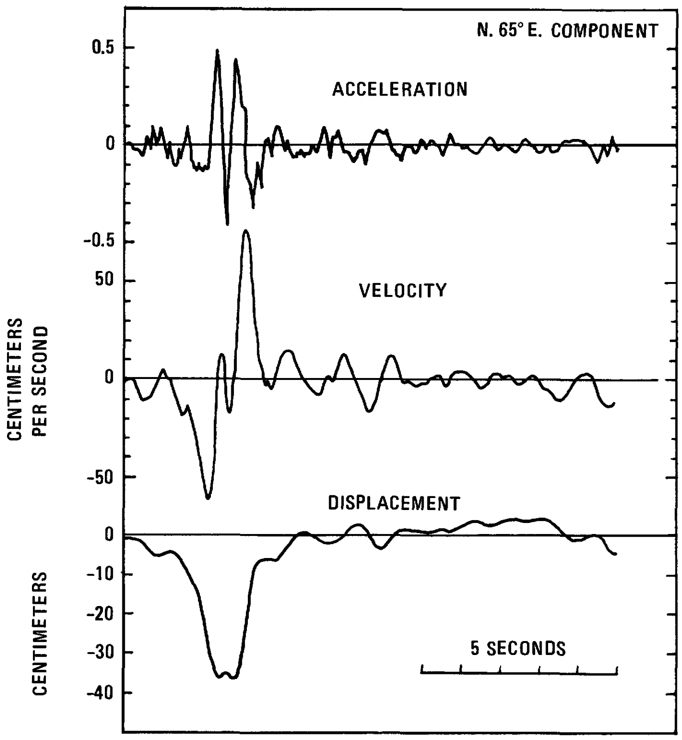


FIGURE 43.—Acceleration, velocity, and displacement seismograms from the 1966 Parkfield, Calif. earthquake recorded at station Cholame-Shannon No. 2.

SUMMARY OF PROCEDURES FOR SITING OF NUCLEAR POWER PLANTS

The U.S. Atomic Energy Commission proposed seismological and geologic criteria in 1971 and 1973; and, under its new name, the U.S. Nuclear Regulatory Commission, proposed a standard review plan in 1975 for determining design earthquakes at a proposed nuclear power plant site. These criteria significantly affect power plant siting and all other engineering applications that require characterization of the earthquake ground motion.

The procedure can be summarized as follows. The parameters of two design earthquakes, the safe shutdown earthquake and the operating basis earthquake, are estimated on the basis of integrated geologic, geophysical, and geotechnical investigations which include:

1. Determination of the lithologic, stratigraphic, and structural geology of the site and surrounding region.
2. Identification of tectonic structures underlying the site and surrounding region.
3. Determination of physical evidence concerning behavior of the surficial unconsolidated materials and the substrata during past earthquakes.
4. Determination of the static and dynamic properties of the materials underlying the site.
5. Determination of the historical seismicity.
6. Correlation of epicenters or regions of highest Modified Mercalli intensity for historically reported earthquakes with tectonic structures, any part of which is located within 322 km (200 miles) of the site. Epicenters or regions of highest intensity that cannot be reasonably correlated with tectonic structures are identified with tectonic provinces.
7. Determination of the capability of each fault or part of a fault system located within 322 km of the site.
8. Estimation of the maximum magnitude earthquake consistent with each active fault in the region.

The current procedures for defining the seismic input and site response of a nuclear power plant are based primarily on empirical data. For sites in the Eastern United States, the historic earthquake that caused the largest Modified Mercalli intensity in the tectonic province containing the site is generally used to define the seismic parameters of the safe shutdown earthquake (SSE). If this earthquake occurred in the tectonic province containing the site, the SSE is assumed to occur near the site and to reproduce its epicentral intensity I_0 at the site. The epicentral intensity is converted into a peak ground acceleration value using empirical correlations between Modified Mercalli intensity and peak ground acceleration. This value of peak ground acceleration (or alternately a value of effective peak ground acceleration) is used to define the anchor of the high-frequency end of a smooth, broadband response spectrum. This design spectrum is a function of damping and has a shape and amplitude level that are based on the mean-plus-one-sigma level of ground motion spectra from a number of past earthquakes. A design time history may also be derived with the constraint that it produces a response spectrum which envelops the smooth, broad-band design response spectrum. The operating basis earthquake (OBE) is also defined and typically has seismic design values that are one-half those of the SSE. When the historic earthquake producing the largest intensity in the tectonic province lies outside the tectonic province containing the site, the SSE is assumed to occur on the province boundary at the closest point to the site. The epicentral intensity is attenuated to the site using empirical relations between Modified Mercalli intensity and epicentral distance that are applicable for the tectonic province. This value of Modified Mercalli intensity is then converted into peak ground acceleration and used to define the high-frequency anchor of the design response spectrum.

For sites in the Western United States where the tectonic faults and structures are comparatively easier to identify than in the Eastern United States, the procedure is similar. All the tectonic structures near the site are evaluated. The largest earthquake that has occurred anywhere on each of the nearby faults is determined and assumed to reoccur on that part of the capable fault that is closest to the site. Thus, the maximum epicentral intensity I_0 and the minimum epicentral distance R are defined, and epicentral intensity is attenuated to the site using applicable attenuation relations and converted into a peak ground acceleration. Alternately, empirical relations that relate magnitude and fault rupture length can be used to define the upper-bound magnitude. This value can be converted into a value of peak ground-acceleration and attenuated to the site using peak ground-acceleration curves inferred or derived from strong ground motion data.

Definition of the seismic input and site response is a controversial process. The controversy is caused in part by the debate about whether the available geologic, geophysical, seismological, and geotechnical data are adequate to specify the seismic input and site response precisely. Controversy also centers on whether the judgments about conservatism in the seismic design specifications are reasonable in view of the uncertainties in the data and whether a given earthquake-resistant design will provide an adequate margin of safety in a future earthquake.

Perhaps the most controversial part of defining the seismic input is the question of how intense the peak ground acceleration should be, especially for the less seismic regions of the United States. The controversy is fed, at present, by the fact that:

1. peak ground acceleration is not a simple function of Modified Mercalli intensity,
2. peak ground acceleration observed in an earthquake can vary by an order of magnitude at any given distance from the source, and
3. peak ground acceleration within 10 km of the causative fault is independent of magnitude for $4.5 \leq M \leq 7.1$ and is a function of the dynamic stress drop and the local distribution of stress.

Several factors are intentionally incorporated into the design process to introduce conservatism in the seismic input for a nuclear power plant. They are:

1. selecting a low-probability, extreme event and moving it to the closest epicentral distance to the site,
2. using smooth, broad-band, mean-plus-one-sigma response spectra, independent of the epicentral distance from the site,
3. using "worst-case" seismic attenuation functions,
4. requiring that the design time histories produce spectra that envelop the smooth, broad-band, mean-plus-one-sigma response spectra.
5. assuming that the two horizontal-component design time histories have equal values of peak ground acceleration; also, that the vertical component has peak values that are ⅔ or more of the peak values of the horizontal components, and
6. modifying the smooth, broad-band, mean-plus-one-sigma response spectra to account for specific local ground response characteristics.

The safe shutdown earthquake is assumed to represent the maximum possible level of earthquake ground shaking at the site. The SSE may or may not have occurred at the site during historic times, but it is defined on the basis of a detailed investigation of the regional and local geology, the regional seismicity, and the characteristics of the underlying soil materials. For the SSE, the facility should be designed so that all systems necessary to protect the health and safety of the public will remain functional both during and after the earthquake. Although structures and their internal components may suffer severe damage from the SSE, the design must allow for a safe and orderly shutdown after an earthquake. The lower bound for the peak horizontal ground acceleration induced at the site by the SSE is 0.1 g. The second level, the operating basis earthquake is assumed to represent the maximum level of ground shaking that can be expected to occur at the site during the 40-year operating life of the nuclear power plant. This earthquake probably has occurred in the vicinity of the site during historic times. It is also based on a detailed investigation of the regional and local geology, the regional seismicity, and the characteristics of the underlying soil materials. For the OBE, the facility should be designed so that those features of the plant necessary for continued operation without undue risk to the public will remain funtional. The maximum horizontal ground acceleration of the OBE must be at least one-half of the SSE, with a lower-bound peak acceleration level of 0.05 g. Table 18 lists the horizontal ground accelerations of the OBE and SSE for a number of nuclear power plant sites.

To obtain information for evaluating the ground response in the site vicinity, a combination of borings, trenches, laboratory measurements, and geophysical methods are used (Shannon and Wilson and Agbabian Associates, 1972, 1975, 1976). The purpose is: (1) to determine the classification, lateral distribution, stratification, geologic structure, and physical prop-

TABLE 18—*Horizontal ground accelerations for the operating basis earthquake and safe shutdown earthquake for nuclear power plant sites in the United States*

[From Johnson and Kennedy (1977)]

Site	State	Operating basis earthquake g level	Safe-shut down earthquake g level
Browns Ferry	Alabama	0.10	0.20
Brunswick	North Carolina	.08	.16
Calvert Cliffs	Maryland	.08	.15
Connecticut Yankee	Connecticut	----	.17
Davis-Besse	Ohio	.08	.15
Dresden	Illinois	.10	.20
Fermi	Michigan	.08	.15
Fort St. Vrain	Colorado	.05	.10
Indian Point	New York	.10	.15
Kewaunee	Wisconsin	.06	.12
Nine Mile Point	New York	.07	.11
Oyster Creek	New Jersey	.11	.22
Peach Bottom	Pennsylvania	.05	.12
Quad Cities	Illinois	.12	.24
Salem	New Jersey	.10	.20
Susquehanna	Pennsylvania	.08	.15
Three Mile Island	do.	.06	.12
Turkey Point	Florida	.03–.05	.15
Vermont Yankee	Vermont	.07	.14
Zion	Illinois	.08	.17
Diablo Canyon	California	.33	.66
Humboldt Bay	do.	.25	.40
Rancho Seco	do.	.33	.66
San Onofre	do.	.66	.75
Trojan	Oregon	.15	.25
WPPSS (Hanford)	Washington	.13	.25

erties of the unconsolidated materials (soil) and rock underlying the site; (2) to obtain samples and cores for laboratory testing; and (3) to establish the elevation and variation of the ground-water table for foundation studies.

The response of geologic materials to ground shaking is governed primarily by: (1) shear wave velocity, (2) density, (3) shear modulus, (4) material damping properties, (5) Poisson's ratio, (6) bulk modulus, (7) static shear strength, and (8) dynamic shear strength. These physical properties are determined from laboratory and field tests and are used in conjunction with finite-element and other computational models to calculate the ground response for the proposed site (Seed and Idriss, 1969; Joyner and Chen, 1975; Joyner, 1975).

The current procedures for specifiying the earthquake ground motion at a nuclear power plant site are based primarily on empirical models. Each empirical model is based on the collection and use of catalogs of seismograms, response spectra, and observational data (for example, intensity data) from past earthquakes. These data are used to derive earthquake recurrence relations, scaling laws, attenuation functions, and to confirm the adequacy of data analysis procedures. The deterministic method uses analytical models to simulate earthquake source mechanics, transmission path effects, and local ground response. In principle, analytical models can be applied any place in the world; the only requirements are that the proper earthquake source, transmission path, and ground response models be selected. The analytical approach has not been acceptable in earthquake-resistant design in the past because the physical processes that occur in the source, path, and site are not well understood. At the present time only local soil conditions are modeled mathematically in earthquake-resistant design.

The data sample is particularly limited for siting of nuclear power plants in the Eastern and Central United States. In these regions, Modified Mercalli intensity data extracted from the historic earthquake record may be the only data available to define the design ground motion. In these cases, an attempt is made to select conservative values. Conservative values are introduced as follows:

1. The location and magnitude of likely earthquakes are uncertain because of the short historical seismicity record; therefore, a rare large-magnitude event located close to the site is selected.
2. The site intensity (as measured by peak ground acceleration or Modified Mercalli intensity) is uncertain due to lack of knowledge about regional seismic wave attenuation and the local ground response; therefore, an upper-bound value is selected.
3. The response spectrum that corresponds to a given site intensity exhibits scatter about a mean value and is uncertain because the details of earthquake ground can vary widely for a given measure of ground motion (fig. 44); therefore, smooth, upper-bound spectral values are used.

SITE-INDEPENDENT RESPONSE SPECTRA

The site-independent procedure, one of two basic methods for specifying design response spectra for nuclear power plant sites, is based on the use of standard spectrum shapes. The standard spectrum shapes are considered to be independent of the characteristics of the site because the ensemble of seismograms from which the spectra were derived depict ground motions for a wide range of geologic and seismological conditions.

The site-independent method was first introduced by G. W. Housner in 1959. He derived smooth normalized acceleration and velocity response spectra (fig. 45) from the two horizontal components of ground acceleration recorded at four sites from four large earthquakes in the Western United States (table 19). The earthquakes were: (1) 1934 Imperial Valley, Calif. (M =6.5); (2) 1940 Imperial Valley, Calif. (M =7.0); (3) 1952 Kern

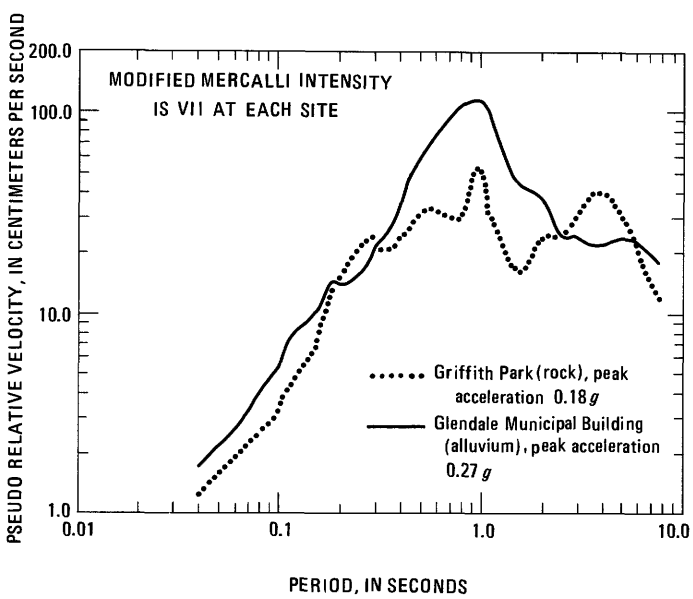


FIGURE 44.—Variation in ground-motion response spectra and peak ground acceleration values for the same value of Modified Mercalli intensity. Spectra were derived from accelerograms of the San Fernando, Calif. earthquake (modified from Murphy and O'Brien, 1977).

County, Calif. (M =7.7); and (4) 1949 Puget Sound, Wash. (M =7.1). The epicentral distances ranged from 8 to 56 km. The recording sites were underlain by rock, stiff soil, and deep cohesionless soil. These spectra are scaled by a factor based on the spectrum intensity rather than the peak ground-acceleration.

In 1969, Newmark and Hall proposed a new technique for estimating site-independent spectra. Their technique as based on the fact that the response spectrum over certain frequency ranges is related by an amplification factor (fig. 46) to the peak values of ground acceleration, velocity, and displacement. The amplification factors were statistically determined from response spectra derived from the accelerogram recorded at El Centro from the 1940 Imperial Valley, California earthquake (table 19) and are a function of the damping of the spectra. The factors correspond to about the 84th percentile of a log-normal distribution. In this method, the estimated values of peak ground acceleration, velocity, and displacement for the site are plotted on tripartite logarithmic paper. Using the amplification factors that correspond to the desired percentage of critical damping, the peak ground motion values are amplified to give a smooth design response spectrum for the site.

Newmark and Hall (1969) also proposed a "standard" earthquake response spectrum for use whenever adequate detail about the site ground-motion parameters was unavailable. These spectra (fig. 47) are based on peak ground motion values observed at El Centro from the 1940 Imperial Valley, California earthquake,

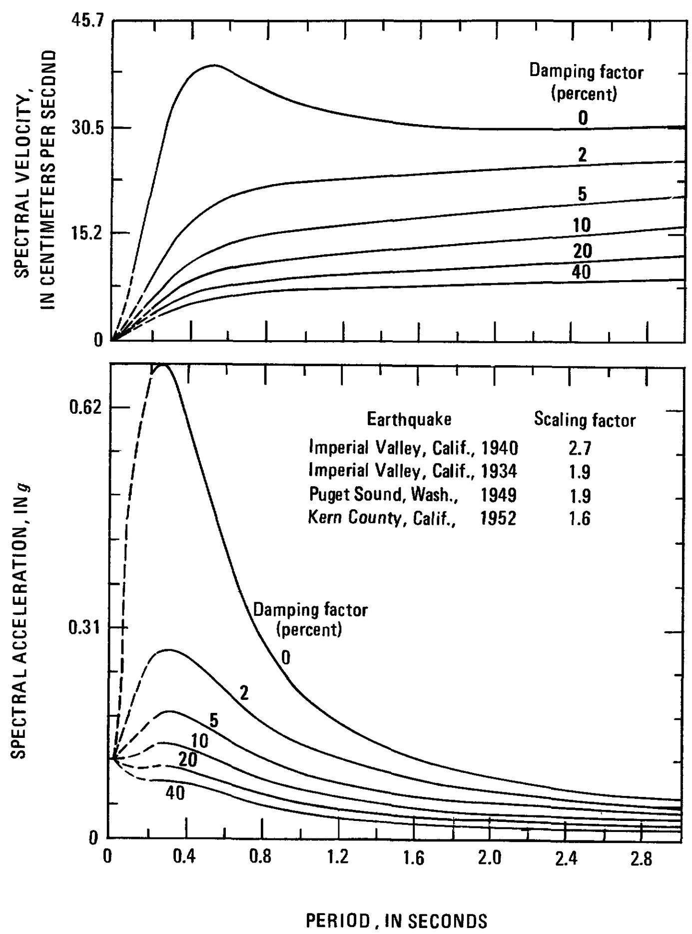


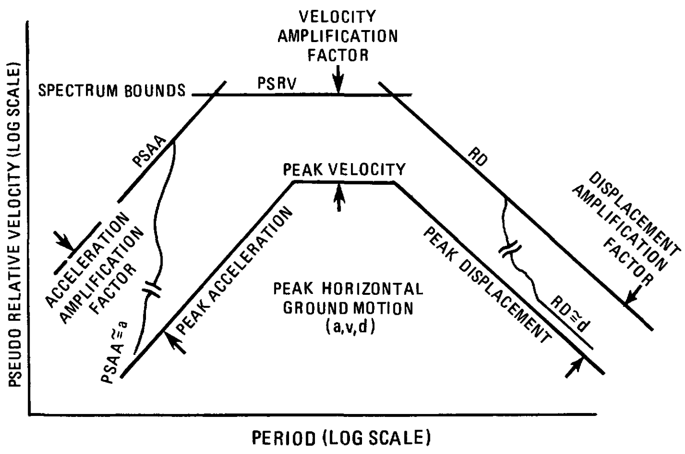
FIGURE 45.—Site-independent velocity and acceleration response spectra (modified from Housner, 1959).

but are about 50 percent more conservative that the El Centro values. The Imperial Valley accelerogram was recorded within 10 km of the fault, the bracketed (5 percent) duration of strong motion was nearly 20 seconds, and the levels of peak horizontal ground acceleration, velocity, and displacement were, respectively, 0.33 g, 34.8 cm/s, and 21.1 cm. The soil column at the El Centro site contained a 30-m-thick layer of stiff clay that amplified the input rock accelerations (Schnabel, Seed, and Lysmer, 1972). The proposed standard earthquake had peak ground motion values of 0.5 g, 60.9 cm/s, and 45.7 cm, but it could be scaled to any peak ground acceleration level on the assumption that the three ground-motion parameters are proportional to each other regardless of the level of ground shaking. Thus, one would use peak ground velocity and displacement values of 121.8 cm/s and 91.4 cm for an earthquake having a peak ground acceleration of 1.0 g.

The studies by Newmark and Hall (1969) also provided an empirical basis for defining vertical ground-motion spectra. They observed that the peak vertical ground-accelerations are about two-thirds of the peak

TABLE 19.—*Earthquake accelerograms used to derive site-independent spectra*

Earthquake and site characteristics								Investigators			
Earthquake	Date	Magnitude	Peak acceleration (g)	Recording site	Epicentral distance (km)	Soil classification	Depth to bedrock (m)	Housner (1959)	Newmark and Hall (1969)	Newmark (1973)	Blume (1973)
Lower California	1934	6.5	0.182	El Centro	58	Stiff	32	X			X
Helena, Mont	1935	6.0	.146	Helena	8	Rock	--				X
Imperial Valley, Calif	1940	7.0	.33	El Centro	8	Stiff	32	X	X	X	X
Puget Sound, Wash	1949	7.1	.28	Olympia	20	Deep cohesionless	132	X			X
Northwest California	1951	5.8	.11	Ferndale	56	do	160			X	
Kern County, Calif	1952	7.7	.179	Taft	56	Rock	--	X			X
				Hollywood Storage							
			.06	a. Basement	119	Stiff	64			X	
			.06	b. P.E. lot	119	do	64			X	
Eureka, Calif	1954	6.6	.257	Eureka	25	Deep cohesionless	160			X	X
			.201	Ferndale	30	do	160			X	
Baja, Calif	1956	6.8	.05	El Centro	126	Stiff	32			X	
San Francisco, Calif.	1957	5.25	.105	Golden Gate Park	11	Rock	--			X	X
Hollister, Calif	1961	5.6	.18	Hollister	40	Deep cohesionless	160				
Puget Sound, Wash	1965	6.5	.198	Olympia	58	do.	134				X
Parkfield, Calif	1966	5.6	.347	Temblor	7	Rock	--				X
			.489	Cholame-Shandon #2	0.1	Stiff	48				X
			.354	Cholame-Shandon #5	5	do	32				X
Peru	1966	7.5	.42	Lima	160	Stiff	321?				X
Borrego Mountain, Calif.	1968	6.5	.13	El Centro	70	do	32			X	
Japan	1968	7.8	.23	Hachinohe	160	Deep cohesionless	250±?				X
San Fernando, Calif	1971	6.6	1.24	Pacoima Dam	3–5	Rock	--			X	
			.26	Orion	22	Deep Cohesionless	256			X	X
			.341	Castaic	19	Stiff	19			X	X
			.231	Bank of California	28	do	22			X	X



	AMPLIFICATION FACTOR		
DAMPING (percent)	ACCELERATION	VELOCITY	DISPLACEMENT
0	6.4	4.0	2.5
0.5	5.8	3.6	2.2
1	5.2	3.2	2.0
2	4.3	2.8	2.0
5	2.6	1.9	1.8
7	1.9	1.5	1.4
10	1.5	1.3	1.2
20	1.2	1.1	1.0

FIGURE 46.—Schematic illustration of technique for developing site-independent response spectra (modified from Newmark and Hall, 1969). The quantities *a*, *v*, and *d* refer to the peak ground acceleration, velocity, and displacement; PSAA, PSRV, and RD refer to the spectral acceleration, velocity, and displacement.

horizontal ground-accelerations when the fault movements are primarily horizontal, and that the vertical motions are approximately equivalent to the horizontal motions when the fault movements involve a large vertical component. Amplification factors are also applied to the estimated peak vertical ground-motion to obtain the design response spectra.

Values of maximum ground velocity and displacement are typically based on those of the standard earthquake when specific information about these parameters is unavailable. The standard earthquake has peak velocity and displacement values that are proportional to those obtained from the 1940 Imperial Valley, Calif., accelerogram (table 20) and are scaled proportionately up or down to correlate with the value of ground acceleration that specifies the SSE. The validity of this scaling procedure has been questioned, but no alternate techniques have been adopted.

The United States Atomic Energy Commission proposed guidelines in 1973 for developing improved site-independent earthquake response spectra. These guidelines, contained in AEC Regulatory Guide 1.60 (1973b), were based on two independent studies of the statistical properties of response spectra (see table 19) of earthquake ground motions by N. M. Newmark Consulting Engineering Services (1973) and J. A. Blume and Associates, Engineers (1973). From the results of these two studies, a unified procedure (Newmark and others, 1973) was developed for defining site-independent earthquake-response spectra that are applicable to most sites. The only exceptions are sites which are relatively close to the epicenter of a postulated earthquake or sites which have physical characteristics (for example, foundation deposits with well-defined frequency-filtering characteristics) that could significantly enhance the spectral characteristics of ground motion in a portion of the spectral band of interest.

The procedure proposed in Regulatory Guide 1.60 is very similar to the one proposed by Newmark and Hall (1969). Spectrum amplification factors (table 21) are based on a much larger number of earthquake ground-motion records than used by Newmark and Hall and represent the mean-plus-one-standard-deviation statistical level (84th percentile of a log-normal distribution). To define horizontal response spectra, the peak horizontal ground acceleration and displacement levels are established. The peak horizontal ground displacement is considered to be proportional to the peak horizontal ground acceleration and is fixed at 91.4 cm for an acceleration of 1.0 *g*. These two values are proportional to the values of 45.7 cm and 0.5 *g* established for the "standard" earthquake. The bounds of each spectrum established by five line segments, similar to the Newmark and Hall procedure. The control points are designated by letters *A*, *B*, *C*, and *D* and have specified frequency ranges for all horizontal component spectra (fig. 48). The amplification factors (table 26) are a function of the percent of critical damping and are specified for each of the control points.

Vertical response spectra are constructed in a similar manner to horizontal response spectra (fig. 49), but three differences are incorporated into the procedure: The frequency for control point *C* is located at 3.5 Hz rather than at 2.5 Hz, (2) The amplification factors (table 22) are different, and (3) The value of peak horizontal acceleration is used as the initial reference value. In the frequency range 0.25–3.5 Hz, the ratio of vertical to horizontal spectral amplitudes varies between two-thirds and one. The horizontal and vertical response spectra are identical in the frequency range 3.5–33 Hz. Beyond 33 Hz, the vertical spectral accelerations decrease from a value equal to the peak horizontal ground acceleration at 33 Hz to two-thirds of the horizontal ground acceleration at 50 Hz (control point, A′).

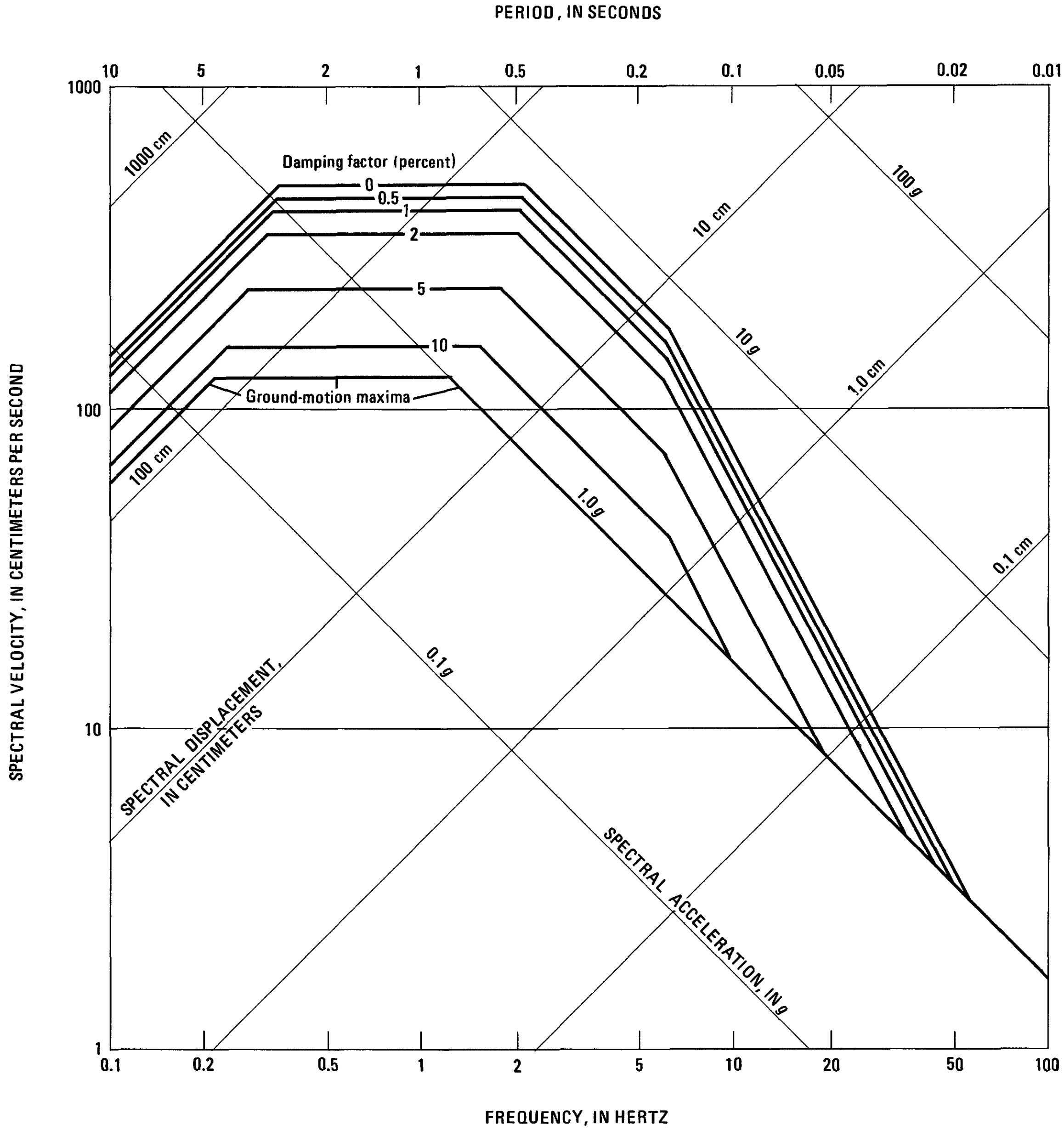


FIGURE 47.—"Standard" site-independent horizontal response spectra (modified from Newmark and Hall, 1969).

TABLE 20.—*Relative values of maximum ground-acceleration, velocity, and displacement; "standard" earthquake*

[From Newmark and Hall (1969)]

Condition	Maximum values of ground motion: Acceleration (g)	Velocity (cm/s)	Displacement (cm)
"Standard" relative values	0.5	60.96	45.72
Typical maxima Imperial Valley (1940)			
Horizontal	.33	40.64	30.48
Vertical	.22	27.94	20.32
Recommended minimum for any region:			
Horizontal	.10	12.70	10.16
Vertical	.07	7.62	7.62

TABLE 21.—*Horizontal design response spectra and relative values of spectrum amplification factors for control points*

[From U.S. Atomic Energy Commission Regulatory Guide 1.60 (1973)]

Percent of critical damping	Acceleration A(33 Hz)	Acceleration B(9 Hz)	Acceleration C(2.5 Hz)	Displacement D(0.25 Hz)
0.5	1.0	4.96	5.95	3.20
2.0	1.0	3.54	4.25	2.50
5.0	1.0	2.61	3.13	2.05
7.0	1.0	2.27	2.72	1.88
10.0	1.0	1.90	2.28	1.70

The horizontal site-independent response spectra (scaled to 0.1 *g*) proposed by Housner (1959), Newmark and Hall (1969), and U.S. Atomic Energy Comm. (1973b) are compared in figure 50. The differences be-

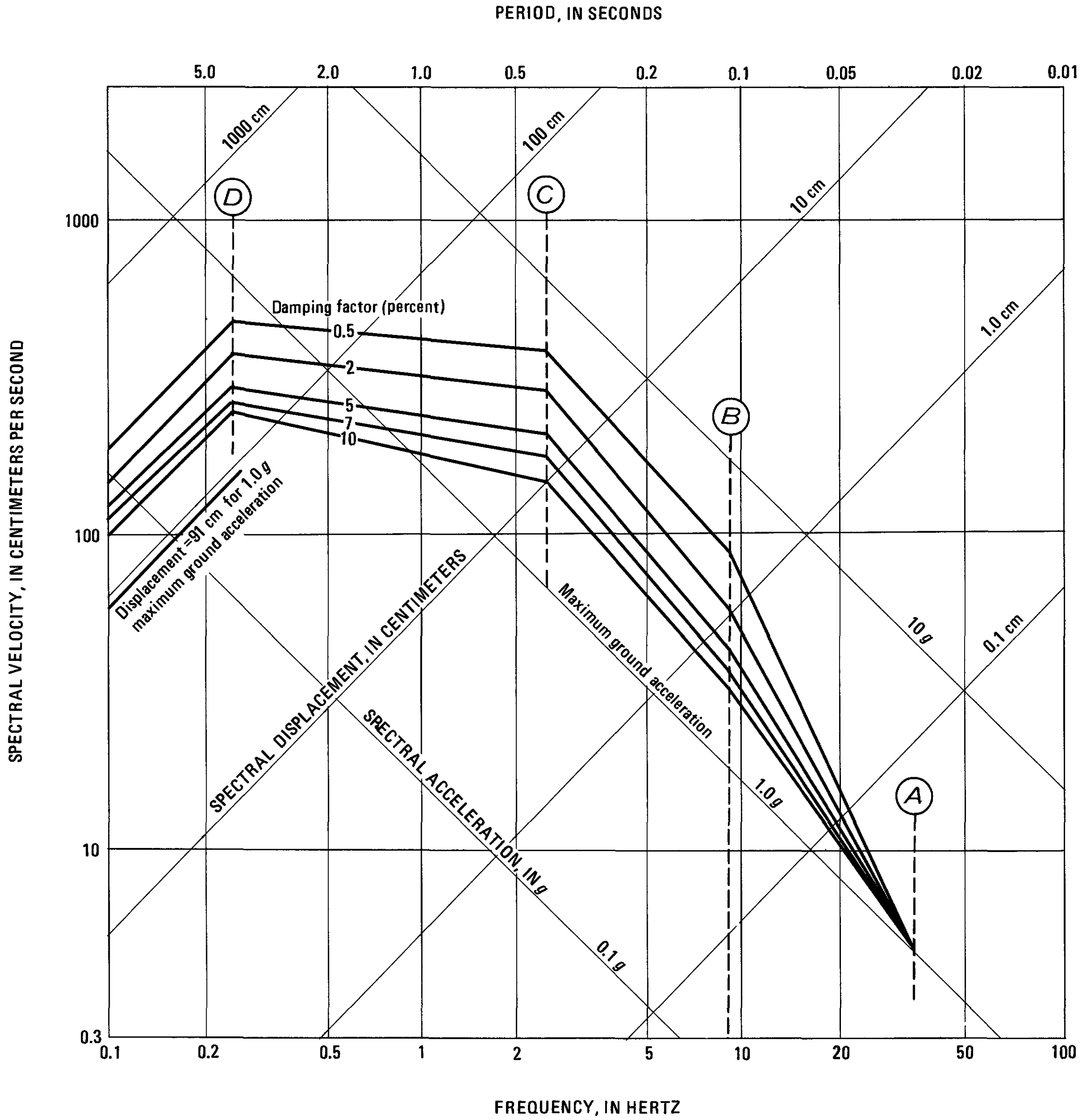


FIGURE 48.—Site-independent horizontal response spectra scaled to 1.0 *g*. See table 21 for amplification factors at control points A–D. Modified from U.S. Atomic Energy Comm. Regulatory Guide 1.60 (1973b).

tween the Newmark and Hall and the AEC Regulatory Guide 1.60 spectra are very small. The Housner spectrum, however, differs significantly from the other two design spectra. This difference is due to the probability level associated with each of the three approaches and the differences in the data samples. The Housner spectrum is an average derived from eight horizontal accelerograms; therefore, it would normally be exceeded 50 percent of the time. The Newmark and Hall and Regulatory Guide 1.60 spectra were derived from a much larger data sample and represent the mean-plus-one-standard-deviation probability level, or the 84th percentile; therefore, it should be exceeded about 16 percent of the time. In addition, the Newmark-Hall and Regulatory Guide 1.60 spectra were based on ultimate strength design concepts instead of the design practice in effect during the time the Housner-type spectra were developed which utilized working stress concepts with allowable stresses being one-third less yield. A more accurate comparison is obtained when the Housner spectrum is increased by 50 percent. In this case, the agreement of all three spectra is good, especially in the 2–10 Hz range that is important in nuclear power plant design.

SITE-DEPENDENT RESPONSE SPECTRA

The current library of strong-motion accelerograms, although limited, contains representative samples of a wide variety of local site conditions (see tables 15, 16).

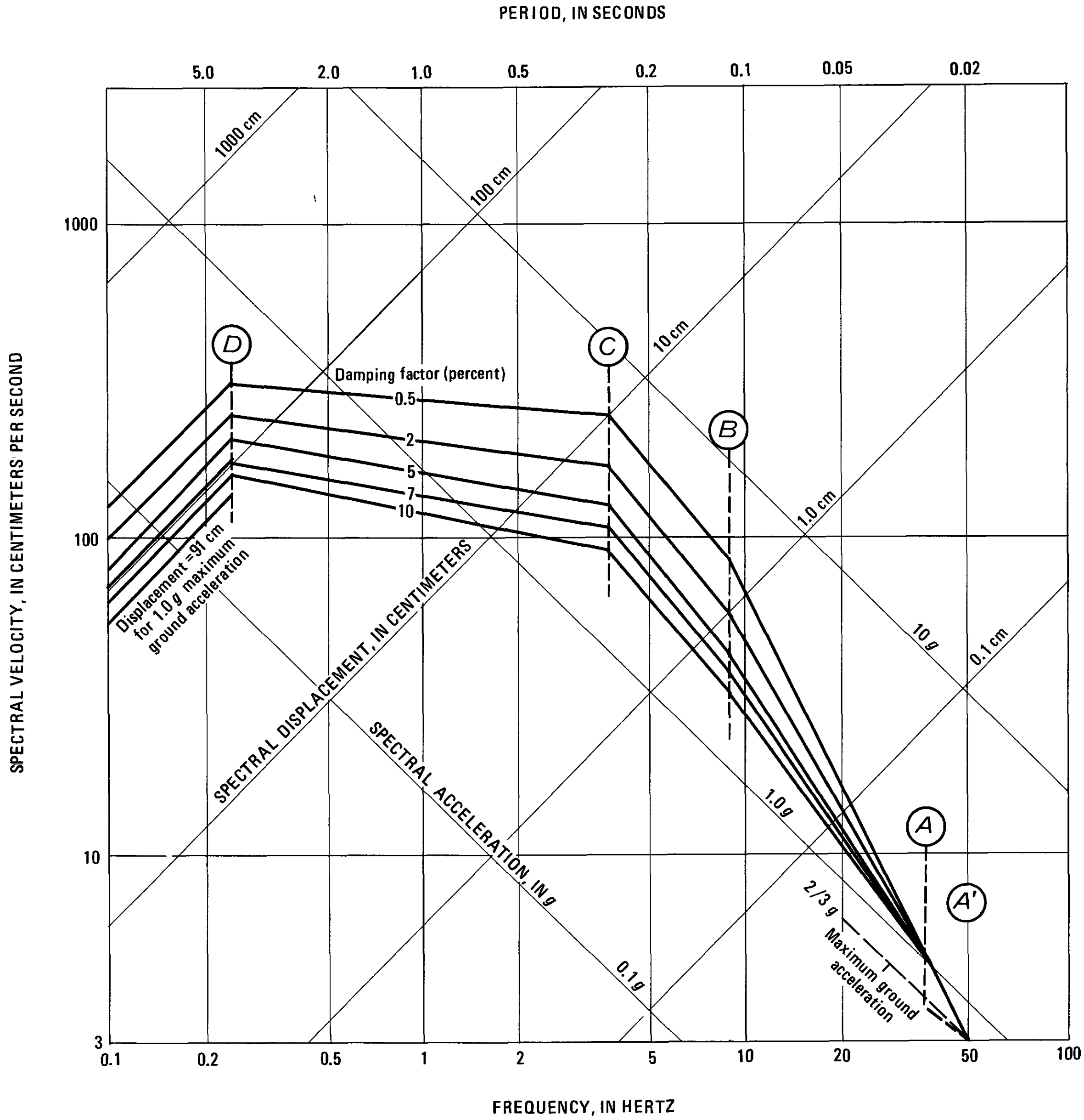


FIGURE 49.—Site-independent vertical response spectra. See table 22 for amplification factors at control points A′–D. Modified from U.S. Atomic Energy Comm. Regulatory Guide 1.60 (1973).

TABLE 22.—*Vertical design response spectra and relative values of spectrum amplification factors for control points*

[From U.S. Atomic Energy Commission Regulatory Guide 1.60 (1973b)]

Percent of critical damping	Acceleration				Displacement
	A′(50 Hz)	A(33 Hz)	B(9 Hz)	C(3.5 Hz)	D(0.25 Hz)
0.5	0.67	1.0	4.96	5.67	2.13
2.0	.67	1.0	3.54	4.05	1.67
5.0	.67	1.0	2.61	2.98	1.37
7.0	.67	1.0	2.27	2.59	1.25
10.0	.67	1.0	1.90	2.17	1.13

In some cases, it is possible to select an ensemble of response spectra that were derived from seismograms whose local site conditions (Duke and Leeds, 1962; Matthiesen and others, 1964; Woodward-Lundgren and Associates, 1973; Shannon & Wilson and Agbabian Associates, 1976; Gibbs and others, 1976) either match or are very similar to those of the proposed construction site. Spectra meeting this condition satisfy the seismic and geologi criteria proposed in 1971 by AEC for nuclear powerplant sites more easily. To date, site-dependent response spectra have not been used extensively in power plant siting because of the limitations of the ground-motion data sample.

The site-matched seismograms and response spectra should also match the source-mechanisms and the transmission-path characteristics of the designated de-

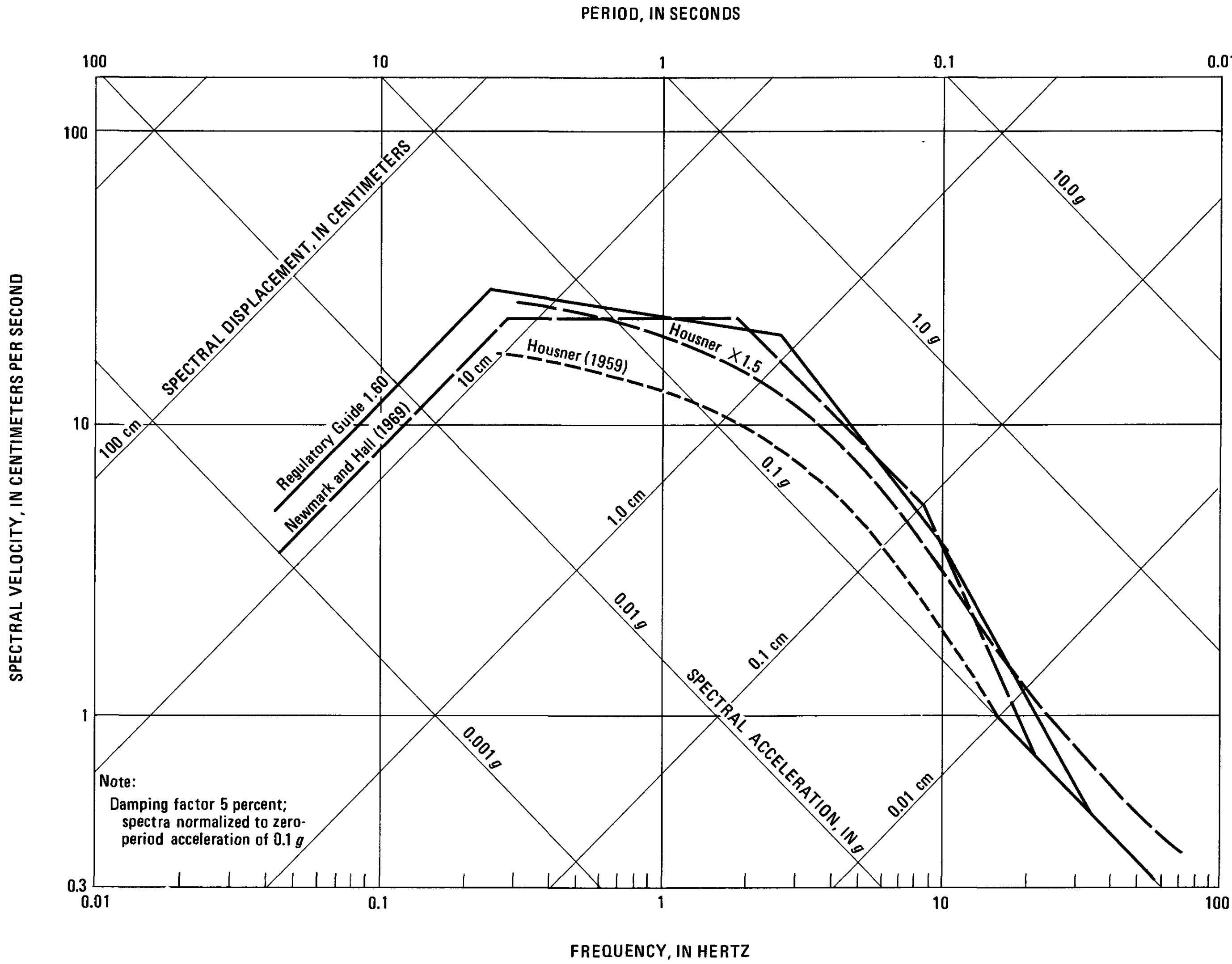


FIGURE 50.—Comparison of site-independent horizontal response spectra produced by three different procedures.

sign earthquake if possible. The ideal case is to have an ensemble of seismograms and response spectra that closely match the source-path-and-site parameters for the proposed construction site. The limits of the data sample usually prevent matching any of the parameters except those associated with the site.

Seed, Ugas, and Lysmer (1976) studied a selected set of 104 accelerograms (see table 6–9) to establish site-dependent response spectra for four site classifications. Their classifications were: (1) rock (28 records), (2) stiff soil (31 records), (3) deep cohesionless soil (30 records), and (4) soft to medium soil (15 records). In their study, ensemble average and mean-plus-one-standard-deviation response spectra were derived for each site classification. These spectra, normalized to 0.1 *g* at zero-period, are shown in figure 51.

Site-dependent spectra exhibit the following frequency-dependent effects. The spectra from sites underlain by soft to medium soil and deep cohesionless soil have larger amplitudes than the spectra from sites underlain by rock and stiff soil for low frequencies (less than 1–3 Hz). For higher frequency responses (above 6 Hz), the spectra from rock and stiff soil sites exhibit larger amplitudes than the spectra for deep and soft site conditions.

The mean-plus-one-standard-deviation site-dependent response spectra are compared in figure 52 with the spectrum developed on the basis of AEC Regulatory Guide 1.60. This comparison shows that differences are most pronounced for frequencies below 2–3 Hz. For sites underlain by stiff soil or deep cohesionless soil, higher frequency components of the site-dependent spectra differ from Regulatory Guide 1.60 spectra by about 25 percent.

The use of site-matched seismograms to develop site-dependent design response spectra is superior to

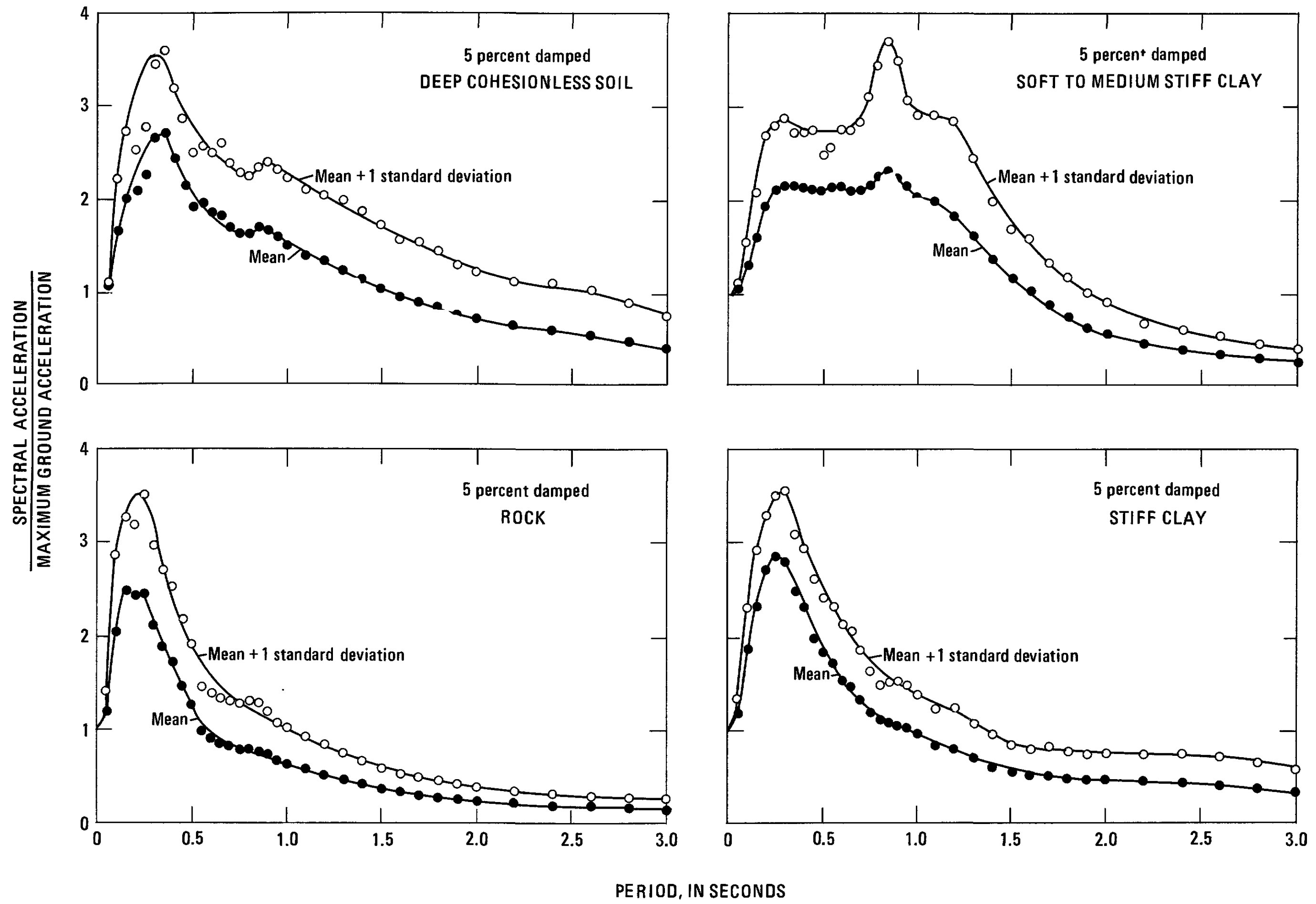


FIGURE 51.—Site-dependent mean and mean-plus-one-standard-deviation response spectra for four site classifications (modified from Seed, Ugas, and Lysmer, 1976). Spectra are normalized by dividing by peak acceleration.

site-independent procedures. Unlike the site-independent procedures, site-dependent procedures will generally produce ground-motion parameters that correspond closely with those expected on the basis of the seismological and geologic conditions at the site. The limiting factor, however, is that the source mechanisms, transmission-path characteristics, and local ground response may not be fully represented by the available data. Also, the ensemble of relevant seismograms may be inadequate to permit meaningful statistical evaluations of the variance in the data. For these reasons, care must be exercised to ensure that the most reasonable procedure for defining the design response spectrum is used.

DESIGN TIME HISTORIES

Time histories of particle acceleration, velocity, and displacement are the most accurate representations of the seismic input. These representations are not needed for all earthquake-resistant design applications, but they are frequently used when analyzing the response of important structures such as nuclear power plants.

At the present time, no model is completely adequate for deterministically computing the acceleration time history of ground motion for arbitrary source-site configurations. Current design practice, therefore, requires design time histories to be developed in conjunction with the design response spectrum. The time histories are constrained to be compatible with the design spectrum for the site and to account for the peak ground shaking parameters, spectral intensity, and duration of shaking. Compatibility is defined to mean that the envelope of all the response spectra derived from the time histories lies above the smooth design response spectrum throughout the frequency range of interest.

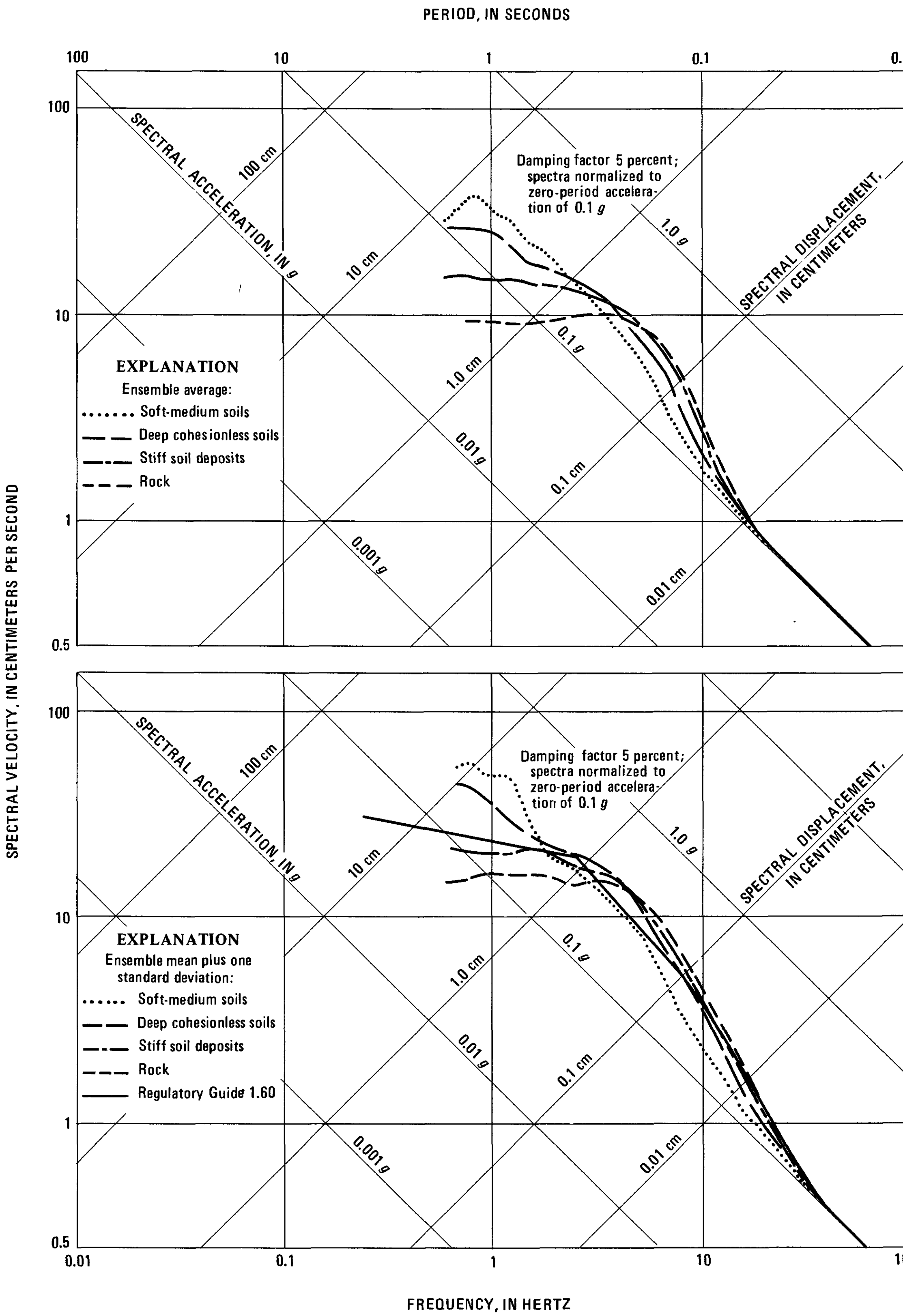


FIGURE 52.—Comparison of site-dependent mean and mean-plus-one-standard-deviation response spectra with AEC Regulatory Guide 1.60 spectrum.

Several techniques have been proposed for generating time histories (for example, Bycroft, 1960; Housner and Jennings, 1969; Rascón and Cornell, 1969; Lynch and others, 1970; Seed and Lysmer, 1972). These techniques can be categorized as follows:

1. *Use of empirical data.* Strong-motion accelerograms of past earthquakes, recorded either in the vicinity of the site or at other locations that have similar source-path-site characteristics, are used with appropriate modification to develop a design time history for the site of interest.
2. *Use of calculational models.* Because earthquake accelerograms recorded at moderate distances have the appearance of random time functions, calculational models have been developed that use white noise, filtered white noise, and stationary and nonstationary filtered white noise to generate design time histories.

The present lack of an adequate ensemble of strong-motion accelerograms is the major limitation in developing design time histories.

DETERMINE LOCAL GROUND RESPONSE

It has been recognized and widely documented since the early 1900's that the physical properties of the geologic materials underlying the recording site can significantly modify the amplitude level and spectral composition of the ground motion recorded there. Structures founded on unconsolidated materials are frequently damaged (Page, Blume, and Joyner, 1975; Steinbrugge and others, 1975) by ground shaking, and the damage distribution on many occasions has been recognized to be related to the site. Buildings of a certain class or type (that is, having a certain natural period) are often damaged from ground shaking when located on geologic materials having a similar characteristic site period, whereas buildings with a different natural period located on the same foundation materials are not damaged. The distribution of damage is explained by the fact that the local geologic materials amplify the ground motion input in a period range that coincides with the natural period of vibration for the damaged structure.

When the unconsolidated material underlying a recording site modifies the seismic input, the amplitude of the surface ground motion increases in a narrow range of frequencies and decreases for other frequencies. The amplitude of the amplified ground motion is a function of the shear wave velocity, the density and material damping, the thickness, water content, and where the surface or bedrock topography is irregular, the geometry of the unconsolidated deposits and underlying rock. The frequency range that is affected is a function of the thickness and physical properties of the unconsolidated materials (Seed and Idriss, 1969; Murphy, Weaver, and Davis, 1971; Joyner and Chen, 1975; Borcherdt and Gibbs, 1976; Hays, 1977a, 1978).

The amplification effect for surface waves is similar to that of body waves except that the thickness of the unconsolidated materials also affects the magnitude of amplification (Murphy and Davis, 1969; Drake and Mal, 1972; Hanks, 1976).

Local ground response is complicated by the fact that unconsolidated materials behave nonlinearly. Soils have a shear modulus and damping characteristics that are strain dependent (fig. 53). Soil nonlinearities and inelasticity may attenuate, rather than amplify, the surface ground motions relative to the rock ground motions under certain conditions.

The topography of the site has also been demonstrated to have an important frequency-dependent effect on ground motion (Bouchon, 1973; Trifunac, 1973a; Rogers and others, 1973; Boore, 1973; Wong and others, 1977).

Figure 54 shows the variation in terms of smooth response spectra that would be expected if the same earthquake was recorded on stiff, medium, and soft soil columns (Smoots and others, 1969). These spectra show that the high-frequency components are usually damped out fairly rapidly by thick soft soils, reducing the level of peak ground acceleration.

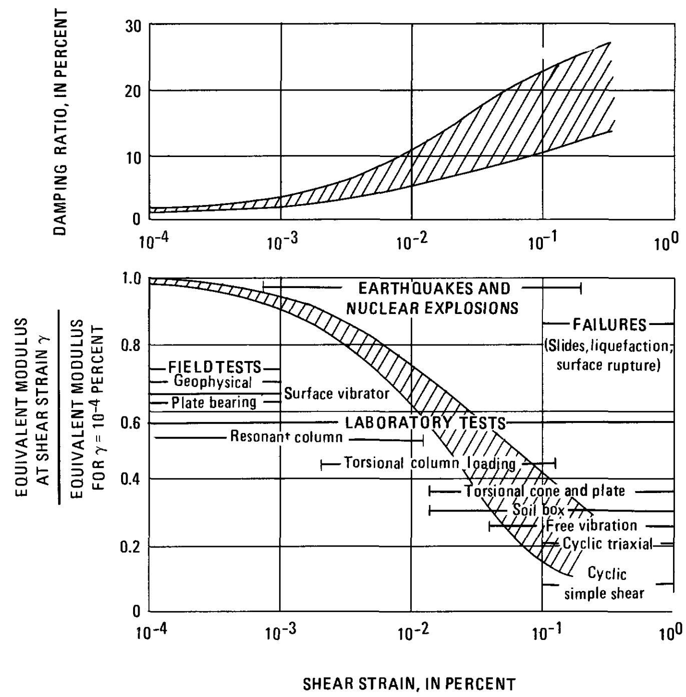


FIGURE 53.—Effect of strain level γ on shear modulus and damping of soils (from Seed and Idriss, 1969).

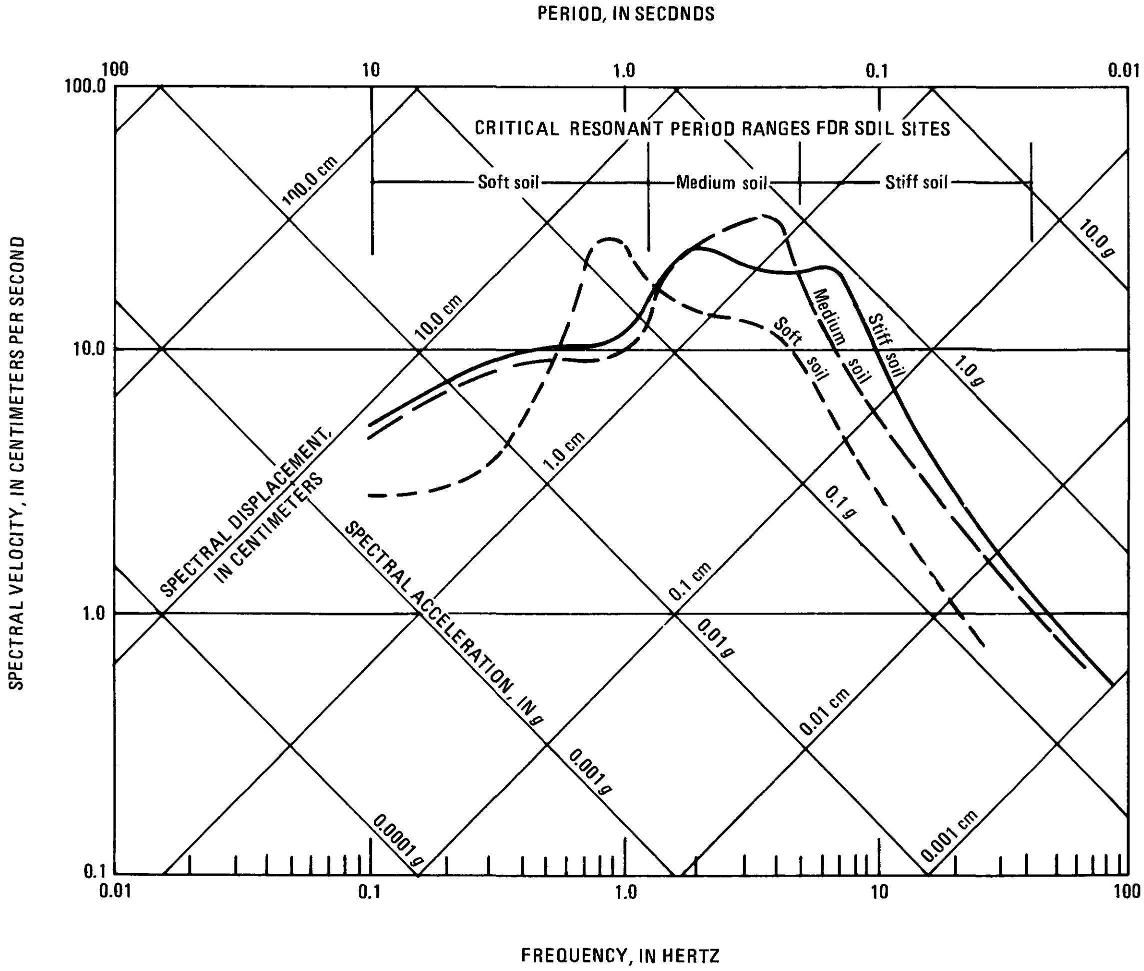


FIGURE 54.—Comparison of smooth response spectra for three soil columns (modified from Smoots and others, 1969).

From the present United States earthquake data sample, 104 horizontal-component accelerograms (see table 15) can be grouped in four broad site classifications: (1) rock or rocklike material having a shear wave velocity at low (0.0001 percent) strains of at least 760 m/s, (2) stiff soil (firm soils less than about 45 m thick), (3) cohesionless soil (sandy soils exceeding 80 m in thickness), and (4) soft to medium-stiff clay. Seed, Ugas, and Lysmer 1976) analyzed the horizontal acceleration spectra representing these four site classifications and determined normalized average spectral response for each classification (fig. 55). Significant amplification relative to rock is indicated for sites underlain by soft-to-medium clay and sandsites for periods greater than 0.5 second.

Empirical data showing the effect of site geology on body waves have been obtained from the nuclear explosion safety program at the Nevada Test Site (Murphy, Weaver, and Davis, 1971; Hays, 1972a, b; Hays, 1978) and earthquake aftershocks (Murphy, Lynch, and O'Brien, 1971; Hays, 1977a). A classic example of body-wave amplification is illustrated by ground-motion data recorded at Tonopah, Nev. (fig. 39). A pair of seismograph stations located 183 m apart and underlain

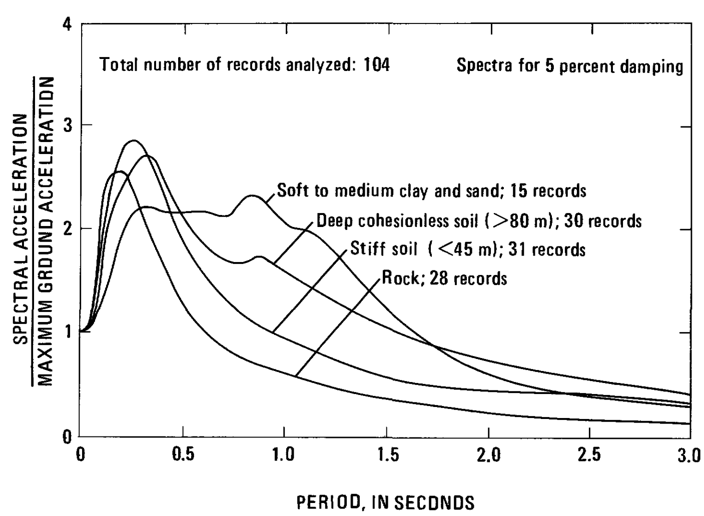


FIGURE 55.—Average acceleration response spectra for four site classifications (from Seed, Ugas, and Lysmer, 1976).

respectively by dacite, an igneous rock, and 13.1 m of mine tailings (fill) have recorded input ground motions with a dynamic range of $10^{-5}-10^{-3}$ *g* from more than 20 nuclear explosions located about 100 km away. The low acoustic-impedance contrast of the fill relative to rock causes the ground-motion spectral components at around 7 Hz to be amplified by a factor of six. The mean site transfer function is repeatable from event to event with a standard deviation (σ) of 1.30. The level of peak ground acceleration is also larger by a factor of about two at the station underlain by fill. The strain levels induced in the fill were low (10^{-5} to 10^{-4}) because of the large source-to-recording site distances; therefore, the fill responds almost elastically to the input ground motions. A second example of body wave amplification was observed in the Glendale, Calif. area. Measurements of ground motion from the aftershocks of the 1971 San Fernando earthquake were made at a number of locations in San Fernando Valley. Two stations in Glendale (fig. 56) exhibit significant relative ground response. The mean site transfer function is repeatable from event to event with a standard deviation (σ) of 1.50.

Las Vegas Valley in southern Nevada is underlain by Cenozoic alluvium of widely varying thickness (Diment and others, 1961; Longwell and others, 1965). It has been recognized since 1970 (Davis and Lynch, 1970, Bennett, 1974) that the horizontal spatial variation of ground response in Las Vegas from nuclear explosions (epicentral distances of about 150 km) is significant. Peak ground-motion parameters differ by a factor of about four and response-spectra amplitudes by a factor of about ten (fig. 57). These differences are consistently observed at stations that are only a few kilometers apart in Las Vegas Valley. The standard deviation for the mean ground-response of any two sites is about 1.30. The consistency of the site transfer functions indicates that the relative ground response depends primarily on the local site geology, not on source or transmission path parameters. The strong frequency-dependent nature of the ground response, with substantial variability at long periods (>1 s) and essentially uniform response at short periods (0.1-0.5 s), suggests that the principal effects are caused primarily by long-period surface waves propagating unevenly in the variable surface alluvium. The ground response derived from the radial component of spectral velocity for the long-period band 3.33–4.50 s correlates fairly well with the estimated thickness of the alluvium in Las Vegas Valley (fig. 58).

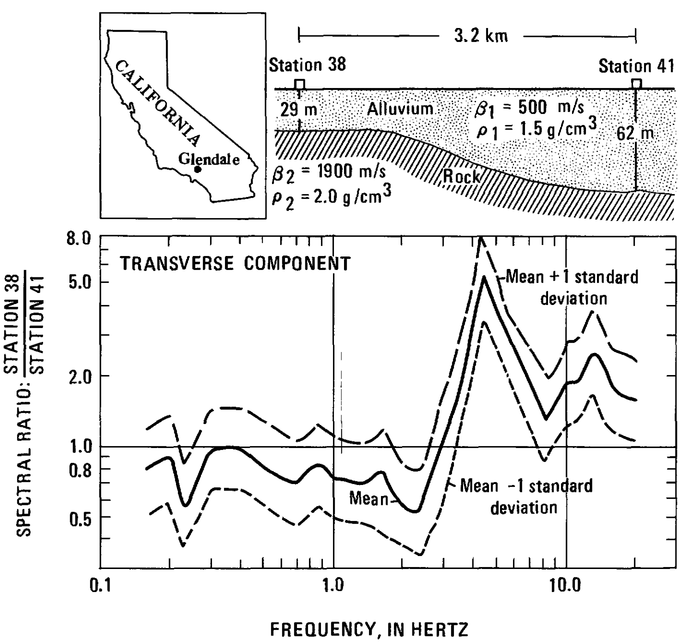


FIGURE 56.—Example of site transfer function for two sites in the Glendale, Calif. area derived from aftershocks of the 1971 San Fernando earthquake.

How ground motion varies with depth is not well known. One of the fairly recent studies (Murphy and West, 1974) used identical seismograph systems emplaced in tuff at the bottom of a 41-m drill hole at Beatty, Nevada and at the surface on alluvium. A large number of nuclear explosions were recorded on this array and established the repeatability of the site transfer function (fig. 59) for low-strain levels. The amplitudes of the spectral components, especially those in the 0.05–0.5 second range, decrease with depth. The most significant decrease occurs for periods in the vicinity of 0.3 second, the characteristic site period (that is, the period that corresponds to four times the thickness of the alluvium divided by its shear wave velocity). This experiment also demonstrated that the input ground motion at the base of the alluvium is essentially identical (except for the free-surface effect) to the ground motion observed at a surface site located on rock. The limited data available at present are inadequate to prove the common assumption of a broad-band spectrum at depth.

The present lack of data to show how ground-motion time histories and their response spectra change with depth is a major source of uncertainty in some earthquake-resistant design engineering applications such as waste isolation.

Although the procedure for predicting site amplification effects still has some elements of controversy, empirical data from past earthquakes and laboratory

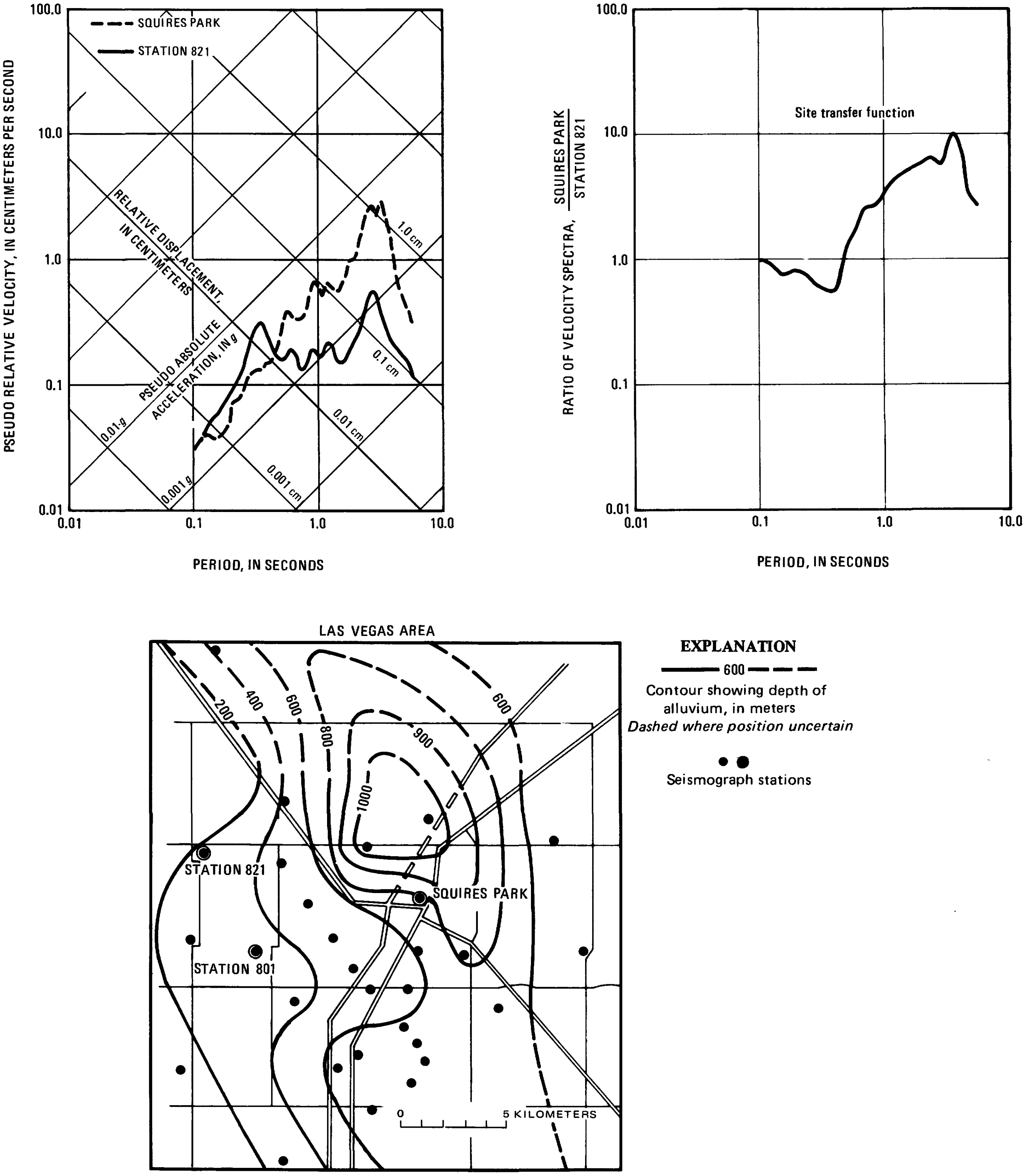


FIGURE 57.—Location of seismograph stations and thickness of alluvium in Las Vegas Valley and variation of horizontal velocity response spectra for two stations and their site transfer function. Ground motions are from nuclear explosions at the Nevada Test Site.

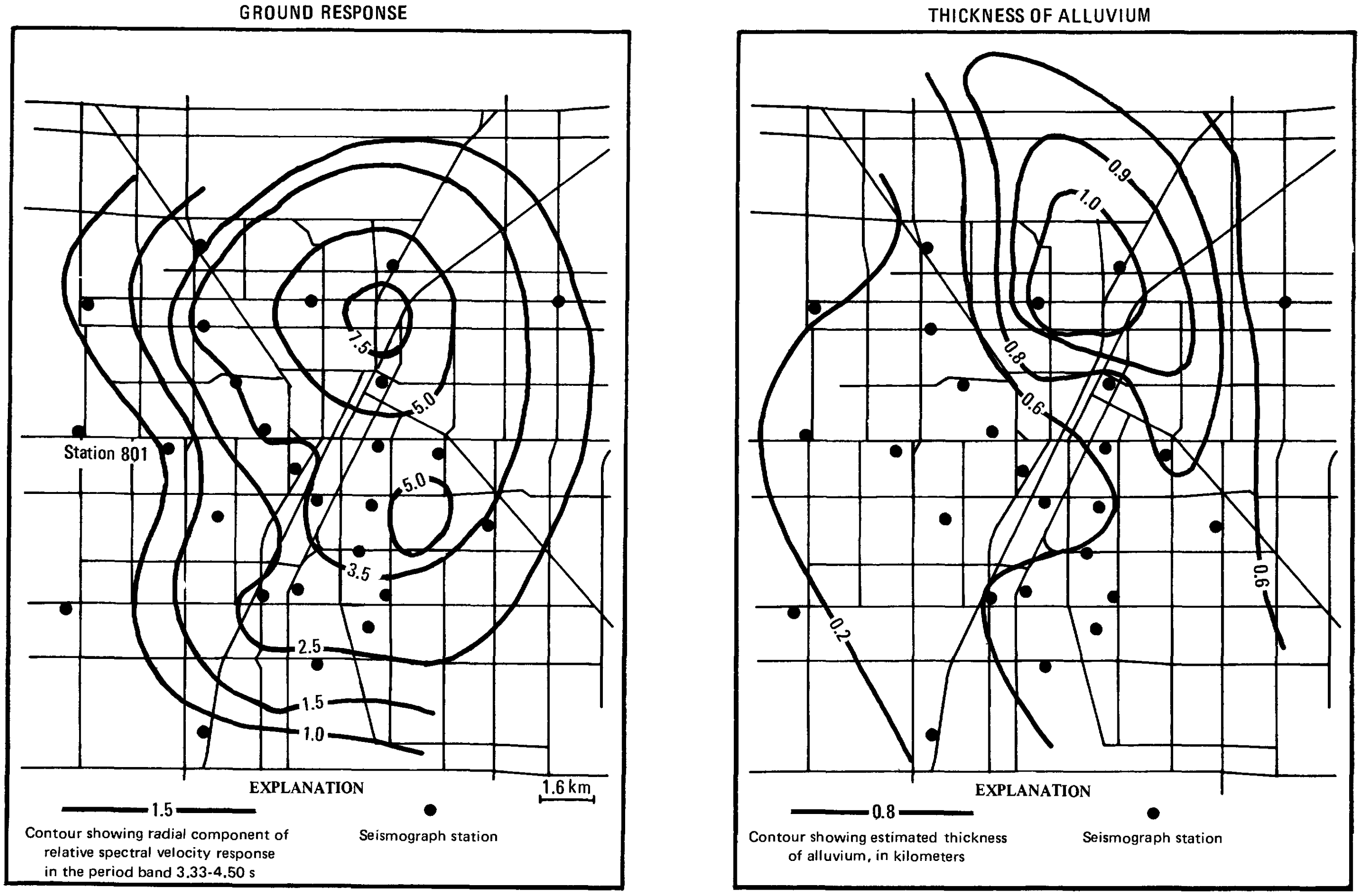


FIGURE 58.—Radial component of relative ground response in the period band 3.33–4.50 s and thickness of alluvium, Las Vegas Valley (from Murphy and Hewlett, 1975). Ground response is calculated relative to station 801.

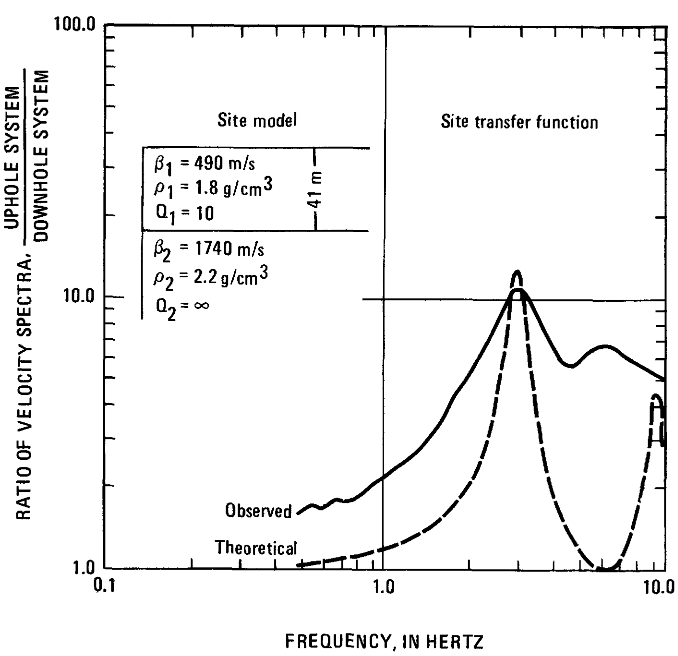


FIGURE 59.—Variation of ground motion with depth, Beatty, Nev.

studies (for example, Idriss and Seed, 1968; Espinosa and Algermissen, 1972; Seed and others, 1972; Hays and King, 1973; Warrick, 1974; Campbell and Duke, 1974; Page, Boore, and Dieterich, 1975; Borcherdt and others, 1975; Seed, 1975; Joyner and Chen, 1975; Hays and others, 1979) suggest the following guidelines:

1. Spectral ratios (transfer functions) of the ground motion at sites underlain by unconsolidated materials and at sites underlain by rock may be as high as 10 to 1 for some periods when low-strain ground motions are involved. However, this ratio is generally thought to decrease substantially for intense high-strain ground motions, depending on the material properties.
2. Amplification is a sensitive function of the thickness of the unconsolidated materials overlying rock; increasing thickness generally lengthens the period at which amplification occurs.
3. The shorter period spectral components are usually damped out fairly rapidly by thick

soft materials. This effect tends to reduce the level of peak ground acceleration when the peak rock acceleration exceeds 0.1 *g*.

4. The top 30 m or so of a deposit of unconsolidated material frequently has the most critical effect upon amplification and should be investigated thoroughly to determine its dynamic properties.
5. Unconsolidated material below the topmost 30 m generally does not need to be investigated for nonlinear behavior unless the specific material is especially sensitive to ground motion.
6. For long-duration high-strain ground motions, nonlinear effects become very important. The general effects of nonlinear behavior are to decrease the amplification level (relative to what would have occurred for linear behavior) and to lengthen the characteristic site period.

For low-strain earthquake ground motions, unconsolidated materials can respond in a manner close to that which the theory of elastic wave propagation predicts. These effects represent realistic upper bounds of ground response. Parametric curves (fig. 60) published by Environmental Research Corporation (1974b) for amplification of incident, plane SH waves (Haskell, 1960) show how the response characteristics of a low-velocity material overlying rock change as the physical properties of the material and the angle of wave incidence change. The curves are plotted against the dimensionless parameter $d/\beta_1 \cdot f$ where d is layer thick-

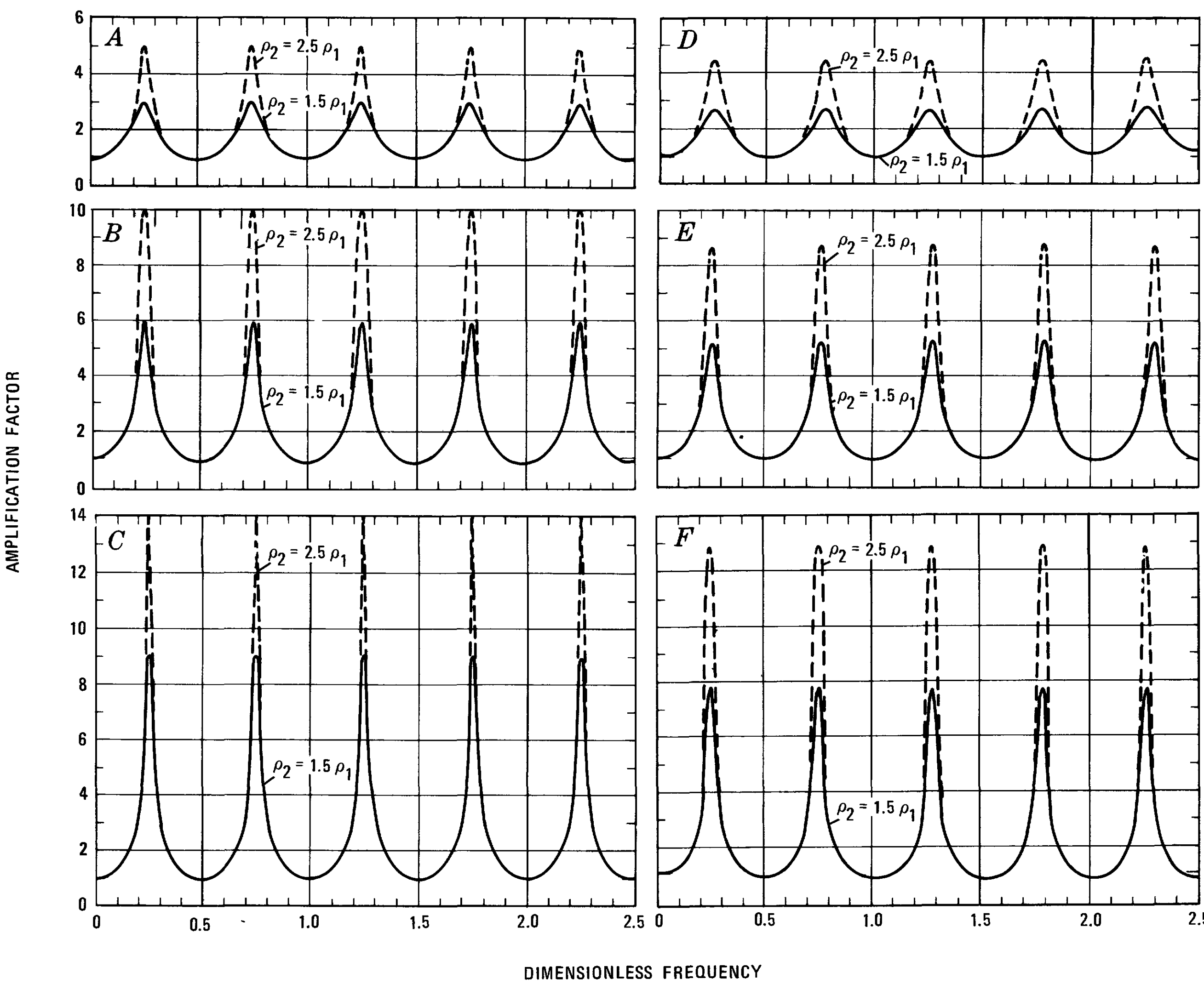


FIGURE 60.—Parametric curves for amplification of SH waves. *A*, $\beta_2 = 2\beta_1$, $i=0$, elastic response. *B*, $\beta_2=4\beta_1$, $i=0°$, elastic response. *C*, $\beta_2=6\beta_1$, $i=0°$, elastic response. *D*, $\beta_2=2\beta_1$, $i=30°$, elastic response. *E*, $\beta_2=4\beta_1$, $i=30°$, elastic response. *F*, $\beta_2=6\beta_1$, $i=30°$, elastic response. From Environmental Research Corporation (1974b).

ness, β_1 is shear wave velocity of the low-velocity layer, and f is frequency. For a fixed angle of incidence, the amplification factor depends only upon the acoustic impedance contrast and not upon the actual values of shear-wave velocity and density. Curves are given for two density contrasts ($\rho_2/\rho_1=1.5$ and 2.5), three shear-wave velocity contrasts ($\beta_2/\beta_1=2$, 4, and 6), and two angles of incidence, ($i=0°$ and 30°).

To use the parametric curves, one needs values of the ratio of shear wave velocities β_1/β_1 and thickness d of the low-velocity material. The ratio d/β_1 provides the scale factor which converts the abscissa to frequency in hertz.

An example showing how the site transfer function is estimated is depicted in figure 61. If the density ratio is 1.35, the velocity ratio 7.5, and the angle of incidence 30°, the amplification factor is interpolated from figure 60*F* as follows:

$$\frac{A}{A'}=\frac{\rho\beta}{\rho'\beta'}$$

$$\frac{7.8}{A'}=\frac{(1.5)\,(6)}{(1.35)\,(7.5)} \quad \text{or } A'=8.8.$$

Thus, the amplification is a factor of 8.8. The resonant frequency is found from the relation (fig. 60 *F*):

$$\frac{d}{\beta_1}\,f=0.25 \text{ or } \frac{6.4}{183}\,f=0.25$$

so f is approximately 7 Hz for elastic response.

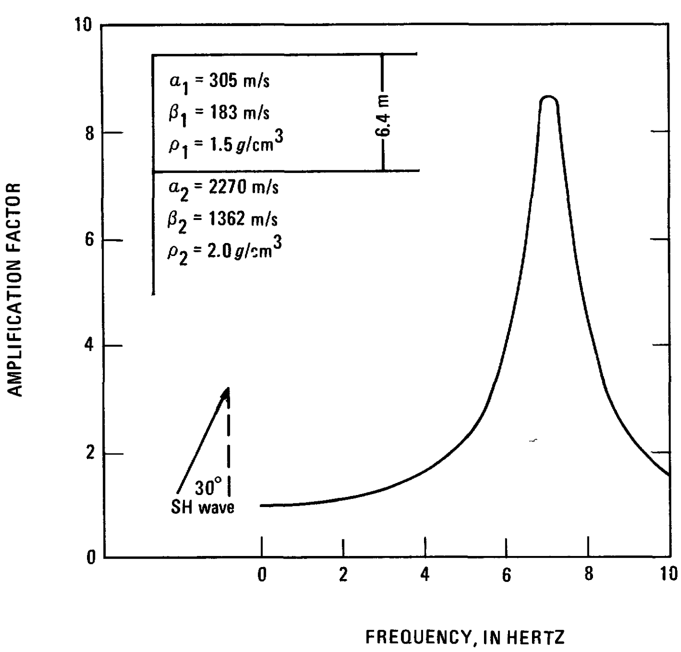


FIGURE 61.—Example of site transfer function, elastic response. α_1 and α_2 are P-wave velocities, β_1 and β_2 are S-wave velocities, and ρ_1 and ρ_2 are densities.

Amplification above 10 Hz is not normally considered because high-frequency shear waves attenuate very rapidly.

The site transfer function for the case of multiple low-velocity layers can also be derived by using the Haskell (1960) matrix formulation or by other numerical methods. An estimate can be obtained by using figure 60 and combining the response calculated for each individual layer.

Site amplification modeling is especailly needed for the case of high-strain ground-motion loads. Because of the increased number of physical parameters and the present gaps in knowledge (Kanninen and others, 1970) about inelastic behavior of solids, comprehensive parametric curves cannot be provided. The empirical procedures proposed for the 1976 Uniform Building Code (see next section) can be used to model the high-strain case and will give reasonable estimates of the effect. Also, some of the general curves (figs. 62–64) that have been published (Imbsen and Gates, 1973) permit estimates to be made for high-strain loading conditions. These curves were derived with the SHAKE program (Schnabel, Lysmer, and Seed, 1972).

Values of the peak horizontal rock acceleration and the thickness of the unconsolidated material are needed when estimating amplification effects for high-strain earthquake ground motion. The acceleration estimates can be derived from maps such as shown in figure 42 or by empirical "deconvolution" techniques (for example, Lysmer and others, 1971; Schnabel, Seed, and Lysmer, 1972; Papadakis and others, 1974). By multiplying the peak rock acceleration by the rock response factor (fig. 62), an estimate of the elastic-response spectrum for rock is obtained. Amplification

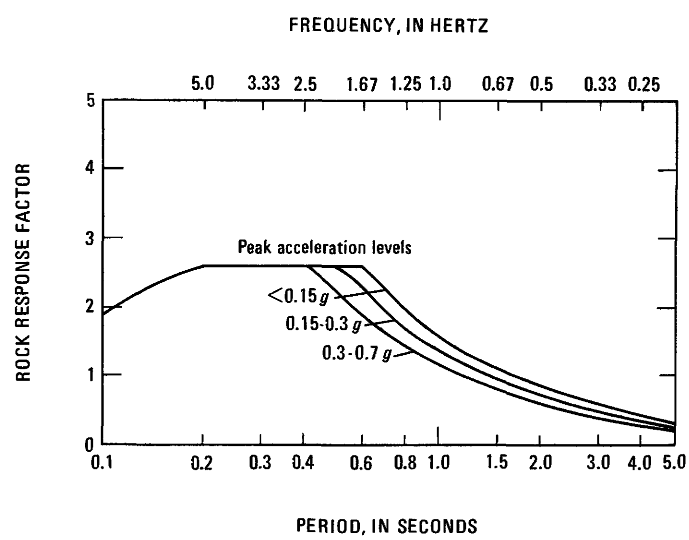


FIGURE 62.—Normalized rock response spectrum, 5-percent damping (modified from Imbsen and Gates, 1973).

effects relative to rock are determined by multiplying the appropriate curve of figure 63 and the estimated elastic-response spectrum for rock (fig. 62). This product gives the approximate amplification effects.

The peak rock acceleration that is transmitted to the soil column has a major effect on the amplification spectra. As the peak rock acceleration increases, the amplification level decreases and the predominant period of resonance lengthens (fig. 64).

The generalized parametric curves of figures 63–65 may not provide the level of precision needed for predicting amplification effects at the site of interest. In this case, it might be desirable to utilize a finite-element program such as SHAKE (Schnabel, Lysmer, and Seed, 1972) or QUAD–4 (Idriss and others, 1973), or the technique proposed by Joyner (1975) to model the site in more detail. The degree of accuracy to which the physical properties of the rock and unconsolidated materials at the site are known is the primary consideration before deciding to use sophisticated calculational procedures.

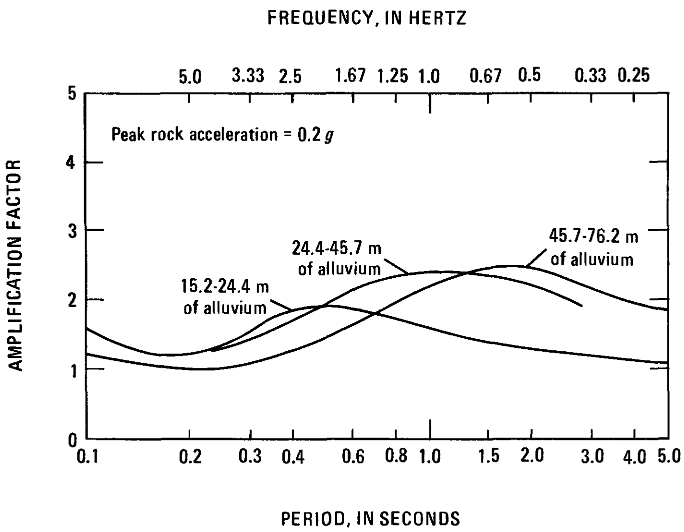


FIGURE 63.—Parametric curves for high-strain amplification of SH waves and three depths of unconsolidated materials (modified from Imbsen and Gates, 1973).

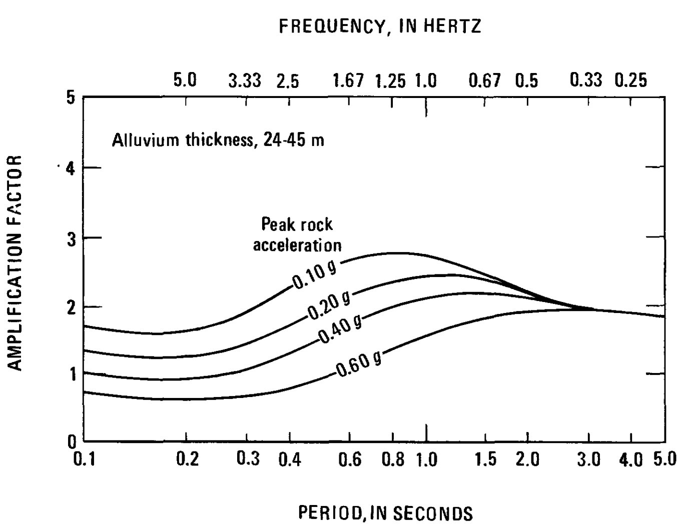


FIGURE 64.—Effect of peak acceleration level on amplification (modified from Imbsen and Gates, 1973).

Several new earthquake-design provisions, including a procedure for estimating the characteristic site period, were proposed for incorporation in the 1976 Uniform Building Code (Freeman, 1975). These provisions will be discussed below.

SUMMARY OF UNIFORM BUILDING CODE PROCEDURES

The most widely used standard for earthquake-resistant design is the Structural Engineers Association of California (SEAOC) Code. The SEAOC Code, which was incorporated into the 1973 Uniform Building Code, contains the following commentary about aseismic design:

> Basically, the problem is that the entire phenomenon, from the earthquake ground motion to the realistic response of structures to this ground motion, is very complex. Codes, of necessity, are generalized simplifications. Complex mathematical analyses have been made on simple and idealized structures subjected to past earthquake ground motions. These have been helpful in improving our understanding of the phenomenon. However, for purposes of design of the vast majority of structures, it is necessary to reduce this complex, dynamic problem to one of equivalent static lateral forces. These can be related to the dynamic characteristics of the structure. They provide the basic code criteria, applied with stresses within the elastic limit. However, in applying these simplified concepts, the structural engineer must do this with sound judgment that can only be developed with experience, observation, and study of the earthquake phenomenon. He must be especially aware of the nature of the response of the particular structure under design and he must evaluate the capabilities of that structure to perform satisfactorily beyond the elastic-code-stipulated stresses.

The SEAOC Code is a minimum standard to assure public safety. The requirements are intended to safeguard against major failures and loss of life. The aim of the code is to provide structures that will:

1. resist minor earthquakes with damage;
2. resist moderate earthquakes without structural damage, but with some nonstructural damage;
3. resist major earthquakes without collapse, but with some structural and nonstructural damage.

The basic formula used in the 1973 Uniform Building Code is

$$V = ZKCW$$

where

V is base shear or total lateral force to be resisted at the base of the structure,

Z is zone factor, based on the Algermissen (1969) U.S. seismic risk map (fig. 65) having four seismic risk zones. The numerical values of Z for the four zones are: $Z=1$ for zone 3; $Z=0.5$ for zone 2; $Z=0.25$ for zone 1; and $Z=0$ for zone 0.

K is an arbitary factor that, in effect, is a safety factor adjustment based on an arbitrary classification of the type of construction. It recognizes that different degrees of hazard against collapse are inherent in different types of construction; K has no relation to the actual forces expected.

C is a coefficient related to the period of the structure. A plot of C against period represents a response spectrum and roughly parallels that derived from the 1940 Imperial Valley, Calif. earthquake accelerogram recorded in El Centro, Calif., and

W is the weight of the structure.

Several new design provisions were proposed for the 1976 Uniform Building Code (Freeman, 1975; Nosse, 1975; Seed, 1975; and Donovan, 1975). The basic consideration is that, in general, structures shall be designed and constructed to resist minimum total lateral seismic forces assumed to act nonconcurrently in the direction of each of the main axes of the structure in accordance with the formula

$$V = ZIKCSW .$$

In this formula, Z is a zoning factor based on the preliminary design regionalization map (fig. 66) prepared by the Applied Technology Council (1976). K is a numerical factor determined by the type of framings,

$$C = \frac{0.067}{\sqrt{T}}$$

where T is the period of the building, and S is the soil-structure interaction factor or resonance coefficient, which is a function of the building period and the characteristic site period T_s. I is the importance factor for the building and W is the total dead load or weight of the building.

The values of Z, the seismic zoning factor, are defined as equal to 1 for locations in zone 4, ¾ for loca-

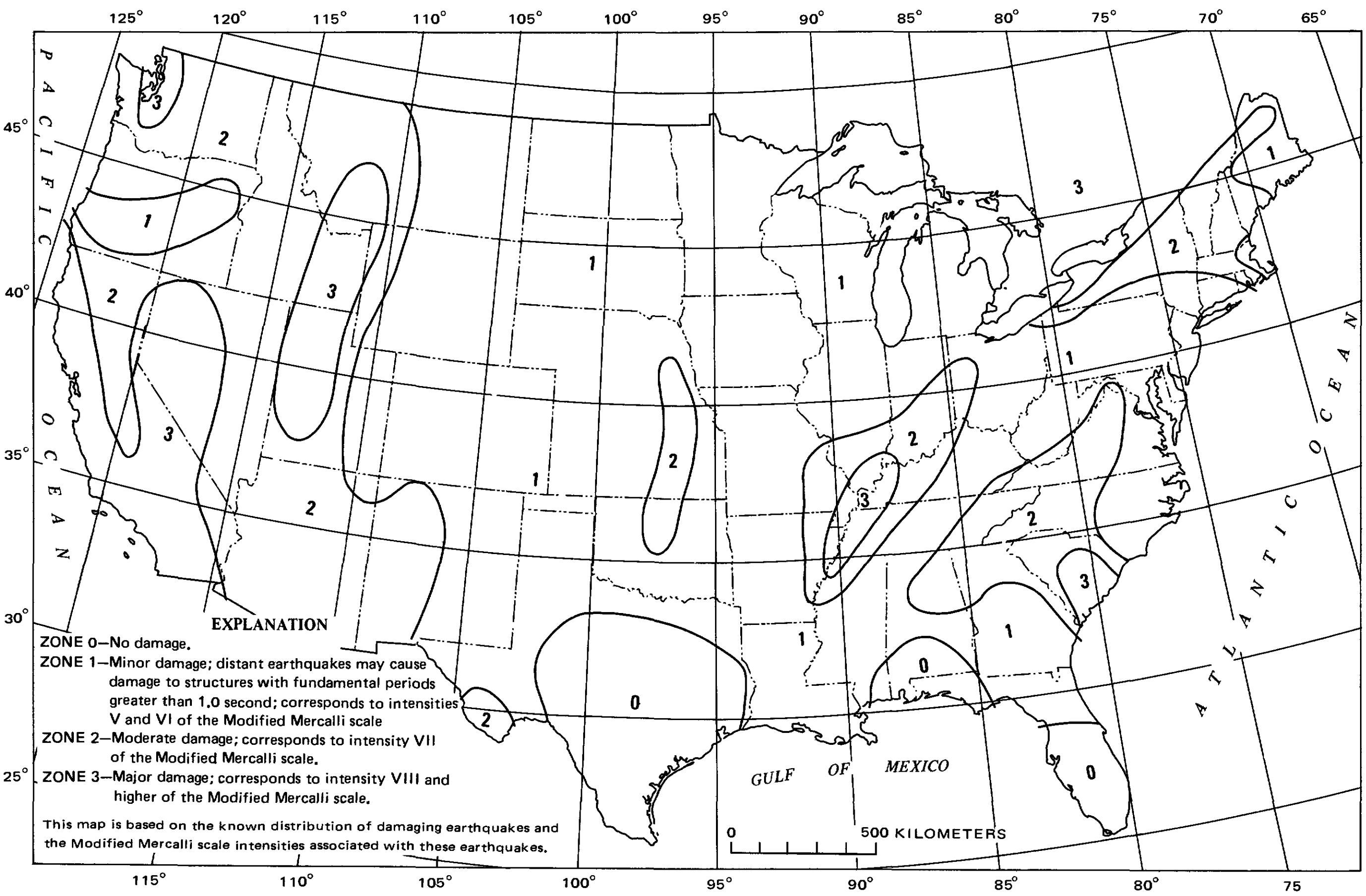


FIGURE 65.—United States seismic risk zones. Based on Modified Mercalli intensity scale and the distribution of damaging earthquakes (from Algermissen, 1969). The map of seismic risk zones in the 1979 Uniform Building Code is based on this map.

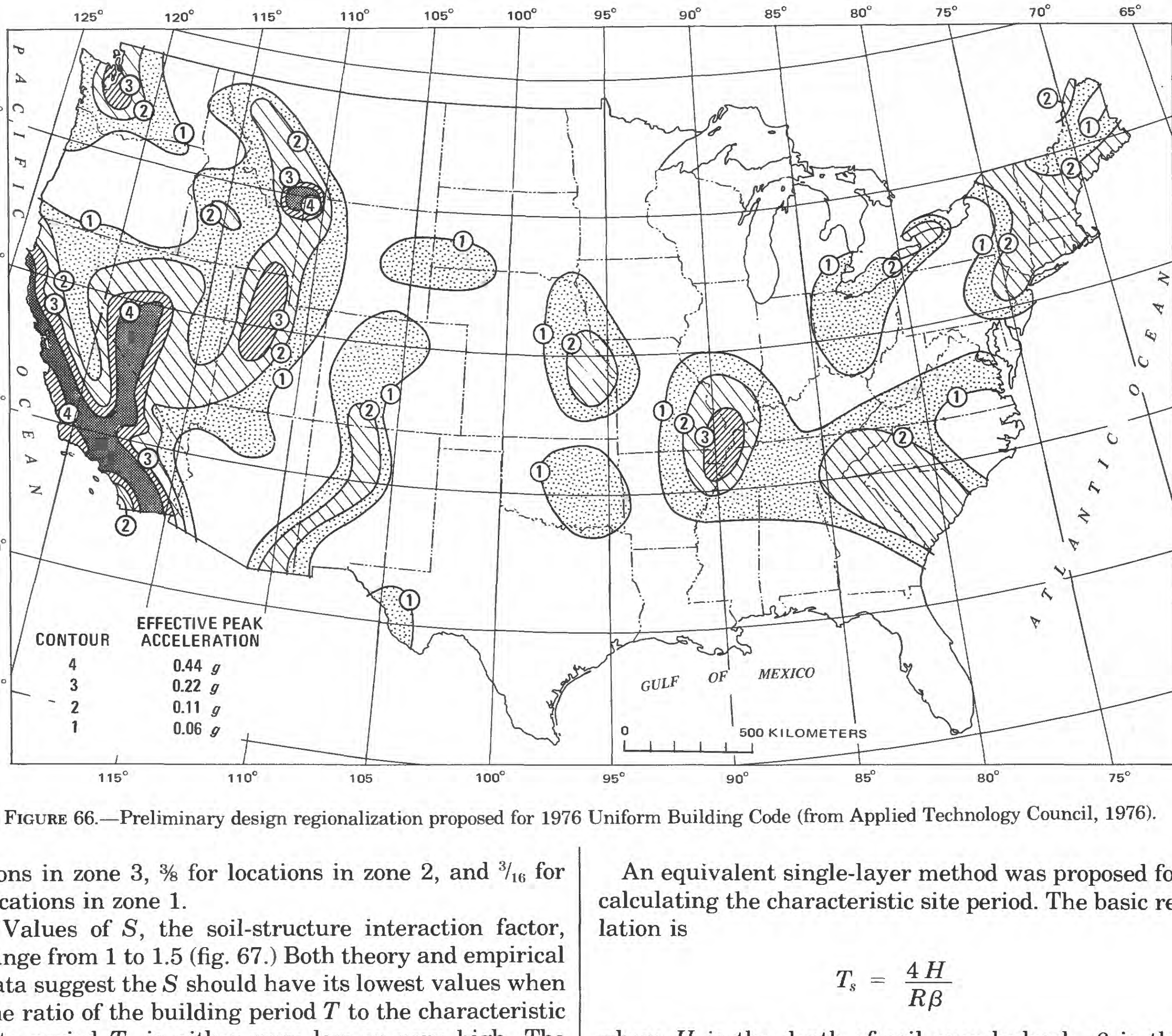


FIGURE 66.—Preliminary design regionalization proposed for 1976 Uniform Building Code (from Applied Technology Council, 1976).

tions in zone 3, 3/8 for locations in zone 2, and 3/16 for locations in zone 1.

Values of S, the soil-structure interaction factor, range from 1 to 1.5 (fig. 67.) Both theory and empirical data suggest the S should have its lowest values when the ratio of the building period T to the characteristic site period T_s is either very low or very high. The maximum value occurs when $T/T_s = 1$.

Determination of the characteristic site period T_s is an important new proposal. Studies of ground-motion characteristics and building damage from past earthquakes have shown that the characteristic period at which maximum damaging effects occur is approximately equal to the fundamental period of the soil deposit overlying rocklike formations. A rocklike formation may be considered as any earth or rock material in which the shear-wave velocity at small strains (0.0001 percent) is about 760 m/s or greater. Shear-wave velocities of soils approach 760 m/s at depths of about 152 m; therefore, it is unnecessary to consider greater depths when determining the value of T_s. Values of T_s will vary from a minimum value of 0.5 s for shallow, stiff soil deposits to a maximum value of 2.5 s for deep, soft soil deposits (Seed, 1975).

An equivalent single-layer method was proposed for calculating the characteristic site period. The basic relation is

$$T_s = \frac{4H}{R\beta}$$

where H is the depth of soil over bedrock, β is the average shear-wave velocity of the soil layer as measured under low-strain conditions in the field, and R is a correction factor to allow for the reduction in shear-wave velocity when the soil is excited by high-strain ground motion during an earthquake. It is necessary to specify the level of base rock excitation in order to assign values to R. Values of R have been established on the basis of the "effective peak acceleration" obtained from the design regionalization map (fig. 66) as follows:

1. zone 1: A magnitude-6 earthquake producing a peak effective acceleration of 0.1 g corresponds to a value of 0.9 for R.
2. zone 2: A magnitude-6 earthquake producing a peak effective acceleration of 0.2 g corresponds to a value of 0.8 for R.
3. zone 3: A magnitude-7 earthquake producing a peak effective acceleration of 0.3 g corre-

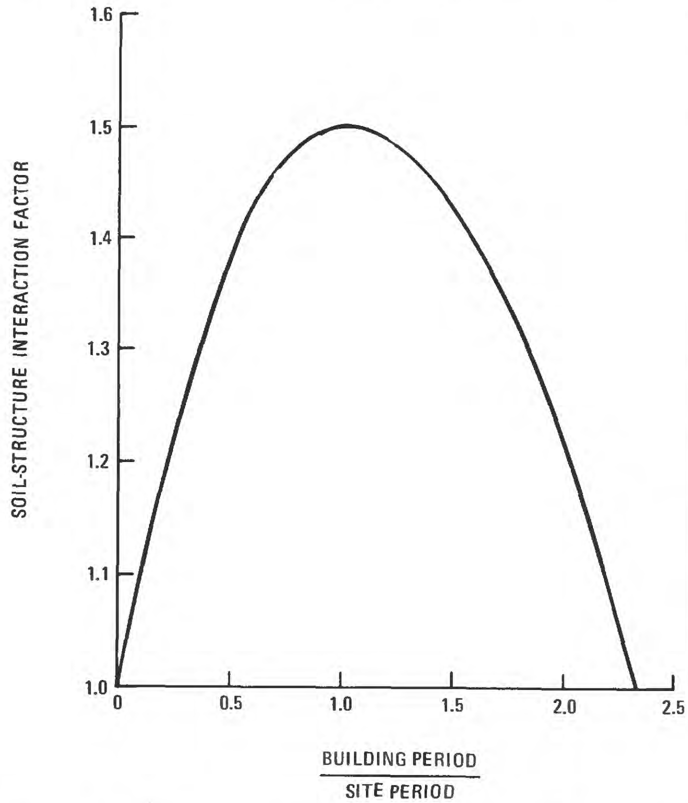


FIGURE 67.—Soil-structure interaction factor proposed for 1976 Uniform Building Code (from Seed, 1975).

sponds to a value of 0.67 for R.

4. zone 4: A magnitude-7 earthquake producing a peak effective acceleration of 0.4 g corresponds to a value of 0.67 for R.

As an example, consider a 12.2-m layer of sand with a shear wave velocity of 274 m/s overlying rock in Los Angeles (zone 4). For this example,

$$T_s = \frac{(4)\,(40)}{(0.67)\,(900)} = 0.27 \text{ seconds}$$

This value is less than the minimum allowable value of 0.5 s, so the value of T_s used in seismic design for this example would be 0.5 second.

For multilayered soil profiles, the equivalent single-layer procedure can be used to compute an approximate value for T_s. The basic relation for T_s,

$$T_s = \frac{4\,H}{R\beta},$$

now let H be the total thickness of the unconsolidated material overlying bedrock and β the mean shear-wave velocity, weighted in proportion to the velocities and thicknesses of the individual layers as follows:

$$\beta = \frac{\sum_{i=1}^{n} \beta_i H}{\sum_{i=1}^{n} H_i},$$

where β_i and H_i are the shear-wave velocity and thickness of each individual layer.

The importance factor I has also been proposed for incorporation in the Uniform Building Code formula for base shear to allow higher force levels to be assigned to structures housing certain facilities. The values of I range from 1.0 to 1.5, with the highest value being assigned to essential facilities such as hospitals, communication centers, and fire stations where the acceptable level of risk from earthquakes is to be reduced.

The overall effect of all the new provisions is to provide for an increase in the design base shear.

The details about structural design in terms of the Uniform Building Codes are beyond the scope of this paper. References such as Degenkolb, Dean, and Wyllie (1971), Freeman (1975), Seed (1975), and Donovan (1975) provide information on this subject for the interested reader.

DEFINE UNCERTAINTIES OF THE GROUND-MOTION DESIGN VALUES

Specification of the uncertainty model for the ground-motion design values is a complex task. The model depends upon the seismotectonic province where the earthquake occurs and the physical parameters controlling the source, path, and local ground-response effects (table 23). The complexity of the problem arises from two factors: (1) the statistical distribution of many of the physical paramenters is either unknown or poorly known and (2) the precise way to combine the uncertainties of the individual physical parameters of the system is not clear, even if the statistical distribution for each parameter were well known. An example of the second factor is illustrated by the problem of combining the uncertainty in magnitude and seismic moment, two parameters that affect the low-frequency ground motion characteristics and are related to the length of fault rupture.

At the present time, it is impossible to specify the exact location and magnitude of the earthquakes that will affect a site during the life of a structure. This difficulty is a consequence of the short incomplete seismicity record, the lack of regional seismicity networks to define current seismicity patterns, and the lack of adequate geologic data to define the earthquake potential of a 3-dimensional volume of rock. An example will illustrate the problem. Yucca Flat and Pahute Mesa, two areas on the Nevada Test Site, are probably the

TABLE 23.—*Uncertainties in physical parameters that affect ground motion*

Physical parameter	Effect on ground motion	Uncertainty and functional dependence
Seismicity Parameters		
Seismic source zones	Zone controls location of earthquakes.	Not known. Function of seismicity record, geologic, and tectonic history.
Recurrence rates (b)	Defines frequency of occurrences.	Average b=0.45 in eastern U.S. where log $N=a-bI$; σ=f(N).
Upper-bound magnitude	Establishes ground-motion design levels.	Not known. Function of completeness and length of seismicity record and geologic data on fault rupture.
Source Parameters		
Epicenter	Establishes location of design earthquake.	Best location accuracy is 1 km; worst is 50 km. Function of regional velocity model and instrument locations.
Focal depth	Affects partition of body-and surface-wave energy	Best location accuracy is 2 km; worst is 50 km. Function of regional velocity model and instrument locations.
Magnitude (m_b,M_L,M_s)	Affects low frequencies and ground-motion scaling.	Best accuracy is 0.1 unit; worst is > 1 unit. Function of instruments and regional calibration.
Seismic moment (M_o)	Affects low frequencies, especially for great earthquakes.	log M_o~3/2 M_s until $M_o \geq 10^{28}$ dyne-cm. M_o=21.9+3 log L with scatter a factor of 2. Function of instrument dynamic range.
Stress drop ($\Delta\sigma$)	Affects high frequencies and peak acceleration.	$\Delta\sigma$ has a log-normal distribution. Earthquakes exhibit a constant average stress drop of about 10 bars 2σ= one order of magnitude. Function of moment determination.
Fault length (L)	Affects magnitude and moment; duration.	M_L=1.235 +1.243 log L; σ=0.93.
Epicentral intensity (I_o)	Affects site acceleration (A_H and A_V).	log A_H = 0.24 I_{MM} + 0.26; σ=2.19 log A_V = 0.28 I_{MM} − 0.40; σ=2.53 (worldwide data)
Path Parameters		
Rate of attenuation of seismic energy with distance.	Establishes peak ground-motion values at site and frequency-dependent signature.	Not well defined because of limitations on data sample. σ for peak acceleration vs distance relation is 2.01 for worldwide data and 1.62 for San Fernando earthquake. σ for peak velocity vs distance is 1.5 for moderate U.S. earthquakes.
Local Ground Response		
Soil/rock acoustic impedance ($\rho\beta$) contrasts.	Affects amplitude of ground motion.	Not well defined. Physical properties depend on geophysical and laboratory measurements. Ground-motion data sample for each rock and soil classification is small.
Soil thickness and geometry.	Affects dominant frequency, duration, pseudo-ellipticity of wave particle motion, and damping.	Not well defined. Depends on geophysical, geologic, borehole, and ground-motion data.
Strain level of input ground motion.	Determines if ground response is linear or nonlinear.	Not well defined because of limitations of the ground-motion data sample, especially near the source.
Site transfer function.	Determines relative ground response between two sites.	Repeatable with σ=1.30 for nuclear explosions and 1.50 for earthquake aftershocks.

only areas in the United States that come close to fulfilling all three requirements listed above. More than 900 man-years of geologic mapping and many deep drill holes have defined the 3-dimensional structure reasonably well. A regional seismicity network has defined the current seismicity patterns. Fairly good correlations have been made between current seismicity and specific active faults. Even with this information, assigning a magnitude to a given active fault on the basis of the assumption that 50-percent of its length is available to rupture gives a magnitude value with a standard deviation of almost 1 unit (see Mark, 1977).

A general model based on the use of mean values for a "lumped parameter" wave-progagation system provides some insight. The basic relation is given by

$$S^2_{\substack{\text{Total}\\\text{system}}} = \left(1 + \frac{1}{N}\right)\left(S^2_{\text{source}} + S^2_{\text{path}} + S^2_{\text{site}}\right)$$

where N is the size of the data sample,

S_{source} is the variance of the source,

S_{path} is the variance of the transmission path.

(Note: variance = S = log σ where σ is the geometrical standard deviation.)

The values of S can be approximated from values of σ reported in the literature. The distribution is assumed to be log-normal in each case, a reasonable assumption. The studies by N. M. Newmark Consulting Engineering Services (1973) and J. A. Blume and Associates, Engineers (1973) provide a value of 0.30 for S_{source} (σ = 1.35). Donovan (1973) studied a worldwide data sample of 515 peak acceleration values to derive a relation for peak acceleration and distance. The variance for this "general" transmission path is 0.70 (σ = 2.01). The studies of ground response by Murphy, Weaver, and Davis (1971) and Murphy, Lynch, and O'Brien (1971) show that the mean site amplification is repeatable for low-strain ground motions with a variance that ranges from 0.26 to 0.41 (corresponding values of σ are 1.30 and 1.50). A reasonable value of the "general" site variance is 0.41. Combining these numbers after adjusting for the size of the data sample gives

$$S^2_{\substack{\text{Total}\\\text{system}}} = 0.095 + 0.491 + 0.178$$
$$S_{\substack{\text{Total}\\\text{system}}} = 0.87407 \text{ and}$$

$$\sigma = \log^{-1} 0.87407 = 2.40$$

Thus, an estimate of the geometrical standard deviation for mean ground motion estimates is about 2.40. However, one should remember that upper-bound values, *not* mean values, are used to define many ground-motion estimates. This practice suggests that the ground-motion estimates in some cases (for example, nuclear powerplants) may be at the one or two-standard deviation level relative to the mean value expected to occur at the site.

It is clear that the uncertainty in the seismic attenuation relation contributes most to the total uncertainty. One significant way to reduce the uncertainty (or the conservatism) in the ground-motion estimates is to "calibrate" the region's attenuation characteristics. As an example, consider the situation where the San Fernando Valley, California attenuation relation can be applied instead of the "general" relation. Donovan (1973) showed that the value of variance is 0.48 (σ = 1.62) for the San Fernando Valley. Substituting 0.48 instead of 0.70 and retaining the other values gives a σ of 2.03 for the total system; therefore, the "calibrated" attenuation function provides a significant reduction in total uncertainty.

SEISMIC DESIGN TRENDS FOR THE FUTURE

There is little doubt that empirical procedures currently used for defining earthquake ground motion will be refined and extended in the future. However, greatly improved capability for specifying earthquake ground motion will require a significantly improved data base. Regional seismicity and strong-motion accelerograph networks must be expanded. Better geologic and geophysical data and analysis are needed to define the earthquake potential and upper-bound magnitude in different geographical regions and to establish the dynamics of faulting and recurrence intervals for specific faults. Knowledge of the origin of intraplate earthquakes, which seem to have different causes than the earthquakes that occur along plate boundaries, is needed in order to assess more accurately the earthquake potential of seismically quiet regions like the Eastern United States.

The quality of the data base is one of the most important factors leading to the capability for precise specification of earthquake ground motion. The "ideal" data base should contain complete information about the site and the region surrounding it, including a well-defined statistical distribution for each parameter and parametric relation used to make predictions of ground motion at the site. The basic components are:

1. Seismicity parameters
   A complete record of all historic earthquakes;
   Information about the source parameters (epicenter, focal depth, source mechanism and dimensions, magnitude, stress drop, effective stress, seismic moment, and rupture velocity) of each historic earthquake;
   Definition of the current seismicity patterns;
   Recurrence relations for the region and for well-defined seismic source zones in the region.
2. Seismotectonic features
   Maps showing seismotectonic provinces and capable faults;
   Information about the earthquake generating potential of each seismotectonic province, including: information about the geometry, amount, and sense of movement, the temporal history of each fault, and the correlation with historic instrumental earthquake epicenters;
   Correlation of historic earthquakes with tectonic models to estimate the upper-bound magnitude of the earthquake likely to be associated with each tectonic feature.
3. Seismic attenuation function
   Isoseismal maps of significant historic earthquakes occurring in the region;
   The uncertainty of Modified Mercalli intensity distance-scaling relations;
   Peak ground-motion distance-scaling relations for the region;
   Frequency-dependent distance-scaling relations for the region.
4. Characteristics of ground shaking
   Isoseismal maps of significant historic earthquakes that have affected the site;
   Ensembles of strong ground-motion records adequate for calibrating the near field, the regional seismic-wave transmission characteristics, and the local ground response for a wide range of earthquake source mechanisms.
5. Earthquake spectra
   Ensembles of spectra (Fourier, power spectral density, and response) adequate for calibrat-

ing the near field, the transmission path, and the local ground response for a wide range of earthquake source mechanisms.

6. Local ground response
   Strong ground-motion records at surface and subsurface locations for a wide range of strain levels;
   Seismic-wave transmission characteristics of a wide range of unconsolidated materials overlying rock for a wide range of strain levels;
   Information on the static and dynamic properties of the near-surface site materials, including: seismic shear-wave velocities, bulk densities, and water content.

The faulting mechanism, more than any other geologic parameter, requires a great deal of additional research. The direction, length, and type of faulting during an earthquake greatly affect the near- and far-field radiation patterns of the body and surface waves generated by the earthquake. As progress is made in understanding faulting, important questions can be answered, such as:

1. What are the important differences in the near- and far-field seismic-radiation patterns for different fault systems?
2. What is the best way to characterize the near- and far-field seismic radiation patterns in areas of the United States where surface faulting is uncommon (for example, New Madrid, Missouri and Charleston, South Carolina areas)?

Although the present empirically based procedures will remain in use for some time, improved procedures will evolve as advances in physical understanding and capability to model numerically occur. Improved procedures will incorporate the continually increasing knowledge in seismology and will improve the precision of earthquake ground-motion estimates. Some of the new approaches that are likely include:

1. Use of seismic moment as a measure of source strength instead of or in addition to magnitude,
2. Use of constant stress-drop source spectra scaled as a function of seismic moment instead of magnitude,
3. Interpretation of peak ground-motion parameters in terms of source spectra,
4. Interpretation of duration of strong ground motion in terms of length of fault rupture and rupture velocity,
5. Development of spectral values to correlate with specific values of the Modified Mercalli intensity scale,
6. Development of frequency-dependent seismic attenuation laws for many different geographic regions of the United States.

Earthquake-resistant design is fortunate to be a dynamic field in which many advances in basic knowledge are being made.

REFERENCES CITED

Aki, Keiiti, 1972, Scaling law of earthquake source time function: Roy. Astron. Soc. Geophys. Jour., v. 31, p. 3–25.

Albee, Arden, and Smith, J. L., 1966, Earthquake characteristics and fault activity in southern California, *in* Lung, R., and Proctor, R., eds, special publication, Engineering geology in southern California: Eng. Geologists Assoc., p. 9–33.

Algermissen, S. T., 1969, Seismic risk studies in the United States: World Conf. on Earthquake Eng., 4th, Santiago, Chile, Proc., v. 1, 14 p.

———1973, The problem of seismic zoning, *in* Wright, R., Kramer, S., and Culver, C., eds., Building practices for disaster mitigation: U.S. Dept. Commerce, Natl. Bur. Standards, Bldg. Sci. ser. 46, p. 112–125.

Algermissen, S. T., Hopper, M. G., Campbell, Kenneth, Rinehart, W. A., and Perkins, D. M., (geologic and seismological portion); Steinbrugge, K. V., Lagorio, H. J., Moran, D. F., Cluff, L. S., Degenkolb, H. J., Duke, C. M., Gates, G. O., Jacobson, D. W., Olson, R. A., and Allen, C. R., (engineering analysis portion), 1973, A study of earthquake losses in the Los Angeles, California, area: U.S. Dept. Commerce, Natl. Oceanic Atmospheric Admin., 331 p.

Algermissen, S. T., and Perkins, D. M., 1976, A probabilistic estimate of maximum acceleration in rock in the contiguous United States: U.S. Geol. Survey Open-File Rept. 76–416, 45 p.

Algermissen, S. T., Rinehart, W. A., and Dewey, J., (geologic and seismological portion), Steinbrugge, K. V., Lagorio, J. J., Degenkolb, H. J., Cluff, L. S., McClure, F. E., Scott, S., and Gordon, R. F., (engineering analysis portion), 1972, A study of earthquake losses in the San Francisco Bay area: U.S. Dept. Commerce, Natl. Oceanic Atmospheric Admin., 220 p.

Allen, C. R., 1975, Geological criteria for evaluating seismicity: Geol. Soc. America Bull., v. 86, p. 1041–1057.

Allen, C. R., St. Amand, P., Richter, C. F., and Nordquist, J. M., 1965, Relationship between seismicity and geologic structure in the southern California region: Seismol. Soc. America Bull., v. 55, p. 753–797.

Ambraseys, N. N., 1973, Dynamics and response of foundation materials in epicentral regions of strong earthquakes: World Conf. on Earthquake Eng., 5th, Rome, Proc., 10 p.

American Nuclear Society, 1975, Guidelines for assessing capability for surface faulting at nuclear power reactor sites (draft): Comm. on Nuclear Standards, ANS 2.7, 17 p.

American Society of Civil Engineers, 1974, Final report to the Technical Activities Committee by the Committee on Lifeline Earthquake Engineering, 64 p.

———1976, Structural analysis and design of nuclear plant facilities (draft): Nuclear Structures and Materials Comm., Am. Soc. Civil Engineers, Struc. Div., 914 p.

Anderson, J. G., and Fletcher, J. B., 1976, Seismic properties of a Blue Mountain Lake, [N.Y.] earthquake: Seismol. Soc. America Bull., v. 66, p. 677–684.

Applied Technology Council, 1976, Working draft of recommended comprehensive seismic design provisions for buildings: DOC. ATC–3–04, 105 p.

Archambeau, C. B., 1975, Developments in seismic source theory: Geophysics and Space Physics, v. 13, p. 304–306.

Baker, L. C., 1971, Availability and desirability of earthquake insurance, *in* Proceedings of the conference on Earthquake risk: Joint Committee on Seismic Safety to the California Legislature, San Jose, Calif., p. 31–34.

Bakun, W. H., Bufe, C. G., and Stewart, R. M., 1976, Body-wave spectra of central California earthquakes: Seismol. Soc. America Bull., v. 66, p. 363–384.

Barosh, P. J., 1969, Use of seismic intensity data to predict the effects of earthquakes and underground nuclear explosions: U. S. Geol. Survey Bull. 1279, 102 p.

Benioff, H., 1934, The physical evaluation of seismic destructiveness: Seismol. Soc. America Bull., v. 24, p. 398–403.

Bennett, T. J., 1974, Amplitude and propagation characteristics of short-period seismic surface waves in Las Vegas valley: Environ. Research Corp. Rept. NVO–1163–242, 75 p.

Berg, J. W., Long, L. T., Sarmah, S. K., and Trembly, L. D., 1971, Crustal and mantle inhomogeneities as defined by attenuation of short-period P-waves: The structure and physical properties of the earth's crust: Am. Geophys. Union, Mono. 14, p. 51–58.

Berry, M. J., 1973, Structure of the crust and upper mantle in Canada: Tectonophysics, v. 20, p. 183–201.

Biot, M. A., 1943, Analytical and experimental methods in engineering seismology: Am. Soc. Civil Engineers Trans., v. 180, p. 365–375.

Blume, J. A., and Associates, Engineers, 1973, Recommendations for shape of earthquake response spectra: Govt. Printing Office, Washington, D. C., WASH–1254, 100 p.

Blume, J. A., Newmark, N. A., and Corning, L. H., 1961, Design of multi-story reinforced concrete buildings for earthquake motions: Chicago, Portland Cement Assoc., 318 p.

Bollinger, G. A., 1972, Historical and recent seismic activity in south Carolina: Seismol. Soc. America Bull., v. 62, p. 851–864.

———1973, Seismicity of the southeastern United States: Seismol. Soc. America, v. 63, p. 1785–1808.

Bollinger, G. A., Langer, C., and Harding, S. T., 1976, The eastern Tennessee earthquake sequence of October through December, 1973, Seismol. Soc. America Bull., v. 66, p. 525–548.

Bolt, B. A., 1972, San Fernando rupture mechanism and the Pacoima strong motion record: Seismol. Soc. America Bull., v. 62, p. 1053–1062.

———1973, Duration of strong ground motion: World Conf. on Earthquake Eng., 5th, Rome, Proc., v. 2, no. 292, 10 p.

Bonilla, M. G., 1967, Historic surface faulting in continental United States and adjacent parts of Mexico: U.S. Geol. Survey Open-File Rept., 36 p.

———1970, Surface faulting and related effects, *in* Wiegel, R. L., ed., Earthquake Engineering: Englewood Cliffs, N. J., Prentice-Hall, p. 47–74.

Boore, D. M., 1973, The effect of simple topography on seismic waves: implications for the accelerations recorded at Pacoima Dam, San Fernando Valley, California: Seismol. Soc. America Bull., v. 63, p. 1603–1610.

Boore, D. M., Joyner, W.B., Oliver, A. A., and Page, R. A., 1978, Estimation of ground motion parameters: U.S. Geol. Survey Circular 795, 43 p.

Boore, D. M., and Page, R. A., 1972, Accelerations near faulting in moderate-sized earthquakes: U.S. Geol. Survey Open-File Rept., 13 p.

Boore, D. M., and Zoback, M. D., 1974, Two-dimensional modeling of the Pacoima Dam strong motion recordings of the February 9, 1971, San Fernando earthquake: Seismol. Soc. America Bull., v. 64, p. 321–342.

Borcherdt, R. D., 1975, Studies of seismic zonation of the San Francisco Bay region: U.S. Geol. Survey Prof. Paper 941–A, 102 p.

Borcherdt, R. D., and Gibbs, J. F., 1976, Effects of local geologic conditions in the San Francisco Bay region on ground motions and the intensities of the 1906 earthquake: Seismol. Soc. America Bull., v. 66, p. 467–500.

Borcherdt, R. D., Joyner, W. D., Warrick, R. E., and Gibbs, J. F., 1975, Response of local geologic units to ground shaking, *in* Borcherdt, R. D., ed., Studies for seismic zonation of the San Francisco Bay region: U.S. Geol. Survey Prof. Paper 941–A, p. A-52–A-67.

Bouchon, M. P., 1973, Effect of topography on surface motion: Seismol. Soc. America Bull., v. 63, p. 615–637.

Brazee, R. J., 1976, An analysis of earthquake intensities with respect to attenuation, magnitude, and rate of occurrence: Natl. Oceanic Atmospheric Admin. Technol. Memo. EDS–NGSDC–2, 98 p.

Brogan, G. E., Cluff, L. S., Korrings, M. K. and Slemmons, D. B., 1975, Active faults of Alaska: Tectonophysics, v. 29, p. 73–85.

Brune, J. N., 1970, Tectonic stress and the spectra of seismic shear waves from earthquakes: Jour. Geophys. Research, v. 75, p. 4997–5009.

Bycroft, G. N., 1960, White noise representation of earthquakes: Eng. Mech. Div. Jour., Am. Soc. Civil Engineers, v. 86, p. 1–16.

California Council on Intergovernmental Relations, 1972, Seismic safety element interim guidelines: California Council Intergovernmental Relations, 14 p.

———1973, General plan guidelines: California Council Intergovernmental Relations, 91 p.

Campbell, K. W., and Duke, C. M., 1974, Bedrock intensity attenuation and site factors from San Fernando earthquake records: Seismol. Soc. America Bull., v. 64, p. 173–186.

Chinnery, M. A., and Rogers, D. A., 1973, Earthquake statistics in southern New England: Earthquake Notes, v. 44, p. 89–103.

Cluff, L. S., Hansen, W. R., Taylor, C. L., Weaver, K. D., Brogan, G. E., Idriss, I. M., McClure, F. E., and Blayney, J. A., 1972, Site evaluation in seismically active regions—An interdisciplinary team approach: Internat. Conf. on Microzonation, Seattle, Wash., Proc., v. 2, p. 957–987.

Cluff, L. S., Hintz, L. F., Brogan, G. E., and Glass, C. E., 1975, Recent activity of the Wasatch fault, northwestern Utah, USA: Tectonophysics, v. 29, p. 161–168.

Coffman, J. L., and von Hake, C. A., 1973, Earthquake history of the United States [revised ed. through 1970]: Natl. Oceanic Atmospheric Admin., pub. 41–1 (GPO Bookstore stock no. 0319–0019), 208 p.

Colton, G. W., 1970, Appalachian Basin—Its depositional sequences and their geologic relationships, *in* Fisher, G. W., ed; Studies of Appalachian geology, central and southern: New York, Interscience Pub. Co., p. 5–47.

Coney, P. J., 1972, Cordilleran tectonics and North American plate motion: Am. Jour. Sci., v. 272, p. 603–628.

Cornell, C. A., and Merz, H. A., 1974, Seismic risk analyses of Boston: Natl. Struc. Eng. mtg., Am. Soc. Civil Engineers, mtg. preprint no. 2260, 29 p.

Coulter, H. W., Waldron, W. H., and Devine, J. F., 1973, Seismic and geologic siting considerations for nuclear facilites: World Conf. on Earthquake Eng., 5th, Rome, Proc., v. 2., paper no. 302, 10 p.

Crossen, R. S., 1972, Small earthquakes, structure and tectonics of the Puget Sound region: Seismol. Soc. America Bull., v. 62, p. 1133–1172.

Crouse, C. B., and Jennings, P. C, 1975, Soil-structure interaction during the San Fernando earthquake: Seismol. Soc. America Bull., v. 65, p. 13–36.

Davenport, A. J., 1972, A statistical relationship between shock amplitude, magnitude, and epicentral distance and its appplication to seismic zoning: Western Ontario University, Eng. Sci. Research Rept. BLWT–4–72, 19 p.

Davies, J. N., and Berg, Eduard, 1973, Crustal morphology and plate tectonics in south central Alaska: Seismol. Soc. America Bull., v. 63, p. 673–677.

Davis, L. L., and Lynch, R. D., 1970, Seismic response characteristics at Las Vegas, Nevada, from underground nuclear detonations: Environ. Research Corp. Rept. NVO–1163–203 to U.S. Atomic Energy Comm., 88 p.

Degenkolb, H. J., Dean, R. G., and Wyllie, L. A., 1971, Structural design seminar on eathquake engineering: Am. Soc. Civil Engineers (lecture notes), 211 p.

Department of Army, Navy, and Air Force, 1973, Seismic design for buildings: Dept. of the Army, Tech. Man. Tm 5–809–10, 50 p.

Dietrich, J. H., 1973, A deterministic near-field source model: World Conf. on Earthquake Eng., 5th, Rome, Proc., paper no. 301, p. 2385–2396.

Diment, W. H., Stewart, S. W., and Roller, J. C., 1961, Crustal structure from the Nevada Test Site to Kingman, Arizona, from seismic and gravity observatons: Jour. Geophys. Research, v. 66, p. 201–217.

Dobry, R., Idriss, I. M., Chang, C. Y., and Ng, E., 1977, Influence of magnitude, site conditions, and distance on significant duration of earthquakes: World Conf. on Earthquake Eng., 6th, New Delhi, Proc., v. 2, p. 131–36.

Donovan, N. C., 1973, A statistical evaluation of strong motion data including the February 9, 1971 San Fernando earthquake: World Conf. on Earthquake Engineering, 5th, Rome, Proc., v. 2, paper 155, 10 p.

———1975, Determination of T_s, the characteristic site period and ongoing code revisions, *in* New earthquake design provisions: Proc. of seminar sponsored by Prof. Development Comm. of Struc. Eng. Assoc. of Northern California and San Francisco sec. of Am. Soc. Civil Engineers, p. 64–82.

Drake, L. A, and Mal, A. K., 1972, Love and Rayleigh waves in the San Fernando valley: Seismol. Soc. America Bull., v. 62, p. 1673–1690.

Duda, S. J., and Nuttli, O. W., 1974, Earthquake magnitude scales, *in* Geophysical surveys: Dordrecht, Holland, D. Reidel Pub. Co., v. 1, p. 429–458.

Duke, C. M., and Hradilek, P. J., 1973, Spectral analysis of site effects in the San Fernando earthquake: World Conf. on Earthquake Eng., 5th, Rome, Proc., v. 1, no. 77, 10 p.

Duke, C. M., and Leeds, D. M., 1962, Site characteristics of Southern California strong motion earthquake stations: Part 1, California Univ. Los Angeles, Eng. Dept. Rept. 62–55, 115 p.

Dutton, C. E., 1887, The Charleston earthquake of August 31, 1886: Ann. Rept. of the Director, 9th, U.S. Geol. Survey, p. 203–528.

Environmental Research Corporation, 1968, Observed seismic data, project Gasbuggy: Environmental Research Corp. Rept. NVO–1163–144 to U. S. Atomic Energy Comm., 70 p.

———1969, Observed seismic data, Rulison event: Environmental Research Corp. Rept. NVO–1163–197 to U. S. Atomic Energy Comm., 88 p.

———1970a, Observed seismic data, Milrow event: Environmental Research Corp. Rept. NVO–1163–199 to U.S. Atomic Energy Comm., 26 p.

———1970b, Observed seismic data, Jorum event: Environmental Research Corp. Rept. NVO–1163–207 to U.S. Atomic Energy Comm., 88 p.

———1970c, Observed seismic data, Handley event: Environmental Research Corp. Rept. NOV–1163–216 to U. S. Atomic Energy Comm., 98 p.

———1974a, Observed seismic data Rio Blanco event: Environmental Research Corp. Rept. NOVO–1163–240 to U.S. Atomic Energy Comm., 57 p.

———1974b, Prediction of ground motion characteristics of underground nuclear detonations: Environmental Research Corp. Rept. NVO–1163–239 to U.S. Atomic Energy Comm. (available from NTIS), 205 p.

Espinosa, A. F., 1976, The Guatemala earthquake of February 4, 1976, a preliminary report: U.S. Geol. Survey Prof. Paper 1002, 90 p.

———1977, Particle velocity attenuation relationships: San Fernando earthquake of February 9, 1971: Seismol. Soc. America Bull., v. 67, p. 1195–1214.

Espinosa, A. F., and Algermissen, S. T., 1972, A study of soil amplification factors in earthquake damage areas, Caracas, Venezuela: Natl. Oceanic Atmospheric Admin. Tech. Rept. ERL 280–ESL 31, 200 p.

Esteva, L., and Rosenblueth, E., 1964, Espectros de temblors a distancias moderadas y grandes: Bol. Soc. Mex. Ing. Seismol., v. 2, p. 1–18.

Evernden, J. F., 1970, Study of regional seismicity and associated problems: Seismol. Soc. America Bull., v. 60, p. 393–446.

———1975, Seismic intensities, "size" of earthquakes and related parameters: Seismol. Soc. America Bull., v. 65, p. 1287–1313.

Evernden, J. F., Hibbard, R. R., and Schneider, J. F., 1973, Interpretation of seismic intensity data: Seismol. Soc. America Bull., v. 63, p. 399–422.

Foote, R. Q., Hays, W. W., Cassity, C. R., Lynch, R. D., Loux, P. C., Perchalski, F. R., O'Brien, L. J., Spiker, S. T., Power, F. W., and Whipple, A. P., 1970, Analysis of ground motions and close-in physical effects, Rulison event: Environmental Research Corp. Rept. NVO–1163–206 to U.S. Atomic Energy Comm., 166 p.

Foote, R. Q., Hays, W. W., and Klepinger, R. W., 1969, Analysis of ground motion data and close-in physical effects, Gasbuggy event: U.S. Atomic Energy Comm. Rept. PNE–1010, 149 p.

Freeman, S. A., 1975, Introduction to new features of the SEAOC blue book, *in* New earthquake design provisions: Proc. of seminar sponsored by Prof. Dev. Comm., Structural Eng. Assoc. of Northern California and San Francisco Sec. of Am. Soc. Civil Engineers p. 1–24.

Fuller, M. L., 1912, The New Madrid earthquake: U.S. Geol. Survey Bull. 494, 119 p.

Gardner, J. K., and Knopoff, Leon, 1974, Is the sequence of earthquakes in southern California with aftershocks removed Poissonian?: Seismol. Soc. America Bull., v. 64, p. 1363–1368.

Garfunkel, Zvi, 1974, Model for the late Cenezoic tectonic history of the Mojave Desert, California, and for its relation to adjacent regions: Geol. Soc. America Bull., v. 85, p. 1931–1941.

Gates, J. H., 1976, California's seismic design criteria for bridges: Jour. Structural Div., Am. Soc. Civil Eng., v. 102, p. 2301–2313.

Gedney, Larry, 1970, Tectonic stresses in southern Alaska in relationship to regional seismicity and the new global tectonics: Seismol. Soc. America Bull., v. 60, p. 1789–1802.

Geller, R. J., 1976, Scaling relations for earthquake source parameters and magnitude: Seismol. Soc. America Bull., v. 66, p. 1501–1524.

Gibbs, J. F., Fumal, T. E., and Borcherdt, R. D., 1976, In-situ measurements of seismic velocities in the San Francisco Bay region: Part III, U.S. Geol. Survey Open-File Rept. 76–731, 145 p.

Gibowicz, S. J., 1973, Stress drop and aftershocks: Seismol. Soc. America Bull., v. 63, p. 1433–1446.

Gordon, D. W., Bennett, T. J., Herrmann, R. B., and Rogers, A. M., 1970, The south-central Illinois earthquake of November 9, 1968: Macroseismic studies: Seismol. Soc. America Bull., v. 60 , p. 953–971.

Grantz, Arthur, 1966, Strike-slip faults in Alaska: Stanford Univ. Ph. D. thesis, Stanford, Calif., 82 p.

Gupta, I. N., and Nuttli, O. W., 1976, Spatial attenuation of intensities for central U.S. earthquakes: Seismol. Soc. America Bull.,

v. 66, p. 743–752.

Gutenberg, B, and Richter, C. F., 1942, Earthquake magnitude, intensity, energy, and acceleration: Seismol. Soc. America Bull., v. 32, p. 163–191.

——1956, Earthquake magnitude, intensity, energy, and acceleration: Seismol. Soc. America Bull., v. 46, p. 105–145.

Guzman, R. A., and Jennings, P. C., 1976, Design spectra for nuclear power plants: Jour. Power Div., Am. Soc. Civil Eng., v. 102, p. 165–178.

Hadley, J. B., and Devine, J. F., 1974, Seismotectonic map of the eastern U.S.: U.S. Geol. Survey Misc. Field Studies Map MF–620, scale 1:5,000,000.

Hamilton, R. M., 1978, Earthquake hazards reduction program—fiscal year 1978 studies supported by the U.S. Geological Survey: U.S. Geol. Survey Circular 780, 36 p.

Hanks, T. C., 1976, Observations and estimation of long period strong ground motion in the Los Angeles Basin: Internat. Jour. Earthquake Eng. and Structural Dynamics, v. 4, p. 473–488.

Hanks, T. C., Hileman, J. A., and Thatcher, W., 1975, Seismic moments of the large earthquakes of the southern California region: Geol. Soc. America Bull., v. 86, p. 1131–1139.

Hanks, T. C., and Johnson, D. A., 1976, Geophysical assessment of peak acceleration: Seismol. Soc. America Bull., v. 66, p. 959–968.

Hanks, T. C., and Wyss, Max, 1972, The use of body wave spectra in the determination of seismic source parameters: Seismol. Soc. America Bull., v. 62, p. 561–590.

Haskell, N. A., 1960, Crustal reflection of plane SH waves: Jour. Geophys. Research, v. 65, p. 4147–4155.

Hays, W. W., 1969, Amplitude and frequency characteristics of elastic wave types generated by the underground nuclear detonation, Boxcar: Seismol. Soc. American Bull., v. 59, p. 2282–2293.

——1972a, Example of the effect of source and recording site parameters on the seismic response observed from Plowshare projects: Gasbuggy and Rulison: Geophysics, v. 37, p. 288–300.

——1972b, A review of the ground motion prediction problem for Plowshare underground engineering applications: Nuclear Technology, p. 655–670.

——1975a, A note on the duration of earthquake and nuclear explosion ground motions: Seismol. Soc. American Bull., v. 65, p. 875–884.

——1975b, The seismic problem associated with gas stimulation nuclear detonations: Geophysics, v. 40, p. 136.

——1977a, The ground shaking hazard an important consideration in land-use planning: California Div. Mines and Geol. Spec. Rept. 129, p. 1–7.

——1977b, Evaluation of the seismic response in the Sylmar-San Fernando area, California, from the 1971 San Fernando earthquake: Am. Soc. Civil Engineers, Eng. Mech. Div., Spec. Conf. on Dynamic Response of Structures, Los Angeles Proc.: Instrumentation, testing methods, and system identification, p. 502–511.

——1978, Ground response maps for Tonopah, Nevada: Seismol. Soc. American Bull., v. 68, p. 451–470.

Hays, W. W., Rogers, A. M., and King, K. W., 1979, Empirical data about local ground response: Earthquake Engineering Research Institute 2nd Natl. Conf. on Earthquake Eng., Stanford, Calif., Proc., p. 223–232.

Hays, W. W., Algermissen, S. T., and Duke, C. M., 1975a, Use of aftershock ground motion data in earthquake engineering: Earthquake Engineering Research Institute Natl. Conf. on Earthquake Eng., Ann Arbor, Mich., Proc., p. 60–69.

Hays, W. W., Algermissen, S. T., Espinosa, A. F., Perkins, D. M., and Rinehart, W. A., 1975b, Guidelines for developing design earthquake response spectra: U.S. Army Construction Eng. Research Lab. Tech. Rept. M–114, 369 p.

Hays, W. W., Bennett, T. J., and Brumley, M. D., 1973, Time dependent spectral analysis of ground motion: Environmental Research Corp. Rept. NVO–1163–TM37 to U.S. Atomic Energy Comm., 42 p.

Hays, W. W., and King, K. W., 1973. Estimates of the main shock ground motion, Managua earthquake: Earthquake Engineering Research Institute Conf. on Managua earthquake, San Francisco, Proc., p. 292–302.

Hays, W. W., King, K. W., and Park, R. B., 1978, Duration of nuclear explosion ground motion: Seismol. Soc. America Bull., v. 68, p. 1133–1146.

Hays, W. W., Mueller, R. A., and Spiker, C. T., 1969, Schooner event, a contribution to the analysis of seismic data from cratering and contained events: Environmental Research Corp. Rept. NVO–1163–188 to U.S. Atomic Energy Comm., 98 p.

Hays. W. W., and Murphy, J. R., 1971, The effect of Yucca fault on seismic wave propagation: Seismol. Soc. America Bull., v. 61, p. 697–706.

Healy, J. H., Rubey, W. W., Griggs, D. T., and Raleigh, C. B., 1968, The Denver earthquakes: Science, v. 161, p. 131–135.

Helmberger, D. V., and Johnson, L. R., 1977, Source parameters of moderate size earthquakes and the importance of receiver crustal structure in interpreting observations of local earthquakes: Seismol. Soc. America Bull., v. 67, p. 301–314.

Herrmann, R. B, 1976, Focal depth determination from the signal character of long-period P-waves: Seismol. Soc. America Bull., v. 66, p. 1221–1232.

Herrmann, R. B., Fischer, G. W., and Zollweg, J. E., 1977, The June 13, 1975, earthquake and its relationship to the New Madrid seismic zone: Seismol. Soc. America Bull., v. 67, p. 209–218.

Herrmann, R. B., and Nuttli, O. W., 1975a, Ground motion modeling at regional distances for earthquakes in a continental interior: I. Theory and observation: Internat. Jour. Earthquake Eng. Structural Dynamics, v. 4, p. 49–58.

——1975b, Ground motion modeling at regional distances for earthquakes in a continental interior: II. Effect of focal depth, azimuth and attenuation: Internat. Jour. Earthquake Eng. Structural Dynamics, v. 4, p. 59–72.

Hershberger, J., 1956, A comparison of earthquake accelerations with intensity ratings: Seismol. Soc. America Bull., v. 46, p. 317–320.

Hoffman, R. B., 1974, State-of-the-art for assessing earthquake hazards in the United States; Factors in the specification of ground motions for design earthquakes in California: U.S. Army Waterways Expt. Station, Rept. 3, misc. paper S–73–1, 93 p.

Hopper, M. G., Langer, C. J., Spence, W. J., Rogers, A. M., and Algermissen, S. T. (geologic and seismological portions); Olsen, B. C., Lagorio, H. J., and Steinbrugge, K. V. (engineering analysis portion), 1975, A study of earthquake losses in the Puget Sound, Washington, area: U.S. Geol. Survey Open-File Rept. 75–375, 298 p.

Housner, G., 1959, Behavior of structures during earthquakes: Jour. Eng. Mechanics Div., Am. Soc. Civil Eng., v. 85, p. 109–129.

——1965, Intensity of shaking near the causative fault: World Cong. on Earthquake Eng., 3rd, New Zealand, Proc., v. 1, p. 94–109.

——1970, Strong ground motion: *in* Weigle, R. L., ed., Earthquake engineering: Prentice Hall, Englewood Cliffs, N.J., p. 75–92.

——1975, Measures of severity of earthquake ground shaking: Earthquake Engineering Research Institute Natl. Conf. on Earthquake Eng., Ann Arbor, Mich., Proc., p. 25–33.

Housner, G. W., and Jennings, P. C., 1969, Generation of artificial earthquakes: Eng. Mechanics Div. Jour., Am. Soc. Civil Engineers, v. 90, p. 113–155.

Howell, G. F., and Schultz, T. R., 1975, Attenuation of Modified Mercalli intensity with distance from the epicenter: Seismol. Soc. America Bull., v. 65, p. 651–666.

Hudson, D. E., 1962, Some problems in the application of spectrum techniques to strong motion earthquake analysis: Seismol. Soc. America Bull., v. 52, p. 417–430.

Husid Raul, 1967, Gravity effects on the earthquake response of yielding structures: California Inst. of Technology, Pasadena, Calif., Ph.D. thesis, 120 p.

Idriss, I. M., Lysmer, John, Hwang, R., and Seed, H. B., 1973, QUAD–4 A computer program for evaluating the seismic response of soil structures by variable damping finite element procedures: California Univ., Berkeley, Rept. no. EERC–73–16, 50 p.

Idriss, I. M., and Seed, H. B., 1968, Analysis of ground motions during the 1957 San Francisco earthquake: Seismol. Soc. America Bull., v. 58, p. 2013–2032.

Imbsen, R., and Gates, J., 1973, Recent innovations in seismic design and analysis techniques for bridge structures: California Div. Bridges and Highways Dept., 39 p.

Jenschke, V. A., 1970, The definition and some properties of shock functions, California Univ., Los Angeles, Rept. no. 70–2, 30 p.

Johnson, J. J., and Kennedy, R. P., 1977, Earthquake response of nuclear power facilities: Am. Soc. Civil Engineers Fall Convention, preprint 2962, 26 p.

Johnson, L. R., and McEvilly, T. V., 1974, Near-field observations and source parameters of central California earthquakes: Seismol. Soc. America Bull., v. 64, p. 1855–1886.

Johnson, R. A., 1973, An earthquake spectrum prediction technique: Seismol. Soc. America Bull., v. 63, p. 1255–1274.

Joyner, W. B., 1975, A method for calculating nonlinear seismic response in two dimensions: Seismol. Soc. America Bull., v. 65, p. 1337–1358.

Joyner, W. B., and Chen, A. T. F., 1975, Calculation of nonlinear ground response in earthquakes: Seismol. Soc. America Bull., v. 65, p. 1315–1336.

Joyner, W. B., Warrick, R. E., and Oliver, A. A., 1976, Analysis of seismograms from a downhole array in sediments near San Francisco Bay: Seismol. Soc. America Bull., v. 66, p. 937–958.

Kagan, Y. Y., and Knopoff, Leon, 1976, Statistical search for nonrandom features of the seismicity of strong earthquakes: Physics of the Earth and Planetary Interiors, v. 12, p. 291–318.

Kanamori, Hiroo, 1970, The Alaska earthquake of 1964: Radiation of long-period surface waves and source mechanism: Jour. Geophys. Research, v. 75, p. 5029–5040.

——— 1977, The energy release in great earthquakes: Jour. Geophys. Research, v. 82, p. 2981–2987.

Kane, M. F., and Hildenbrand, T. G., 1977, The structural locus of major Mississippi embayment seismicity: EOS, Trans. Am. Geophys. Union, v. 58, no. 6, p. 431.

Kanninen, M. F., Adler, W. F., Rosenfield, A. R., and Jaffee, R. I., 1970, Inelastic behavior of solids: New York, McGraw-Hill Book Co., 740 p.

Kelleher, John, and Savino, John, 1975, Distribution of seismicity before large strike-slip and thrust-type earthquakes: Jour. Geophys. Research, v. 80, p. 260–271.

King, K. W., and Hays, W.W., 1977, Comparison of seismic attenuation in northern Utah with attenuation in four other regions of the western United States: Seismol. Soc. America Bull., v. 67, p. 781–792.

Knopoff, Leon, 1964, Q: Rev. of Geophysics, v. 2, p. 625–655.

Knopoff, Leon, and Mouton, J. O., 1975, Can one determine seismic focal parameters from the far-field radiation?: Roy. Astron. Soc. Geophys. Jour. 42, p. 591–606.

Krinitzsky, E. L., 1975, State-of-the-art for assessing earthquake hazards in the United States; Fault assessment in earthquake engineering: U.S. Army Eng. Waterways Exp. Sta. Misc. Paper S–73–1, Rept. 2, 82 p.

Krinitzsky, E. L., and Chang, F. K., 1975, State-of-the-art for assessing earthquake hazards in the United States, Earthquake intensity and the selection of ground motions for earthquake design: U.S. Army Waterways Exp. Sta. Misc. Paper S–73–1, Rept. 4, 58 p.

Lastrico, R. M., Duke, C. M., and Otta, Y., 1972, Effects of site and progagation path on recorded strong earthquake motions: Seismol. Soc. America Bull., v. 62, p. 919–940.

Lawson, A. C., 1908, The California earthquake of April 18, 1906: State Earthquake Investigation Comm. Rept., Carnegie Institute, Washington, pub. 87, 2 v.

Liu, S. C., and Fagel, L. W., 1973, A fast fourier transform approach to earthquake soil-structure interaction problems: World Conf. on Earthquake Eng., 5th, Rome, Proc., v. 2, no. 231, 10 p.

Lomenick, T. F., 1970, Earthquakes and nuclear power plant design: Oak Ridge National Lab. Rept. ORNL–NSIC–28, 215 p.

Lomnitz, Cinna, 1974, Global tectonics and earthquake risk, developments, and geotectonics 5: New York, Elsevier Pub. Co., 320 p.

Long, L. T., 1974, Earthquake sequences and b values in the southeast United States: Seismol. Soc. America Bull., v. 64, p. 267–274.

Longwell, C. R., Pampeyan, E. H., Bowyer, B., and Roberts, R. J., 1965, Geology and mineral deposits of Clark County, Nevada: Nevada Bur. Mines Bull. no. 62, 150 p.

Lynch, R. D., 1969, Response spectra for Pahute Mesa nuclear events: Seismol. Soc. America Bull., v. 49, p. 2295–2310.

——— 1973, Distance attenuation of response spectra from underground nuclear detonations: Environmental Research Corp. Rept. NVO–1163–TM38 to U.S. Atomic Energy Comm., 69 p.

Lynch, R. D., Murphy, J. R., Hays, W. W., and Williams, S. L., 1970, Models for generating synthetic seismograms: Environmental Research Corp. Rept. NVO–1163–217 to U.S. Atomic Energy Comm., 50 p.

Lysmer, John, Seed, H. B., and Schnabel, P. B., 1971, Influence of baserock characteristics on ground responses: Seismol. Soc. America Bull., v. 61, p. 1213–1232.

M & H Engineering and Memphis State University, 1974, Regional earthquake risk study: Rept. to Mississippi-Arkansas-Tennessee Council of Governments, Memphis Delta Development District, Tech. Rept. MATCOG–DD–MHMSH–74–1013–12, 300 p.

McClain, W. C., and Meyers, O. H., 1970, Seismic history and seismicity of the United States: Oak Ridge Natl. Lab. Rept. ORNL–4582, 46 p.

McGuire, R. K., 1977a, Seismic design spectra and mapping procedures using hazard analysis based directly on oscillator response: Internat. Jour. Earthquake Eng. Structural Dynamics, v. 5, p. 211–234.

——— 1977b, Effects of uncertainty in seismicity on estimates of seismic hazard for the East Coast of the United States: Seismol. Soc. America Bull., v. 67, p. 827–848.

Mark, R. K., 1977, Application of linear statistical models of earthquake magnitude versus fault length in estimating maximum expectable earthquakes: Geology, v. 5, p. 464–466.

Matthiesen, R. B., Duke, C. M., Leeds, D. M., and Fraser, J. C., 1964, Site characteristics of southern California strong motion earthquake stations, part 2: California Univ., Los Angeles, Eng. Dept. Rept. 64–15, 121 p.

Mayer-Rosa, D., 1973, Travel time anomalies and distribution of earthquakes along the Calaveras fault zone: Seismol. Soc. America Bull., v. 63, p. 713–730.

Meyers, H., 1976, A historical summary of earthquake epicenters in and near Alaska: Natl. Oceanic Atmospheric Admin. Tech. Memo. EDS NGSDC–1, 76 p.

Molnar, Peter, Tucker, B. E., and Brune, J. N., 1973, Corner frequencies of P- and S-waves and models of earthquake sources, Seismol. Soc. America Bull., v. 63, p. 2091–2104.

Morgan, W. J., 1973, Plate motions and deep mantle convection, studies in earth and space sciences: Geol. Soc. America Mem., v. 132, p. 7–22.

Murphy, J. R., and Davis, A.H., 1969, Amplification of Rayleigh waves in a surface layer of variable thickness: Environmental Research Corp. Rept. NVO–1163–175 to U.S. Atomic Energy Comm., 75 p.

Murphy, J. R., and Hewlett, R. A., 1975, Analysis of seismic response in the city of Las Vegas, Nevada; A preliminary microzonation: Seismol. Soc. America Bull., v. 65, p. 1575–1598.

Murphy, J. R., Lynch, R. D., and O'Brien, L. J., 1971, Predicted San Fernando earthquake spectra: Environmental Research Corp. Rept. NVO–1163–TM30, 38 p.

Murphy, J. R., and O'Brien, L. J., 1977, Analysis of a worldwide strong motion data sample to develop an improved correlation between peak acceleration, seismic intensity, and other physical parameters: Computer Sciences Corporation, Rept. NUREG–0402 to U. S. Nuclear Regulatory Commission, 68 p.

Murphy, J. R., Weaver, N. L., and Davis, A. H., 1971, Amplification of seismic body waves by low-velocity surface layers: Seismol. Soc. America Bull., v. 61, p. 109–146.

Murphy, J. R., and West, L. R., 1974, An analysis of surface and sub-surface seismic measurements demonstrating the amplification effect of near-surface geology: Environmental Research Corp. Rept. NVO–1163–TM41 to U.S. Atomic Energy Comm., 21 p.

Nason, R. D., 1973, Fault creep and earthquakes on the San Andreas fault *in* Kovach, R. L., and Nur, Amos, eds., Proceedings of the conference on tectonic problems of the San Andreas fault system: Stanford Univ. Pubs., Geol. Sci., v. 13, p. 275–285.

National Science Foundation and U.S. Geological Survey, 1976, Earthquake prediction and hazard mitigation options for USGS and NSF programs: U.S. Gevt. Printing Office, Washington, D.C., 76 p.

Neumann, F., 1954, Earthquake intensity and related ground motion: Washington Univ. Press, 40 p.

Newmark, N. M., 1974, Comments on conservatism in earthquake resistant design: Oral presentation, Atomic Industrial Forum, Washington, D.C.

Newmark, N. M., Consulting Engineering Services, 1973, A study of vertical and horizontal earthquake spectra: Gevt. Printing Office, Washington, D.C., WASH–1255, 151 p.

Newmark, N. M., Blume, J. A., and Kapur, K. K., 1973, Seismic design spectra for nuclear power plants: Am. Soc. Civil Eng., Power Div. Jour., v. 99, p. 287–303.

Newmark, N. M., and Hall, W. J., 1969, Seismic design criteria for nuclear reactor facilities: World Conf. on Earthquake Eng., 4th, Santiago, Chile, Proc., sess. B, p. 37–50.

——— 1973, Seismic design spectra for trans-Alaska pipeline: World Conf. on Earthquake Eng., 5th, Rome, Proc., v. 1, paper no. 60, 10 p.

Newmark, N. M., and Rosenbleuth, E., 1971, Fundamentals of earthquake engineering: Englewood Cliffs, N.J., Prentice-Hall, 234 p.

Nichols, D. R., and Buchanan-Banks, J. M., 1974, Seismic hazards and land-use planning: U.S. Geol. Survey Circ. 690, 33 p.

Nosse, J. H., 1975, Variations of 1976 UBC seismic provisions from SEAOC recommendations, in New earthquake design provisions: Proc. of seminar sponsored by Prof. Dev. Comm., Structural Eng. Assn. of Northern California and San Francisco sec. of Am. Soc. Civil Engineers, p. 25–37.

Nuttli, O. W., 1972, Magnitude, intensity, and ground motion relations for earthquakes in the central United States: Intl. Conf. on Microzonation, Seattle, Wash., Proc., v. 1, p. 307–318.

——— 1973a, State-of-the-art for assessing earthquake hazards in the United States; Design earthquakes for the central United States: U.S. Army Corps of Eng., Misc. Paper S–73–1, rept. 1, 75 p.

——— 1973b, The Mississippi Valley earthquakes of 1811 and 1812, intensities, ground motion, and magnitudes: Seismol. Soc. American Bull., v. 63, p. 227–248.

——— 1974, Magnitude recurrence relation for central Mississippi Valley earthquakes: Seismol. Soc. America Bull., v. 64, p. 1189–1208.

Nuttli, O. W., and Zollweg, J. E., 1974, The relation between felt area and magnitude for central United States: Seismol. Soc. America Bull., v. 64, p. 73–86.

O'Brien, L. J., Murphy, J. R., and Lahoud, J. A., 1977, The correlation of peak ground acceleration amplitude with seismic intensity and other physical parameters: Computer Sciences Corp. Rept. NUREG–0143 to U.S. Nuclear Regulatory Comm., 80 p.

Office of Emergency Preparedness, 1972, Disaster preparedness: Rept. to Congress of the United States, v. 3., 143 p.

Orphal, D. L., and Lahoud, J. A., 1974, Prediction of peak ground motion from earthquakes: Seismol. Soc. America Bull., v. 64, p. 1563–1574.

Packer, D. B., Brogan, G. B., and Stone, D. B., 1975, New data on plate tectonics of Alaska: Tectonophysics, v. 29. p. 87–102.

Page, R. A., 1972, Crustal deformation on the Denali fault: Jour. Geophys. Research, v. 77, p. 1528–1533.

Page, R. A., Blume, J. A., and Joyner, W. B., 1975, Earthquake shaking and damage to buildings: Science, v. 189, p. 601–608.

Page, R. A., Boore, D. M., and Dieterich, J. H., 1975, Estimation of bedrock motion at the ground surface, *in* Borcherdt, R. D., ed., Studies for seismic zonation of the San Francisco Bay region: Geol. Survey Prof. Paper 941–A, p. A31–A38.

Page, R. A., Boore, D. M., Joyner, W. B., and Coulter, H. W., 1972, Ground motion values for use in the seismic design of the trans-Alaska pipeline system: U.S. Geol. Survey Circ. 672, 23 p.

Papadakis, C. N., Streeter, V. L., and Wylie, E. B., 1974, Bedrock motions computed from surface seismograms: Jour. Geotech. Eng. Div., Am. Soc. Civil Engineers, v. 100, p. 1091–1105.

Park, R. B., and Hays, W. W., 1977, Use of hybrid computer in engineering seismology research: U.S. Geol. Survey Jour. Research, v. 5, p. 651–661.

Peak, W. W., 1973, Conservatism in the selection of design earthquakes for safety of dams in California, Geology, seismicity and environmental impact: Eng. Geol. Assoc. Spec. Pub., p. 349–359.

Perez, V., 1973, Peak ground accelerations and their effect on the velocity response envelope spectrum as a function of time: World Conf. on Earthquake Eng., 5th, Rome, Proc., v. 1., no. 152, 10 p.

Pfossel, M. R., and Slosson, J. E., 1974, Repeatable high ground accelerations from earthquakes: California Geology, September, p. 195–199.

Plafker, George, 1965, Tectonic deformation associated with the 1964 Alaska earthquakes: Science, v. 148, p. 1685–1687.

——— 1967, Surface faults on Montague Island associated with the 1964 Alaska earthquake: U.S. Geol Survey Prof. Paper 543–G, 42 p.

Randall, M. J., 1973, The spectral theory of seismic sources: Seismol. Soc. American Bull., v. 63, p. 1133–1144.

Rankin, D. W., 1975, The continental margin of eastern North America in the southern Appalachians; The opening and closing of the Proto-Atlantic Ocean: Am. Jour. Sci., v. 275A, p. 298–336.

Rascón, O. A., and Cornell, C. A., 1969, A physically based model to simulate strong earthquake records on firm ground: World Conf. on Earthquake Eng., 4th, Santiago, Chile, Proc., v. 2, p. 84–96.

Rasmussen, N. H., Millard, R. C., and Smith, S. W., 1975, Earthquake hazard evaluation of the Puget Sound region, Washington state: Washington Univ. Geophysics program, 99 p.

Richter, C. F., 1935, An instrumental earthquake magnitude scale: Seismol. Soc. America Bull., v. 25, p. 1–32.

Rogers, A. M., 1972, The question of ground motion duration for nuclear explosions and earthquakes: Environmental Research Corp. Rept. NVO–1163–TM24, 33 p.

Rogers, A. M., Algermissen, S. T., Hays, W. W., Perkins, D., (geologic and seismological portion), Van Strien, D. O., Hughes, H. C., Hughes, R. C., Lagorio, H. J., and Steinbrugge, K. V., (engineering analysis portion), 1976, A study of earthquake losses in the Salt Lake City, Utah, area: U.S. Geol. Survey Open-File Rept. 76–89, 357 p.

Rogers, A. M., and Hays, W. W., 1978, Preliminary evaluation of site transfer functions developed from earthquakes and nuclear explosions: 2d Internat. Conf. on Microzonation, San Francisco, Proc., v. 2, p. 753–764.

Rogers, A. M., Katz, L. J., and Bennett, T. J., 1973, Topographic effects on ground motion for incident P-waves: A model study: Seismol. Soc. America Bull., v. 64, p. 437–456.

Rogers, A. M., Perkins, D. M., and McKeown, F. A., 1976, A catalog of seismicity within 400 km of the Nevada Test Site: U.S. Geol. Survey Open-File Rept. 76–832, 44 p.

——— 1977, A preliminary assessment of the seismic hazard of the Nevada Test Site region: Seismol. Soc. America Bull., v. 67, p. 1587–1606.

Rogers, T. H., and Nason, R. D., 1971, Active displacement on the Calaveras fault zone at Hollister, California: Seismol. Soc. America Bull., v. 62, p. 1649–1664.

Ryall, Alan, 1977, Earthquake hazard in the Nevada region: Seismol. Soc. America Bull., v. 67, p. 517–532.

Ryall, Alan, Slemmons, D. B., and Gedney, L. D., 1966, Seismicity, tectonism, and surface faulting in the western United States: Seismol. Soc. America Bull., v. 56, p. 1105–1135.

Savage, J. C., 1966, Radiation from a realistic model of faulting: Seismol. Soc. America Bull., v. 56, p. 577–592.

——— 1972, Relation of corner frequency to fault dimensions: Jour. Geophys. Research, v. 77, p. 3788–3795.

——— 1974, Relation between P- and S-wave corner frequencies in the seismic spectrum: Seismol. Soc. America Bull., v. 64, p. 1621–1628.

Sbar, M. L., and Sykes, L. R., 1973, Contemporary compressive stress in eastern North America; An example of intra-plate tectonics: Geol. Soc. America Bull., v. 84, p. 1861–1882.

Schnabel, P. B., Lysmer, John, and Seed, H. B., 1972, SHAKE—A computer program for earthquake response of horizontally layered sites: California Univ., Berkeley, rept. no. EERC 72–12, 88 p.

Schnabel, P. B., and Seed, H. B., 1973, Accelerations in rock for earthquakes in the western United States: Seismol. Soc. America Bull., v. 62, p. 501–516.

Schnabel, P. B., Seed, H. B., and Lysmer, John, 1972, Modification of seismograph records for effects of local soil conditions: Seismol. Soc. America Bull., v. 62, p. 1649–1664.

Seed, H. B., 1975, Design provisions for assessing the effects of local geology and soil conditions on ground and building response during earthquakes, *in* New earthquake design provisions: Proc. of seminar sponsored by Prof. Dev. Comm. of Struc. Eng. Assn. of Northern California and San Francisco Sec. Am. Soc. Civil Engineers, p. 38–63.

Seed, H. B., and Idriss, I. M., 1969, Influence of soil conditions on ground motions during earthquakes: Jour. Soil Mechanics Foundations Div., Am. Soc. Civil Engineers, v. 95, p. 1199–1218.

——— 1971, Simplified procedure for evaluating soil liquefaction potential: Jour. Soil Mechanics Foundations Div., Am. Soc. Civil Engineers, v. 97, p. 1171–1182.

Seed, H. B., Murarka, R., Lysmer, John, and Idriss, I. M., 1976, Relationships of maximum acceleration, maximum velocity, distance from source, and local site conditions for moderately strong earthquakes: Seismol. Soc. America Bull., v. 66, p. 1323–1342.

Seed, H. B., Ugas, C., and Lysmer, John, 1976, Site dependent spectra for earthquake resistant design: Seismol. Soc. America Bull., v. 66, p. 221–244.

Seed, H. B., Whitman, R. V., Dezfulian, H., Dobry, R., and Idriss, I. M., 1972, Soil conditions and building damage in 1967 Caracas earthquake: Jour. Soil Mechanics Foundations Div., Am. Soc. Civil Engineers, v. 98, p. 787–806.

Shannon & Wilson, Inc., and Agbabian Associates, 1972, State-of-the-art evaluation of soil characteristics for seismic response analyses: Natl. Tech. Inf. Service, TID–26444, 349 p.

——— 1975, Procedures for evaluation of vibratory ground motions of soil deposits at nuclear power plant sites: U.S. Nuclear Reg. Comm. rept. no. NUREG–75–072, 294 p.

——— 1976, Geotechnical and strong motion earthquake data from U.S. accelerograph stations, U.S. Nuclear Reg. Comm. rept.no. NUREG–0029, v. 1, 300 p.

Shoja-Taheri, J., and Bolt, B. A., 1977, A generalized strong motion accelerogram based on spectral maximization from two horizontal components: Seismol. Soc. America Bull., v. 67, p. 863–876.

Slemmons, D. B., and McKinney, R., 1977, Definition of "active fault": U.S. Army Corps of Engineers, Misc. Paper S–77–8, 22 p.

Smith, R. B., and Sbar, M. L., 1974, Contemporary tectonics and seismicity of the western United States with emphasis on the intermountain seismic belt: Geol. Soc. America Bull., v. 85, p. 1205–1218.

Smith, S. W., 1976, Determination of maximum earthquake magnitude: Geophys. Research Letter, v. 3, p. 351–354.

Smoots, V. A., Gates, W. E., Leeds, D. J., and Mendenhall, J. D., 1969, The effect of foundation soils on seismic motion: Soil-Structure Interaction Subcommittee, Struc. Eng. Assoc. of Southern California, Seismol Comm., ann. rept., p. 43–66.

Springer, D. L., and Kinneman, R. L., 1971, Seismic source summary of U.S. underground nuclear explosions, 1961–1970: Seismol. Soc. America Bull., v. 61, p. 1073–1098.

——— 1975, Seismic source summary for U.S. Underground nuclear explosions, 1971–1973: Seismol. Soc. America Bull., v. 65, p. 343–350.

State of California, 1933, Field act for design of public school buildings.

Stauder, W., Kramer, M., Fischer, G., Schaefer, S., and Morrissey, S. T., 1976, Seismic characteristics of southeast Missouri as indicated by a regional telemetered microearthquake array: Seismol. Soc. America Bull., v. 66, 1953–1964.

Steinbrugge, K. V., Schader, E. E., and Moran, D. F., 1975, Building damage in San Fernando valley, San Fernando, California earthquake of 9 February, 1971: California Div. Mines and Geology Bulletin 196, p. 323–354

Stepp, J. C., 1972, Analysis of completeness of the earthquake sample in the Puget Sound area and its effect on statistical estimates of earthquake hazard: Internat. Conf. on Microzonation, Seattle, Wash., Proc., v. 2, p. 898–909.

Stover, C. W., Simon, R. B., and Person, W. J., 1976, Earthquakes in the United States, January-March, 1974: U.S. Geol. Survey Circ. 723–A, 18 p.

Sykes, L. R., 1972, Seismicity as a guide to global tectonics and earthquake prediction: Tectonophysics, v. 13, p. 393–414.

Tarr, A. C., and King, K. W., 1974, South Carolina seismic program: U.S. Geol. Survey Open-File Rept., 74–58, 25 p.

Thatcher, Wayne, and Hamilton, R. M., 1973, Aftershocks and source characteristics of the 1969 Coyote Mountain earthquake: Seismol. Soc. America Bull., v. 63, p. 647–662.

Thatcher, Wayne, and Hanks, T. C., 1973, Source parameters of southern California earthquakes: Jour. Geophys. Research, v. 78, p. 8547–8576.

Thatcher, Wayne, Hileman, J. A., and Hanks, T. C., 1975, Seismic slip distribution along the San Jacinto fault zone, southern California, and its implications: Geol. Soc. America Bull., v. 86, p. 1140–1146.'

Tobin, D. G., and Sykes, L. R., 1968, Seismicity and tectonics of the northeast Pacific Ocean: Jour. Geophys. Research, v. 73, p. 3821–3845.

Townley, S. D., and Allen, M. W., 1939, Descriptive catalog of earthquakes of the Pacific coast of the United States: Seismol. Soc. America Bull., v. 29, p. 1–20.

Trifunac, M. D., 1970, Low frequency digitization errors and a new method for zero baseline correction of strong motion accelerograms: Pasadena, Calif., California Inst. Technology, Earthquake Eng. Research Lab. Rept. EERL 70–07, 30 p.

———1971, Response envelope spectrum and interpretation of strong earthquake ground motion: Seismol. Soc. America Bull., v. 61, p. 343–356.

———1972a, Stress estimates for San Fernando, California, earthquake of February 9, 1971: Main event and thirteen aftershocks: Seismol. Soc. America Bull., v. 62, 0. 721–770.

———1972b, Tectonic stress and the source mechanism of the Imperial Valley, California, earthquake of 1940: Seismol. Soc. America Bull., v. 62, p. 1283–1302.

———1973a, Scattering of plane SH waves by a semi-cylindrical canyon: Intl. Jour. Earthquake Eng. Struc. Dynamics, v. 1, p. 267–282.

———1973b, Analysis of strong earthquake ground motion and prediction of response spectra: Intl. Jour. Earthquake Eng. Struc. Dynamics, v. 2, p. 59–69.

———1976a, Preliminary analysis of the peaks of strong earthquake ground motion-dependence of peaks on earthquake magnitude, epicentral distance, and recording site condition: Seismol. Soc. America Bull., v. 66, p. 189–220.

———1976b, Preliminary empirical model for scaling Fourier amplitude spectra of strong ground acceleration in terms of earthquake magnitude, source-to-station distance, and recording site condition: Seismol. Soc. America Bull., v. 66, p. 1343–1374.

Trifunac, M. D., and Brady, A. G., 1975a, Correlations of peak acceleration, velocity, and displacement with earthquake magnitude, and site condition: Intl. Jour. Earthquake Eng. Struc. Dynamics, v. 4, p. 455–471.

———1975b, A study on the duration of strong earthquake ground motion: Seismol. Soc. America Bull., v. 65, p. 581–626.

———1975c, On the correlation of seismic intensity scales with the peaks of recorded ground motion: Seismol. Soc. America Bull., v. 65, p. 139–162.

Trifunac, M. D., Udwadia, F. E., and Brady, A. G., 1971, High frequency errors and instrument corrections of strong-motion accelerograms: Pasadena, Calif., California Inst. Technology, Earthquake Eng. Research Lab. Rept. EERL 71–05, 40 p.

Trifunac, M. D., and Westermo, B. D., 1977, Dependence of the duration of strong earthquake ground motion on magnitude, epicentral distance, geologic conditions at the recording station, and frequency of motion: Southern California Univ., Dept. of Civil Eng., rept. CE76–02, 64 p.

Uniform Building Code, 1973, International Conference of Building Officials, Whittier, California (updated every 3 years) 704 p.

———1976, International Conference of Building Officials, Whittier, California (updated every 3 years) 728 p.

U.S. Atomic Energy Commission, 1971, Reactor site criteria: Appendix A: seismic and geologic siting criteria for nuclear power plant sites: Federal Register, v. 36, p. 22601–22626.

———1973a, Reactor site criteria, seismic and geologic siting criteria (amendments): Federal Register, v. 38, no. 318, 2 p.

———1973b, Design response spectra for seismic design of nuclear power plants, (revision), Regulatory Guide 1.60, 8 p.

U.S. Department of Commerce, 1970, Seismicity of Alaska: Washington, D.C., NEIC Pub. 3011, U.S. Coast and Geodetic Survey, Environ. Sci. Adm., 34 p.

———1974, Catalog of strong motion seismograph stations and records, Brazee, R. J., ed.: Boulder, Colo., Environ. Data Service, 96 p.

U.S. Department of Commerce, ESSA/NOAA, 1928–1973, United States earthquakes, Annual Issues (subsequent issues are joint publications of NOAA and USGS).

U.S. Geological Survey, 1975, Studies for seismic zonation of the San Francisco Bay region, Borcherdt, R. D., ed.: Prof. Paper 941–A, 102 p.

———1976a, The Guatemalan earthquake of February 4, 1976, a preliminary report, Espinosa, A. F., ed.: Prof. Paper 1002, 90 p.

———1976b, Seismic engineering program report April-June, 1976: Circ. 736–B, 12 p.

U.S. Nuclear Regulatory Commission, 1975, Standard review plan: Rept. NUREG 75/087, 50 p.

URS/J. A. Blume and Associates, Engineers, 1975, Effects prediction guidelines for structures subjected to ground motion: URS/J. A. Blume and Associates, Engineers Rept. JAB–99–115, UC–11 to U.S. Energy Research and Development Admin., 373 p.

Van Wormer, J. D., Davies, John, and Gedney, Larry, 1974, Seismicity and plate tectonics in south central Alaska: Seismol. Soc. America Bull., v. 64, p. 1467–1476.

Veterans Administration, 1973, Earthquake resistant design requirements for VA hospital facilities: Handbook H–08–8, 36 p.

Wallace, R. E., 1970, Earthquake recurrence intervals on the San Andreas fault: Geol. Soc. America Bull., v. 81, p. 2875–2899.

Walper, J. L., 1976, State-of-the-art for assessing earthquake hazards in the United States: Plate tectonics and earthquake assessment, U.S. Army Eng. Waterways Exp. Sta. Misc. Paper S–73–1, Rept. 5, 104 p.

Warren, D. H., and Healy, J. H., 1973, Structure of the crust in the conterminous United States: Tectonophysics, v. 20, p. 203–213.

Warrick, R. E., 1974, Seismic investigations of a San Francisco Bay mud site: Seismol. Soc. America Bull., v. 64, p. 375–386.

Weetman, B. G., Davis, L. L., Hays, W. W., and Mueller, R. A., 1970, Seismic response characteristics at NRDS from underground nuclear detonations: Environmental Research Corp. Rept. NVO–1163–TM22 to U.S. Atomic Energy Comm., 60 p.

Werner, S. D., 1970, A study of earthquake input motions for seismic design: Agbabian Assoc. Rept. to U.S. Atomic Energy Comm., TID–25438, 192 p.

———1975, Evaluation of earthquake ground motion characteristics at nuclear plant sites; Agbabian Assoc. Rept. to Reactor Research and Development Div., Energy Research and Dev. Admin., SAN/1011–107, 29 p.

Werner, S. D., and Ts'ao, H. S., 1975, Investigation of vertical ground motion characteristics for nuclear plant design: Agbabian Assoc. report to Reactor Research and Development Div., Energy Research and Devel. Admin., SAN/1011–108, 93 p.

West, L. R., 1971, Ground motions recorded in Las Vegas from seven underground nuclear events: Environmental Research Corp. Rept. NVO–1163–229 to U.S. Atomic Energy Comm., 96 p.

West, L. R., and Christie, R. K., 1971, Observed ground motion data, Cannikin event: Environmental Research Corp. Rept. NVO–1163–230 to U.S. Atomic Energy Comm., 26 p.

Wiggins, J. H., and Moran, D. F., 1971, Earthquake safety in the city of Long Beach based on the concept of balanced risk: J. H. Wiggins Company rept. to City of Long Beach, 129 p.

Wilson, J. T., 1973, Mantle plumes and plate motions: Tectonophysics, v. 19, p. 149–164.

Wong, H. L., Trifunac, M. D., and Westermo, B., 1977, Effects of surface and subsurface irregularities on the amplitudes of monochromatic waves: Seismol. Soc. America Bull., v. 67, p. 353–368.

Woolard, G. P., 1958, Areas of tectonic activity in the United States as indicated by earthquake epicenters, transactions: Am. Geophys. Union Trans., v. 39, p. 1135–1150.

Woodward-Lundgren and Associates, 1973, Geotechnical data compilation for selected strong motion seismograph sites in California: Woodward-Lundgren and Associates rept. to Natl. Oceanic Atmospheric Admin., 362 p.

Woodward-McNeill and Associates, 1973, Seismic considerations for landuse planning Los Angeles County: Woodward-McNeill and Associates Rept. no. CPA–CA–09–16–1002 G to County of Los Angeles, 3 v., 373 p.

Wyss, Max, and Molnar, Peter, 1972, Efficiency, stress drop, apparent stress, effective stress, and frictional stress of Denver, Colorado, earthquakes: Jour. Geophys. Research, v. 77, p. 1433–1438.

Young, G. A., 1976, Problem areas in the application of seismic hazard analysis procedures: Agbabian Assoc. Rept. SAN/1011–101 to Reactor Devel. and Demonstration Div., Energy Research and Devel. Admin., 153 p.

GPO 689-143