EARTHQUAKES AND EARTHQUAKE RISK IN TRINIDAD

By

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Abstract

The essentials of seismological theory and practice are presented, so far as these affect the problems faced by the seismologist in defining earthquake risk, and the engineer in taking measures to meet it. In developing economies lack of data is a major problem.

However, the seismologist is now beginning to define earthquake risk in the West Indies; now is the time for the engineer, and others, to decide what to do about it.

1. Earthquake Mechanism

Earthquakes are generated by fracture within the rocks forming the outer few hundred kilometers of the earth and the consequent release of stored elastic strain energy.

In the laboratory, fracture in rocks follows the Coulomb-Navier criterion for failure (Jaeger, 1962),

$$2S = \sqrt{2}\ (\sigma_1 - \sigma_2) - (\sigma_1 + \sigma_2),$$

where the constant μ, the coefficient of internal friction, is equal to unity, S is the shear strength of the rock and σ_1 and σ_2 are the maximum and minimum principal stresses in the rock. For natural rocks S is about 100 to 300 kg/cm^2 (1.3 to 1.9 tons/in^2) so that the maximum stress difference ($\sigma_1 - \sigma_2$) required for failure is about 500 to 1500 kg/cm^2 (3.2 to 9.5 tons/in^2) at the surface of the earth, and about 2000 to 3200 kg/cm^2 130 to 200 tons/in^2) at a depth of 10 km (6 miles). These large stress differences required for failure permit the accumulation of considerable strain energy, which may be released when failure occurs. If the stress field and the fracture are such that strain release is possible through a large volume of rock the instantaneous energy release may be very large, of the order of 10^{24} ergs in the case of the largest earthquakes. The strain energy so released radiates outwards from the fracture in the form of elastic waves. Primary waves or 'P' waves travel with a velocity given by the relation

$$V_P = \left((4/3 . G + K)/p \right)^{\frac{1}{2}} \tag{1}$$

where V_P is the velocity of P, G is the modulus of rigidity, K is the compressibility and p is the density of the material through which the wave propagates, Secondary or 'S' waves travel with a velocity, V_S given by

$$V_S = (G/p)^{\frac{1}{2}} \qquad (2)$$

A third type of wave the 'Surface' wave propagates at the surface of the earth with a velocity similar to that of an S wave.

Reflection, refraction, dispersion, transformation and selective attenuation of these several types of waves gives rise in practice to a very complicated earth motion for which there is no exact mathematical expression.

2. Seismographs and Microseisms

The passage of elastic waves is detected at the earth's surface by means of seismographs. A modern seismograph consists of an inertia mass with an electromagnetic transducer fixed between it and the earth. The transducer in turn is coupled to a sensitive galvanometer which records the output of the transducer, usually by means of photographic paper on a drum recorder. Both the inertia mass and the galvanometer are critically damped. Since elastic waves having a wide range of frequencies are generated near the point of failure and since the higher frequencies are more rapidly attenuated during the propagation of the waves, it is normal for the seismograph station to have two sets of seismographs, a 'short period' set having maximum sensitivity to periods of about 1 second and a 'long period' set having maximum sensitivity to periods of about 60 seconds. For both kinds of instrument the sensitivity falls off roughly by a factor of four for a change in frequency by a factor of two on either side of the centre frequency. The short period instruments are useful for recording earthquake motion within 1000 km of the source, since within this range earthquake periods vary from c. 0.1 to 2 secs. The long period instruments are useful for recording more distant earthquakes. The useful sensitivity of both types of instrument is limited by the continuous microseismic disturbance of the ground.

Microseismic earth motion is generated by standing waves at sea, by waves breaking on the coast and by human activity (by reciprocating machinery for example). At the most quiet sites in the West Indies the periodic ground displacement caused by human activity is less than 10 mu (millimicrons) at the frequencies of a few cycles per second (normally that part of the frequency spectrum for artificial disturbances where the greatest energy occurs). Natural microseisms at the most quiet sites in the West Indies have two predominant periods, one at 1 second where the periodic ground displacements are about 30 mu and one at 4 seconds where the periodic ground displacements are about 1000 mu in amplitude. These natural microseisms limit the useful sensitivity of seismographs to a peak displacement sensitivity of about 25,000 at 1 cycle/sec for short-period seismographs and about 1,500 at 0.02 cycles/sec for long-period instruments. It may be noted in passing that the amplitude of natural microseisms varies with the kind of geological material on which it is measured. The data given above refer to well consolidated rocks such as the phyllites of the Northern Range of Trinidad. On alluvium the amplitude of natural microseisms may be larger by an order of magnitude. In general there is a similar variation in earthquake amplitude with geological material so that an earthquake writes a seismogram showing amplitudes several times larger when the seismograph is on alluvium than when it is on phyllite at the same distance from the source. This is in part the reason for the "ground factor" which many earthquake design codes contain and it may be noted that methods have been developed for determining this factor from measurements of microseism amplitudes.

3. Earthquake Location

The time of arrival of P and S waves is easily measured from seismograms written by near earthquakes. It follows from (1) and (2) that when Poissons' ratio is $\frac{1}{4}$, as it is, approximately, for rocks,

$$V_p / V_s = \sqrt{3}\ ,$$

so that if the interval between the arrival times of P and S is measured and multiplied by a constant (1.37) the travel time of the earthquake waves is determined. If this quantity is determined at three or more stations, and if V_p is known, the coordinates of the earthquake epicentre (the point on the earth's surface below which the earthquake occurred) the focal depth (the distance from the epicentre to the fracture point or focus) can be estimated. In practice more refined computations are made but the method described above is often used to make rapid determination of epicentre and focal depth.

4. Earthquake Magnitude and Energy

In principle the energy released by any earthquake can be determined if the energy content of the earthquake waves can be determined from a seismogram written at a known distance from the earthquake focus, or hypocentre, and this energy is integrated over the surface of a sphere of radius equal to the hypocentral distance. In practice, because of the effects mentioned at the end of section 1, this operation is difficult to accomplish and is inexact, so seismologists have adopted a convention of ranking earthquakes on an arbitrary scale called the Magnitude scale. Earthquake magnitude M_B is defined by

$$M_B = \log A/T + Q \quad \text{(Gutenberg \& Richter, 1956A)} \qquad (3)$$

where A is the maximum ground amplitude for the P wave in millimicrons, T is the period of P in seconds and Q is a quantity given in a series of tables and charts, which varies with the distance and depth of the earthquake. Q has been adjusted so that all seismograph stations, whatever their distance, determine approximately the same magnitude for the same earthquake, from which it follows that the magnitude is a measure of the energy released at the focus, though the relationship between energy and magnitude is not known precisely and is subject to periodic adjustment.

A recent relation (Gutenberg & Richter, 1956B) is

$$\log E = 9.4 + 2.14\ M_B - 0.054\ M_B^2$$

where E is the energy release in ergs. Thus a change in the magnitude of one unit corresponds to a change in the energy by a factor of one hundred. The smallest earthquakes ordinarily detected by seismographs are about magnitude 3 with an energy of about 10^{15} ergs and the largest ever recorded had a magnitude of 8.6 with an energy of about 10^{24} ergs.

There is a relation between earthquake magnitude and frequency for any region of the form

$$\log N = a + b\,(8 - M_B) \qquad (4)$$

where N is the annual frequency and a and b are constants characteristic of the region. For many regions b is about 1, so that in these regions, if there are x earthquakes of magnitude y, there are about 10x earthquakes of magnitude y - 1.

5. Earthquake Intensity

The larger earthquakes are observed by the public at large and may cause damage to structures. The large scale, or macroseismic effects of earthquakes were, of course, observed long before modern seismographs and modern methods of locating earthquakes were devised. These effects were classified and graded and scales devised to measure the intensity of an earthquake at any locality. One of the oldest of these scales is widely used in Europe and North America; this is the Modified Mercalli Scale of Earthquake Intensity and it is set out in full as an appendix to this paper. Another Intensity Scale very similar to the Mercalli Scale but setting out the earthquake effects more systematically and in slightly more detail has recently been proposed by Medveden, Sponheur and Karnik. Since this scale is likely to be widely used also, this too is set out in full as an appendix.

Earthquake intensity, then, is defined by the effects described on these arbitrary scales. Instrumental observations have, however, been made during strong earthquakes and a relation between ground acceleration and intensity has been established empirically.
This relation is given by

$$\log a = I/3 - 1/2 \qquad (5)$$

where a is the maximum ground acceleration in cm/sec and I is the intensity on the Mercalli Scale. Thus a change in intensity by one unit corresponds to a change in the maximum ground acceleration by a factor of two.

6. Magnitude and Intensity Relations

Given the relation between ground velocity and magnitude (3) and ground acceleration and intensity (5) and other relations not quoted here but given in Gutenberg & Richter (1956B) it is possible to derive a relation between intensity, epicentral distance, focal depth and magnitude.

We have

$$I = F - 3 \log (D^2 + h^2)/h \qquad (6)$$

where I is the intensity on the Mercalli Scale, D is the distance in kilometers between the point where I is observed and the epicentre and h is the focal depth in kilometers. F is given by the relation,

$$F = 2.1\ M_B - 1.43 \tag{7}$$

these relations involve some approximations and assumptions and take no account of ground effects, but they can be used to estimate approximately the intensity distribution for any earthquake for which the focal parameters are known.

7. Earthquake Risk from Instrumental Data

If in any earthquake region we know the volume within the earth in which earthquakes occur and if we know the frequency, distribution and magnitude of earthquake within this volume we can use relations such as (4), (5) and (6) together with a knowledge of the rate of occurrence of earthquakes of any given magnitude to estimate the current risk of a given intensity. Such estimates are one of the objectives of modern seismology, though a very comprehensive knowledge of the seismic activity in the region over a period of several tens of years will be required before very precise estimates of the year to year change in earthquake risk are possible.

8. Earthquake Risk from Historical Data

In the interim until useful instrumental determinations are possible, the engineer required some estimate of earthquake risk which he can use in designing structures. A useful estimate of the risk can be derived empirically from the earthquake history of the region. In Trinidad, for example, using the historical data of Robson (1964) for the past 160 years we find a relation between intensity and average return period (the reciprocal of the average frequency) of the form

$$\log R = 0.6\ I - 2.7 \tag{8}$$

where R is the average return period in years for a given intensity I is the period considered. This relation defines the average risk as it was in the period 1800 - 1960 and does not tell us how this risk may be changing with time. But in the absence of any evidence to the contrary we must assume that it defines, approximately, the risk as it is now.

No intensity greater than VIII has occurred in Trinidad in the period considered so that some caution must be exercised in extrapolating the equation to intensities greater than VIII. One would expect (8) to define, to a reasonable approximation, the average return period for an intensity of IX which is, perhaps, as high an intensity as the engineer is prepared to design for.

9 Preventive Measures

Practical measures to minimise loss of life and property as a result of earthquakes and matters which most closely concern those who plan and build engineering structures; but a seismologist may, perhaps, help to define the problems. Some of the more important appear to be:-

1. What earthquake damage to a given structure is acceptable?

2. What earthquake intensity will cause, a) unacceptable damage to a given structure, b) total destruction and so endanger lives?

3. What risks of 2a) and 2b) are acceptable?

4. Is the acceptable risk smaller in the case of structures such as power plant, hospitals, water supply and sewerage plant, and if so, how much smaller?

5. Should a) the public, b) the private sectors of the community be required to build structures resistant to earthquakes, and, if so, resistant to what intensity of earthquake?

6. What would be the cost of an earthquake in Trinidad of a given intensity?

7. What preventive measures can we afford to pay for?

REFERENCES

Gutenberg, B. and Richter, C. F. (1956A) Magnitude and energy of earthquakes. Annali di Geofisica, Vol. 9, pp. 1-15.

Gutenberg, B. and Richter, C. F. (1956B) Earthquake magnitude, intensity, energy and acceleration. Bull. Seism. Soc. America, Vol. 46, pp. 105-145.

Jaeger, J. C. (1962) Elasticity Fracture and Flow. Methuen, London.

Robson, G. R. (1964) An earthquake catalogue for the Eastern Caribbean 1530-1960. Bull. Seism. Soc. America, Vol. 54, pp. 785-832.

A good general text for the engineer is:

Richter, C. F. Elementary Seismology, Freeman & Co., San Francisco, 1958

THE MODIFIED MERCALLI SCALE OF EARTHQUAKE INTENSITIES

1956 Version*

I. Not felt. Marginal and long-period effects of large earthquakes.

II. Felt by persons at rest, on upper floors, or favourably placed.

III. Felt indoors. Hanging objects swing. Vibration like passing of light trucks. Duration estimated. May not be recognized as an earthquake.

IV. Hanging objects swing. Vibration like passing of heavy trucks: or sensation of a jolt like a heavy ball striking the walls. Standing motor cars rock. Windows, dishes, doors rattle. Glasses clink. Crockery clashes. In the upper range of IV wooden walls and frame creak.

V. Felt outdoors; Direction estimated. Sleepers wakened. Liquids disturbed, some spilled. Small unstable objects displaced or upset. Doors swing, close, open. Shutters, pictures move. Pendulum clock stop, start, change rate.

VI. Felt by all. Many frightened and run outdoors. Persons walk unsteadily. Windows, dishes, glassware broken. Knickknacks, books, etc., off shelves. Pictures off walls. Furniture moved or overturned. Weak Plaster and Masonry D cracked. Small bells ring (church, school). Trees, bushes shaken (visibly, or heard to rustle).

VII. Difficult to stand. Noticed by drivers of motorcars. Hanging objects quiver. Furniture broken. Damage to masonry D, including cracks. Weak chimneys broken at roof line. Fall of plaster, loose bricks, stones, tiles, cornices (also unbraced parapets and architectural ornaments). Some cracks in masonry C. Waves on ponds: water turbid with mud. Small slides and caving in along sand or gravel banks. Large bells ring. Concrete irrigation ditches damaged.

VIII. Steering of motor cars affected. Damage to masonry C; partial collapse. Some damage to masonry B: none to masonry A. Fall of stucco and some masonry walls. Twisting, fall of chimneys, factory stacks, monuments, towers, elevated tanks. Frame houses moved on foundations if not bolted down: loose panel walls thrown out. Decayed piling broken off. Branches broken from trees. Changes in flow or temperature of springs and wells. Cracks in wet ground and on steep slopes.

IX. General panic. Masonry D destroyed; masonry C heavily damaged, sometimes with complete collapse; masonry B seriously damaged. (General damage to foundations). Frame structures, if not bolted, shifted off foundations. Frames racked. Serious damage to reservoirs. Underground pipes broken. Conspicuous cracks on ground. In alluviated areas sand and mud ejected, earthquake fountains, sand craters.

X. Most masonry and frame structures destroyed with their foundations. Some well-built wooden structures and bridges destroyed. Serious damage to dams, dikes, embankments. Large landslides. Water thrown on banks of canals, rivers, lakes, etc. Sand mud shifted horizontally on beaches and flat land. Rails bent slightly.

XI. Rails bent greatly. Underground pipelines completely out of service.

XII. Damage nearly total. Large rock masses displaced. Lines of sight and level distorted. Objects thrown into the air.

Masonry A,B,C,D. To avoid ambiguity of language, the quality of masonry, brick or otherwise, is specified by the following lettering (which has no connection with conventional Class A.B,C. construction).

Masonry A. Good workmanship, mortar, and design; reinforced especially laterally and bound together by using steel, concrete, etc., designed to resist lateral forces.

Masonry B. Good workmanship and mortar; reinforced, but not designed in detail to resist lateral forces.

Masonry C. Ordinary workmanship and mortar; no extreme weaknesses like failing to tie in at corners, but neither reinforced nor designed against horizontal forces.

Masonry D. Weak materials, such as adobe; poor mortar; low standards of workmanship; weak horizontally.

An approximate empirical relation between ground acceleration and intensity on the 1956 Mercalli scale is given by

$$\text{Log } a = I/3 - 1.5,$$

where a is the ground acceleration expressed as a percentage of the acceleration due to gravity and I is the intensity.

From Richter's Elementary Seismology,
W.H. Freeman and Company, San Francisco, 1958.

THE MSK SCALE OF EARTHQUAKE INTENSITIES

Compiled by S. Medveden, W. Sponheuer and V. Karnik

(This scale is very closely similar to the Modified Mercalli Scale of Earthquake Intensities, 1956 version).

Definition of Terms used in the Scale.

I. Type of structure

Structure A: Buildings in field-stone, rural structures, adobe houses, clay houses.

Structure B: Ordinary brick buildings, buildings of the large block and prefabricated type, half-timbered structures, buildings in natural hewn stone.

Structure C: Reinforced buildings, well-built wooden structures.

2. Definition of quantity.

Single, few: about 5 per cent.
Many : about 59 per cent.
Most : about 75 per cent.

3. Classification of damage to buildings.

Grade 1: Slight damage—Fine cracks in plaster; fall of small pieces of plaster.

Grade 2: Moderate damage—Small cracks in walls; fall of fairly large pieces of plaster; pantiles slip off; cracks in chimneys; parts of chimneys fall down.

Grade 3: Heavy damage—Large cracks in walls; fall of chimneys.

Grade 4: Destruction—Gaps in walls; parts of buildings may collapse; separate parts of the building lose their cohesion; inner walls collapse.

Grade 5: Total damage—total collapse of buildings.

The MSK Intensity scale

1. Not noticeable.

a) The intensity is below the limit of human sensitivity; the tremor is detected and recorded by seismographs only.

II. Scarcely noticeable (very slight).

a) Vibration is felt only by individual people at rest in houses, especially on the upper floors of buildings.

III. Weak, partially observed only.

a) The earthquake is felt indoors by a few people; outdoors only in favourable circumstances. The vibration is like that due to the passing of a light truck. Attentive observers notice a slight swinging of hanging objects.

IV. Largely observed.

a) The earthquake is felt indoors by many people, outdoors by few. Here and there people waken, but no one is frightened. The vibration is like that due to the passing of a heavily loaded truck. Windows, doors and dishes rattle. Floors and walls creak. Liquids in open vessels are slightly disturbed. In standing motor cars the shock is noticeable.

V. Awakening.

a) The earthquake is felt indoors by all, outdoors by many. Many sleeping people waken. A few run outdoors. Animals become uneasy. Buildings tremble throughout. Hanging objects swing. Pictures knock against walls or swing out of place. Occasionally pendulum clocks stop. Unstable objects may be overturned or shifted. Doors and windows are thrust open and slam back again. Liquids spill in small amounts from well-filled containers. The sensation of vibration is, like that due to a heavy object falling inside the building.

c) Slight waves may occur on standing water; sometimes there may be a change in the flow of springs.

VI. Frightening.

a) Felt by most indoors and outdoors. Many people inside buildings are frightened and run outdoors. A few persons lose their balance. Domestic animals run out of their stalls. In many instances dishes and glassware break, books fall down, pictures move and unstable objects overturn. Heavy furniture may move and small steeple bells may ring.

b) Damage of Grade 1 is sustained in single buildings of Type B and in many buildings of Type A. Damage in some buildings of Type A is of Grade 2.

c) Cracks up to widths of 1 cm are possible in wet ground; in mountains occasional land-slips occur. There may be a change in the flow of springs and in the level of well-water.

VII. Damage to buildings.

a) Most people are frightened and run outdoors. Many find it difficult to stand. The vibration is noticed by persons driving motor cars. Large bells ring.

b) In many buildings of Type C, damage of Grade 1 is caused; in buildings of Type B damage is of Grade 2. Most buildings of Type A suffer damage of Grade 3, some of Grade 4. In single instances there are land-slips of the roadway on steep slopes. cracks in road seams of pipelines damaged; cracks in stone walls'

c) Waves are formed on water, and water is made turbid by stirred-up mud. Water levels in wells change, and the flow of springs changes. Sometimes dry springs have their flow restored and existing springs stop flowing. In isolated instances parts of sandy or gravely banks slip off.

VIII. Destruction of buildings.

a) Many people are frightened and panic; persons driving motor cars are disturbed. Here and there branches of trees break off. Even heavy furniture moves and partly overturns. Hanging lamps are in part damaged.

b) Most buildings of Type C suffer damage of Grade 2. Most buildings of Type B suffer damage of Grade 3, and most buildings of Type A suffer damage of Grade 4. Occasional breakage of pipe seams occurs. Memorials and monuments move and twist; tombstones overturn; stone walls collapse.

c) Small land-slips occur in hollows, on banked roads and on steep slopes; cracks in the ground of width up to several centimetres form. The water in lakes becomes turbid. New lakes are formed. Dry wells refill and existing wells become dry; in many cases there is a change in the flow and the level of the water.

IX. General damage to buildings.

a) There is general panic. Considerable damage to furniture is caused. Animals run to and fro in confusion and cry.

b) Many buildings of Type C suffer damage of Grade 3, some of Grade 4. Many buildings of Type B show damage of Grade 4; a few of Grade 5. Monuments and columns fall. Considerable damage to reservoirs occurs and underground pipes are partly broken. In individual cases railway lines are bent and roadways damaged.

c) On flat land the outflow of water, sand and mud is often observed. On flat ground cracks of widths up to 10 cm occur and on slopes and river banks of more than 10 cm. There is a large number of slight cracks in flat ground. Falls of rock, landslides and earth flows occur. Large waves are generated on water. Dry wells renew their flow and existing wells dry up.

X. General destruction of buildings.

b) Many buildings of Type C suffer damage of Grade 4, some of Grade 5, Many buildings of Type B show damage of Grade 5; most of Type A show damage of Grade 5. There is critical damage to dams and dykes and severe damage to bridges. Railway lines are bent slightly. Underground pipes are broken or bent. Road paving and asphalt may show waves after the earthquake.

c) On flat ground, cracks up to widths of several tens of centimetres; sometimes up to 1 metre are formed. Broad fissures form parallel to water courses. Loose earth slides off steep slopes. Considerable landslides are possible from river banks and steep coasts. In coastal areas there is displacement of sand and mud. Changes of water level in wells occur. Water from canals, lakes and rivers is thrown on land. New lakes are formed.

Destruction.

b) There is severe damage even to well-built buildings, bridges, dams and railway lines; highways become useless; underground pipes are destroyed.

c) The ground is considerably distorted by broad cracks and fissures. as well as by movement in the horizontal and vertical directions. numerous land slips and falls of rock occur.

I. Landscape changes.

b) Practically all structures above and below ground are greatly damaged or destroyed.

c) The surface of the ground is radically changed. Considerable ground cracks with extensive vertical and horizontal movements are observed. Falls of rock and slumping of river banks occur over wide areas; lakes are dammed; waterfalls appear, and rivers are deflected.

GROUND MOTION FOR EARTHQUAKES OF DIFFERENT INTENSITIES

I (Grade)	a (cm sec $^{-2}$)	v (cm sec^{-1})	x (mm. ^{o})	a* (Log a= I/3 - 0.5)
5	12 - 25	1.0 - 2.0	0.5 - 1.0	15
6	25 - 50	2.1 - 4.0	1.1 - 2.0	31
7	50 - 100	4.1 - 8.0	2.1 - 4.0	68
8	100 - 200	8.1 -16.0	4.1 - 8.0	145
9	200 - 400	16.1 -32.0	8.1 -16.0	315
10	400 - 800	32.1 -64.0	16.1 -32.0	692

I - Intensity

a - Ground acceleration in cm/sec ^{2} for periods between 0.1 and 0.5 sec.

v - Velocity of ground oscillation in cm/sec for periods between 0.5 and 2.0 sec.

x_0 - Amplitude of movement of centre of gravity of a pendulum mass in mm when the natural period of the pendulum is 0.25 and the logarithmic decrement is 0.5.

* - Ground acceleration in cm/sec ^{2} for intensities on the Modified Mercalli Scale of Earthquake Intensities according to C. F. Richter, **Elementary Seismology**, Freeman & Co., San Francisco, 1958.