EARTHQUAKES AND EARTHQUAKE ENGINEERING

George W. Housner

SYNOPSIS

Crustal plate motions provide the source of the energy that produces earthquakes. The mechanism of earthquake generation involves four types of faulting. The size of an earthquake is described by the Richter magnitude and an informative relation exists between earthquake magnitude and fault length. The estimation of seismic hazard is made on the basis of the seismic history of a region and it provides the basis for the construction of a seismic zoning map. Special insensitive strong-motion earthquake accelerographs are used to record strong earthquake ground shaking and building motions. Earthquake accelerograms provide the basic data for the development of earthquake design procedures. Analyses of the dynamic response of structures to earthquake ground motions provide a tool for the seismic design of major structures. The response spectrum provides a basis for a simple method of seismic design. The application of the design spectrum is described and its relation to the building code requirements is discussed.

RESUME

Les mouvements de la croûte terrestre sont la source de l'énergie qui provoque les tremblements de terre dont le mécanisme de génération implique quatre types de faille. L'intensité d'un séisme est mesurée à l'échelle Richter et une relation informative existe entre cette intensité et la longueur de la faille. L'évaluation d'un danger sismique est basée sur l'évolution sismique de la région et elle constitue la base pour la construction d'une carte de zones de séisme. Des accélérographes spéciaux sont employés pour enregistrer les mouvements du sol et les vibrations des édifices durant les séismes. Des accélérogrammes donnent les informations de base pour le développement de techniques de calcul sismique. Les analyses du comportement dynamique des structures sujettes au séisme permettent leur calcul sismique. Le spectre de comportement constitue la base d'une méthode simple de calcul sismique. L'application du spectre utilisé est décrite et sa relation par rapport aux critères du code du bâtiment est discutée.

George W. Housner is C F Braun Professor of Engineering at the California Institute of Technology. He is past President of the International Association for Earthquake Engineering and of the Earthquake Engineering Research Institute. He is Chairman of the California State Consulting Board for Earthquake Analysis.

INTRODUCTION

Earthquakes constitute a natural hazard that endangers cities in many parts of the world. The main responsibility for the protection of cities against earthquakes rests with engineers. If a city is not prepared for the earthquake shaking to come it can suffer severe economic penalties and also large loss of life. For example, the building code of the city of Tangshan, China did not require earthquake resistant design, with the consequence that the large earthquake of 28 July 1976 devastated the city. The magnitude 7.8 earthquake occurred close to this industrial city of 1.5 million inhabitants, causing the collapse or severe damage of most of the buildings (unreinforced brick) and killing an estimated 750,000 inhabitants.

An informative comparison can be made between the 9 February 1971 San Fernando, California earthquake (magnitude 6.4) and the 23 December 1972 Managua, Nicaragua earthquake (magnitude 6.2), both of which were approximately the same size and both affected approximately the same number of inhabitants with very strong ground shaking (400,000±). There were 60 deaths in the San Fernando earthquake and approximately 6,000 deaths in the Managua earthquake. This difference can be attributed mainly to the earthquake design which was required in California but not in Nicaragua.

It is important, in a region where earthquakes will occur, for the engineering community to assess the nature of the seismic risk involved and to establish appropriate standards of earthquake resistant design. In regions where potentially destructive earthquakes occur relatively frequently, such as California, it is comparatively easy to collect seismic data and to establish appropriate levels of design. In regions where earthquakes do not occur so frequently there is less seismic data available and it is more difficult to assess the true seismic hazard and to formulate appropriate design standards. The objective of earthquake resistant design is to prevent future damage, but this should not be done at a cost that exceeds the damage losses prevented. This economic evaluation of earthquake resistant design tends to lead to lower design standards on the reasoning that in the long term it is less costly to rebuild some earthquake damaged structures than to make all structures highly resistant. However, a second objective is to prevent disasters, that is, to avoid unacceptable loss of life and unacceptable social impact and economic loss. This requires a sufficiently high level of earthquake design so that a Tangshan, or a Managua, type of disaster will not occur. A key problem in earthquake engineering is how to establish earthquake design procedures that will meet both of the above objectives. If it were known when and where future earthquakes would occur, how large they would be and how strong the ground shaking, it would be relatively easy to establish optimum design requirements. However, since it is not possible to predict earthquakes, it is necessary to estimate future hazard, and this requires the utilization of all information that has a bearing on the problem, such as how earthquakes are generated, when and where they have occurred in the past, and the nature of the ground shaking. Since the available information is limited, especially in regions of infrequent occurrence of earthquakes, considerable judgment must be used. A particularly troublesome point is how to establish the approximate size of the largest earthquakes that can be expected in a region and how often such large events might occur, for it is this type of earthquake that can produce a disaster if a city is not prepared.

The Causes of Earthquakes

The earthquakes felt on the surface of the earth are the consequences of sudden stress failures in the rock of the earth's crust. The abrupt reduction of stress associated with the stress failure generates seismic waves (stress waves) which propagate away from the origin. Stress waves, as is well-known, transport strain-energy and kinetic-energy, and these energies are gradually dissipated by material damping as the waves travel over large distances. The persistent occurrence of earthquakes over a long geological period of time and the associated dissipation of energy require that there be a source that supplies energy to the earth's crust. The energy source is inferred to be thermal convection currents within the interior of the earth. These currents are thought to be associated with circulatory convection cells that exert horizontal shearing forces on the lower portions of the earth's crustal rock. These forces continue to build up the strain energy in the earth's crust which, in turn, leads to stress failures and the dissipation of energy through propagation of seismic stress waves. In the crustal rock beneath the oceans lines of upwelling have been identified where two adjacent convection cells are moving with upward motion. The upwelling produces new sea floor crustal material which spreads outward from the line of upwelling, with crustal plate velocities of 2 to 6 cm/yr. The earth's crust is segmented into ten major crustal plates which are moving with noncongruent velocities; so that along some boundaries there is upwelling and a spreading motion between plates (usually beneath an ocean), and along other boundaries one crustal plate thrusts beneath the adjacent plate, producing what is called a sub-duction zone. Such sub-duction zones along the western coast of South America, the Aleutian Islands and Japan are the sources of many large earthquakes. In some instances, instead of thrusting against each other, the two crustal plates may have a relative velocity parallel to the boundaries so that there is a horizontal shearing displacement between the two plates. An example of this is the San Andreas Fault Zone in California which is the boundary between the Pacific crustal plate and the North American crustal plate. The relative shearing displacements between these two plates is accomplished by episodic stress failures such as the 1906 San Francisco earthquake and the 1857 Fort Tejon earthquake, during which there were sudden relative displacements of 300 to 600 cm (10 to 20 ft). The crustal plate motions produce internal stresses in the plates away from the boundaries and these cause stress failures and sometimes produce major earthquakes. Examples of such earthquakes are: the St. Lawrence Valley events of 1638, 1663, 1732 and 1925; the Missouri Valley earthquakes of 1811 and 1812; the Charleston, South Carolina shock of 1886; and the Tangshan, China earthquake of 1976.

The major stress failures in the western United States originate mostly at a depth of 8 to 15 km (5 to 10 miles) beneath the surface of the earth and produce so-called shallow earthquakes. Although in some parts of the world stress failures originate at greater depths, for example, up to 300 km in the lower parts of subduction zones, the deeper the stress failure the less intense is the shaking at ground surface. Most destruction is caused by shallow earthquakes. The action of gravity on the earth's crust tends to produce a pure (hydrostatic) compression of approximately 4,000 psi per mile of depth, so at the depths of 5 to 10 miles the pure compression stress ranges from 20,000 to 40,000 psi. The sea floor spreading process produces additional stresses in the crust which cause the state of stress to deviate from pure compression but the compressive stresses are sufficiently large so that the stress failures are of the shearing type rather than tension or compression type. Where shearing type failure has produced a relative slip displacement across the failure surface, it is called a "fault" in the rock. Four common types of faults are shown in Figure 1. These are called 1) thrust (compressional) fault; 2) normal (extensional) fault; 3) strike-slip (horizontal shearing) fault; 4) sub-duction fault. In the case of earthquakes a thrust fault or a normal fault usually has a component of strike-slip (horizontal) displacement also, and vice versa.

It appears that earthquakes (stress failures) now occur only on existing faults, as these are surfaces of weakness. There are many such existing surfaces of weakness in seismic regions so that it is not possible, in general, to predict where and when future stress failures will occur.

Size of an Earthquake

The severity of ground shaking during an earthquake depends upon the amount of energy carried by the seismic waves and also upon the energy density, that is, the energy per unit volume. As the seismic waves spread out from the causative fault the energy is spread over a greater volume of rock and, consequently, the energy density and the intensity of shaking decrease with distance from the causative fault.* Thus an earthquake will affect a certain surface area with perceptible shaking which has greater intensity close to the causative fault and

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*Compression waves travel at a speed of approximately 3 miles per second; shear waves travel at approximately 2 miles per second; surface waves travel at approximately 90% the speed of shear waves.

decreasing intensity away from the fault, as shown in Figure 2. It is clear that a large earthquake, that is, a large stress failure, will affect with strong shaking a larger ground surface area than would a small earthquake (small stress failure), and the area affected would be a logical measure of the size of an earthquake. Practical difficulties in collecting the necessary data prevents the use of the affected surface area as a measure of size of an earthquake and, instead, the intensity of motion recorded by a standard seismograph at a standard distance is used. It is clear that at the same distance, the stronger the motion the larger the earthquake. The magnitude of an earthquake was originally defined by C. F. Richter as

$$M = \log_{10} (A_{100}/A_0)$$

where A_0 is a constant and A_{100} is the amplitude recorded at a distance of 100 km by a seismograph that has a natural period of 0.8 seconds, approximately critical damping, and a static amplification of 2800. This definition of magnitude is suitable for stress failures whose slipped fault area has a length appreciably less than 100 km, however where the length of fault is very large the recording seismograph should be at a sufficient distance so that the intensity of shaking is not unduly sensitive to the orientation of the fault with respect to the seismograph, see Figure 2. Also, it is necessary to take into account the fact that the character of seismic waves changes with increasing distance from the origin. The designation M_S is used to indicate that the magnitude has been calculated from the amplitude of surface waves which are predominant when the recording is made at a distance of hundreds or thousands of kilometers. The local magnitude $M_L = M$ is used when the recording is made at a distance less than a couple hundred kilometers.

For engineering purposes, the main advantage of knowing the earthquake magnitude number is that it gives an idea of the length of slipped fault, shown in Figure 3, which indicates the size of the area affected by strong ground shaking, as shown in Figure 2. An earthquake of magnitude 8 affects with strong shaking a much larger area than an earthquake of magnitude 6.

Measuring Earthquake Motions

For seismological studies it is customary to record ground motions with very sensitive seismographs that will detect distant earthquakes, with the consequence that these instruments go off-scale if the ground shaking is strong enough to be just barely perceptible to humans. For engineering purposes the interest is in ground shaking strong enough to be potentially damaging to structures and, therefore, special insensitive recording instruments are required. It is customary to record strong ground accelerations with an accelerograph having a natural frequency of vibration of about 18 cps, about 60% of critical damping, and capable of recording accelerations of 100% g, or more.*

*These earthquake accelerographs are commercially available at a cost of approximately $2000.

The instrument remains inactive till it senses the beginning of an earthquake and then it turns on and records the motion till the end of the shock, at which time it turns off and is ready for the next event. Figure 4 shows a reproduction of the accelerogram recorded two miles from the causative fault of the magnitude 6.2 Managua, Nicaragua earthquake of 23 December 1972. Two horizontal components and one vertical component of ground acceleration were recorded; and this would be considered rather strong ground shaking. The significant features of the record are 1) the intensity of shaking, that is, the amplitude of the acceleration peaks, 30-40% g in the horizontal motions and approximately 25% g in the vertical; 2) the duration of strong ground shaking, about 6 or 7 secs; and 3) the frequency content of the motion, that is, the number of times per second that the trace crosses the axis, about 7-8 times per sec for horizontal accelerations and 15 to 16 times per sec for vertical accelerations. These three factors have an important influence on the vibrations induced in structures, and all three are affected by distance from the causative fault. The intensity of shaking attenuates with distance, the rate of attenuation being greater for small earthquakes than for large shocks. The duration of shaking increases with increasing distance because of the dispersion of the seismic waves caused by non-uniformities in the earth's crust. The number of axis crossings per sec decreases with distance for the high frequency waves attenuate more rapidly with distance than do long period waves. At larger distances the character of the ground motion is different than at short distances from the fault.

In the eastern parts of North America strong ground shaking has not yet been recorded by instruments, but past destructive earthquakes are described in the seismological literature. The severity of the ground motion in these past earthquakes is indicated by so-called Intensity Numbers that range from I to XII. These numbers are associated with shorthand descriptions of earthquake affects such as perceptibility, different degrees of observable damage, surface faulting, etc. The intensity numbers are only poorly correlated with intensity of ground acceleration but they do provide a convenient way of describing the effects of an earthquake. An inexpensive seismoscope is used to provide an instrumental recording that indicates the intensity of ground shaking. This consists of a universal pendulum whose motion is scratched on a smoked glass plate. The pendulum has a period of vibration of 0.75 secs and has 10% of critical damping. The smoked glass record shows the maximum amplitude attained by the pendulum during the earthquake thus, in effect, determining the maximum response of a building with 0.75 secs period and 10% damping. The seismoscope gives a reliable measure of the intensity of ground shaking.

A complication in the study of ground motions is that in certain cases local geology and soils have been observed to exert a significant influence on the nature of strong ground motions. This has been particularly noticeable in two cases, Mexico City and Lima, Peru. The central portion of Mexico City is founded on an old volcanic ash lake-bed, and this bowl-of-jelly shakes in a characteristic fashion during an earthquake, with amplification of motion around a period of

2.5 seconds, which is the natural period of vibration of the bowl of jelly. The earthquake motions that have been recorded in Lima, Peru show much higher frequencies in the ground acceleration than do California or Nicaragua ground motions. Studies are underway on the degree to which surface ground shaking is influenced by the passage of seismic waves through heterogeneous rock and soil formations, but, as yet, this is an unsolved problem.

Seismic History and Seismic Hazard

The first step in assessing the likelihood of future strong ground shaking at a site is to examine the earthquake history of the region, that is, when and where have earthquakes of various magnitudes occurred in the past. In most regions, a reliable seismic history is available only for the past 50 years, or so; beyond that, the reliability falls off, though the occurrence of very large earthquakes ($M \geq 7$) in a region is usually known reliably over a much longer time period than the occurrence of smaller shocks ($M \leq 6$). The statistics of world earthquakes, based on large numbers of occurrences, are very reliable, see Figure 5. In regions with inadequate seismic histories it is usually assumed that the relative frequencies of occurrence of earthquakes of different magnitudes is approximately the same as for world earthquakes, or California earthquakes, and the available earthquake data are compared to California data, or world data, and inferences are drawn. This approach is based on the premise that the future will be statistically similar to the past, and the seismic hazard is expressed in terms of probability of earthquakes of magnitude M, or greater, occurring in a specified region during a 100 year period; or, it may be expressed in terms of probability of experiencing, at a site, a certain intensity, or greater, of ground shaking in a 100 year period.

In addition to the short-term seismic history of a region, information can also be obtained about the long-term earthquake activity from geological studies of faults, that is, studies of past fault displacements which are presumed to have occurred during earthquakes. It is sometimes possible to date the movement on a fault as well as to obtain estimates of the displacement that occurred during this event, although this is easier to do in a seismically active region such as California than in a less active region. The frequency of occurrence of comparable earthquakes per unit of area is approximately 10 times as great in California as in the eastern United States.

In view of the incomplete nature of the available data, estimates of seismic hazard can be only approximate, and it is clear that in addition to seismological knowledge considerable judgment is required. For major projects, special consultants are usually retained to make assessments of seismic hazard, and other consultants are retained to make recommendations on seismic design criteria. The seismological reports and geological reports giving an assessment of earthquake hazard are first prepared and, from these an earthquake engineering report with recommended design criteria is developed.

Seismic Zoning

For ordinary projects it is not feasible to engage seismological and geological consultants to make special studies. Instead, the building code contains a seismic zoning map which is an inexpensive substitute for these studies; an example is shown in Figure 6. The zoning map is usually prepared by a committee that takes a broad look at the seismic history of the entire country. The zoning map shows the relative intensity of earthquake design forces prescribed by the building code. It should be noted that a zoning map in a building code is not a seismic hazard map that expresses the probability of experiencing shaking, it is more than this. Presumably a seismic hazard map was available to the committee along with information about damage by past earthquakes, type of building materials used, code allowable stresses and strains, acceptable degree of damage, political practicalities, etc., and this information was combined with judgment in preparing the zoning map. The result lies somewhere between a scientific diagram and a work of art. Since a large investment in construction is guided by the building code, it is important that the zoning map be in as good as possible agreement with future earthquake activity. A good zoning map is one that need not be redrawn after each earthquake.

Earthquake Design of Structures

Earthquake produced motions of buildings have been recorded by accelerographs installed in the upper parts of structures as well as in the basements, as shown in Figure 4. Computer analyses have been made to calculate the building vibrations that theoretically would be produced by the recorded basement accelerations, and these were compared with the recorded motions. Knowing the masses and stiffnesses of the structure, the periods and shapes of the different natural modes of vibration can be calculated and the damping in each mode can be estimated. The time-history of vibration of a mode can then be calculated using the recorded basement acceleration as excitation. When the vibration response is calculated for each mode that is significantly excited by the ground motion, the modal responses can be combined to give the vibratory motion of each floor. When such computed responses are compared with the responses recorded in the upper parts of the buildings, they are in satisfactory agreement. It is possible, therefore, after making a preliminary design of a building to compute the motion of the floors that would be produced if the base of the building were subjected to a recorded ground acceleration. Knowing the displacements and accelerations of the floors at a given instant of time, it is possible to calculate the corresponding story shear-forces and bending-moments and the individual column and beam moments and shears. This procedure has been used to design high-rise buildings; for example, a number of tall buildings ($H > 40$ stories) in Los Angeles have been designed by the following procedure. Major potentially active faults within 50 miles of the site were identified and an estimate was made of the largest likely earthquake that might originate on each fault. For example, a magnitude 8+ earthquake on the San Andreas fault that is 35 miles distant was considered a likely possibility, and smaller earthquakes on smaller, closer faults were estimated to have the potential for producing strong shaking at the site. For each magnitude of earthquake and distance, a corresponding site ground acceleration time-history was prepared for use in computing building response. This was done for four different earthquake ground motions ranging from magnitude 8+ at 35 miles, to a magnitude 5 immediately adjacent to the site. The columns and beams of the structural building frame were then designed to withstand the deformations induced by these ground motions, taking into account the probabilities of occurrence when setting allowable strains. Similar earthquake analyses and designs have also been carried through for major offshore oil-drilling platforms, nuclear power plants, long-span suspension bridges, and major dams.

It has been established that if the proper structural masses, stiffnesses and dampings are used in computer analyses of earthquake-induced vibrations, the displacements, shears and moments can be calculated with accuracies satisfactory for design purposes. Although the masses can always be determined with good accuracy, the determination of stiffnesses is less accurately done, and the estimation of damping is probably still less accurate. It is, therefore, necessary to measure stiffnesses and dampings of real buildings during vibrations so that this information can serve as a guide in estimating these quantities for design purposes. Figure 7 shows how the period of a 9-story steel frame building changed during construction, presumably due to the addition of interior partitions, fireproofing, etc., and during the earthquake the observable period lengthened considerably.

A complicating feature in the dynamic analysis of structures is that the foundation of a structure may significantly influence the earthquake response. It appears that for ordinary structures on ordinary ground the soil-structure interaction is not important, but for structures on soft ground, particularly if the structure is massive and rigid, the interaction can be of engineering significance. Also if the horizontal dimensions of the foundation of a structure are very large, as would be the case for very long buildings, large dams, long span bridges, etc., the interaction between the seismically deformed soil and the foundation of the structure may be of engineering importance.

During an earthquake the structure may induce dynamic stresses in the underlying soil that cause undesirable deformations in the foundation material. Also, the passage of seismic waves may produce undesirable deformations in the soil. During the Japan earthquake of 1964 many buildings in the city of Niigata suffered large settlements, tilting and structural damage from the liquefaction of the underlying poorly consolidated sandy soil with high water table. During the 1964 Alaska earthquake large landslides, and sub-aqueous slides, caused extensive damage.

Simplified Method of Design

Elaborate computer analyses of earthquake vibrations are usually done for major structures but are not, in general, feasible for ordinary buildings. A simpler and more easily applied method of analyzing the earthquake response of structures was originally developed at the California Institute of Technology in the 1930's and 1940's. This method was based on the so-called spectrum analysis of recorded ground accelerations. If, as shown in Figure 8, a simple structure with mass m, displacement x, story stiffness k and story shear force kx, velocity dx/dt = v and damping force cv, has its base subjected to ground acceleration 'a' that was recorded during an earthquake, the vibratory response can be calculated for any specified natural period of vibration, $T = 2\pi\sqrt{m/k}$, and specified fraction of critical damping, $n = 2c/\sqrt{km}$. The computed response would appear as shown in Figure 9. For engineering purposes, it is the maximum displacement, x_{max}, that is of interest for this produces the maximum story shear force, $Q_b = kx_{max}$. The maximum displacement can be computed for a specific period of vibration, T, and fraction of critical damping, n. To make the calculation it is necessary first to digitize the ground accelerations and to write the computer program for the vibration calculations; but when this has been done the calculations can be repeated quickly and inexpensively. Therefore, it is a simple matter to repeat the calculations for 100 different values of T, ranging from 0.1 seconds to 10 seconds, and thus to determine 100 values of x_{max} for a specified damping, n. A plot of x_{max} versus T can then be drawn as shown in Figure 10. Such a plot is called the Displacement Response Spectrum, S_d, of the ground motion; the name spectrum being derived from the theory of optics and the analysis of light. Such a response spectrum is a convenient way of describing the nature of the ground acceleration in terms of its maximum effect on structures. When the response spectrum has been calculated, the maximum displacement of a structure with given period and damping can be read directly from the plot of S_d. Since force equals mass times acceleration, the acceleration that would be produced by the story shear acting on the mass m is given by (kx_{max}/m), and a plot of this quantity is called the Acceleration Response Spectrum, S_a. Note that $S_a = (2\pi/T)^2 S_d$. Often the response spectra are plotted on special three-way logarithmic graph paper as shown in Figure 11. In this way a single graph gives:

$$S_d = kx_{max}$$

$$S_v = (2\pi/T)S_d$$

$$S_a = (2\pi/T)^2 S_d$$

The significance of these three quantities is that if a structure were vibrating sinusoidally with maximum displacement S_d, its maximum velocity would be S_v and its maximum acceleration would be S_a.

It is seen from the foregoing, that the simple seismoscope recording instrument gives one point on the displacement response spectrum, which is a good indication of the intensity of ground shaking.

Application of Response Spectrum to Multi-Story Buildings

The response spectrum presents information about the peak response of a simple, one-mass structure, but it can also give information about the earthquake response of a multi-story building. The vibration of a multi-story building can be expressed as the combination of the responses of its individual natural modes of vibration, two of which are shown in Figure 12. Each mode, when it vibrates with its natural period has a base shear Q_b and a base moment M_b, which are analogous to the base shear and base moment of the simple structure shown in Figure 8. In fact if the natural period of vibration of the simple structure is made the same as that of a mode of vibration, and the mass of the simple structure is adjusted to give the same base shear, and the height, h, of the simple structure is adjusted so that the base moments are also the same, then the simple structure is dynamically equivalent to the mode of vibration. There are well-known methods of calculating the equivalent simple structure for any given mode shape and period, so it is possible to determine Q_b and M_b of a mode from the response spectrum, S_d. This can be done for each building mode that is excited by the earthquake, thus the response spectrum determines the maximum response of each mode. However, the maximum response of each mode does not, in general, occur at the same instant of time, so that it would be overestimating to simply add the maximum values for each mode. To allow for this, it is customary to estimate the maximum base shear of the structure as

$$Q_{max} = (Q_1{}^2 + Q_2{}^2 + Q_3{}^2 + \cdots)^{\frac{1}{2}}$$

where Q_1, Q_2, Q_3 are the maximum values for the first, second, and third modes as determined from the response spectrum. Other quantities are estimated in the same way; for example

$$M_{max} = (M_1{}^2 + M_2{}^2 + M_3{}^2 + \cdots)^{\frac{1}{2}}$$

or the bending stress, σ, at point A on the structure

$$\sigma_{max} = (\sigma_1{}^2 + \sigma_2{}^2 + \sigma_3{}^2 + \cdots)^{\frac{1}{2}}$$

It is usually found that the largest contribution comes from the first mode and that the contributions of increasingly higher modes die out rapidly.

Design Spectrum

The response spectrum curves calculated from a recorded ground motion have an irregular appearance with peaks and valleys. These irregularities are fortuitous and are different from earthquake to earthquake. Therefore, when designing a structure for future earthquake ground motion it would not be logical to use an irregular spectrum that represents past ground motion. It is customary to use smooth Design Spectrum curves for purposes of design, as shown in Figure 11b. Such a Design Spectrum, although based on spectra of recorded accelerations, is usually adjusted to fit the particular situation. It is intended to establish the appropriate design level and to give the same factor of safety for different structures having different periods of vibration and different dampings.

The earthquake requirements in the Uniform Building Code are roughly equivalent to a Design Spectrum method of analysis, except that all buildings are tacitly assumed to have the same damping, and the shape of the single design spectrum curve is given certain arbitrary features. In addition to expediency, the use of this single spectrum curve can, perhaps, be justified on the grounds that during very strong shaking code-designed buildings are expected to undergo yielding, cracking, etc., and to have relatively large damping.

Some Important Remaining Problems

The generation of earthquakes, the nature of the ground shaking, and the dynamic response of structures are well understood. However, there is still a lack of data needed to establish the best design procedures. Some of the topics where more data are required are 1) more instrumental recordings of destructive ground motions are needed to give increased confidence in engineering estimates; 2) more statistical data on the occurrence of large earthquakes is needed to enable better estimates of seismic hazard to be made; 3) behavior of soils under the action of strong seismic deformations needs additional research; 4) additional strong-motion recordings in strongly vibrating structures are needed to throw light on the inelastic behavior of buildings that are vibrating so strongly that progressive damage is taking place through cracking, plastic deformations, etc. Since the field of earthquake engineering research is of such recent origin, it is not surprising that the development of basic information is not yet complete. However, the information presently available is sufficient to develop suitable methods of design and suitable design criteria even though it is not known precisely how close these are to the optimum.

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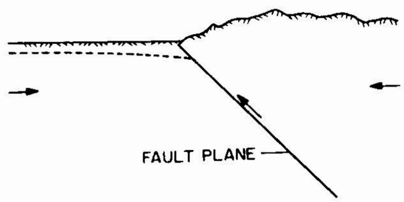

Figure 1a. Thrust faulting under lateral compressive strains. Example, San Fernando, California earthquake of 9 February 1971; 6.4 magnitude.

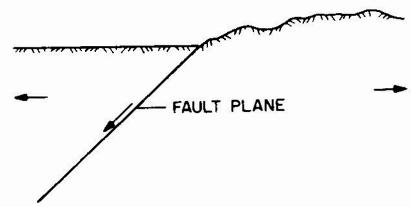

Figure 1b. Normal faulting resulting from lateral extensional strains. Example, Dixie Valley, Nevada earthquake of 16 December 1954; 7.1 magnitude.

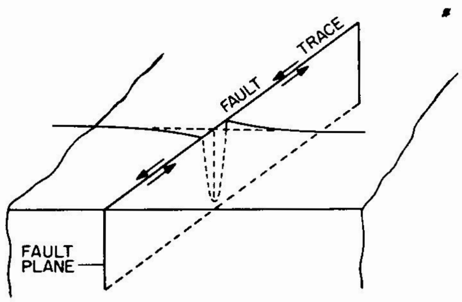

Figure 1c. Strike-slip displacement on a vertical fault plane. Example, San Andreas fault in California, San Francisco earthquake of 18 April 1906; 8.2 magnitude.

Figure 1d. Underthrust faulting in a sub-duction zone. Example, Alaska earthquake of 27 March 1964; 8.4 magnitude.

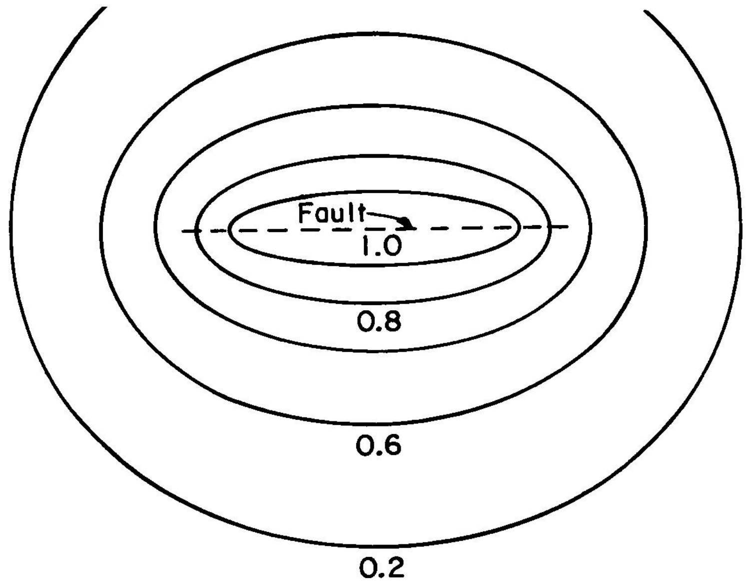

Figure 2. Idealized contour lines of equal intensity of shaking around a causative fault of a magnitude 7.5 earthquake. The contour lines are elongated ovals near the fault but approach circular shapes at large distances. The actual contour lines of an earthquake would be irregular (not smooth) in shape, reflecting nonuniformities in the source mechanism and the geological strata through which the seismic waves travel.

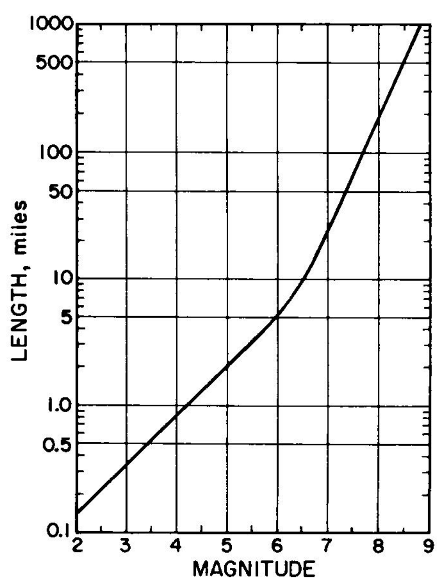

Figure 3. Diagram relating the magnitude of an earthquake with the horizontal dimension of the slipped fault area. This idealized diagram represents an average relation but is useful in estimating the surface area affected by earthquakes of different magnitudes.

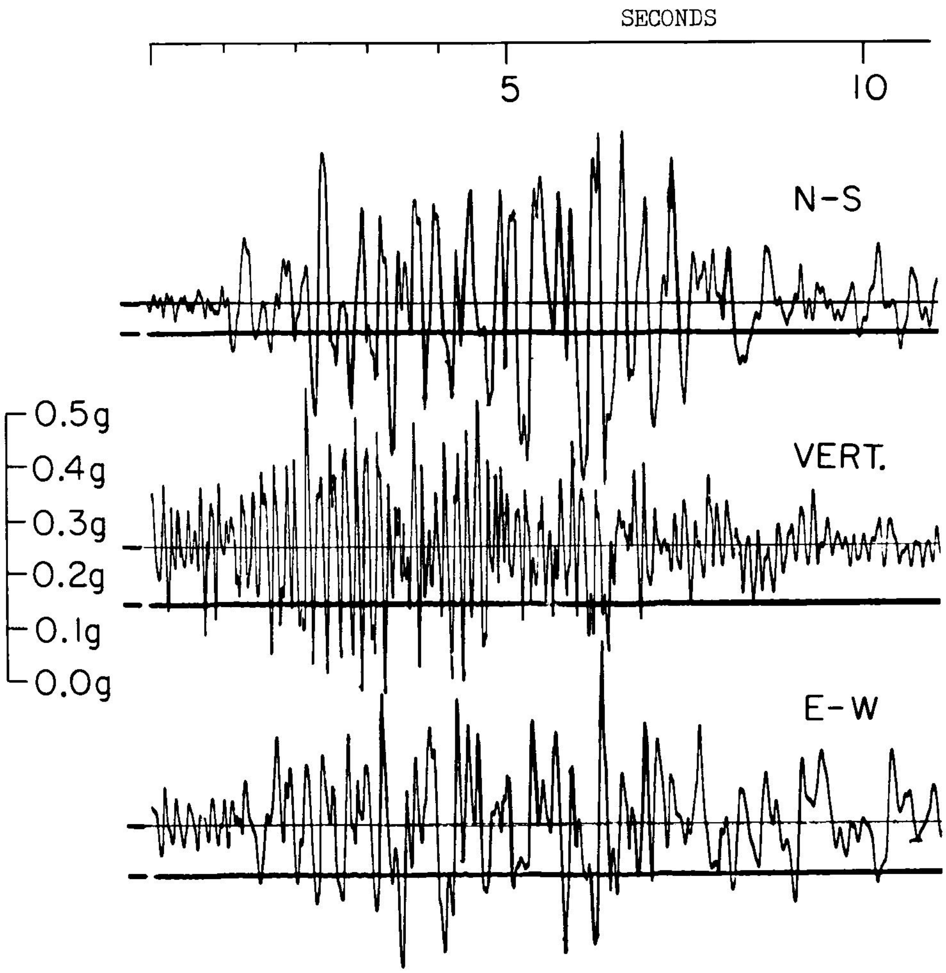

Figure 4. Reproduction of the accelerogram that was recorded during the 23 December 1972 Managua, Nicaragua earthquake. This strong ground shaking was recorded two miles from the causative fault of the magnitude 6.2 earthquake. The standard strong-motion accelerograph records two horizontal components of motion and the vertical component. The instrument is contained in a strong metal box approximately 12 x 12 x 18 inches. The box is anchored to the floor whose motion the instrument will record. The recorded accelerations can be integrated to obtain the velocity and displacement during the earthquake. Such accelerographs are now installed in most seismic regions in the world, however, in most regions the number of instruments is not enough to give adequate coverage.

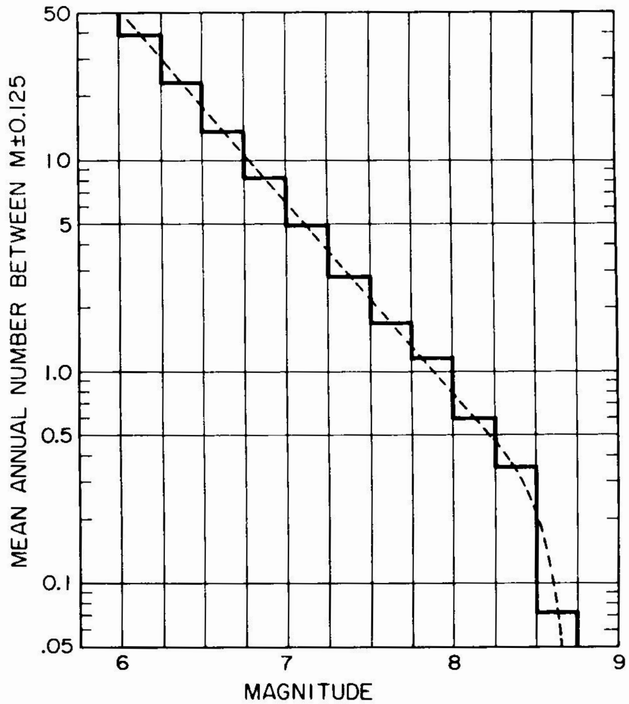

Figure 5. Annual number of earthquakes occurring in the world. The graph gives the expected number having magnitudes between 7.0 and 7.25, and 7.25 and 7.5, etc. The graph is based on the 43 year earthquake record given by Gutenberg and Richter in their book Seismicity of the Earth. When plotted on log paper, the data fit closely to a straight line except that beyond M = 8.5 the number of earthquakes falls off, indicating an upper bound.

Figure 6. Zoning map that appears in the 1976 Uniform Building Code. The code describes the zones as: Zone 0 - no damage; Zone 1 - minor damage; Zone 2 - moderate damage; Zone 3 - major damage; Zone 4 - indicates Zone 3 regions near major fault systems. The zone numbers determine the seismic forces to be used in design, according to a table provided in the code.

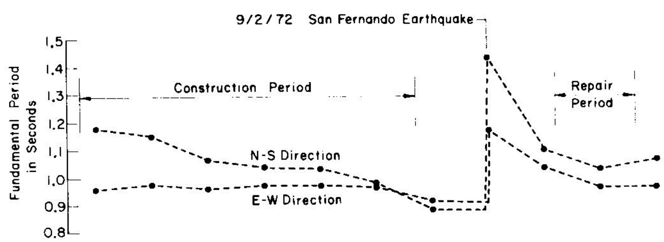

Figure 7a. Variations of the period of vibration of the first modes of the Jet Propulsion Laboratory Building. The building, 200 feet long in E-W direction and 40 feet wide single-span in N-S direction, had its periods measured after completion of the structural portions, while interior partitions, windows, fireproofing, etc., were installed. The motion during the earthquake showed that the building vibrated with a marked lengthening of periods. Repair of cracked partitions, etc., caused some shortening of periods. Each plotted point is a measurement. Since the period is proportional to the square root of the stiffness, the changes in period represent much larger changes in stiffness.

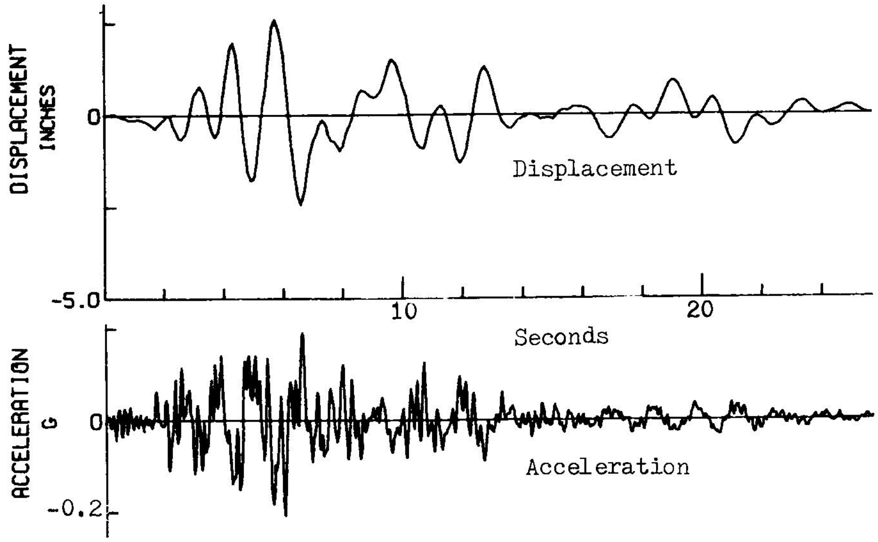

Figure 7b. Motion recorded on the roof of the 9-story steel-frame Jet Propulsion Laboratory Building during the San Fernando earthquake. This motion produced maximum stresses in the frame that almost reached yield point. The building suffered only minor damage, such as cracking of plaster partitions, cracking of concrete fireproofing, etc.

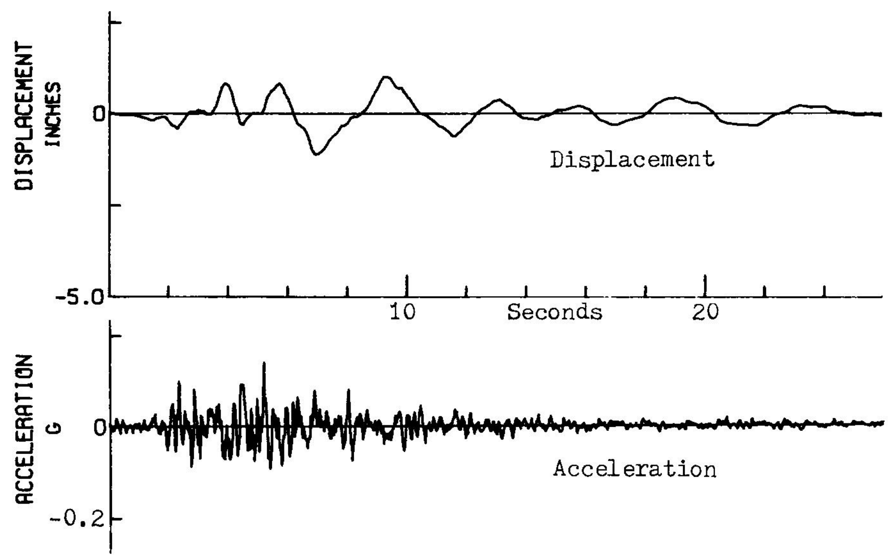

Figure 7c. Motion recorded in the basement of the California Institute of Technology Jet Propulsion Laboratory Building during the 9 February 1971 San Fernando earthquake. The building was located approximately 12 miles from the causative fault of this 6.4 magnitude earthquake.

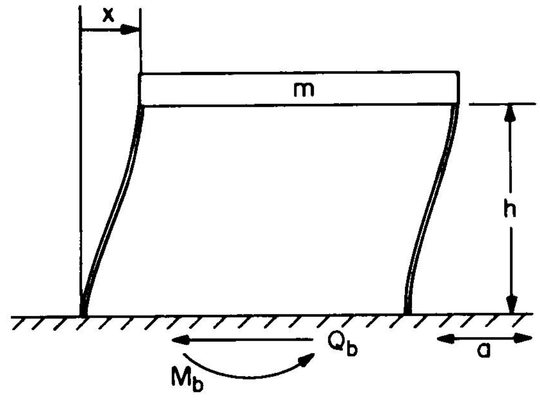

Figure 8. A simple one mass structure having a mass m, relative displacement x, story stiffness k, base shear $Q_b = kx$, and base moment $M_b = h(kx) = hm(\ddot{x} + a)$. The ground acceleration 'a' causes the structure to vibrate as illustrated in Figure 9.

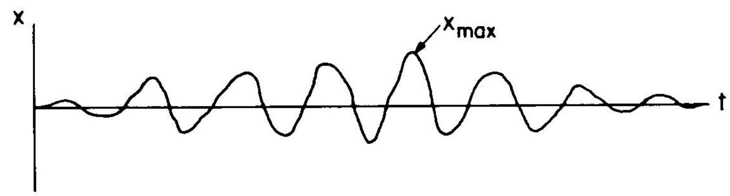

Figure 9. Illustration of the computed displacement of a simple structure of one second period that is subjected to earthquake motion similar to that of the 1972 Managua earthquake.

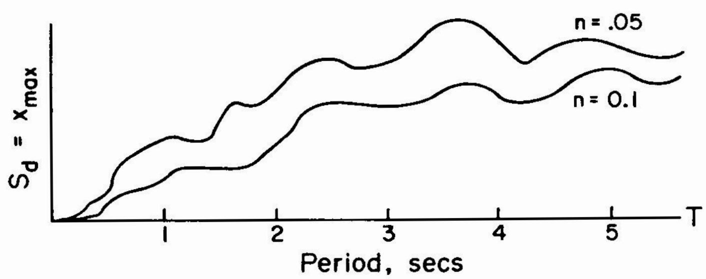

Figure 10. Illustration of Displacement Response Spectrum, S_d, for two different values of damping, n. The maximum displacement, x_{max}, is plotted for a range of periods of vibration.

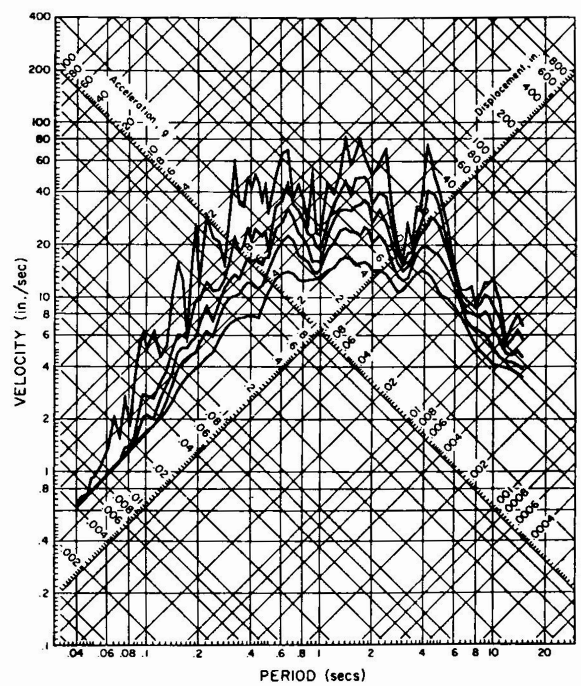

Figure 11. Response spectrum plotted on three-way log paper for the ground acceleration recorded at the Holiday Inn during the San Fernando earthquake, approximately 5 miles from the causative fault. For periods approaching zero, the spectrum curves approach the peak ground acceleration; and for very long periods the spectrum curves approach the peak ground displacement. (The spectrum curves are for 0, .02, .05, 0.1, 0.2 of critical damping.)

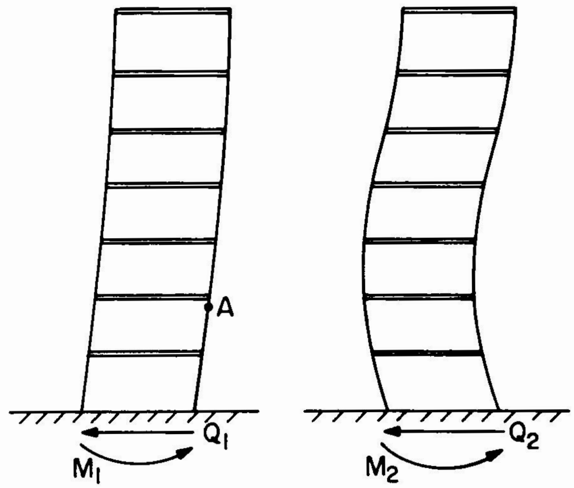

Figure 12. First and second mode shapes of a multi-story building. The natural periods of vibration of the modes of such a building become shorter for the higher modes and are usually in the approximate ratios of 1:1/3:1/5:1/7 etc. When such a building vibrates during an earthquake, approximately 80% of the energy of vibration is in the first mode, and approximately 10% is in the second mode. It has been observed that for small amplitude vibrations the periods of buildings are shorter than for large amplitude vibrations. This presumably results from cracking and loosening of nonstructural elements.

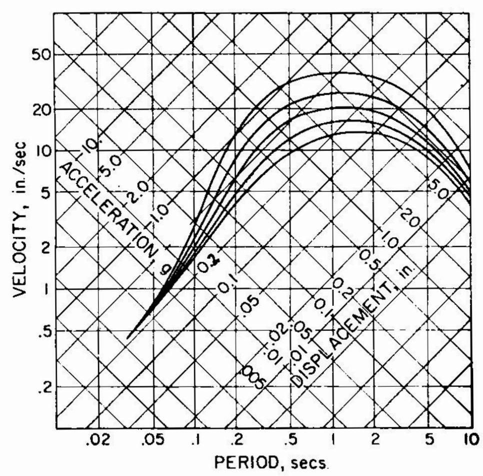

Figure 13. Smooth Design Spectrum from the Response Spectrum of Figure 11. The specification of the design spectrum and the specification of the allowable stresses and strains should be done by the same person who knows what overall strength and what factor of safety the structure should have. (The spectrum curves are for 0, .02, .05, 0.1, 0.2 of critical damping.)