Zeitschrift: IABSE surveys = Revue AIPC = IVBH Berichte
Band: 11 (1987)
Heft: S-38: Earthquake engineering for practising engineers

Artikel: Earthquake engineering for practising engineers
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DOI: https://doi.org/10.5169/seals-50713

Earthquake Engineering for Practising Engineers

Génie sismique à l'intention de l'ingénieur de la pratique

Erdbebenbemessung für den praktizierenden Bauingenieur

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SUMMARY

A brief review is presented of earthquake engineering and its current practice for mitigating earthquake hazards. Sections are provided for terminology in earthquake engineering, a concept of aseismic design of structures, methods of dynamic analysis, liquefaction of sandy soil in earthquakes, and engineering practice in aseismic design and construction. Seismic coefficients for aseismic design designated in the Codes and Regulations of thirty one countries are presented.

RÉSUMÉ

Quelques aspects fondamentaux du génie sismique sont rappelés ainsi que les pratiques courantes appliquées afin de diminuer les conséquences dues aux tremblements de terre. L'article traite de la terminologie du génie sismique, d'un concept de dimensionnement de structures vis-à-vis des séismes, des méthodes de calcul dynamique, de la liquéfaction des sols lors des séismes, et de la pratique de l'ingénieur civil lors de projet et de construction vis-à-vis des séismes. Les coefficients sismiques pour le calcul asismique retenus dans les Normes et Réglements de trente-et-un pays sont également présentés.

ZUSAMMENFASSUNG

Es wird eine kurze Übersicht der Erdbebenwissenschaft und der heutigen Praxis zur Verminderung des Erdbebenrisikos gegeben. Kapitel behandeln die Erdbebenterminologie, ein Konzept für eine erdbebensichere Bemessung von Bauwerken, Methoden der dynamischen Berechnung, Verflüssigung von sandigen Böden im Erdbebenfall und die Praxis der erdbebensicheren Bemessung und Konstruktion. Koeffizienten für eine erdbebensichere Bemessung, welche in 31 Ländern in Normen und Vorschriften enthalten sind, werden aufgeführt.

1. INTRODUCTION

The damage caused by earthquakes is always a sharp reminder of the importance of aseismic design and construction of structures. The conclusions drawn from observations and experiences in seismic zones agree, in general, with the fact that conservatively designed and constructed structures survive with minor damage, whereas structures not properly designed and/or with poor construction to resist earthquakes may collapse, Housner [1].

It was already known from experience in several countries including Japan and the United States that improper design and construction leads to damage during an earthquake so that fewer lessons were learned in the recent events of Tangshan in China 1976, El Asnam in Algeria 1980, Southern Italy 1980, Chilian Earthquake 1985 and Mexican Earthquake 1985. However, very interesting behavior of buildings and other structures was shown by those which were damaged more or less seriously but did not collapse.

At a first glance, many of these cases seemed paradoxical. For example, some structures were so badly damaged with failed frames and walls that from a stress analysis point of view it appeared that hardly any lateral strength remained. Since the duration of ground motion was as long as one minute or more, these structures must have been in an advanced stage of damage before the end of the earthquake but yet they survived.

In other cases a damaged structure remained standing even though a standard lateral strength analysis of the structure in its damaged state would indicate that its strength was so small that it should have collapsed. On the other hand, some relatively sturdy structures having much greater lateral resistance suffered some damage.

It does not seem economically justifiable that, in a seismically active region, all structures should be designed to survive the strongest possible ground motion without any damage. It is more reasonable to take the point of view that the design should be such that the structures will survive the more frequent, moderate ground motions without damage but in a rare event of very strong ground motion, damage would be tolerated as long as there was not a hazard to life. This is the usual point of view of engineers in earthquake areas. It is seen from the material presented in this paper that this point of view is equivalent to requiring two different design analyses for each structure. One would be to ensure that no damage resulted from moderate, elastic vibrations, and the other would be a "limit design" type of analysis to ensure that there was sufficient energy-absorbing capacity to give an adequate factor of safety against collapse in the event of extremely strong ground motion.

For a simple structure such as a rod-braced elevated highway bridge it is not difficult to make a reasonable limit design. However, in the case of more complicated structures the problem becomes very difficult, particularly because we do not at present have much precise information about the energy absorbing characteristics of structural materials, foundation materials and structures during vibrations. This is an important problem now facing engineers.

It is, of course, true that the lateral forces prescribed for design by building codes are based to a certain extent on the observed damage behavior of structures during earthquakes and in this sense they do reflect the energy absorbing properties of typical structures. The application of these code reqirements to non-typical and unusual structures is not warranted, for the energy absorbing capacity of such structures may be quite different from that of ordinary buildings.

2. TERMINOLOGY

2.1 Earthquakes[2]

Under the conditions wherein vast quantities of energy are stored in the earth's interior and the continents are constantly in the process of growth, various changes also occur in the surface portion of the earth. Earthquakes comprise one type of such changes. An earthquake is a phenomenon of strong vibrations occurring on the ground due to release of a large amount of energy within a short period of time through a sudden disturbance in the earth's crust or in the upper part of the mantle, which comprises the outer part of the earth with a thickness of 2900 km except the crust or lithosphere of the earth with thicknesses of 5 to 40 km.

In regard to the cause of earthquakes, various theories have been advanced to take into account such characteristics as intermittent occurrence, differences in size, and uneven regional distribution. The principal concepts currently accepted are the theories of the effect of magma and of the effect of orogenic forces. The former theory treats the problem in terms of sudden changes in the earth's crust due either to the upheaval penetration of magma into parts of the semi-hardened crust, where equilibrium of heat and stress have been lost, widening existing fissures or creating new fissures, or else to abrupt variations in the condition of the magna itself. In the latter theory, it is postulated that, broadly speaking, the orogenic forces are produced by convection within the mantle.

The location at which an earthquake originates is called the hypocenter or focus and the point at the surface of the earth directly above the hypocenter is termed the epicenter.

The amplitude of earthquake motions on the surface first shows a slight trembling which then abruptly increases. Two types of motions, primary longitudinal or dilatational waves and secondary transverse or distortional waves, are transmitted within the earth's crust. Since the propagation velocity of the former is greater than that of the latter, the differences in time of arrival give us a distance from hypocenter to an observation site as follows,

$$s = (1/V_s - 1/V_p)^{-1} \; T \qquad (1)$$

where

s : distance from hypocenter to observation site,
V_s: propagation velocity of secondary wave,
V_p: propagation velocity of primary wave, and
T : difference in time of arrival of primary and secondary waves.

2.2 Seismic Intensity

The term "seismic intensity" is used to denote the severity of an earthquake at a particular location. Since it is attempted to quantitatively express such a complex phenomenon as an earthquake by a single numerical value there is a tendency for much simplification.

The Modified Mercalli Intensity Scale established in 1931 is widely used in North America and elsewhere. The scale is graded with division into twelve categories as shown in Table-1. Recently, a new classification, known as the MSK Intensity Scale, has been suggested by Medvedev, Sponheuer and Karnik [3]. It is also divided into twelve categories and is roughly similar to the Modified Mercalli Intensity Scale. In 1949 the Japan Meteorological Agency adopted the JMA Intensity Scale shown in Table-2, which has become the standard

Table-1 Modified Mercalli Intensity Scale,[2]

Scale	Maximum Acceleration in gal*	Definitions
I	under 1.0	Not felt except by a few under especially favorable conditions.
II	1.0 - 2.0	Felt only by persons at rest in places such as upper floors of buildings. Delicately suspended objects may swing.
III	2.0 - 5.0	Felt by many persons in places such as upper floors of buildings but of a degree that most persons do not recognize it as an earthquake. Standing automobiles may rock slightly as if from vibration caused by passing trucks. Duration may be measured.
IV	5.0 - 10.0	In daytime, felt by many indoors but by only a few outdoors. Dishes, windows, doors disturbed, and walls creak. Sensation like a heavy truck striking a building. Standing automobiles rocked considerably.
V	10.0 - 21. 0	Felt by all, many awakened. Some dishes and window glasses broken, wall plaster may crack. Unstable objects overturned. Disturbance of telephone poles, trees, and other tall objects sometimes noticed. Pendulum clocks stopped.
VI	21.0 - 44.0	People are frightened and run outdoors. Heavy furniture may be moved; some instances of fallen plaster and toppling of chimneys. Slight damage.
VII	44.0 - 94.0	Everybody runs outdoors. Damage negligible in buildings of good design and construction, slight to moderate in ordinary structures, and considerable in poorly built or badly designed structures. Chimneys broken. Felt in moving automobiles.
VIII	94.0 - 202.0	Some damage even in buildings of good design and construction. Considerable damage in ordinary buildings. Panel walls thrown out of frame structures. Falling of houses and factory chimneys, columns, monuments and walls. Heavy furniture overturned. Sand and mud ejected in small amounts. Changes in well water. Hinders driving of automobiles.
IX	202.0 - 432.0	Damage considerable in buildings of good design and construction. Structures thrown out of alignment with foundations. Ground cracked conspicuously. Underground pipes damaged.
X	over 432.0	Wooden houses of good design and construction collapse. Most masonry and frame structures destroyed together with foundations. Ground cracked causing damage. Rails bent. Slopes and embankments slide. Water surface rises.
XI		Almost all masonry structures collapse. Bridges destroyed. Fissures over entire surface of ground. Underground pipelines completely out of service. Earth slumps and land slips in soft ground. Rails bent prominently.
XII		Damage total. Waves seen transmitted at ground surface. Topography changed. Objects thrown into air.

* 1 g $\approx$ 1000 gal

for seismic intensity in Japan.

Table-2 Japan Meteorological Agency Intensity Scale,[2]

Scale	Maximum Acceleration in gal*	Definitions
0	under 0.8	No sensation: registered by seismographs but no perception by the human body.
I	0.8 - 2.5	Slight: felt by persons at rest or persons especially sensitive to earthquakes.
II	2.5 - 8.0	Weak: felt by most persons; slight rattling of doors and Japanese latticed paper sliding doors (shoji).
III	8.0 - 25.0	Rather strong: shaking of houses and buildings; heavy rattling of doors and shoji, swinging of chandeliers and other hanging objects; movement of liquids in vessels.
IV	25.0 - 80.0	Strong: strong shaking of houses and buildings; overturning of unstable objects; spilling of liquids out of vessels four-fifths full.
V	80.0 - 250.0	Very strong: cracking of plaster walls; overturning of tombstones and stone lanterns; damage to masonry chimneys and mudplastered warehouses.
VI	250.0 - 400.0	Disastrous: demolition of up to 30% of Japanese wooden houses; numerous landslides and embankment failures; fissures on flat ground.
VII	over 400.0	Ruinous: demolition of more than 30% of Japanese wooden houses.

* 1 g ≈ 1000 gal

2.3 Earthquake Magnitude

The seismic intensity just described indicates the severity of an earthquake at a given location, but does not give the size of the earthquake as a whole. In order to define the size an index of earthquake magnitudes is widely used in Richter scale denoted by,

$$M = \log_{10} A \qquad (2)$$

where M represents an earthquake magnitude in Richter scale, A is the trace amplitude in micrometer recorded at a site distant 100 km from epicenters, by using a standard Wood-Anderson seismograph with magnification of 2800, a natural period of 0.8 seconds and a damping coefficient of 0.8.

The magnitudes of great earthquakes of the past are estimated to have been 7.9 in the Nobi Japan Earthquake of 1891, 8.6 in the Colombian Earthquake of 1906, and 8.3 in the Sanriku Japan Earthquake of 1933. The earthquake of 1897 in Assam in India, is said to have had a felt radius of 2000 km, making it the greatest earthquake in human history, but an accurate value of the magnitude is unknown.

There is a close relationship between the magnitude and the energy, E, released as seismic waves, and the following equation has been empirically derived,

$$\log_{10} E = 11.8 + 1.5M \qquad \text{in ergs} \qquad (3)$$

When the magnitude is increased by 0.2, the energy is doubled; and when increased by 1.0, the energy is increased 32-fold. It is estimated that the energy of the greatest earthquake possible is 5×10^{25} erg; and when this is substituted in Eq.3., the maximum value of magnitude becomes 9.2.

2.4 Seismic Zone

An examination of the geographical locations of recorded earthquakes shows they are not evenly distributed. Rather, the areas in which great earthquakes occur are extremely limited, and since they generally take the form of a belt they are called earthquake belts or seismic zones. Seismic zones are classified into the four types listed in Table-3. The hypocenters are within the mantle in the case of the oceanic and island-arc types and in the earth's crust in the case of the orogenic geosyncline and continental plateau types. Actual examples of each type are given in Table-3.

Table-3 Classification of Seismic Zones,[2]

Type	Description	Hypocenter location	Examples
Oceanic	Follows rifts at ocean bottoms	Mantle	Central Indian Ocean Ridge.
Island-arc	Follows island arcs comprised of small islands	Mantle	Aleutians, Kuriles, Marianas, Ryukyus
Orogenic geosyncline	Follows arc-shaped mountain ranges on continents or island arcs comprised of large islands	Crust and Mantle	Japanese islands, Philippine Archipelago, South American West Coast, North American West Coast, Iran, Turkey.
Continental plateau	In interiors of continents	Crust	Eastern Siberia, Appalachian region.

In the case of the Japanese island chain, the central part is an orogenic geosyncline type seismic zone, with earthquakes being mostly crustal. However, the island-arc type seismic belts of the Kuriles and the Marianas extend into Japan on the east and the Ryukyu island-arc type seismic belts intrudes on the southwest, so that in Japan earthquakes originating within the mantle also occur frequently.

2.5 Earthquake Risk

In engineering, it is necessary to predict the following information 1) the areas in which great earthquakes are likely to occur in the future; 2) the frequency of occurrence; 3) the size of the earthquakes; and 4) the area in which damage will occur from these earthquakes. In reality, such prediction is rather difficult. The approaches to the problem can be done through judgement by statistical models of the situation of the earthquake in the past or by existing geological feature of the area. In areas like Japan, where there have been a great number of earthquakes in the past, statistical models tend to be emphasized; but if geological conditions are also taken into account, prediction will become more accurate.

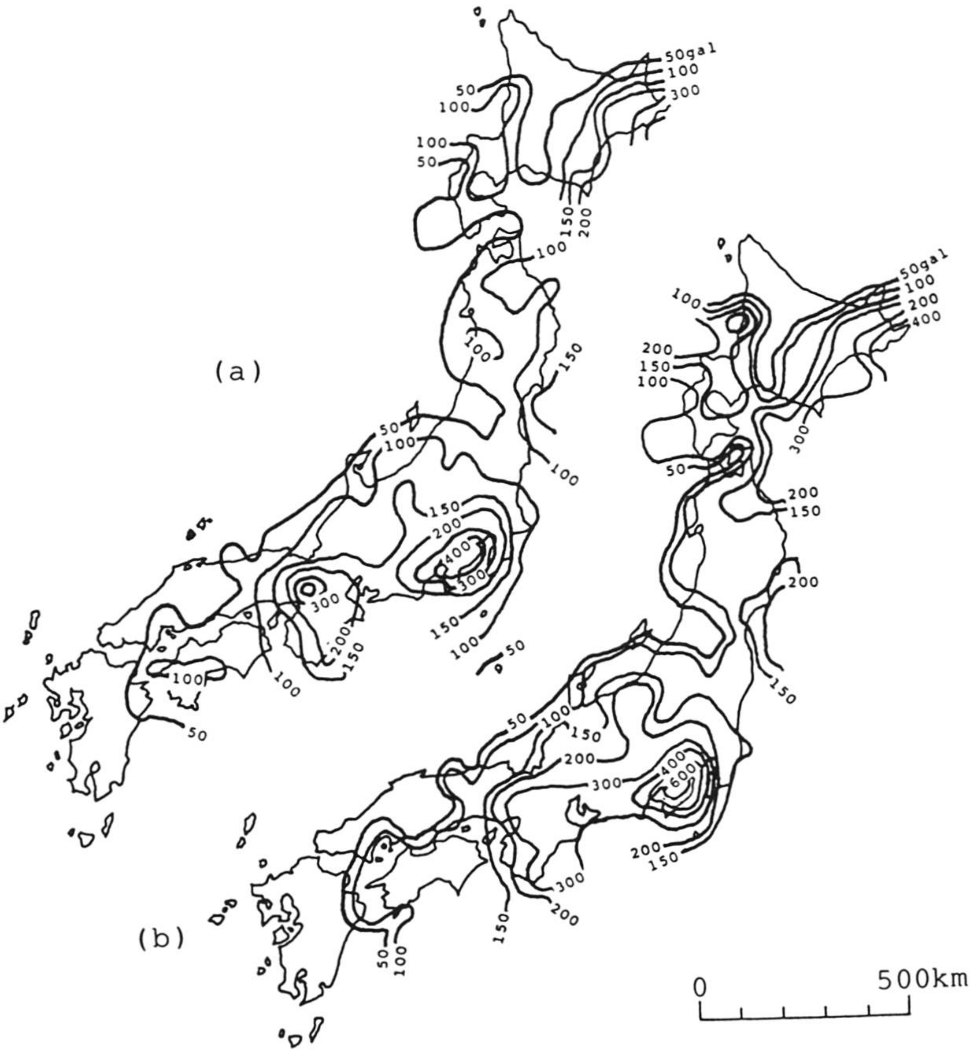

Fig.1 Expectancy of maximum acceleration of earthquakes in (a) 75 and (b) 100 years of return periods, T_r,[4]

In order to employ a historical record of seismic intensity at a given site, the following equation is available,

$$I \propto \frac{T_s}{T_r} \qquad (4)$$

where I represents seismic intensity, T_r return period, and T_s the service duration such as durable life of structures. By employing Eq.4. Kawasumi [4] proposed expectancy maps of maximum accelerations of earthquakes in Japan as shown in Fig.1. after investigation of 343 earthquakes which had occurred in Japan since 599 A.D.

2.6 Determination of Design Earthquakes

In determining a design earthquake at a site, physical conditions such as the maximum intensity of the expected earthquake, the structure of the surface layer of the ground, etc., are fundamental data but they do not represent all of the factors. Other factors, such as social and economic conditions, should be added. However, almost no studies of this problem have been made in the past and this has put engineers in a predicament with regard to the ultimate determination of design earthquakes. The following indicates a way of thinking regarding this problem, but it is not a decisive one. Further development in this respect is much to be desired.

For example, the seismic intensity expectancy map shown in Fig.1 is looked upon as the basis for determining design seismic intensity in many standards and regulation in Japan. Here, it would ordinarily be acceptable to take the life of the structure as the period of expectancy. But in what manner the life should be considered from the aspect of earthquake resistance has not been given much consideration. When earthquake damage is not a hazard to life, the life of the structure may be determined on the basis of economic considerations. The following is an outline of a tentative proposal by Okamoto [2].

In the case of public facilities, such as civil engineering structures, it is more suitable to consider the overall economic safety of all facilities in the country rather than the economic safety of individual structures. A structure designated as S with the same degree of structural and economic safety as others is considered and it is assumed there are N of these structures in an area of similar seismic conditions. Because of reasons other than earthquakes, such as fatigue, wear, etc., a number of these structures must be discarded each year due to annual depreciation; this number is assumed to be n. The cost of providing one unit of S per year is designated as q, the net profit produced per year due to construction of one unit of S is taken to be p, and the indirect loss due to destruction of one S from earthquake damage annually is taken as r. Since these structures will be destroyed by earthquakes whose intensities exceed a design seismic intensity of I, if an earthquake stronger than I in the past T years occurred, a ratio of N/T of the structures would be subjected to earthquake damage for one year. If the economic growth is not taken into consideration, it would be acceptable for the following relation to exist in order for economic activity to be maintained continuously,

$$\left(n + \frac{N}{T} \right) q + \frac{N}{T} r = N\, p \qquad (5)$$

Considering that n will be proportional to N, Eq.5 may be changed to

$$n = fN$$

$$\left(f + \frac{1}{T} \right) q + \frac{r}{T} = p \qquad (6)$$

$$T = \frac{1 + r/q}{p/q - f}$$

Therefore, if T, determined from the above equation, is taken as the durable life and the expectancy for a period of T years is used to establish the design seismic intensity, it should be possible to achieve stable economic activity.

Kuribayashi [5] made some minor alternations in the equation for application to road improvement works.

N : total length of road (km);
n : length of improved sector per year (km/yr);
q : construction cost per unit length of road (yen/km);
p : net profit per year gained by construction of 1 km of road (yen/km/yr);
r : indirect damage amount converted to amount per km of road (yen/km);
T : durable life of road (yr);
f : n/N (1/yr); and
τ : r/p (yr).

Substituting these into Eq.6, the result is

$$T = \frac{1 + \tau\left(\frac{p}{q}\right)}{\frac{p}{q} - f} \qquad (7)$$

Taking the amount of damage in the Niigata earthquake in 1964 as an example, the indirect damage due to this earthquake may be evaluated at 122.1 billion yen. Assuming a profit ratio p/q as 0.1, the value which should be considered as the number of years for depreciation of the initial investment would be 9.4 years. In 1964 when the Niigata earthquake occurred, for first-class national highways, N=27,728 km and n=1,854 km/yr, from which f=0.067.

Substituting these figures into the above equation, T becomes

$$T = \frac{1 + 9.4 \times 0.1}{0.1 - 0.067} = 58.8 \quad \text{(years)}$$

2.7 Seismic Intensity in Engineering

Among structural engineers it is a common practice to express the intensity of an earthquake by its maximum acceleration. This is based on the premise that the effect of an earthquake on buildings and civil engineering structures is determined chiefly by the maximum acceleration. This concept is more or less valid for judging elastic damage when the structure can be regarded as very stiff. However, flexible structures such as chimneys, high-rise buildings and long span bridges cannot be discussed in terms of maximum acceleration alone, and the frequency, displacement, velocity, and waveforms of seismic tremors also become involved. Recently, flexible structures have increased in number and there are thus more and more cases in which the maximum acceleration concept is not applicable.

When seismic intensity is expressed in terms of maximum acceleration, the ratio between the maximum acceleration of earthquake ground motions and the acceleration due to gravity is employed. Thus if the maximum acceleration of an earthquake in the horizontal direction is α_h, the ratio employed is

$$\alpha_h/g = k_h \tag{8}$$

where k_h is called the horizontal seismic coefficient. Similarly, if the maximum acceleration of the earthquake in the vertical direction is α_v, then

$$\alpha_v/g = k_v \tag{9}$$

and k_v is called the vertical seismic coefficient.

Since it is not often the case that a seismograph has been located beforehand in an earthquake-damaged district, the maximum acceleration is in practice only estimated from observations of natural phenomena and the extent of damage to structures, as in the case of the intensity scale shown in Table-1 and Table-2. In such cases, damage to chimneys, buildings, wooden houses and bridges, which can be found everywhere throughout residental areas, is utilized.

A detailed relationship between strong motion earthquake records and visually observed earthquake damage has been deduced by Neumann [6] from data on earthquakes in the U.S.A. of about 100 gal or under in maximum accelerations. According to his findings, the damage is related to both acceleration and period; even if the acceleration is the same, damage in the case of shorter periods is not as great as with long periods. However, when the velocity is the same, the same degree of damage is produced regardless of periods. For example, the peak velocity of an earthquake of the extent that cracks are formed in the walls of buildings is about 2.4 cm/sec, while the peak velocity of an earthquake in which the wall collapse is approximately 4.7 cm/sec.

Again, Housner et al [7] educed a quantity termed SI, so-called spectral intensity, from the standpoint that the vibration energy possessed by a structure for the entire duration of an earthquake contributed to its ultimate failure.

Structures vibrate during earthquakes, the vibrations being termed response vibrations. If the maximum value of the velocity of the response vibration is denoted by S_V , the natural period of the structure by T, and the damping constant by h, S_V is generally determined by T and h. Thus, if the relation between S_V and T for a particular earthquake is plotted, a curve such as shown in Fig.2 is obtained. On this curve S_V is more or less constant, except when

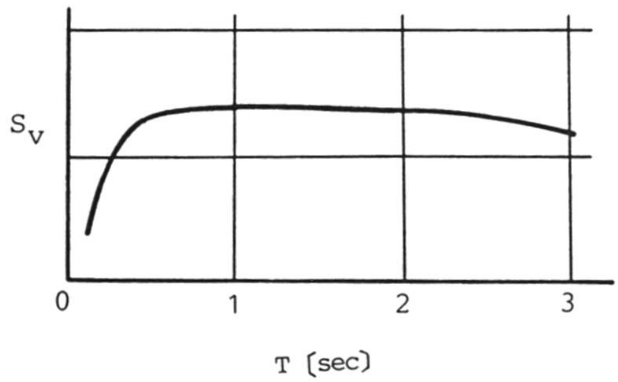

Fig.2 Spectral intensity curve,[7]

T is small. Therefore, the average value of S_V over the relatively constant section or the area between the curve and the horizontal axis over this section serves as an indicator of the maximum value of the response velocity. In practice, the range of T considered is 0.1 - 2.5 sec, and S_V is integrated over this range; thus the average value of S_V in this section is given by

$$SI = \frac{1}{2.4} \int_{0.1}^{2.5} S_V \, dT \, . \tag{10}$$

Spectral intensity of earthquakes can be defined as in Eq.10.

3. ASEISMIC DESIGN

3.1 Seismic Coefficient Method

3.1.1 Seismic Coefficient

A number of approaches can be considered in evaluating the seismic force to be applied to a structure to analyze its stress and deformation at the time of an earthquake. The simplest approach may be that which is based on the following assumptions:

i. The seismic force acts as a static external load on the mass of each element of the structure.

ii. The seismic force acts in a horizontal direction. Its magnitude is proportional to the mass; the proportionality constant divided by the gravitational acceleration defines the seismic coefficient. Therefore,

$$f = k \, g \, m \tag{11}$$

where f denotes the seismic force, m the mass, g the gravitational acceleration and k the seismic coefficient. Since m g is the weight of the mass, the seismic force is obtained as a product of the weight and the seismic coefficient.

iii. The value of the seismic coefficient is the same for each mass.

iv. The seismic force in the vertical direction should also be considered if the structure is expected to experience a severe vertical motion when earthquakes occur. The seismic coefficient for the vertical seismic force is defined in the same manner as for the horizontal one.

The method of analysis and design of earthquake-resistant structures based on these assumptions is called the seismic coefficient method. When a structure is built in an area where severe earthquakes are likely to occur, or a great amount of damage is expected by the destruction of the structure, large values are used for the seismic coefficient. On the other hand, when the structure is built in an area where severe earthquakes rarely occur, or when the structure is of less importance, small values of the seismic coefficient are used.

Since the value of the seismic coefficient has not been determined theoretically but is based on experience, its value may be changed as experience is accumulated and it can be modified on the basis of structure types. Furthermore, the use of the same seismic coefficient value for the design of structures of different types does not imply that they have the same degree of resistance against earthquakes, if each is analyzed and designed according to a different concept with the allowable stresses defined according to different criteria. This is a logical weakness and a drawback of this method.

However, it is an advantage of this method that it may easily be applied to any complicated structure because only statical analysis of earthquake-resistant structures is made. Therefore, a more improved static method, in other words, a revised seismic coefficient method, in which the seismic coefficients for structures are determined in view of present knowledge of daynamic analyses, is desirable.

The seismic force acting upon a mass during an earthquake can be divided into two components; k_h m g in the horizontal direction and k_v m g in the vertical direction. Here, k_h and k_v are the seismic coefficients and are referred to as the horizontal and vertical seismic coefficients, respectively.

During an earthquake, in addition to the gravitational force, the seismic force acts upon the mass as shown in Fig.3. In the case shown in (a) only the horizontal seismic force exists. Cases where the vertical seismic force acts are shown in (b) downward and (c) upward, respectively.

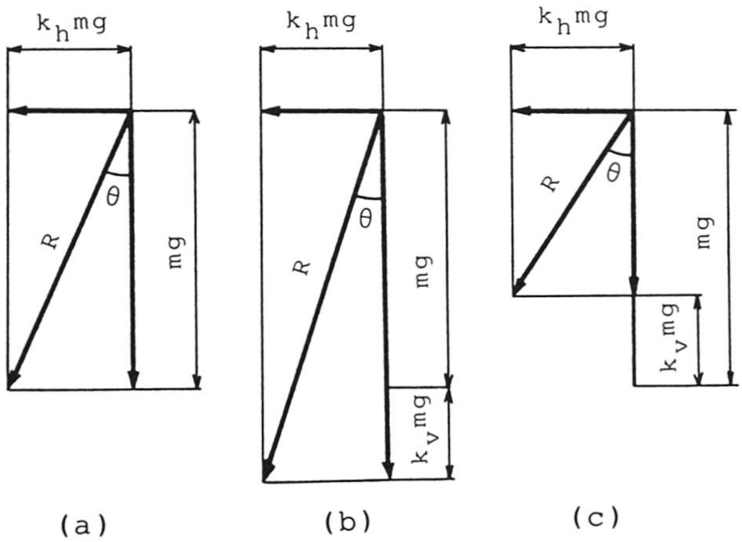

Fig.3 Seismic coefficients

Thus, the resultant force R and the direction θ is given by the resultant of gravitational and the seismic forces.

$$R = m\ g\ \sqrt{k_h{}^2 + (1 \pm k_v)^2}$$
$$\tan\theta = \frac{k_h}{1 \pm k_v} = K \qquad (12)$$

where K represents the resultant seismic coefficient.

Since R is a static force, it can be stated that an earthquake is a phenomenon in which the magnitude of the gravitational force changes from m g to R and the horizontal plane is inclined by the angle of θ. A physical meaning may be provided for the seismic coefficient even though its value is determined through experience. Assuming that the structure moves rigidly together with the ground during an earthquake, the accelerations of the ground and the structure are the same, and the seismic force defined by the seismic coefficient method is nothing but the inertial force produced in the structure by the earthquake motion of the ground. The inertial force acting upon the structure varies with time, but as its maximum value is of greatest technical importance, it may be stated that the seismic coefficient is the ratio of the maximum acceleration of the structure due to an earthquake to the acceleration of gravity.

In reality, however, it has been observed that structures, even those appearing to be sufficiently rigid, do not move in the same mode as the ground. It is, therefore, rarely justifiable to consider the seismic coefficient as the ratio of the maximum acceleration of the earthquake motion of the ground to the gravitational acceleration. The seismic coefficient currently used should instead be considered as a coefficient evaluated empirically.

3.1.2 Earth Pressure during Earthquakes

The theory of earth pressure under normal conditions was developed further for calculation of the earth pressure during earthquakes by Mononobe [8].

According to the seismic coefficient theory, the effect of an earthquake is in essence a change in magnitude of gravitational forces and inclinations of the ground by a given angle. The ratio of the apparent gravitational acceleration during an earthquake to the gravitational acceleration is

$$\frac{g'}{g} = \sqrt{(1-k_v)^2 + k_h^2} \qquad (13)$$

and the angle which attempts to rotate the ground is given by

$$\theta = \tan^{-1} \frac{k_h}{1-k_v} = \tan^{-1} K \qquad (14)$$

The values of θ are as shown in Table-4.

Table-4 Value of θ defined by Eq.14,[8]

k_h	k_v				
	0	0.05	0.1	0.15	0.20
0.1	5°40′	6°00′	6°20′	6°50′	7°10′
0.2	11°20′	11°50′	12°30′	13°20′	14°00′
0.3	16°40′	17°30′	18°30′	19°30′	20°30′
0.4	21°50′	22°50′	24°00′	25°10′	26°30′

3.1.3 Hydrodynamic Pressure

Westergaard [9] derived a hydrodynamic pressure during earthquakes by employing the assumption of a solid wall moving against an incompressible mass of water, as a two dimensional problem, and suggested an approximate formula as follows,

$$p = \frac{7}{8} k\, w \sqrt{H\, y} \qquad (15)$$

where

p : hydrodynamic pressure during earthquake in kgf/m^2,
k : seismic coefficient,
w : density of water in kg/m^3,
H : depth of stored water in m, and
y : distance of cross section from top of wall in m.

3.2 Dynamic Analysis

3.2.1 Earthquake Response Spectrum

For the purpose of designing structures, maximum values of relative displacement y_{max}, relative velocity v_{max} and absolute acceleration α_{max} of the response vibrations are important quantities. Their maximum values are not attained at the same instant and the time when each of these quantities assumes its maximum value may be determined by numerical computations.

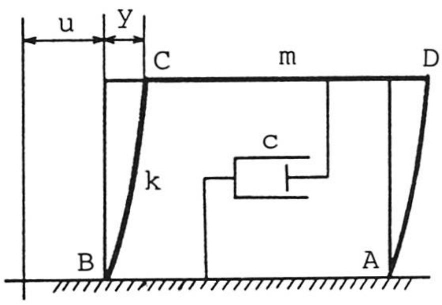

Fig.4 One degree of freedom system

It can, however, be approximately evaluated in one degree of freedom systems with damping as shown in Fig.4 by the aid of the Duhamel integral formula,

$$\begin{aligned} y_{max} &= S_V / p = S_D \\ v_{max} &= S_V \qquad (16) \\ \alpha_{max} &= p\, S_V = S_A \end{aligned}$$

where

$$S_V = \left| \int_0^t \ddot{u}(\tau) e^{-ph(t-\tau)} \sin p_d (t-\tau) d\tau \right| \qquad (17)$$

S_V: velocity response spectrum
S_D: displacement response spectrum
S_A: acceleration response spectrum
$\ddot{u}(\tau)$: input acceleration
p : circular natural frequency without damping
p_d: circular natural frequency with damping
h : damping constant ie, ratio of damaping to critical damping
t : duration of ground motion
τ : time variables

Those spectra, S_D, S_V, and S_A, depend on natural frequency and damping.

Typical examples of the response spectra were presented by G.W. Housner et al in 1953 [7] as shown in Fig.5. The average velocity response spectum, S_V in Eq.17 was obtained from many strong earthquake ground motion records in the United States and the acceleration and displacement spectra were derived from Eq.16.

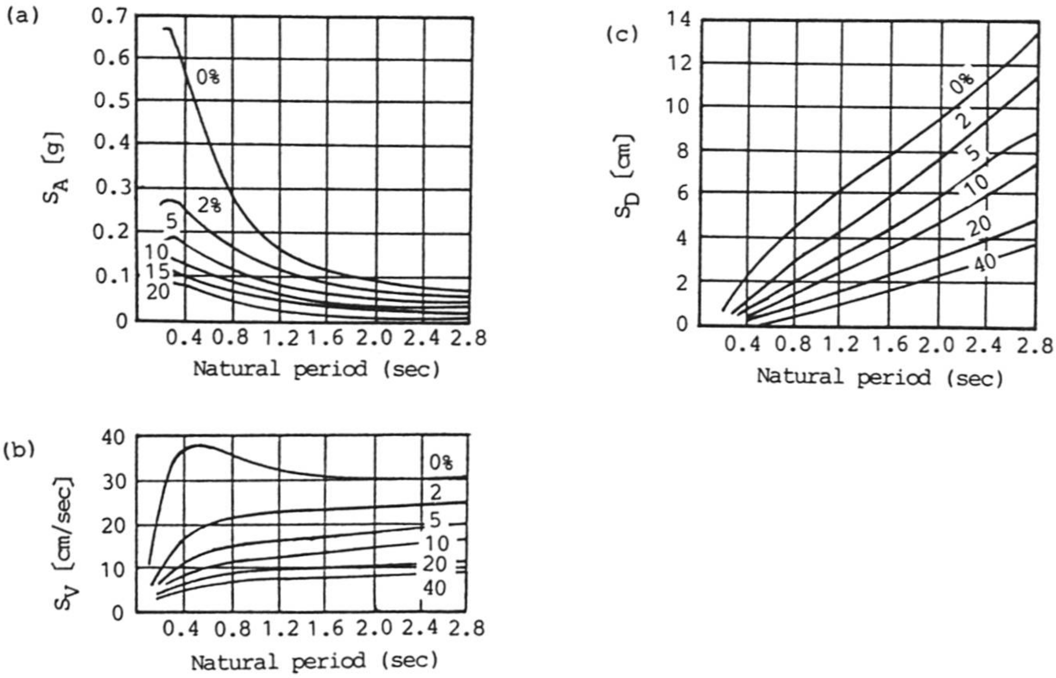

Fig.5 Response spectra,[7]

The general trend of the velocity spectrum shows that, for natural period of 0.8 to 2.8 second, the spectrum remains almost at a constant value and that it becomes smaller as the damping constant increases.

3.2.2 Dynamic Analysis

More realistic methods of analysis have been developed in the last three decades for use with electronic computers so that seismic forces acting upon structures are determined in accordance with behavior of structures subjected to earthquake ground motions. The structural analysis based on the seismic forces thus evaluated is called dynamic analysis. Though it has not been long since the analysis was developed, the method of analysis has been highly recognized as one of the most effective in measuring the quantitative responses of complex systems composed of subsoil, foundations, substructures, superstructures, and interior equipment.

Dynamic analysis as currently used can be classified into two categories; one for elastic structures and the other for elasto-plastic ones. This classification stems from the fact that structures can also be classified into two kinds depending on importance and purposes; those which will never exceed the elastic limit even under any severe earthquake conditions, and those which may exceed the elastic limit and are allowed to sustain light cracking or a slight plastic deformation. For example, atomic power plants and large scale dams belong to the former and office buildings and bridges to the latter.

3.3 Liquefaction of Soil in Earthquakes

Sandy soil saturated with pore water may exhibit liquefaction when subjected to strong ground motions. Ground is severely destroyed during earthquakes when the phenomenon actually occurs. The liquefaction of the soil is caused by the failure of the skeleton of sand particles which are loaded by increased pore-water pressures due to alternative shearing stresses in the soil masses.

The strength of sand is roughly proportional to the effective confining stresses, which are larger at greater depth in the soil mass than at a shallow one. The latest studies indicate the following causes of the phenomenon, Iwasaki [10]:

i Ground motion,
ii Void ratio or grading of soil material,
iii Overburden stress of soil mass,

In recent events, the Alaskan Earthquake of March, 1964, produced a large scale slope failures at Turnagain Heights in Anchorage due to liquefaction in sand layers located 18 meters below the ground surface, Seed and Wilson [11]. In the Niigata Earthquake of June, 1964, a large scale ground failures at a depth of 10 meters was observed in saturated sandy grounds along Shinano river, which has given rise to sand sedimentation of more than 600 meters thickness during the last 2000 years or more.

Through a literature survey on liquefaction phenomena caused by earthquakes in

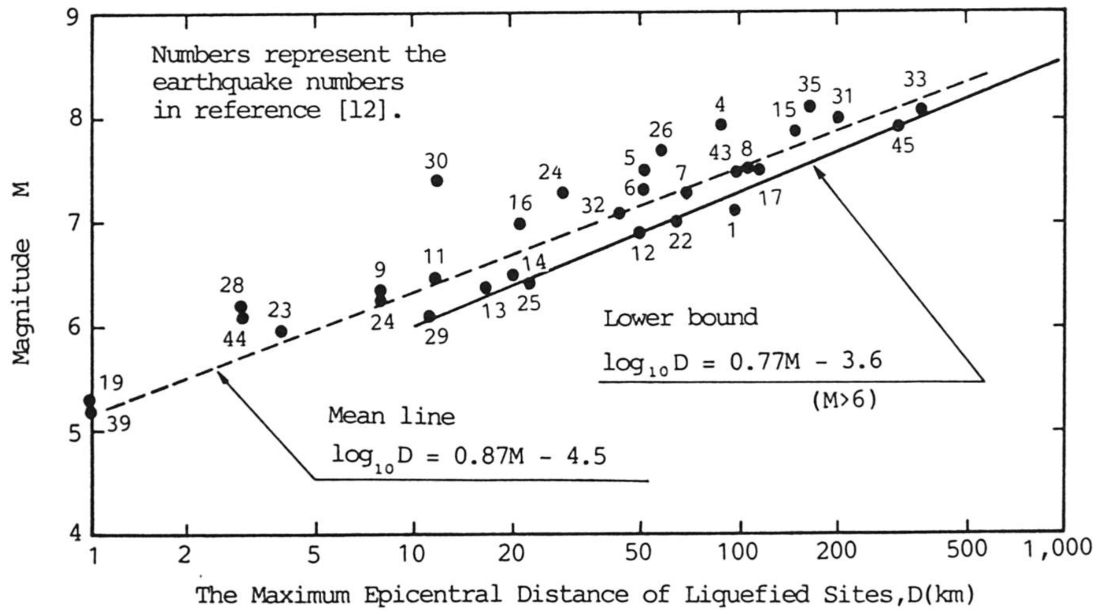

Fig.6 Relationships between the maximum epicentral distances of liquefied sites (D) and earthquake magnitude (M), [12]

the last century in Japan, at some hundred sites of alluvial deposites in 44 earthquakes, the extent of liquefied zones is estimated to be limited by the

Table-5 Earthquake Resistant Design Regulations,[13]

Country	Year of Issue	Seismic Zones	Seismic Coefficients		Dynamic Effects
			Horizontal	Vertical	
Algeria	1955	3	0~0.175	0~0.35	-
Argentina	1980	4	0~0.234	0	designated
Austria	1979	4	0.016~0.384	0.01~0.24	designated
Bulgaria	1964	4	0~0.389	0	designated
Canada	1980	4	0~0.39	0	designated
Chile	-	1	≦0.144	0	designated
China	1979	5	0~0.284	0.1~0.2	designated
Cuba	1964	2	0.04~0.20	0	designated
El Salvador	1966	2	0~0.39	0	designated
Ethiopia	1978	5	0~0.585	0	designated
France	1967	4	0~0.303	0~0.606	designated
Germany (West)	1975	6	0~0.21	$\frac{1}{2}$ x horizontal	designated
Greece	1959	3	0.04~0.16	0	-
India	1976	5	0.01~0.72	0	designated
Indonesia	1970	6	0~0.96	0	designated
Iran	-	1	0.08~0.10	0	designated
Israel	1975	3	0~0.936	0	designated
Italy	1975	2	>0	0.2~0.4	designated
Japan	1980	See Table 6			
Mexico	1977	4	>0	0	designated
New Zealand	1980	3	0.064~2.16	0	designated
Peru	1968	3	>0	>0, partially	designated
Philippines	1972	3	0.04~0.40	0	designated
Portugal	1961	3	0~0.2	0	-
Rumania	-	3	0.02~0.45	0	designated
Spain	1974	3	0.02~0.24	(1~2) x horizontal	designated
Turkey	1975	4	0.018~0.3	0	designated
USA (UBC)	1979	5	0~0.36	designated	designated
U.S.S.R.	1970	3	0.02~0.45	0	designated
Venezuela	1967	4	0~0.15	designated	designated
Yugoslavia	1964	4	0~0.27	0	designated

Table-6 Earthquake Resistant Design Regulations in Japan, [13]

Regulations	Year of Issue	Seismic Zones	Seismic Coefficients		Dynamic Effects
			Horizontal	Vertical	
Buildings	1982	4	>0.035	0	designated
Dams	1971	2	0.10~0.25	0	-
Highway Bridges	1980	3	0.10~0.39	0	designated
Submerged Tennels	1975	-	designated	designated	designated*
Petroleum Pipelines	1975	3	0.10~0.24	0	designated*
Ports and Harbors	1978	3	0.20~0.27	0	-
Water Supply Systems	1979	3	>0	$\frac{1}{2}$ x horizontal	designated*

* : Ground strain is taken into account for stress analyses in linelike structures installed under ground surface.

magnitude of the earthquakes as shown in Fig.6. In this figure the magnitude of 8 could cause liquefaction to a site 500 km away from earthquake epicenters, Kuribayashi and Tatsuoka[12].

4. ENGINEERING PRACTICE

4.1 Earthquake Resistant Design and Construction in the World, IAEE [13]

As shown in Table-5 thirty one countries have at least introduced codes and regulations for aseismic design and construction. In almost all of them seismic coefficients for the design are quantitatively specified in the provisions with supplementary articles on dynamic considerations.

4.2 Earthquake Resistant Design and Construction in Japan, IAEE [13]

Seven different regulations or codes of practice on aseismic design and construction for use with structures or facilities have been provided in Japan as shown in Table-6.

ACKNOWLEDGEMENTS

The author would like to express his acknowledgement to those who provided information on the articles cited here and also other relevant literature. He would also like to express his sincere appreciation to Professor Yukio Maeda, Kinki University and former Professor of Osaka University for his encouragement throughout the drafting of the text, and to Professor Nobuhiro Yotsukura, Toyohasi University of Technology, Professor Shiro Kato, Toyohashi University of Technology and Professor Jiang Tong, Toyohashi University of Technology and formerly of Tongji University in China, for their kind cooperation in improving the manuscript.

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