Selection of Design Earthquake

Background

A structural engineer needs to know the earthquake or earthquake for which a structure must be designed. Selection of such earthquake is uncertain, and requires considerable judgement. Deterministic and probabilistic methods are available.

Deterministic method : Based on the earthquake history, maximum probable earthquakes at the site are estimated considering the magnitudes and using attenuation laws. Then, based on the engineer's judge, a design earthquake is chosen.
Specific EQs are considered independently. Design EQ is determined according to the engineer's decision.

Probabilistic method : regional earthquakes are expressed as the function of occurrence probability. By using attenuation laws, the occurrence probabilities are transformed to those at the site. The overall occurrence probability at the site is calculated by summing the regional probabilities. Then for the design of structures, a level of earthquake is selected.
Design EQ is determined according to the target occurrence probability.

Selection of design earthquakes is based on the following factors:

1. Regional Geologic Setting : (within 100 to 300 km of the site)
1) tectonic mechanisms
2) geological history
3) description of current geological formation, rock, and soil deposits
4) location of major geological features
5) identification of active faults, type, and history of movement
6) Data on fault activity: average slip, slip per event, recurrence intervals between earthquakes

2. Seismic History: Complete Documentation of known earthquakes, including the following information for each:
1) date, time, epicentral location
2) isoseismal map, magnitude
3) focal depth

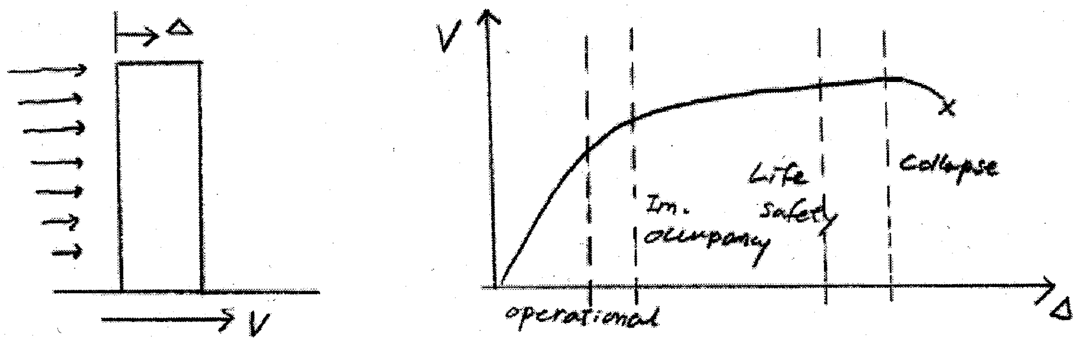
4) felt area
5) induced effects on surface
6) relevant strong motion recordings

3. Local Geological Setting :
1) complete map of soil and rock formations
2) documentation of local faulting
3) hydrological conditions, water table, underground flow conditions, permeability characteristics

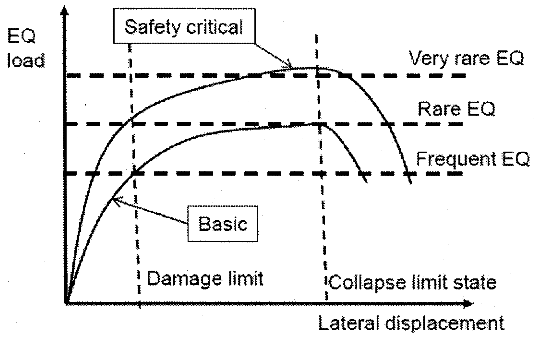
Concept of Limit States

In strong and frequent earthquake regions, because of the uncertainty associated with earthquake loadings, and the likelihood of inelastic response under extreme earthquakes, we generally do not design a structure for a single level of earthquake. Rather, the structure is designed for several limit states. Under each limit state, its performance must meet specific criteria.

On the other hand, in moderate and infrequent earthquake regions like Korea, consideration of collapse limit state is sufficient for ordinary buildings, except for essential buildings and facilities. This is because the occurrence probability of both strong and weak earthquakes is very low, and preparation for the weak earthquakes is not required. However, essential and critical structures are required to function even under strong earthquakes. Thus, multiple design criteria are required.



For nonseismic loading, limit states are classified by the level of load.
For seismic loading, limit states are classified by the level of deformation.



Performance levels are different according to the importance of the structure and its function.

Life safety limit state and Collapse Limit State :

This is based on the largest reasonably conceivable earthquake that is possible along recognized active faults. The largest conceivable earthquake should be based on geological evidence, rather than just historical data. Little consideration is given to probability of occurrence. The structure is expected to resist this ground motion without collapse. Inelastic response is possible in most cases.

Damage Limit State (immediate occupancy limit state):

During the life of the structure, it is possible that it might be subject to an earthquake which would not cause collapse, but which might cause sufficient damage to make the building worthless from an economic viewpoint. To design the building to control this type of damage, the damage limit state is based on an earthquake with a reasonable probability of not being exceeded duri2ng the life of the structure. For example, a damage limit state earthquake might have a 50% probability of not exceeded over a 100 year period.

Service Limit State (operational limit state):

In a seismic region, a structure might be exposed during its economic life to a number of small earthquakes. The structure would be expected to remain functional after such earthquakes. The service limit state is based on an earthquake with a reasonable probability of not being exceeded over a short period of time, perhaps 10 years.

Table 2-3 Damage Control and Building Performance Levels

	Building Performance Levels			
	Collapse Prevention Level	**Life Safety Level**	**Immediate Occupancy Level**	**Operational Level**
Overall Damage	Severe	Moderate	Light	Very Light
General	Little residual stiffness and strength, but load-bearing columns and walls function. Large permanent drifts. Some exits blocked. Infills and unbraced parapets failed or at incipient failure. Building is near collapse.	Some residual strength and stiffness left in all stories. Gravity-load-bearing elements function. No out-of-plane failure of walls or tipping of parapets. Some permanent drift. Damage to partitions. Building may be beyond economical repair.	No permanent drift. Structure substantially retains original strength and stiffness. Minor cracking of facades, partitions, and ceilings as well as structural elements. Elevators can be restarted. Fire protection operable.	No permanent drift; structure substantially retains original strength and stiffness. Minor cracking of facades, partitions, and ceilings as well as structural elements. All systems important to normal operation are functional.
Nonstructural components	Extensive damage.	Falling hazards mitigated but many architectural, mechanical, and electrical systems are damaged.	Equipment and contents are generally secure, but may not operate due to mechanical failure or lack of utilities.	Negligible damage occurs. Power and other utilities are available, possibly from standby sources.
Comparison with performance intended for buildings designed, under the *NEHRP Provisions,* for the Design Earthquake	Significantly more damage and greater risk.	Somewhat more damage and slightly higher risk.	Much less damage and lower risk.	Much less damage and lower risk.

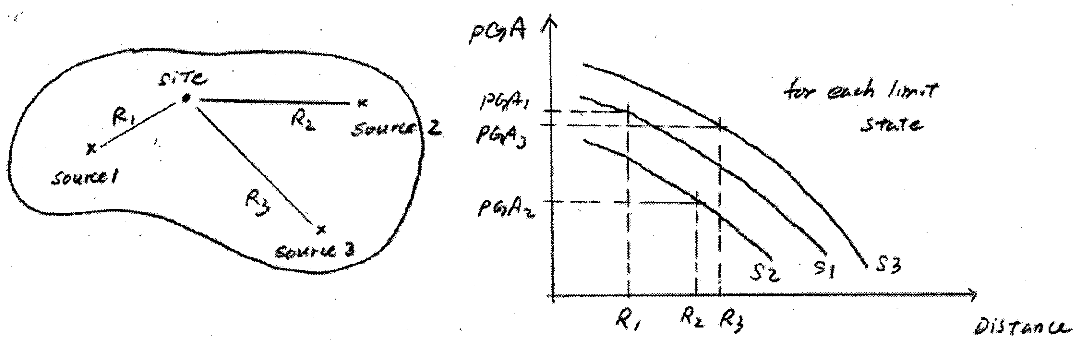
Table 2-4 Structural Performance Levels and Damage[1]—Vertical Elements

		Structural Performance Levels		
Elements	**Type**	**Collapse Prevention S-5**	**Life Safety S-3**	**Immediate Occupancy S-1**
Concrete Frames	Primary	Extensive cracking and hinge formation in ductile elements. Limited cracking and/or splice failure in some nonductile columns. Severe damage in short columns.	Extensive damage to beams. Spalling of cover and shear cracking (< 1/8" width) for ductile columns. Minor spalling in nonductile columns. Joint cracks < 1/8" wide.	Minor hairline cracking. Limited yielding possible at a few locations. No crushing (strains below 0.003).
	Secondary	Extensive spalling in columns (limited shortening) and beams. Severe joint damage. Some reinforcing buckled.	Extensive cracking and hinge formation in ductile elements. Limited cracking and/or splice failure in some nonductile columns. Severe damage in short columns.	Minor spalling in a few places in ductile columns and beams. Flexural cracking in beams and columns. Shear cracking in joints < 1/16" width.
	Drift[2]	4% transient or permanent	2% transient; 1% permanent	1% transient; negligible permanent

Deterministic Method :

Summary of Design Earthquake Selection Procedure – Deterministic Approach

1) Study the region and the site.
2) Select earthquake parameters (magnitude, frequency content, duration, pulse structure) for each limit state.
3) Use attenuation laws to estimate peak ground motion at the site.
4) In each limit state, determine the design response spectrum for the given structure.



select PGA_1 as Design earthquake

Example of Deterministic Approach

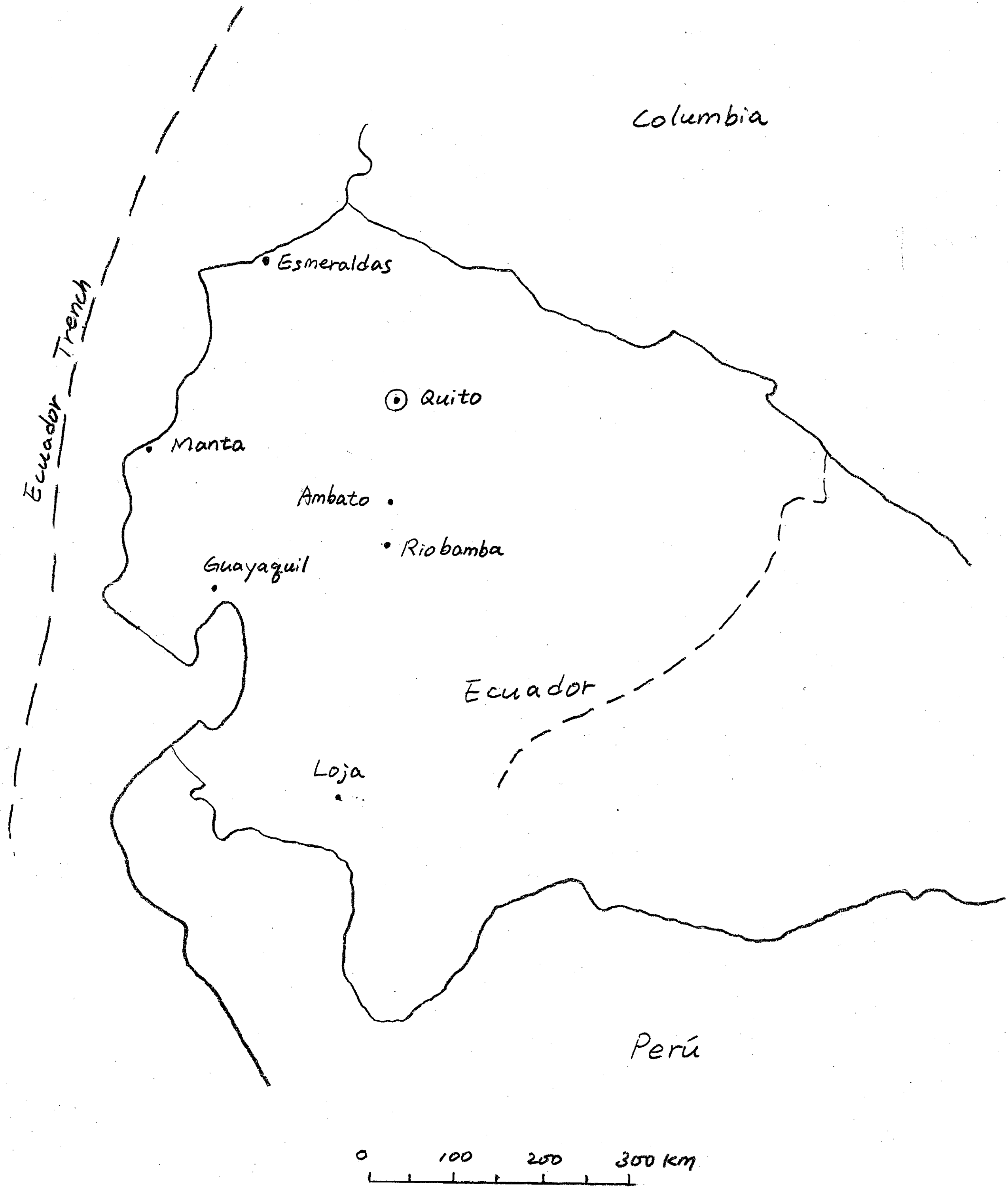
Selection of Design Earthquake for Quito in Ecuador (South America)

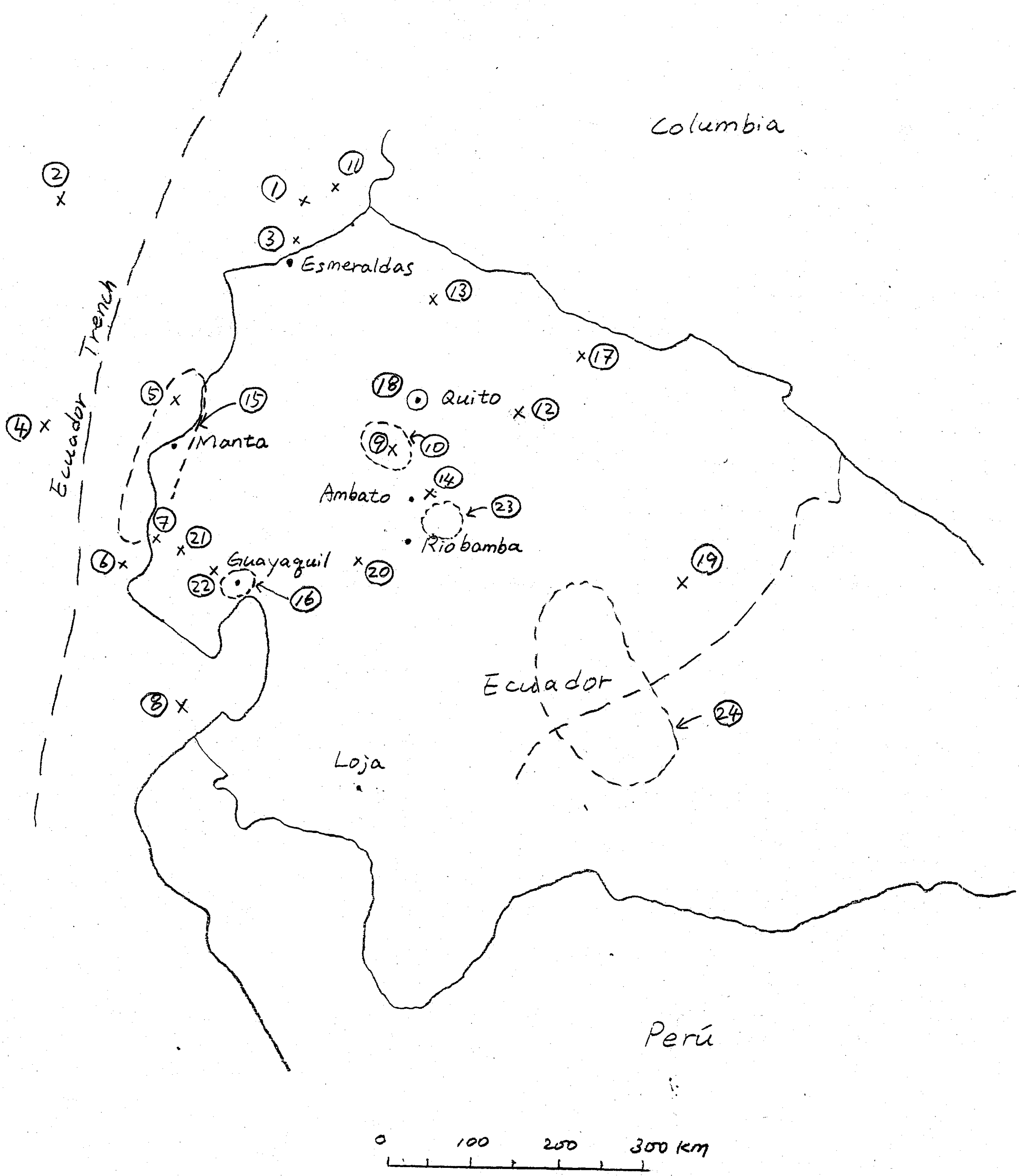
The republic of Ecuador is located in the northwest part of South America. It is an appropriate subject for a deterministic seismic study because it is highly seismic, with a number of possible earthquake sources.

This example will use the deterministic approach outlined above to propose design earthquakes for various limit states for the capital city of Quito, located in the mountains.

Historical Seismicity of Ecuador

During this century Ecuador has been shaken by a number of destructive earthquakes. These are identified in the map below, and are listed in the accompanying table.


Columbia
Ecuador Trench
Esmeraldas
Quito
Manta
Ambato
Riobamba
Guayaquil
Ecuador
Loja
Perú
0
100
200
300 km

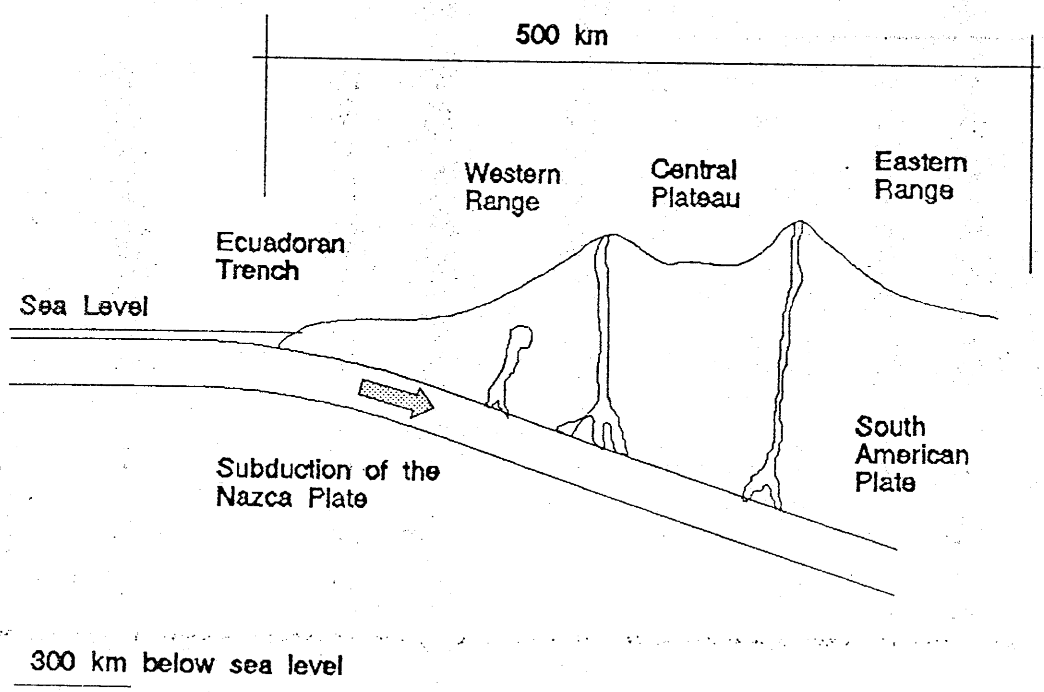


Locations of All Earthquakes

Event	Location	Date	Magnitude	Depth (km)
1	Esmeraldas	01/19/58	7.8	<33
2	Esmeraldas	01/31/06	8.7	<33
3	Esmeraldas	04/14/58	6.8	<33
4	Manta	05/14/42	8.1	<33
5	Manta	01/16/56	7.1	<33
6	Santa Elena	10/02/33	6.9	<33
7	Manglaralto	10/11/62	6.1	<33
8	Machala	12/12/53	7.9	<33
9	Saquisili	10/06/76	5.7	12
10	Saquisili	Various	4.5	12
11	Esmeraldas	02/01/58	6.8	34-75
12	Baeza	05/11/55	6.75	39
13	Otavalo	12/04/61	6.4	34-75
14	Ambato	08/05/49	6.75	45
15	Manta	Various	5.1	34-75
16	Guayaquil	Various	5.1	34-75
17	Coca	06/23/25	6.75	180
18	Quito	03/02/67	5.8	128
19	Amazon Basin	07/19/37	7.1	199
20	Chillanes	09/28/06	7.5	150
21	Guayaquil	01/30/43	6.9	>75
22	Guayaquil	07/22/24	5.7	>75
23	Riobamba	Various	5.7	180
24	Pastaza River	Various	6.5	>75

Geological Causes of Earthquake in Ecuador

We have previously seen that earthquakes are associated with subduction zones, transform boundaries, and volcanic action. Ecuador is an excellent example of a highly seismic zone; it has all of these. The figure below is a schematic section through the subduction zone underneath Ecuador, looking from south to north. As that figure shows, the Nazca Plate is being subducted beneath the South American Plate. This subduction process has created the Ecuador Trench, and is uplifting the Andres Mountains. Those mountains have a western and an eastern range; between the two ranges lies a central plateau, referred to geologically as a "graben," or block that is settling. Volcanic activity is present along both ranges.



The following sections contain a review of the geologic causes of earthquakes in Ecuador, going from shallow earthquakes (<33km) to deep ones.

Causes of Shallow Earthquakes (< 33 km)

In the map, the shallow earthquakes are indicated separately, using the same identification numbers corresponding to the previous map and table. In referring to these earthquakes, it must be pointed out that this focal depth is arbitrary applied to all earthquakes for which a focal depth cannot be instrumentally determined. Usually, that refers to earthquakes recorded only at distant stations in North America. Many earthquakes which occurred before Ecuador had a seismographic network were recorded only at large distances, and were arbitrary assigned this depth. Ecuador has had a working seismographic network since the late 1970's, so far fewer earthquakes are explained below:

1) Ecuadoran Trench:

This trench passes along the Ecuadoran coast, and marks the start of the subduction of the Nazca Plate underneath the South American Plate. The trench is associated with focal depths of at least 20 km, and has been the source of many strong earthquakes, such as events 1 through 8 in the maps and table. Among these is Event 2 (01/31/06), probably the largest earthquake ever recorded by instruments.

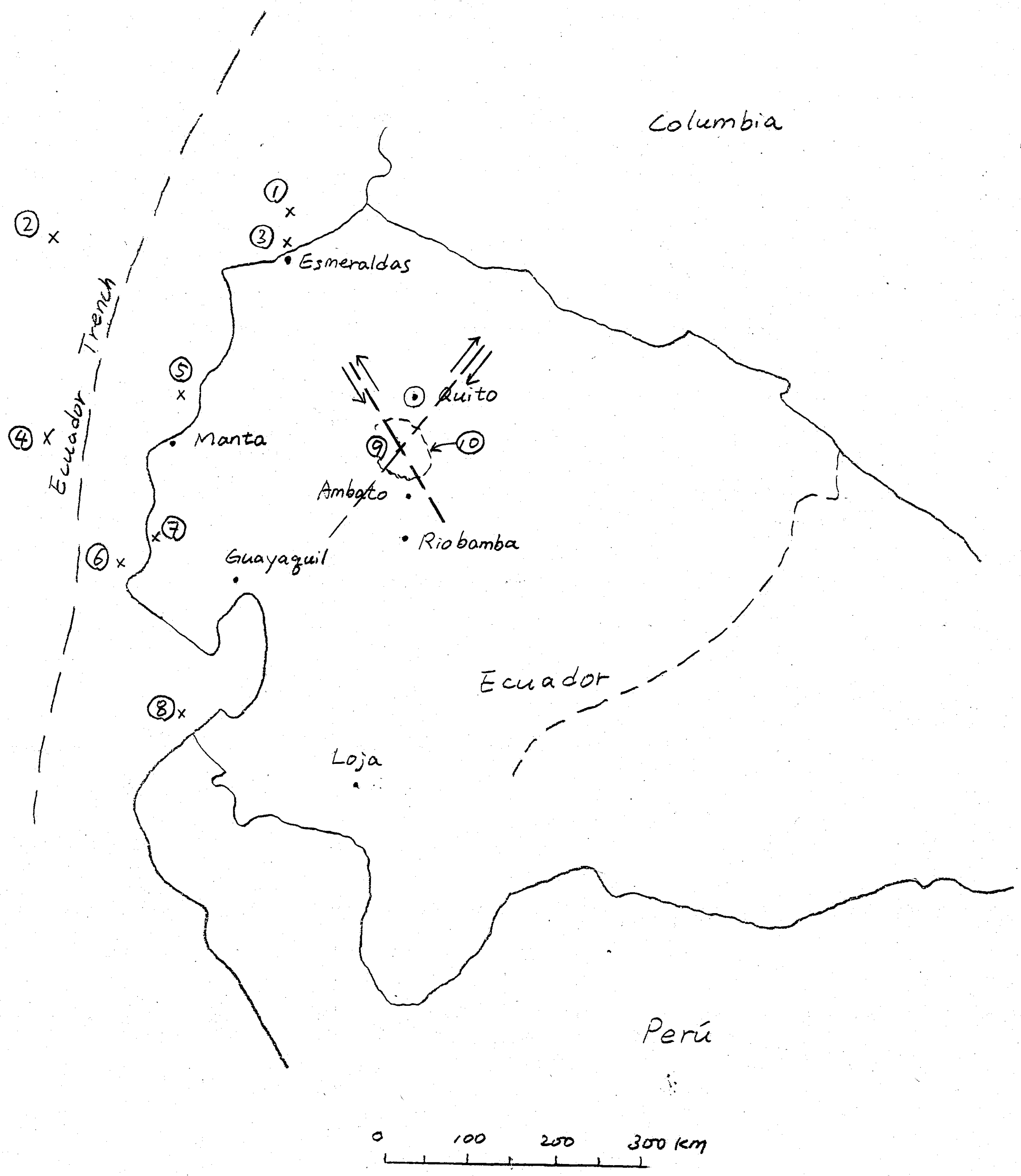
2) Local Faults of the Central Plateau :

There are two distinct fault zones, indicated by the dashed lines on the map. They do not represent continuous faults, but rather two sets of short faults, aligned more or less in the direction indicated, and which are undergoing movement in the senses shown by the arrows on the map. According to microtremor data, the fault zone running from southwest to northeast has typical focal depth of about 12 km, while the other zone, running from southeast to northwest, typical focal depths of about 30 km. It is possible that the first fault zone extends southwest to Guayaquil, and the second, to the northwest to Esmeraldas.

The region around the capital city of Quito is crossed by many short faults forming part of the first fault zone. It is interesting to note that the intersection of these two fault zones corresponds to the region around Saquisili and Pastocallle, which has been seismicallu very active in recent years. As shown in the shallow-earthquake map, Event 9 occurred there, Like the other events surrounded by dotted lines, Event 10 does not represent a single earthquake, but rather a group. The magnitude value in the preceding table is an average value.

3) Volcanic Activity :

As indicated in the map below, Ecuador has 8 historically active volcanoes: Pichincha, Quilotoa,



Earthquake with Focal Depth < 33 km

Cotopaxi, Antisana, Sumaco, Tunhurahua, and Sangay. Other active volcanoes lie just on the other side of the Colombian border. There are no data regarding the probable magnitude of an earthquake that might be associated by the eruption of one of those volcanoes. Based on information from other geologically similar volcanoes, such an eruption might be associated with a magnitude 5.0 earthquake, with focus 5 to 10 km below the summit of the volcano.

Causes of Medium Depth Earthquake (> 33 km)

4) Other Fault Zones :

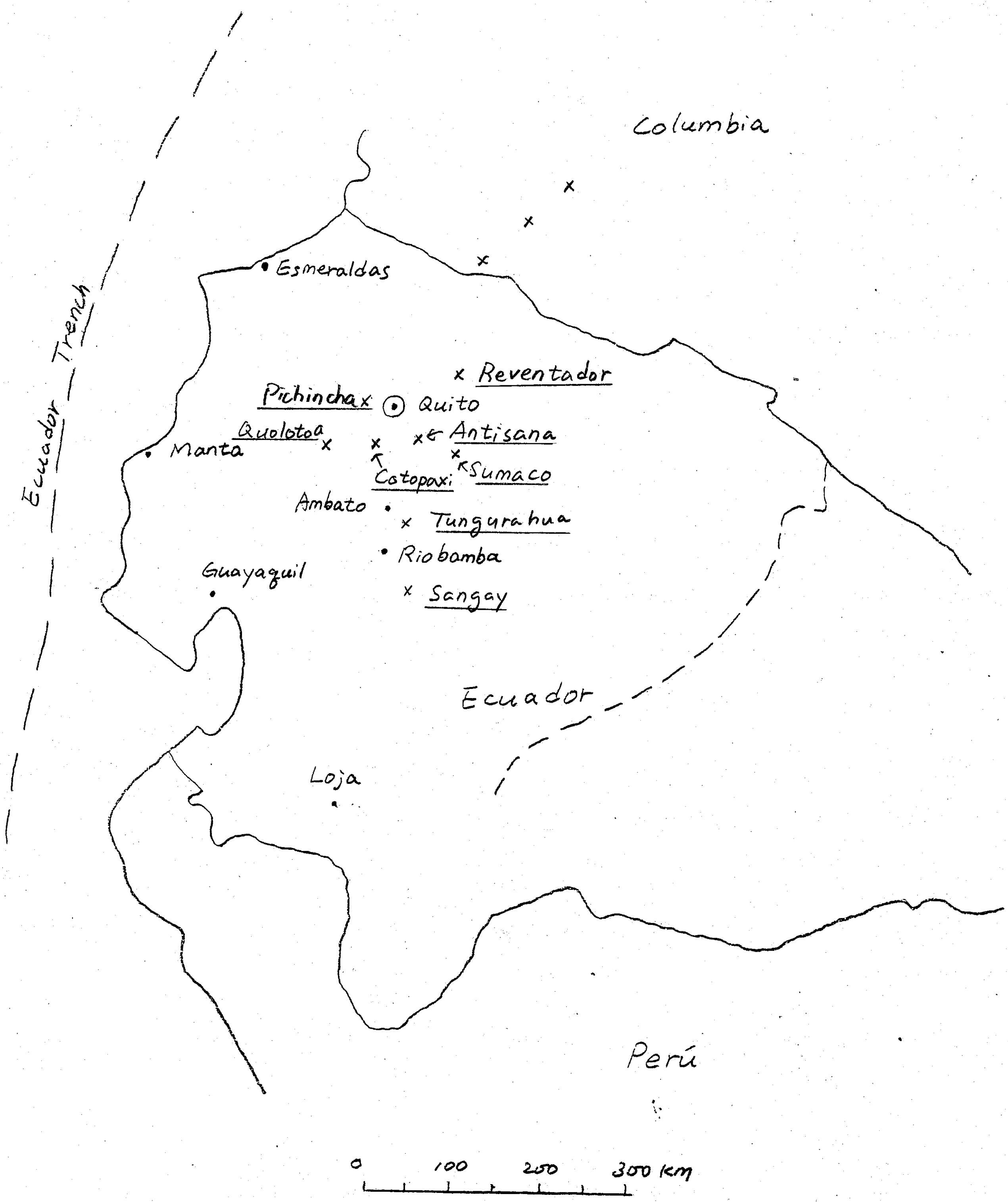
Events such as 12 and 13 suggest the presence of another fault zone extending from southeast of Quito, passing through Otavalo, and on to Esmeraldas. This zone is indicated on the map below by a dashed line, and the direction of movement is indicated by arrows. In the above table, it can be seen that the focal depths in this fault zone are greater that in the fault zones of the Central Plateau. It is probable that Event 14 (08/05/49), which seriously damaged Ambato, was associated with this fault zone, since there are other faults running parallel to the dashed lined on the map. Such parallel faults are indicated by the dotted line on the map for medium depth earthquakes.

5) Subduction Zone of Central Ecuador :

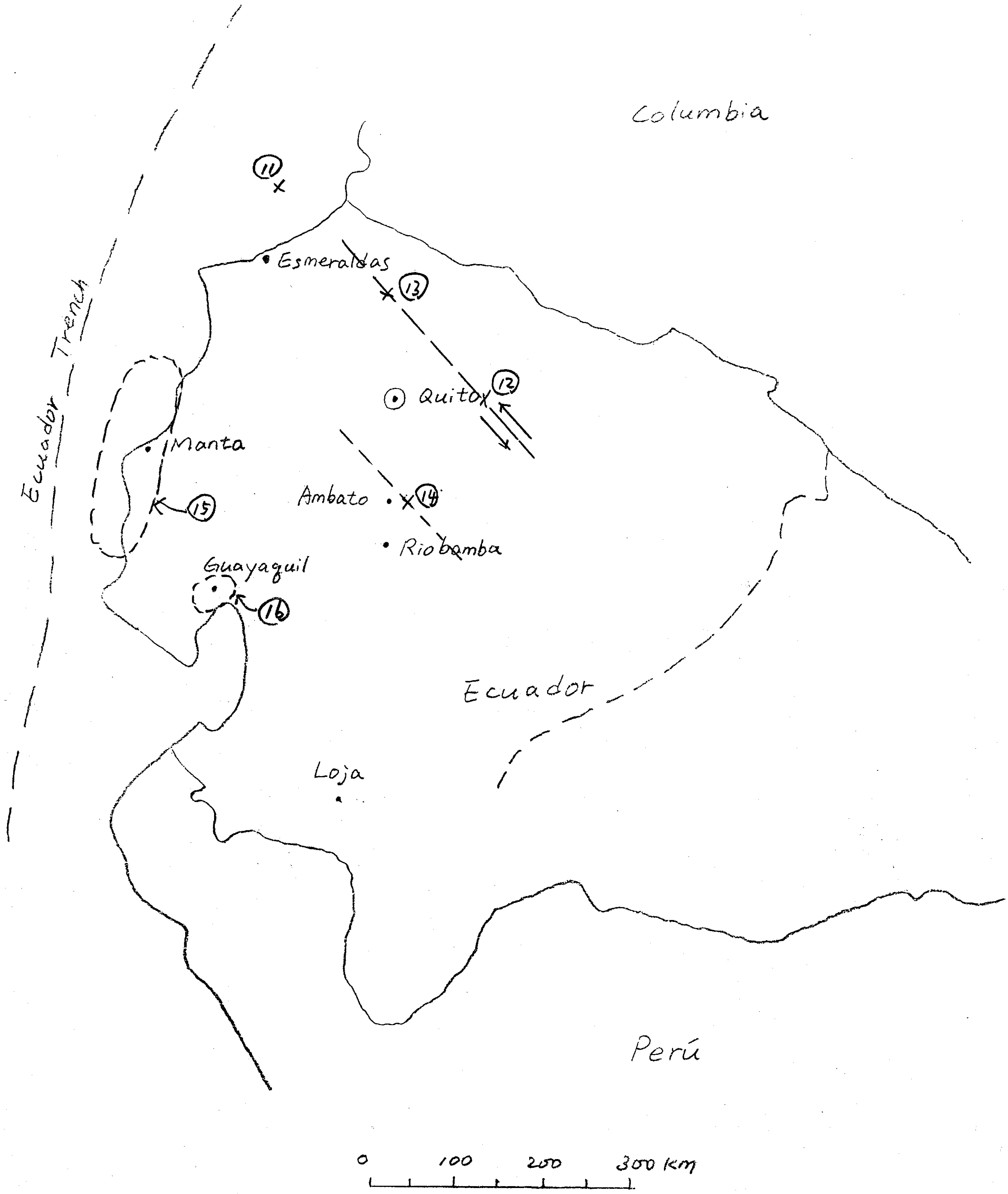
Referring to the previous figure showing a section through the subduction zone, earthquakes might be expected along the contact zone between the two plates. Those near the Ecuadoran Trench would have shallow focal depths, while those occurring farther from the Trench would be deeper. Events 11 and 15 represent earthquakes that occurred further inland and therefore deeper along the contact interface. The subduction zone of Central Ecuador has not been very active seismically, and Event 18 is the only significant recent earthquake. The Nazca Plate is believed to dip towards the southeast in the region.

6) Subduction Zone of Southeastern Ecuador :

It is believed that the Nazca Plate dips towards the northeast here, in contrast to its direction under Central Ecuador. This implies the existence of a fracture zone within the Nazca Plate, possibly associated with the presence of the southwest-to-northeast-running faults in the Central Plateau. Unlike the subduction zone is very active seismically. Events 16, 21, and 22 occurred close to the Ecudadoran Trench at shallow focal depths, and Events 19, 20, 23, an 24 occurred farther from the Trench, at greater depths.



Historically Active Volcanoes



Earthquake with Focal Depths between 34 and 75 km

Earthquake with Focal Depths > 75 Km

Example : Determination of Design Earthquakes for Quito

Our first example deals with deterministic procedures for establishing design earthquakes for Ecuador's capital city of Quito. In this example, we will study each possible seismic source that might affect Quito, and we will estimate critical design motions for the collapse, damage, and service limit states.

Five seismic source are possible :

1) Ecuadoran Trench
2) Local faults of the central plateau
3) Volcanic activity
4) Other fault zone
5) Subduction zones

Considerations when possible events are chosen.

1) magnitude
2) focal distance
3) focal depth

Each possibility will now be discussed in greater detail :

1) Ecuadoran Trench : Possible Event 1

Many strong earthquakes have occurred at or near the Trench (Events 1-8). It is therefore reasonable to suppose that a similar event could occur anywhere along the Trench. The largest event is Event 2, with M=8.7.

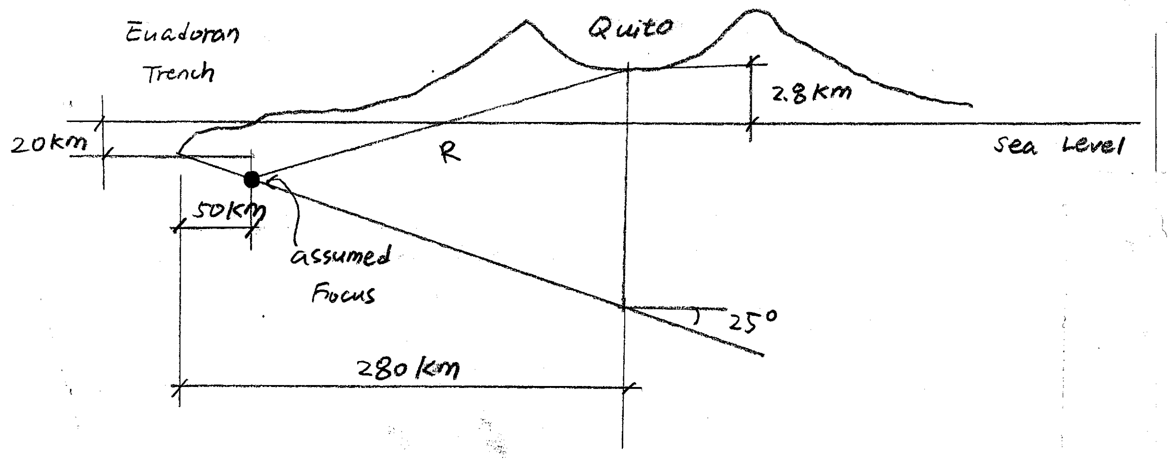
a) For the collapse limit state, we should therefore consider a magnitude 8.7 earthquake anywhere along the Trench.
b) For the damage limit state, with a 50 to 100 year return period, we should perhaps consider a magnitude 8 event.
c) For the service limit state, with a 10 year return period, we should perhaps consider a magnitude 7 event.

At its nearest point, the trench is about 280 km from Quito. However, the point of energy release would probably be somewhere along the contact zone, closer to Quito than the trench itself. Suppose that we assume this point to be located at 50 km east of the trench, toward Quito. We would then have the following situation:

Assuming an average dip angle of 25 degrees, the vertical projection of the focal distance R is

Rv = altitude of Quito + depth of Trench + vertical component

= 2.8 + 20 + 50 tan 25 = 46.1 km



and the horizontal projection is

Rh = horizontal distance from Trench to Quito - horizontal distance from Trench to Focus

= 280 - 50 = 230 km

The focal distance is therefore

$$R = \sqrt{R_v^2 + R_h^2} = \sqrt{230^2 + 46.1^2} = 235\ km$$

2) Local Faults of the Central Plateau : Possible Event 2

An earthquake could occur in the faults that pass through Quito.

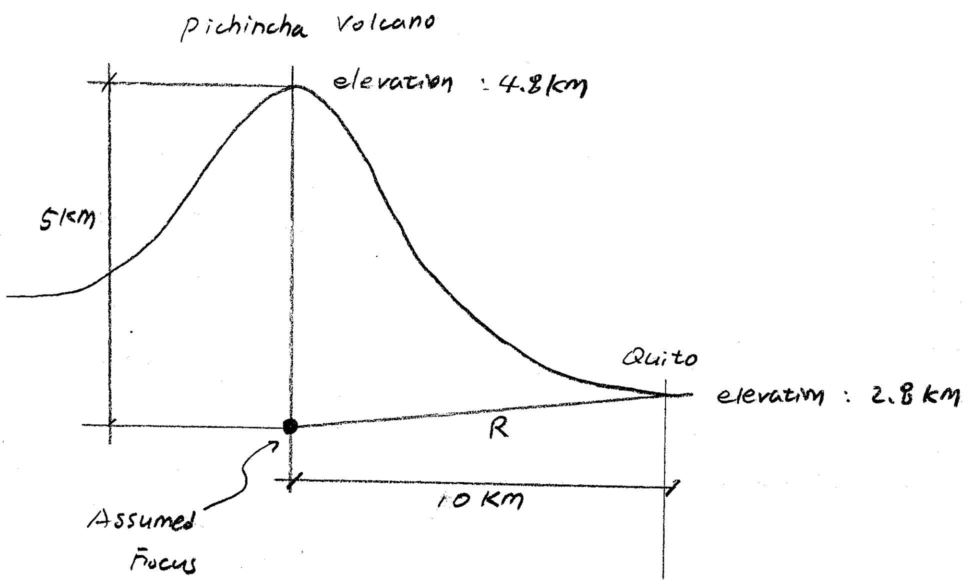
a) The largest earthquake that has occurred along these faults is Event 9 with magnitude 5.7. For the collapse limit state, we should therefore consider a magnitude 6 earthquake occurring at the worst possible place, directly under Quito, at a focal depth of 12 km.

b) For the damage limit state, with a 50 to 100 year return period, we should perhaps consider a magnitude 5.5 event.

c) For the service limit state, with a 10 year return period, we should perhaps consider a magnitude 5 event.

3) Volcanic Activity : Possible Event 3

The worst possible case would e an eruption of the Pichincha volcano, right next to the city of Quito :



Rv = 2.8 + 0.2 = 3 km

Rh = 10 km

The focal distance is therefore

$$R = \sqrt{R_v^2 + R_h^2} = \sqrt{10^2 + 3^2} = 10.5\ km$$

a) For the collapse limit state, we should consider a magnitude 5 earthquake occurring 5 km below the summit of Pichincha.

b) For the damage limit state, with a 50 to 100 year return period, we should probably not include the possibility of volcanic eruption.

d) For the service limit state, with a 10 year return period, we should probably not include the possibility of volcanic eruption.

4) Other Fault Zones :

Possible Event 4 : An earthquake like Events 12 or 14 (M=6.75) could occur near Ambato or Baeza, at a focal depth of about 40 km and an epicentral distance of 90 km.

Possible Event 5 : An earthquake like Event 13 (M=6.4) could occur anywhere along the fault passing through Baeza and Otavalo. The focal depth would again be about 40 km, and the minimum epicentral distance would be about 50 km.

a) For the collapse limit state, we should consider two events :

Possible Event 4 : magnitude = 7.2
Focal depth = 40 km
Epicentral distance = 90 km

Possible Event 5 : magnitude = 6.8
Focal depth = 40 km
Epicentral distance = 50 km

b) For the damage limit state, with a 50 to 100 year return period, we should again consider two events :

Possible Event 4 : magnitude = 6.75
Focal depth = 40 km
Epicentral distance = 90 km

Possible Event 5 : magnitude = 6.4
Focal depth = 40 km
Epicentral distance = 50 km

c) For the service limit state, with a 10 year return period, we should again consider two events :

Possible Event 4 : magnitude = 6
Focal depth = 40 km
Epicentral distance = 90 km

Possible Event 5 : magnitude = 5.5
Focal depth = 40 km
Epicentral distance = 50 km

5) Ecuadoran Subduction Zones :

Possible Event 6 : An earthquake like Events 18 could occur directly underneath Quito, with a magnitude 5.8 and a focal depth of 128 km.

Possible Event 7 : An earthquake like Events 23 could occur near Riobamba, with a magnitude 5.7 and a focal depth of 180 km, and an epicentral distance of 130 km.

Possible Event 8 : An earthquake like Events 24 could occur in the Pastaza River area, with a magnitude 6.5 and a focal depth of 75 km, and an epicentral distance of 250 km.

Possible Event 9 : An earthquake like Events 17 could occur near Coca, with a magnitude 6.75 and a focal depth of 180 km, and an epicentral distance of 170 km.

Possible Event 10 : An earthquake like Events 19 could occur in ther Amazon River basin, with a magnitude 7.1 and a focal depth of 199 km, and an epicentral distance of 300 km.

a) For the collapse limit state, we should consider 5 events :

Possible Event 6 : a magnitude 6 and a focal depth of 128 km and an epicentral distance of zero.

Possible Event 7 : a magnitude 6 and a focal depth of 180 km, and an epicentral distance of 130 km.

Possible Event 8 : a magnitude 6.8 and a focal depth of 75 km, and an epicentral distance of 250 km.

Possible Event 9 : a magnitude 7 and a focal depth of 180 km, and an epicentral distance of 170 km.

Possible Event 10 : a magnitude 7.3 and a focal depth of 199 km, and an epicentral distance of 300 km.

b) For the damage limit state, with a 50 to 100 year return period, we should again consider 5 events:

Possible Event 6 : a magnitude 5.8 and a focal depth of 128 km and an epicentral distance of zero.

Possible Event 7 : a magnitude 5.7 and a focal depth of 180 km, and an epicentral distance of 130 km.

Possible Event 8 : a magnitude 6.5 and a focal depth of 75 km, and an epicentral distance of 250 km.

Possible Event 9 : a magnitude 6.75 and a focal depth of 180 km, and an epicentral distance of 170 km.

Possible Event 10 : a magnitude 7.1 and a focal depth of 199 km, and an epicentral distance of 300 km.

c) For the service limit state, with a 10 year return period, we should again consider 5 events:
Possible Event 6 : a magnitude 5 and a focal depth of 128 km and an epicentral distance of zero.
Possible Event 7 : a magnitude 5 and a focal depth of 180 km, and an epicentral distance of 130 km.
Possible Event 8 : a magnitude 6 and a focal depth of 75 km, and an epicentral distance of 250 km.
Possible Event 9 : a magnitude 6 and a focal depth of 180 km, and an epicentral distance of 170 km.
Possible Event 10 : a magnitude 6.5 and a focal depth of 199 km, and an epicentral distance of 300 km.

In each limit state, all the possible earthquakes can be tabulated. Using attenuation curves appropriate for the region, the maximum ground acceleration for each earthquake can be estimated. For the purpose of these calculations, the attenuation relationships proposed by McGuire and by Donovan will both be used, for comparison purposes. The calculations can quickly be performed on a spreadsheet.

Critical Earthquakes for Collapse Limit State

Possible Event	Magnitude	Depth (km)	Epicentral Distance(km)	Distance (km)	PGA (g) McGuire	PGA (g) Donovan
1	8.7	46.1	230	234.6	0.09	0.05
2	6.0	12	0	12	0.21	0.18
3	5.0	3	10	10.4	0.12	0.12
4	7.2	40	90	98.5	0.09	0.07
5	6.8	40	50	64	0.11	0.09
6	6.0	128	0	128	0.03	0.03
7	6.0	180	130	222	0.02	0.02
8	6.8	75	250	261	0.02	0.02
9	7.0	180	170	247.6	0.03	0.02
10	7.3	199	300	360	0.02	0.02

Critical Earthquakes for Damage Limit State

Possible Event	Magnitude	Depth (km)	Epicentral Distance(km)	Distance (km)	PGA (g) McGuire	PGA (g) Donovan
1	8.0	46.1	230	234.6	0.06	0.04
2	5.5	12	0	12	0.15	0.14
3	-	3	10	10.4	-	-
4	6.75	40	90	98.5	0.07	0.05
5	6.4	40	50	64	0.09	0.07
6	5.8	128	0	128	0.03	0.03
7	5.7	180	130	222	0.01	0.01
8	6.5	75	250	261	0.02	0.02
9	6.75	180	170	247.6	0.02	0.02
10	7.1	199	300	360	0.02	0.01

Critical Earthquakes for Service Limit State

Possible Event	Magnitude	Depth (km)	Epicentral Distance(km)	Distance (km)	PGA (g) McGuire	PGA (g) Donovan
1	7.0	46.1	230	234.6	0.03	0.02
2	5.0	12	0	12	0.11	0.11
3	-	3	10	10.4	-	-
4	6.0	40	90	98.5	0.04	0.04
5	5.5	40	50	64	0.05	0.05
6	5.0	128	0	128	0.02	0.02
7	5.0	180	130	222	0.01	0.01
8	6.0	75	250	261	0.01	0.01
9	6.0	180	170	247.6	0.02	0.01
10	6.5	199	300	360	0.01	0.01

From the above summary, the following ground motions can be identified as critical in each limit state :

<u>Collapse Limit State</u> :
<u>Possible Events 2 and 3</u> (corresponding to local faults and a nearby volcanic eruption) are serious near-field earthquakes. Near-field earthquakes will be rich in short-period waves, and will be of short duration. Possible Event 2 is more serious, with PGA of 0.21 g (McGuire).
However, Possible Event 1 (corresponding to a large earthquake in the Ecuadoran Trench) is also significant. It would be rich in long period waves, and would be of long duration. This earthquake might provoke significant response of soft soil layers even at very large focal distances. Possible Event 1 has a PGA of 0.09 g (McGuire).

<u>Damage Limit State</u> :
Possible Event 2 (corresponding to local faults) is a serious near-field earthquake. Near-field earthquake will be rich in short-period waves, and will be of short duration. Possible Event 2 has a PGA of 0.15 g (McGuire).
However, Possible Event 1 (corresponding to a large earthquake in the Ecuadoran Trench) is also significant. It would be rich in long period waves, and would be of long duration. This earthquake might provoke significant response of soft soil layers even at very large focal distances. Possible Event 1 has a PGA of 0.06 g (McGuire).

<u>Service Limit State</u> :
Possible Event 2 (corresponding to local faults) is a serious near-field earthquake. Near-field earthquake will be rich in short-period waves, and will be of short duration. Possible Event 2 has a PGA of 0.11 g (McGuire).
However, Possible Event 1 (corresponding to a large earthquake in the Ecuadoran Trench) is also significant. It would be rich in long period waves, and would be of long duration. This earthquake might provoke significant response of soft soil layers even at very large focal distances. Possible Event 1 has a PGA of 0.03 g (McGuire).

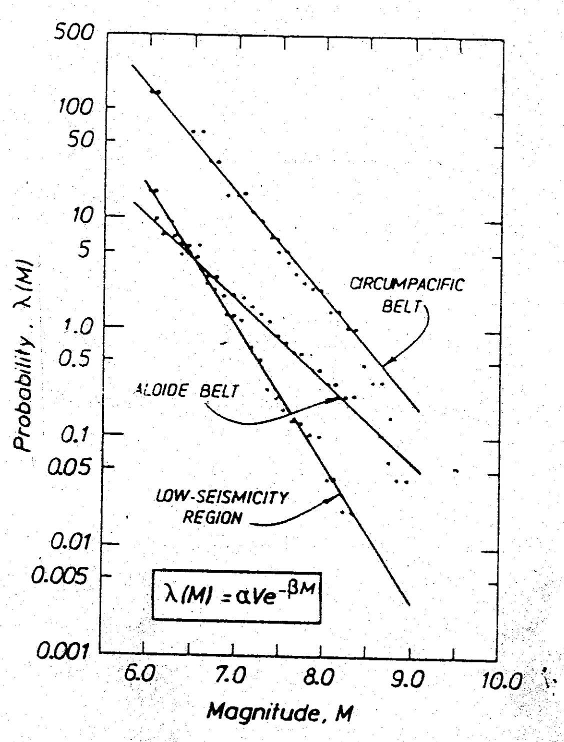
Probabilistic Approaches to Selection of Design Earthquakes

Seismicity is the study of the number and size of earthquakes that have occurred in a given region. If seismicity studies of a region have been done (and they usually have been for seismically active areas), the data can be used to **estimate the probabilities of occurrence of various size earthquakes.** For a given structural limit state, different size earthquakes are chosen as a function of the return period associated with the limit state.

Large earthquakes occur less frequently than small ones. Over much of the range of possible earthquake magnitudes the probability of occurrence (effectively, the inverse of the return period) of earthquakes of different magnitude M are well represented by

$$\lambda = \alpha \ \mathrm{V} \exp(-\beta M)$$

where $\lambda(M)$ is the probability of an earthquake of magnitude M or greater occurring in a given volume V of the earth's crust per unit time, and α and β are constants related to the location of the given volume. Figure below shows data for different tectonic zones compared with predictions of the above equation calibrated to the data by Esteva.



MACROZONE	αV	β
Circumpacific Belt	6.5×10^7	2.16
Aloide Belt	2.8×10^5	1.71
Low-seismicity Region	3.9×10^8	2.82

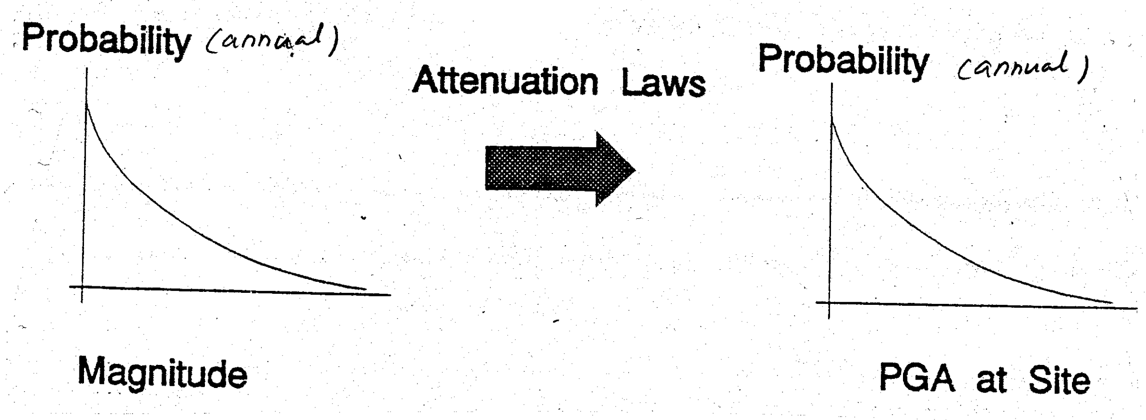
Fig. 2.15 Magnitude–probability relationships.

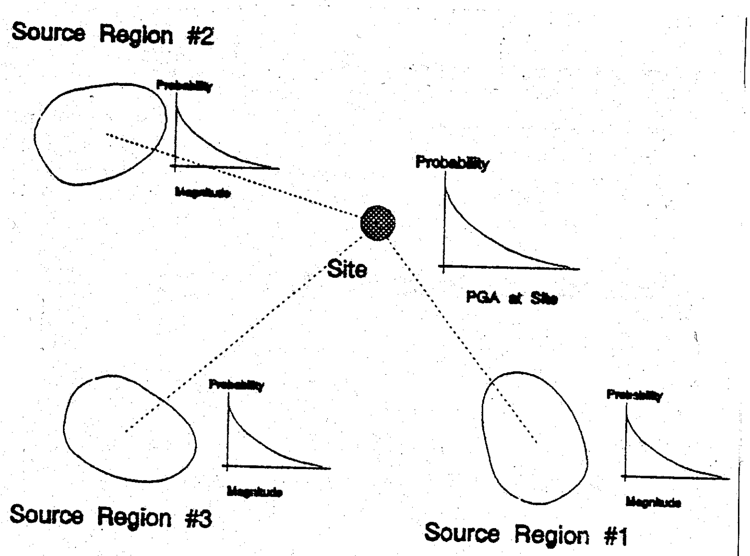
In recent years, probabilistic approaches have been used to prepare seismic risk maps. This requires a probabilistic study of the seismicity of different source regions, and of attenuation between those sources and all possible sites.

It is usually assumed that earthquakes are generated following a Poisson process ; that is , that they are statistically independent of each other in time space, and that their probability at each point is given by a Poisson distribution (i.e. exponential distribution).

Summary of Steps Involved in Probabilistic Selection of Design Earthquakes

1) Divide the Nation (or other region of interest) into known **source regions** and a grid of **sites.**
2) For each source, **the probabilistic relationship between the magnitude and the occurrence** is determined based on the history of the earthquake. The average number of earthquakes per annum of magnitudes greater than or equal to a magnitude from the source is determined.
3) **Using an attenuation law** which is fitted to the region of interest, the magnitude is expressed with a known focal distance(from a site) and design ground motion. Therefore, the annual occurrence which was defined in terms of earthquake magnitude in step 2) is transformed to **the annual occurrence of design ground motion.**
4) For different sources, perform steps 2) and 3).
5) In a site, **the total number of earthquakes per annum** which may result in a peak ground acceleration greater than or equal to a specific ground acceleration can be estimated by **the sum of the occurrence of earthquakes from various sources** which were obtained in steps 2) through 4).
6) **Determine the return periods(or annul occurrence)** which can be allowed to satisfy the limit states.
7) From the probabilistic relationship obtained in step 5), **select design ground acceleration** corresponding to the return period for each limit state.
8) For each return period, **plot contours connecting the sites** with the same design ground motion. As a result, **the national seismic maps** for earthquakes with specific return periods can be developed.





Relationship between annual probability of earthquake and the probability that a building experience an earthquake.

Let p be the annual probability of a given event (a particular level of earthquake) at a given site. The annual probability that the event will not occur (that the particular level of earthquake will not be exceeded) is therefore (1-p). The probability that the event will not occur in 50 consecutive years is therefore $(1-p)^{50}$. The probability that the event will occur at least once in the 50 year period is therefore $(1-(1-p)^{50})$. *Life span of a ordinary building = 50 years*
If this probability is equal to 10%, we can solve for p :

$$(1-(1-p)^{50}) = 0.10$$
$$(1-p)^{50} = 0.90$$
$$p = 2.10 \times 10^{-3}$$
$$1/p = 475.06$$

$$\lim_{x \to \infty} (1 - p)^n = e^{-np}$$

$$(1 - p)^n \approx e^{-np}$$ Poisson distribution

The assumption of a Poisson process is not obvious. Along a given fault zone, the occurrence of earthquakes in a certain region increases the probability of earthquakes in previously inactive regions.

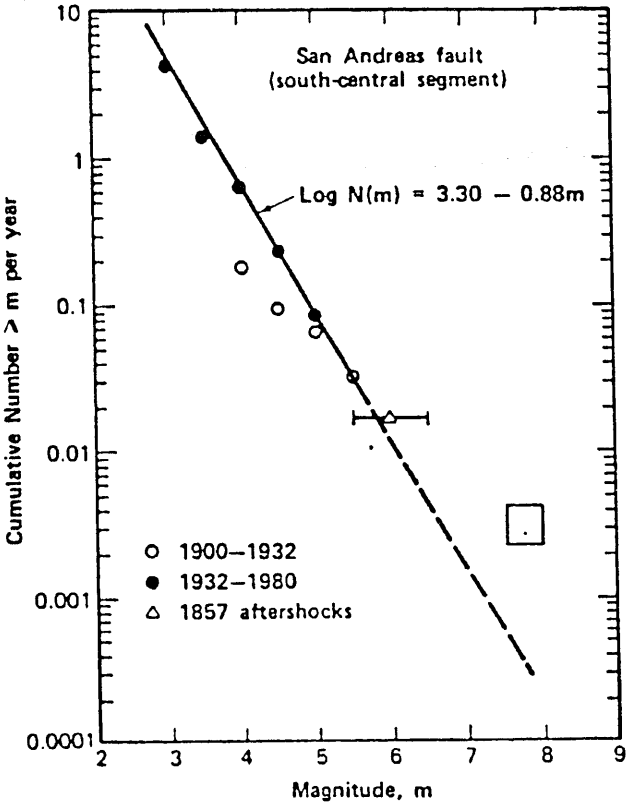


Figure 2-28. Cumulative frequency-magnitude plot. The box in the figure represents range of recurrence based on geological data for earthquake magnitudes of 7.5-8. [After Schwartz and Coppersmith (2-66); reproduced from Idriss (2-33).]

Cornell [2-68] introduced a simplified method for evaluating seismic risk. The method incorporates the influence of all potential sources of earthquakes. His procedure as described by Vanmarcke [2-69] can be summarized as follows:

1. The potential sources of seismic activity are identified and divided into smaller sub-sources (point sources).
2. The average number of earthquakes per annum $N_i(m)$ of magnitudes greater than or equal to m from the ith sub-source is determined from the Gutenberg-Richter relationship (Equation 2-31) as

$$\log N_i(m) = A_i - B_i m \qquad (2\text{-}32)$$

where A_i and B_i are known constants for the ith sub-source.

3. Assuming that the design ground motion is specified in terms of the peak ground acceleration a and the epicentral distance from the ith sub-source to the site is R_i, the magnitude $m_{a,i}$ of an earthquake initiated at this sub-source may be estimated from

$$m_{a,i} = f(R_i, a) \qquad (2\text{-}33)$$

where $f(R_i, a)$ is a function which can be obtained from the attenuation relationships. Substituting Equation 2-33 into Equation 2-32, one obtains

$$\log N_i(m_{a,i}) = A_i - B_i\left[f(R_i, a)\right] \qquad (2\text{-}34)$$

Assuming the seismic events are independent (no overlapping), the total number of earthquakes per annum N_a which may result in a peak ground acceleration greater than or equal to a is obtained from the contribution of each sub-source as

$$N_a = \sum_{all} N_i(m_{a,i}) \qquad (2\text{-}35)$$

4. The mean return period T_a in years is obtained as

$$T_a = \frac{1}{N_a} \qquad (2\text{-}36)$$

In the above expression, N_a can be also interpreted as the average annual probability λ_a that the peak ground acceleration exceeds a certain acceleration a. In a typical design situation, the engineer is interested in the probability that such a peak exceeds a during the life of structure t_L. This probability can be estimated using the Poisson distribution as

$$P = 1 - e^{-\lambda_a t_L} \qquad (2\text{-}37)$$

Development of seismic maps in US

1. Algermissen and Perkins developed isoseismal maps for peak ground accelerations and velocities.

2. ATC (Applied Technology Council)-40 used the map developed by Algermissen and Perkins to develop similar maps for effective peak acceleration A_a and effective peak velocity-related acceleration A_v, corresponding to 10% probability of being exceeded in 50 years. According to McGuire, A_a and A_v are obtained by dividing the spectral accelerations between periods of 0.1 and 0.5 sec and the spectral velocity at a period of 1.0 sec by a constant amplification factor (2.5 for a 5% damped spectrum).

3. 1985, 1988, 1991 and 1994 NEHRP(National Earthquake Hazard Reduction Program) Recommended Provisions for seismic regulations for New buildings (FEMA, Federal Emergency Management Agency, 222a) include the ATC A_a and A_v maps.

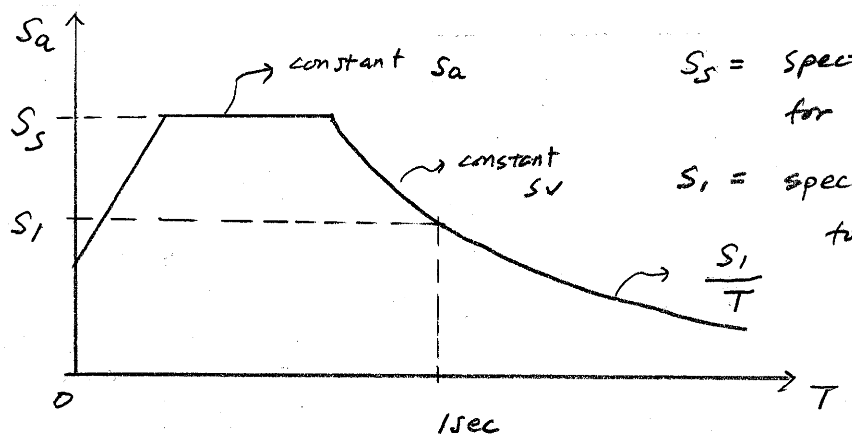
4. 1991 NEHRP provided spectral response acceleration maps for 10% probability of being exceeded in 50 years and for 10% probability of being exceeded in 250 years (a return period of 2375 years). This maps including elastic spectral response accelerations were introduced to present new and relevant data for estimating spectral response accelerations an reflect the variability in the attenuation and in fault rupture length.

5. The 1997 NEHRP introduced the maps corresponding to the maximum considered EQ, defined as the maximum level of earthquake ground shaking that is considered reasonable for design of structures. The maximum considered EQ is defined with a uniform probability of exceeding 2% in 50 years (a return period of approximately 2500 years). The use of the maximum considered earthquake was adopted to provide a uniform protection against collapse at the design ground motion. While the conventional approach in earlier editions provided for a uniform probability that the design ground motion will not be exceeded, it did not provide for a uniform probability of failure for structures designed for that ground motion. In particular, in low and moderate seismic zone, 500 year period is not sufficient to define the maximum earthquake that possibly occurs in the region. Thus, higher return period EQs should be selected to prevent collapse of structures under maximum EQ. The design ground motion is based on a lower bound estimate of the margin against collapse which is judged,

based on experience, to be 1.5: The design ground motion is 2/3 the maximum considered earthquake motion. It is assumed that concrete and steel design codes provide design strengths corresponding to life safety limit state. Thus, the design ground motion corresponding to the life safety limit state is defined as 2/3 value of the maximum considered earthquake motion which corresponds to collapse limit state.

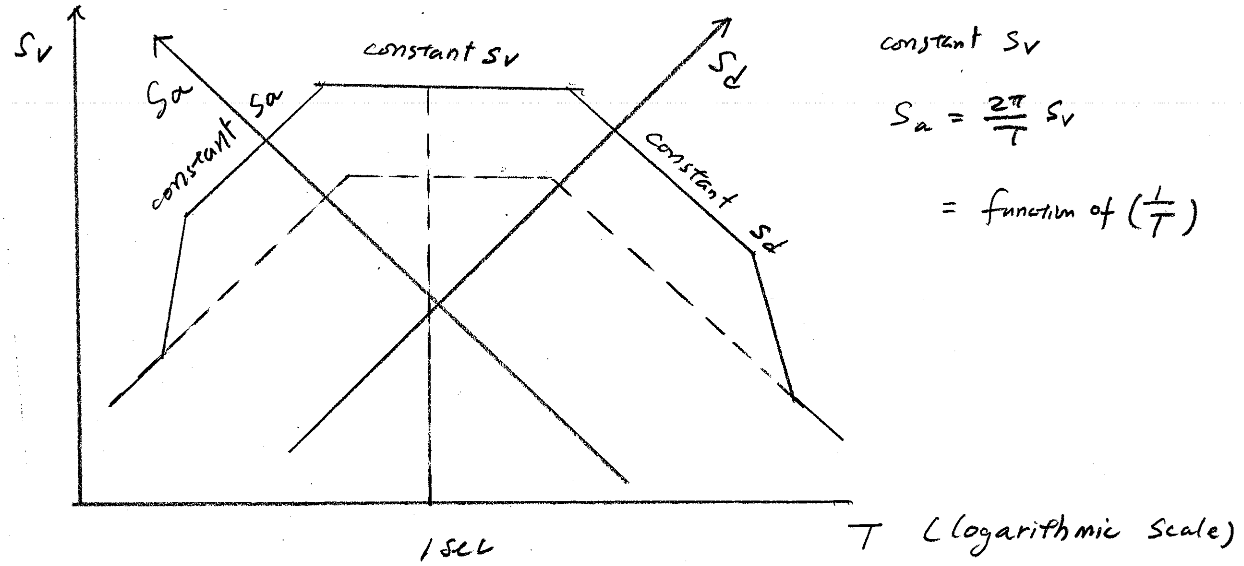
6. The 1997 NEHRP Guidelines for the seismic rehabilitation of buildings (FEMA-273) introduce the performance-based design. Therefore multiple levels of ground shaking need to be defined by the designer. FEMA-273 provides two sets maps: 10% probability of being exceeded in 50 years (Basic safety earthquake 1) and for 2% probability of being exceeded in 50 years (Basic safety earthquake 2). Each set includes spectral accelerations at 0.2 and 1.0 secs.

7. IBC (International Building Code) uses the maps corresponding to the maximum considered EQ, defined as the maximum level of earthquake ground shaking that is considered reasonable for design of structures. They provides 0.2 sec spectral response acceleration Ss and 1.0 sec spectral response acceleration S1. The concept of Ss and S1 in IBC are equivalent to Aa and Av specified in NEHRP



S_s = spectral acceleration for short period

S_1 = spectral acceleration for T = 1sec. (constant velocity regime)



constant S_v

$S_a = \frac{2\pi}{T} S_v$

$= \text{function of } \left(\frac{1}{T}\right)$

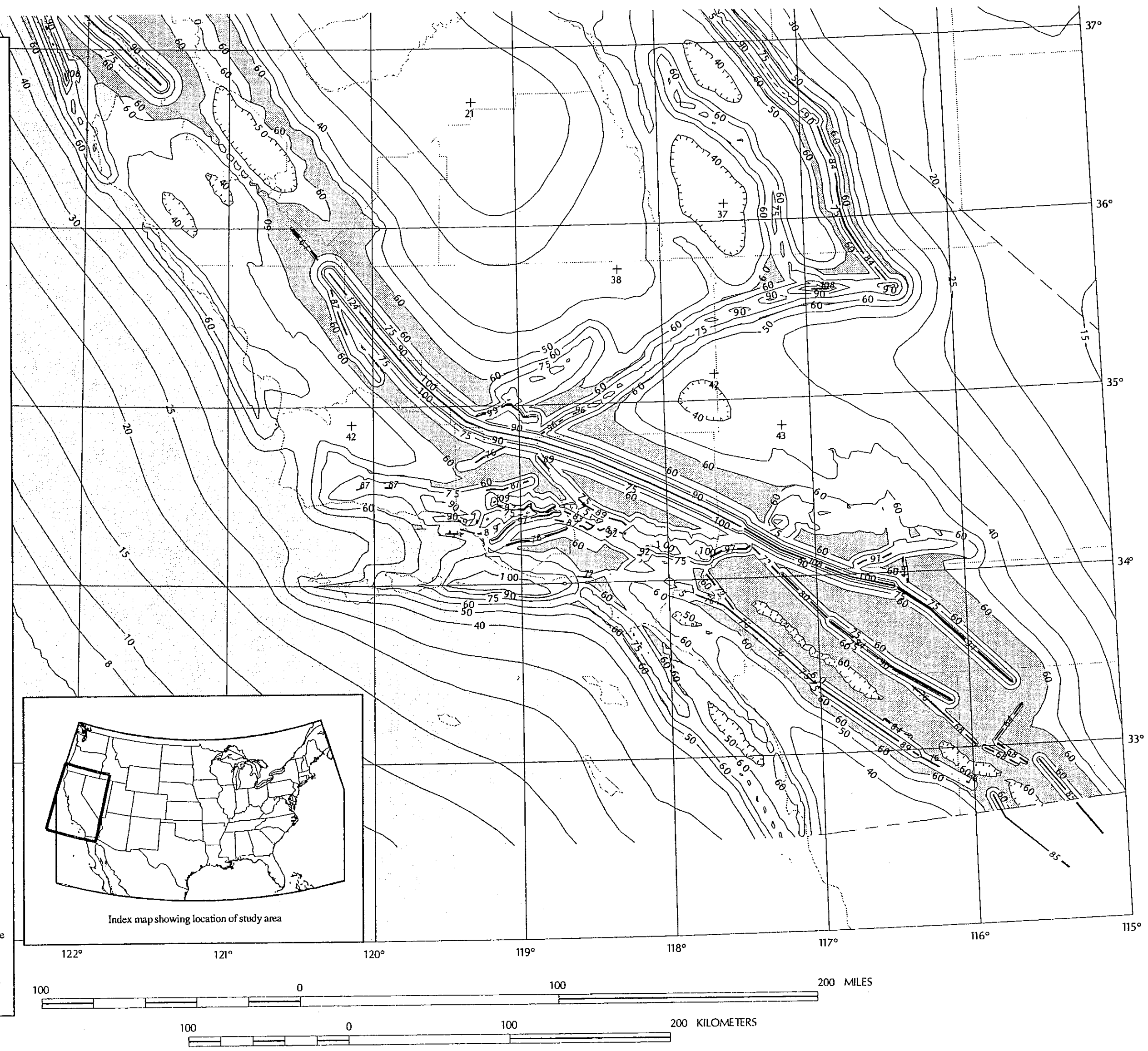
tripartite log. spectrum

$S_d = \frac{1}{\omega} S_v \qquad S_a = \omega S_v$

$\log S_v = -\log T + \log S_d + \log 2\pi \qquad \log S_v = y \text{ axis}$

$\log S_v = +\log T + \log S_a - \log 2\pi \qquad \log T = x \text{ axis}$

3-33



Explanation

Contour intervals, % g

— 150 —
— 125 —
— 100 —
— 90 —
— 75 —
— 60 —
— 50 —
— 40 —
— 30 —
— 25 —
— 20 —
— 15 —
— 10 —
— 8 —
— 6 —
— 4 —
— 2 —
— 0 —

Note: contours are irregularly spaced

[shaded box] Areas with a constant spectral response acceleration of 60% g

+ 6.2 Point value of spectral response acceleration expressed as a percent of gravity

— 10 — Contours of spectral response acceleration expressed as a percent of gravity. Hachures point in direction of decreasing values.

— 248 — Locations of faults (see DISCUSSION). The number on the fault is the median spectral response acceleration times 1.5, expressed as a percent of gravity.

DISCUSSION

A line shown as a fault location is the projection to the earth's surface of the edge of the fault rupture area located closest to the earth's surface. Only the portion of the fault used in determining design values is shown. The number on the fault is the deterministic median spectral response acceleration times 1.5. The values on the fault portion shown may be used for interpolation purposes.

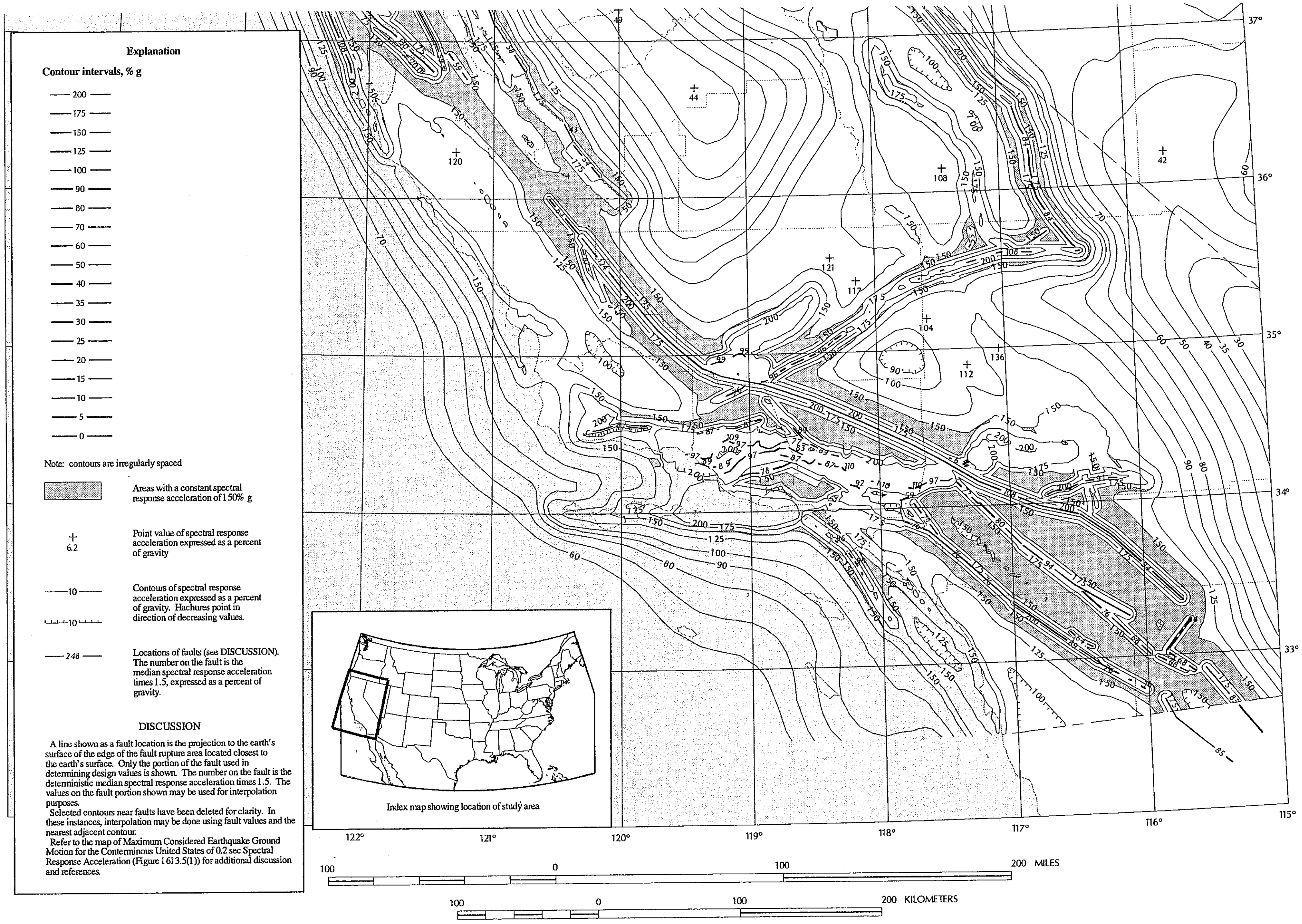
Selected contours near faults have been deleted for clarity. In these instances, interpolation may be done using fault values and the nearest adjacent contour.

Refer to the map of Maximum Considered Earthquake Ground Motion for the Conterminous United States of 1.0 sec Spectral Response Acceleration (Figure 1613.5(2)) for additional discussion and references.

<S, map>

FIGURE 1613.5(4)—continued
MAXIMUM CONSIDERED EARTHQUAKE GROUND MOTION FOR REGION 1 OF 1.0 SEC SPECTRAL RESPONSE ACCELERATION (5% OF CRITICAL DAMPING), SITE CLASS B

3-34



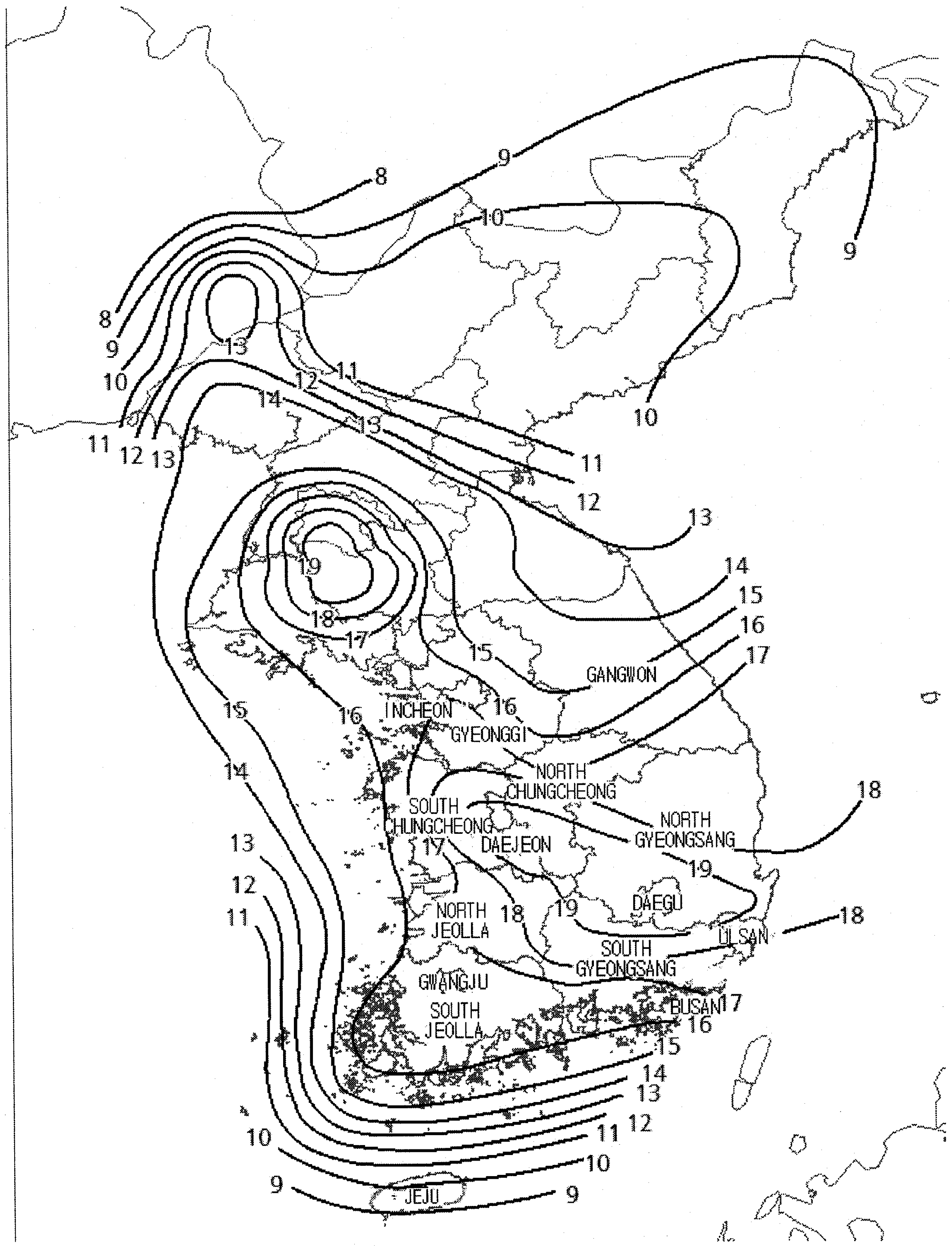
<S5 map>

FIGURE 1613.5(3)—continued
MAXIMUM CONSIDERED EARTHQUAKE GROUND MOTION FOR REGION 1 OF 0.2 SEC SPECTRAL RESPONSE ACCELERATION (5% OF CRITICAL DAMPING), SITE CLASS B

Development of seismic maps in Korea

1. In 1988, for the first time, the earthquake design code for buildings was developed. In the code, the design ground acceleration 0.12 g specified in the code was regarded as that related to earthquake with 500 year return period. In concrete and steel design for earthquake, load factors greater than 1.0 was used for the earthquake load combination. According to the Building law at that time, only buildings more than 5 stories are required to be designed for earthquake loads. Low-rise and small buildings were exempted from the earthquake design.
2. In early 1990's, earthquake design was introduced in the bridge code (1992).
3. In 1997, a project " 내진설계기준연구 II" was performed. In the project, studies for establishing seismic maps of Korea were performed. The seismic maps for the earthquakes with 100, 500, 2500 year return periods were developed by the seismologists in Korea.
4. In year 2000, in 건축물하중기준, the design ground acceleration was changed from 0.12g to 0.11g. based on the result of " 내진설계기준연구 II".
5. In ~~1995~~ 2005, Korean Building Code (KBC) -2005 came into effect. In KBC, the design acceleration was defined based on the 2400 year return period earthquake, following IBC. Also, the shape of the response spectrum and the soil factors were revised following that used in IBC. Considering the inherent safety margin of structures, the design ground motion was determined as 2/3 the maximum considered earthquake motion. Since the 2400 year return period earthquake was considered as the probable maximum earthquake, the load factors for material design were set to 1.0.
6. In Year ~~2005~~ 2015, the building law was revised so that all buildings over two stories are designed for earthquake load.
7. Currently, KBC-2016 is being under review for publication. In KBC-2016, the soil factors were revised, considering the shallow soil depth in Korea. Further, performance-based earthquake design was included for the first time, in Korea (In EQ design, the earthquake load depends on the deformation capacity of the structure.).

3-36



[Fig. 0306.3.1] SEISMIC HAZARD MAP, EFFECTIVE GROUND ACCELERATION(S, %) OF MAXIMUM CONSIDERED EARTHQUAKE WITH A 2400-YEAR MEAN RECURRENCE INTERVAL; (NATIONAL EMERGENCY MANAGEMENT AGENCY, 2013)

1. 우리나라에서도 1988년에 가장 먼저 건축물에 내진설계기준이 도입되었고 당시 미국 UBC (uniform building code)의 zone II (중약진지역) 의 지진강도를 모델로 하여 내진설계기준이 법제화되었습니다. 이후에 건축기준의 영향을 받아서 1992년 교량등 infrastructure 에 대한 내진설계기준들이 도입되었습니다.

2. 내진설계기준에서 지진하중은 확률적으로 정의되는데 (그 이유는 대형지진은 일어날 가능성이 크지 않기 때문) 전통적으로 50년동안(건축물의 life span) 적어도 1번 발생할 가능성이 10%인 지진으로 정의해 왔습니다.
그에 해당하는 지진이 500년 재현주기 지진입니다.

3. 그러나 오랜기간 전세계적인 지진피해를 연구해온 지진학자들과 미국 fema 등 재난대책관리기관에서는 다음과 같은 문제점을 발견하게 됩니다.
즉, "중약진지역(우리나라와 같은 지진의 크기)에서 대형지진이 발생할 가능성이 적기는 하지만 발생할 가능성이 있고 그러한 지진이 발생하는 경우, 막대한 피해를 입힐 수 있기 때문에 이에 대한 대비가 필요하다."

4. 따라서 미국의 새로이 통합된 건축기준인 IBC(international building code)기준에서는 지진하중을 정의하는 지진의 크기를 새로이 정의하게 되는데 그 개념은 가능성이 있는 최대지진 (maximum considered earthquake)에 대하여 설계한다는 것입니다.
이 최대지진은 재현주기 2400년의 지진으로 정의하게 됩니다.
따라서 붕괴방지 수준의 지진은 2400년 재현주기(최대지진)으로 정의하게 됩니다.

5. 지진하중이 적용되는 일반적인 건축물들의 설계기준(콘크리트구조, 강구조)들이 제시하는 강도내력은 인명안전수준으로 판단되어 IBC 기준의 설계지진하중은 인명안전수준으로 환산하여 2400년 주기 최대지진하중의 2/3 값으로 정의하고 있습니다.

6. 우리나라에서도 1988년 도입된 내진설계기준을 유지하다가 2005년 KBC (korean building code)의 체계로 바뀌면서 IBC와 동일한 지진하중정의를 사용하여 붕괴방지수준의 지진하중을 2400년 재현주기의 지진으로 정의하고 그것의 2/3 값을 인명안전수준의 설계지진하중으로 정의하여 건축물의 설계에 사용하고 있습니다.

7. 지진하중의 정의가 달라지면서 지진하중의 크기가 커지지 않았는지에 대하여 의문을 가질 수 있는데, 이는 그렇지 않습니다.
1988년 지진하중도입당시 설계지반가속도가 0.12g 였습니다. (후에 0.11g로 조정)
그런데 그 당시는 콘크리트기준과 강구조기준을 설계할때 지진하중계수를 곱하여 설계하였기 때문에 실제로 건축물의 내진설계시에 사용하는 지반가속도는 0.11 x 1.3 =0.143g 이었습니다.
설계지진을 2400년재현주기로 정의를 수정한 이후에는 2400년재현주기에 대한 지반가속도는 0.22g 이고, 설계에는 이값의 2/3를 사용하므로 0.147g 입니다. 그러나 이때 이 지진하중은 극한하중으로 취급되어 구조물의 설계기준에서 하중계수가 1.0으로 조정되었습니다.
따라서 설계지반가속도와 지진하중의 크기는 변동이 없습니다.(0.143g vs 0.147g) 지진하중의 개념만 달라졌을 뿐입니다.

따라서 건축물의 내진설계에 사용하는 기본적인 지진하중의 크기는 제정된 1988 년부터 변함없이 유지되고 있어서 국가기준의 연속성이 확보되고 있습니다.
물론 기타 설계계수들의 조정은 있었습니다.

8. 지진하중은 설계지반가속도 뿐만아니라 반응수정계수(연성도)등 다양한 설계변수에 영향을 받습니다. 구조물의 형태와 구법이 다르기 때문에 지진발생시에 구조물의 연성도가 큰 차이가 있고 따라서 동일한 설계지반가속도라고 하더라도 건축물의 설계지진하중과 교량의 설계지진하중은 크게 다릅니다.

1962 년 **건축법 제 10 조** : 건축법에 따른 내진 안전성. 건축물은 지진 등에 안전한 구조를 가져야 한다.
1987 년 **내진설계지침서에 관한 연구** : 대한건축학회
1988 년 **건축물의 구조기준 등에 관한 규칙**, 건설부령 제 432 호 개정 1992 년 2 월, 1995 년 12 월 일부 개정 : 대한건축학회 연구(AIK1988), 1985 년 멕시코지진에 의한 피해 발생 우리나라 내진설계의 필요성 제기
1997 년 **지진공학회 연구(EESK1997)** : 내진설계 상위 개념과 관련 수행. "내진설계기준연구"에서 제시한 방법. UBC97 의 방법의 채택
2000 년 **대한건축학회 연구(AIK2000)** : 1994 년 노스리지 지진(미국), 1995 년 고베지진 (일본). 기본구성은 AIK1988 과 같음. EESK 1997 을 바탕으로 일부 개정
2005 년 **건축구조설계기준연구(KBC2005)** : 지반가속도는 EESK 1997 의 제안값 사용. 설계응답스펙트럼등의 설계 방법은 IBC 2000 에 의한 방법 채택
2009 년 **건축구조기준(KBC2009)** : 대한건축학회
2016 년 **건축구조기준(KBC2016)** : 대한건축학회. 지반계수, 성능기반설계도입, 면제진장치

CURRENT DESIGN RESPONSE SPECTRA

Table 1 and Figure 1 compare the site class criteria and the corresponding design response spectra of eight current design codes. The effective peak ground acceleration of the design response spectra was normalized as 0.4g, except for the Canadian code, Australia, and New York City. For the Canadian code (Figure 1 (d)), 0.44g (PGA for Vancouver) was used. For moderate seismic zones of Australia and New York City, respectively, 0.13g and 0.24g were used.

Table 1. List of current design codes

Codes	Nation (Year)	Seismic hazard Probability	Site class criteria	T_2 (s) [1)]
IBC 2009	USA (2009)	2% in 50 years x 2/3	$V_{S,30}$ [2)]	-
NYCDOT	USA (1998) New York	10% in 50 years 2% in 50 years x 2/3	$V_{S,30}$	-
EuroCode 8	EC (2003)	10% in 10 years 10% in 50 years	$V_{S,30}$	2.0
NBCC 2005	Canada (2005)	2% in 50 years x 2/3	$V_{S,30}$	2.0
BCJ	Japan (1997)	50% in 30 years 10% in 50 years	T_G [3)]	-
GB50011-2001	China (2001)	Site dependent	T_G	$5T_G$
MOC-2008	Mexico (2008)	Site dependent	T_G	2.0
AS1170.4	Australia (2007)	10% in 50 years	T_G	1.5

[1)] T_2 = long-period transition period defining the constant-displacement range
[2)] $V_{S,30}$ = average shear-wave velocity of the top 30m soil
[3)] T_G = site period

Figure 1(a) shows the design response spectrum of IBC 2009 [1]. The site class criteria is the average shear wave velocity $V_{S,30}$ of top 30m soil from the surface. The short-period amplification factor F_a and the mid-period amplification factor F_v, are defined according to the site classifications from S_A to S_E. The amplification of response spectrum is determined by the F_a and F_v.

Since the site classification of the IBC 2009 does not properly address the effect of shallow soil deposits, the New York City Department of Transportation (NYCDOT) published a design guideline containing new design response spectra for the New York City area where the soil depths to bedrock are relatively shallow (Figure 1(b)) [2]. The site class criteria is the same as IBC 2009: $V_{S,30}$. For stiff rock sites of S_A and S_B, the constant-acceleration range does not exist. For very soft soil of S_E, the amplification of the short-period acceleration is the same as that of S_D while the amplification of the long-period acceleration is greater.

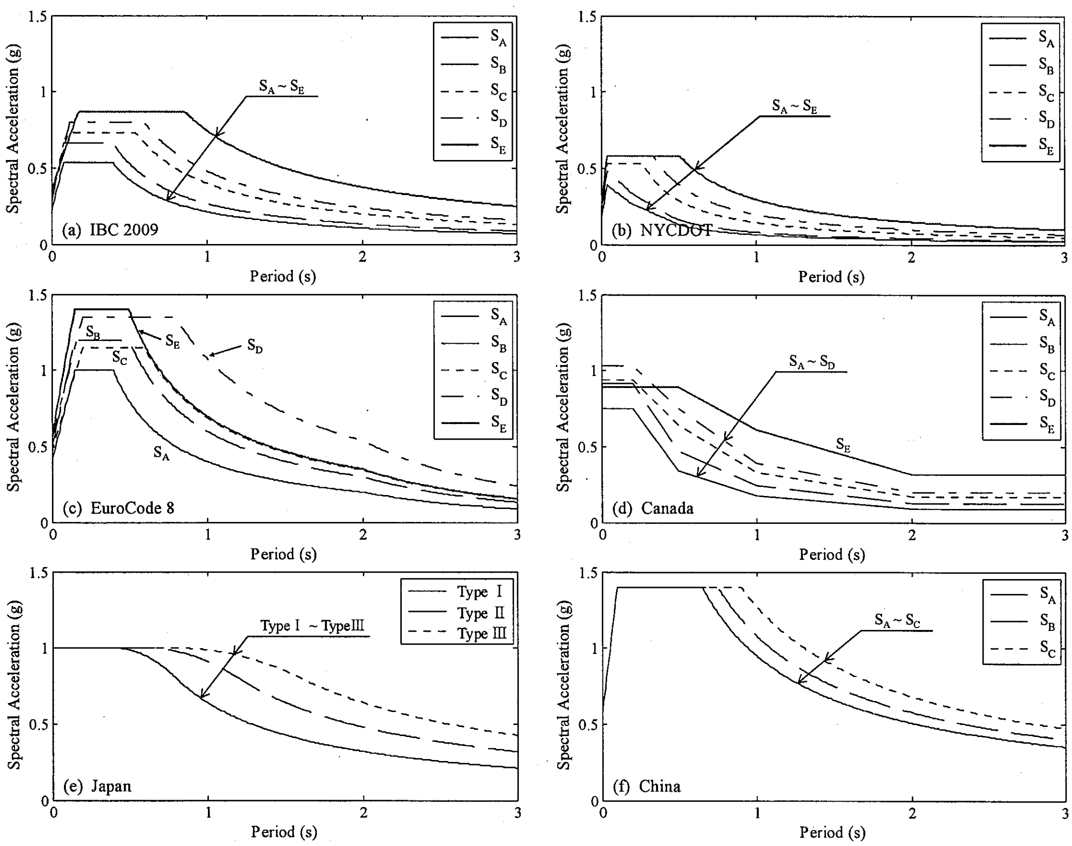
Figure 1(c) shows the design response spectra of EuroCode 8 (European Committee for Standardization) [3]. The site class criterion is the same as $V_{S,30}$ which is used in IBC 2009. However, the site classes S_A, S_B, S_C and S_D correspond to S_B, S_C, S_D and S_E in IBC 2009, respectively. When the soil depth to bedrock is less than 30m and the property of the stiff bedrock is included in the estimation of $V_{S,30}$, the site class is categorized as S_E. In this case, the short-period acceleration of S_E is greater than that of S_D, while the long-period acceleration is close to that of S_C, which is less than that of S_D. This trend of the design response spectrum for the shallow soil depth is similar to the results of previous studies [4-6] reporting that only the short-period accelerations are amplified by shallow soil deposits. In the EuroCode 8, the constant-displacement range is defined for the structures with periods greater than 2.0s. The spectral acceleration of the constant-displacement range is defined as the function of $1/T^2$.

In the Canadian code (Figure 1(d)), the site class criteria is $V_{S,30}$, and the design accelerations are defined by using linear interpolation between the values at the periods 0.2, 0.5, 1.0, and 2.0s [7]. From the S_A to S_D sites, the spectral acceleration gradually increases. In case of S_E, the short-period acceleration is smaller than that of S_B, but the long-period acceleration is greater than that of S_D. For the periods greater than 2.0s, a constant acceleration is used.

Figures 1(e) and (f) show the design response spectra of Japan and China [8], [9]. Unlike other design codes, the site class criteria is defined by the site period T_G, and only three site classes are used. The short-period acceleration is uniform regardless of the site classes, while the long-period acceleration increases with the site period. In the Chinese code, a constant-displacement range is used for the periods greater than $5T_G$.

In the Mexican code [10], the spectral accelerations are defined by the site period. As the site period increases, the short-period accelerations decrease, and the long-period accelerations increase or decrease (Figure 1(g)). However, the difference in the spectral accelerations according to the site period is not significant, when compared to other design codes. As shown in the figure, the shape of the response spectrum curve varies with the site class. This is because the site amplification factor is defined addressing the resonance between the site and structures: In case of soft soil, an amplitude reduction factor is used to address the damping effect due to the nonlinear behavior of soft soil; and to consider the decrease of the soil stiffness, a site period shift factor is used. For the structure periods greater than 2.0s, the spectral acceleration in the constant-displacement range is defined as the function of $1/T^2$.

Figure 1(h) shows the design response spectra in the Australian code [11]. While other design codes defines the spectral accelerations using the period - acceleration (*T-A*) relationship, the Australian code uses the spectral displacement - acceleration (S_d-S_a) relationship. By using the short-period amplification factor and the mid-period amplification factor, the highest acceleration and velocity spectral values (RSA_{max} *and* RSV_{max}) are computed. The period T_2 for the definition of the constant-displacement range is 1.5 sec.



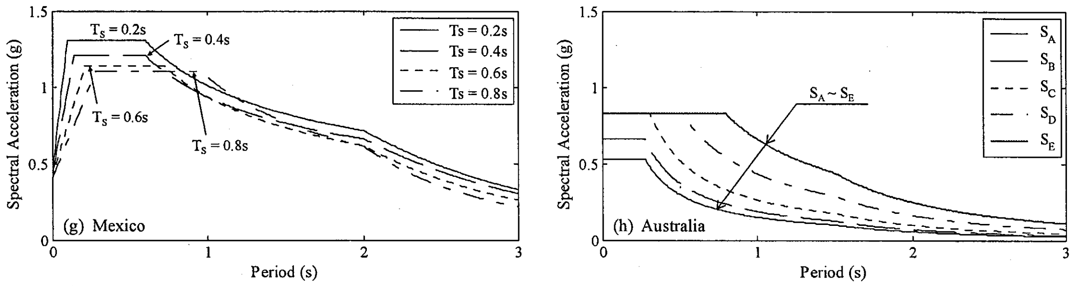


Figure 1. Current design response spectra