PLANT ENGINEERING IN EARTHQUAKE COUNTRY

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Abstract

Plant equipment has suffered major damage in past earthquakes. Elevators, heavy tanks and motors, lighting fixtures, and unsupported equipment have been damaged causing plant down time and requiring expensive repairs. Historical review of earthquakes and the damage they cause has led to design and retrofit recommendations that will greatly increase the seismic preparedness of plant equipment.

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I. Introduction

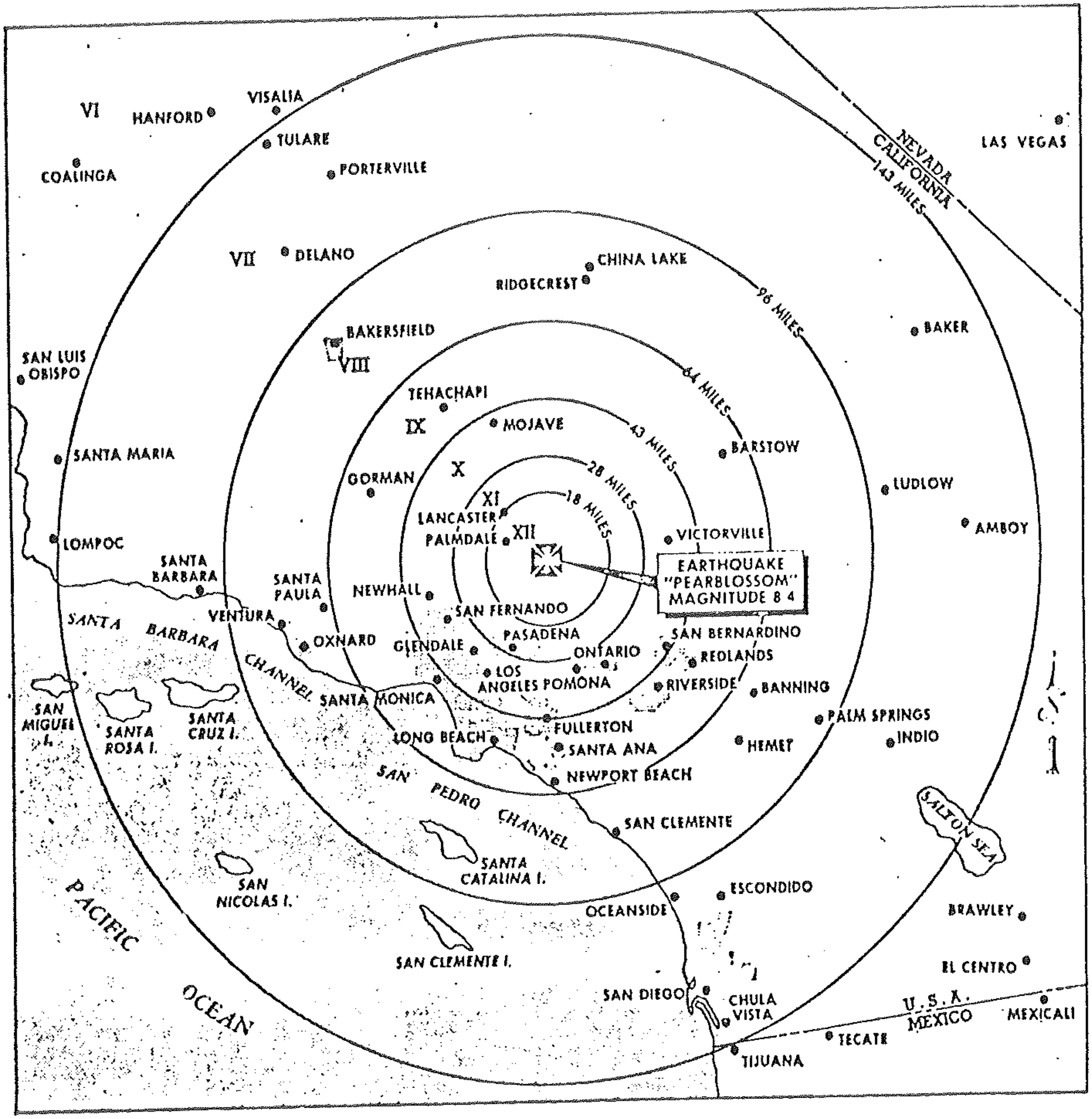
People often ask if there will be a large earthquake in the Los Angeles area. The question is not if, but when. The "Pearblossom" scenario developed by Duke[1] points out that there is a 15 percent probability that the Los Angeles basin will experience at least one major earthquake during each century. Using typical locations for such an earthquake, Duke estimates the felt area, intensity patterns, types of damage, and damage consequences (see Figure 1). His study indicates that 2000 to 3000 people could be killed and damage would be in the range of 40-50 billion dollars. Approximately 40,000 structures would collapse, many more would be damaged, and freeways and overpasses would fail on a large scale.

During the "Pearblossom" earthquake and as has occurred in the past, many buildings and especially plant equipment suffer major damage. During the San Fernando earthquake of 9 February 1971, most buildings in the Los Angeles area survived the earthquake without serious structural failures. In many of these buildings, however, elevators, mechanical systems, lighting fixtures, air conditioning systems, ceilings, partitions, window glass, electrical panels, motors, generators, and storage racks were extensively damaged.[2]

In most cases this damage to plant equipment could have been avoided with proper design, bracing, and choice of equipment. Several groups of engineers, equipment manufacturers, and government agencies have produced standards for guiding the design and retrofitting of plant equipment to survive earthquakes. This paper will review the

FIGURE 1

HYPOTHETICAL QUAKE



sources of earthquakes, how they cause damage, and how your plant equipment can be made to withstand earthquakes safely.

II. Earthquakes

Earthquakes are naturally occurring events within the earth which generate elastic waves. They have probably rocked the earth since its formation and have been analyzed by everyone from the ancient Babylonian philosophers to modern day seismologists.(3) Griffin (4) indicates that many hypotheses of earthquake causes were offered until the general acceptance of at least two modern theories: (i) "elastic rebound" and (ii) the "dilational source theory." The first, and the more popular, was formulated soon after the great California earthquake of 1906. H.F. Reid hypothesized that the earth's crust was slowly distorted and that the resulting elastic strains stored potential energy in crustal rock strata. This slow displacement is due to relative motion of several great continental plates drifting on the viscous mantel of the earth.(5) When the strains and corresponding stresses become greater than the shear strength of the rock strata, the rock ruptures, causing an earthquake. As the rock ruptures, it rebounds to an unstrained state and released all stored potential energy in the form of elastic waves which propagate outwards. The passage of these waves is felt as vibrations in the ground, while the rupture, also referred to as a "fault," will often reach the surface and create relative ground displacements.

Earthquakes can give rise to several types of damaging phenomena.

Ground vibrations with accelerations equal to the acceleration of gravity (1 g) are possible and can cause failure of structures many miles from the location of the rupture (hypo-center). Structures located on or across a surface fault can be damaged by relative displacements as great as five meters (∿ 15 feet). This vibration and faulting can also cause soil failures such as landslides and loss of bearing capacity (soil liquefaction). Vibration and faulting near or under bodies of water cause tsunamies (tidal waves) which can result in coastal waves tens of meters in height and equally destructive seiches in lakes.

The great emphasis on earthquake faults is essential because relations exist between the length of a fault and the magnitude of an earthquake that can occur along the fault.* Data applicable to California and Nevada are shown in Figure 2 where the magnitude of a potential earthquake is plotted vs. the length of the fault. The magnitude of an earthquake is a measure of the size of an earthquake and is related to the energy released in the form of seismic waves. "Magnitude" means the numerical value on a Richter scale. Thus, we see that a magnitude 8.4 earthquake (such as "Pearblossom") is to be anticipated from a fault break of length 1000 kilometers (∿ 600 miles). The magnitude 6.5, 9 February 1971 San Fernando earthquake, however, came from a fault of about 20 kilometers. Many variables affect the data, such as the length of break in the fault, geography, geology, and the depth of earthquake focus. Extensive studies are required to arrive at final results.

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*See Appendix A for definition of earthquake magnitude.

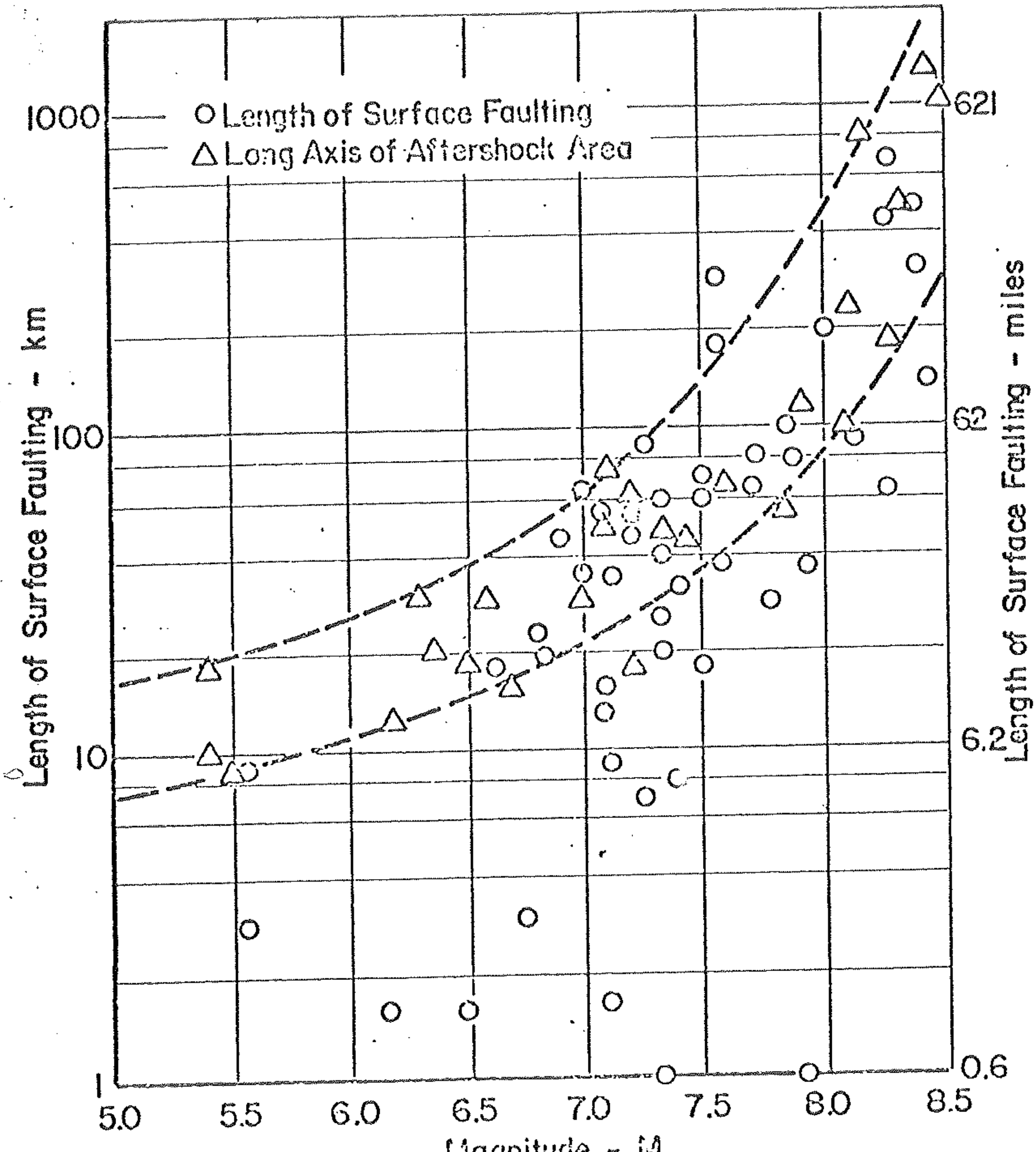


Fig. 2 RELATIONSHIP OF MAGNITUDE TO FAULT LENGTH
(Albee and Smith, 1966)

A relation also exists between an earthquake's magnitude and intensity. The intensity of an earthquake is a measure of its effects on man, man-built structures, and on the earth's surface at a particular location. An earthquake has one magnitude but its intensity varies over the felt area. "Intensity" means the numerical value on the Modified Mercalli Scale (see Appendix A). The relation between magnitude and intensity is even more uncertain than the relation between magnitude and fault length. Correlations exist between maximum ground acceleration and intensity (3,4) and between acceleration and distance from the fault. These correlations are only approximate because local geology, site conditions, nearby structures, and the size of earthquake can change the relationships.

In Figure 3, the estimated acceleration-distance-magnitude relationship is presented.[6] These are values of horizontal acceleration. Vertical acceleration is usually less than or equal to horizontal values. Within ten kilometers ($\sim$ 6 miles) of the epicenter* of Pearblossom (8.4 magnitude), we anticipate over 1 g acceleration (1 g = the vertical acceleration due to earth's gravity = 9.8 meters/sec^2 = 32.2 ft/sec^2). The acceleration decreases to less than 0.2 g for greater than 80 kilometers (50 miles) from the epicenter. For the 6.5 magnitude San Fernando earthquake, we find maximum epicential acceleration of about 1.0 g, which, in fact, was observed. 64.4 kilometers (40 miles) away, 0.15 g would occur, and in fact was observed in sections of Los Angeles.

In the western United States, it is usually possible to correlate

*Hypocenter is subsurface location of rupture; epicenter is surface location on top of hypocenter.

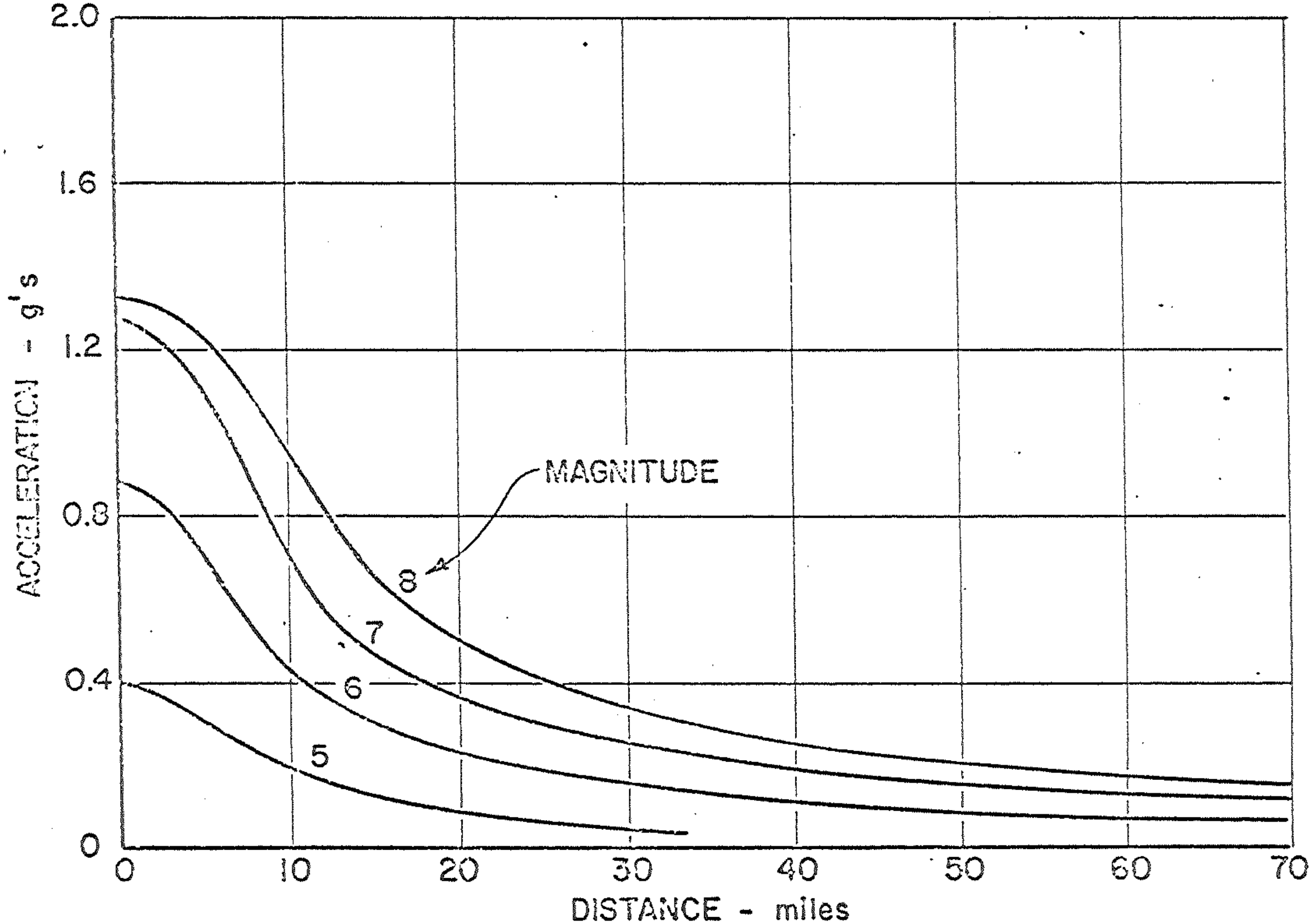


Fig. 3 ESTIMATED ACCELERATION-DISTANCE-MAGNITUDE RELATIONSHIPS

occurrence and magnitude of earthquakes with known active faults. The seismicity of the eastern United States is considerably less than that of the West; however, there have been a number of large earthquakes in the eastern region. In the East, the earthquake sources are not well understood and, presently, we must depend almost completely on meager historic records to project a future pattern of earthquake occurrence and magnitude.

III. Earthquake Damage to Plant Equipment

This paper is not concerned with damage to plant equipment due to structural failure of the building itself; instead, it is concerned with damage to equipment due to building vibration. The San Fernando earthquake offered many examples of equipment damage without building collapse. Much of the discussion below comes from the extensive studies of non-structural damage carried out after this earthquake.(2)

Elevator systems in the Los Angeles area were significantly damaged by the earthquake. Hundreds of counter weights were thrown out of their guide rails and many struck cars moving in the opposite direction. Debris from crushed shaft walls fell on cars. Elevator motors shifted off their basis and ripped out electrical conduits. Hydraulic elevators faired much better than traction units.

Earthquake-resistive design for elevators should consider the following:(2)

1. Vibration isolators under generators should be bolted to the floor and to the generator legs. Isolators should have sufficient strength to withstand the earthquake forces, or be provided with snubbers to limit the amount of lateral movements.

2. Selector and controller panels should be bolted to the floor and provided with sway braces at the top. All electrical components within the panels should be secured to the panel frame and all doors and hinged panels fitted with positive locking latches.

3. Counterweight guide rails should be heavier than the typical 8 pounds per foot rolled steel section and installed with improved brackets.

4. Safety shoes for roller guides, similar to that shown in Figure 4, should be provided to protect the roller assemblies.

5. A manually reset safety switch should be mounted on the counterweight guide rail assembly to shut off the power when counterweights are derailed. Signal transmission using wireless methods should be considered to avoid additional wires in the hoistway.

6. Ventilation, communication, and lighting systems in the cars should be connected to an emergency power system designed to operate when the normal power system fails.

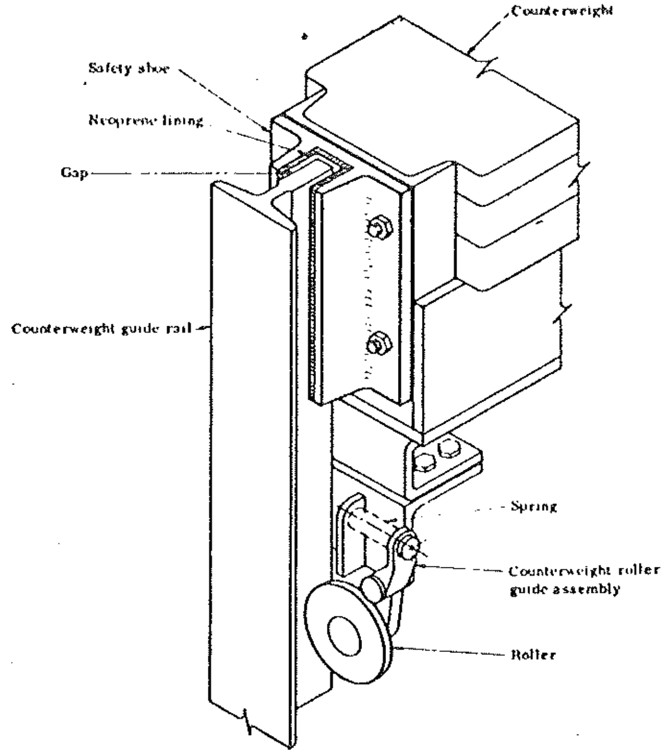
7. High-rise buildings with multiple elevators and other buildings with critical occupancies should have at least one elevator connected to an emergency system.

8. Elevator hoistway and surrounding structural system should be reinforced adequately and braced to prevent distortion at the door openings and minimize breakage of the wall materials.

9. A screen should be installed on the tops of cars to catch falling debris.

Mechanical systems--boilers, furnaces, flues, chimneys, plumbing, tanks, piping, fans, ducts, refrigeration compressors, water chillers, cooling towers, evaporative condensors, etc.--survived the San Fernando earthquake better than elevator systems. Electrical panels, tanks, and other tall heavy equipment occasionally fell over if they were not braced at the top. Cabinets without locking latches and

FIGURE 4



-Proposed safety shoe design to prevent damage to counterweight roller guide assembly.

storage shelves often emptied their contents onto the floor. Heavy equipment not bolted to the floor shifted up to several feet and severed fuel, electrical, and control lines. Equipment on vibration isolation elements often broke loose. Molded neoprene mounts faired better than spring isolators and other designs.

Fire sprinkler systems faired well, probably due to National Fire Protection Association (NFPA) regulations (Standard 13) requiring lateral bracing for 50 percent of dead load and flexible joints. The failure of piping systems was usually due to differential displacement between support points. Mechanical joints faired better than threaded joints. Piping fans, ducts, and diffusers faired well when lateral bracing was present. Pendular lighting fixtures sustained heavy damage if support details and safety wires were not adequate. Recessed lighting faired well.

Earthquake resistant design of mechanical systems should consider the following:[2]

1. Vibrating and noisy equipment should be located away from critical occupancies, so the equipment can be anchored to the structure and vibration isolation is not required.

2. Avoid mounting heavy equipment on the top or upper floors of tall buildings, unless all vibration isolation mounts and supports are analyzed carefully for earthquake-resistant design.

3. When equipment and attached piping must be isolated from the structure by vibration isolators, provide lateral constraints similar to those shown in Figure 5.

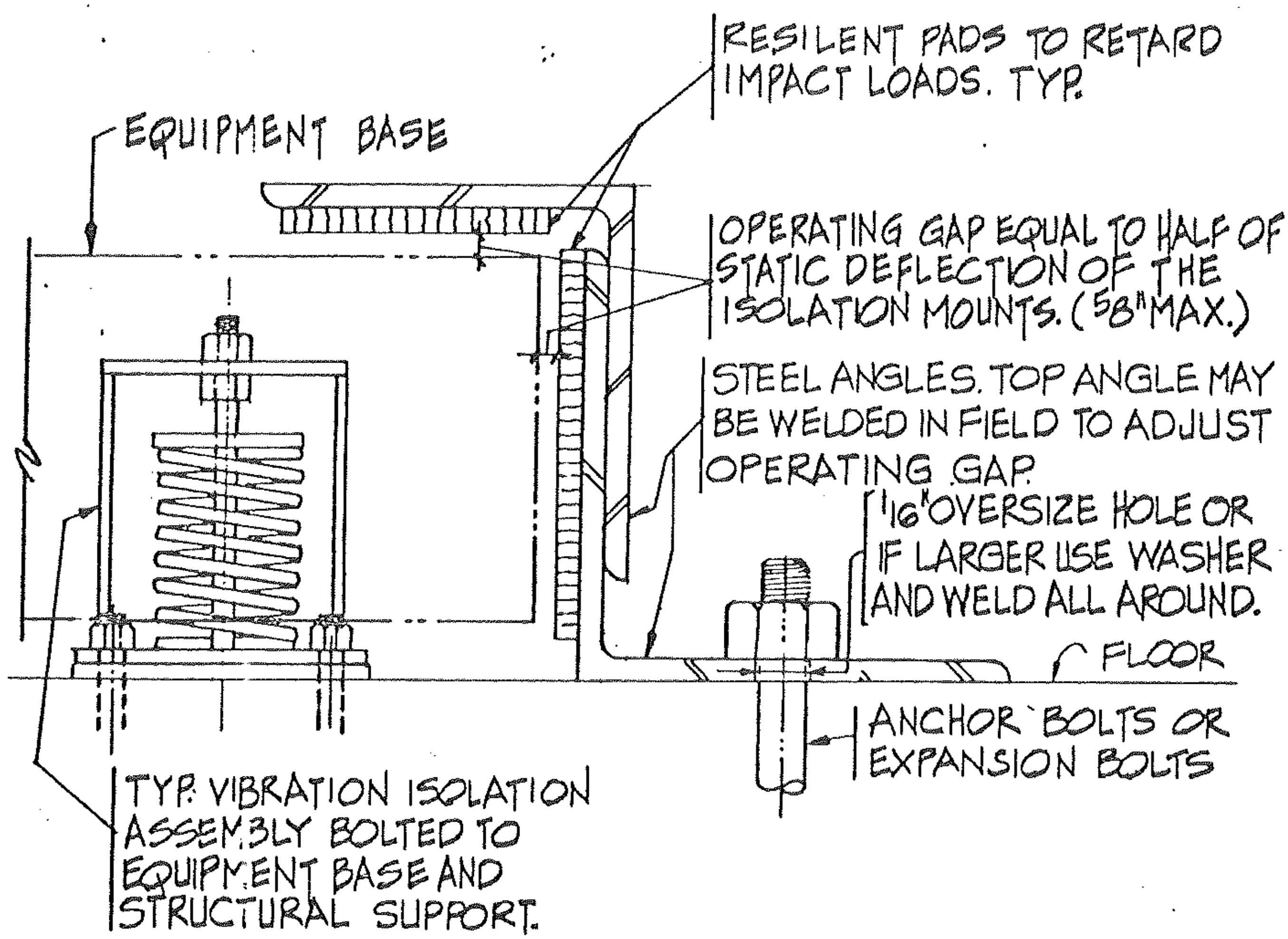
4. To reduce inertia forces, avoid the use of concrete bases under equipment that is mounted on vibration isolators.

5. Anchor all vibration isolators for equipment to the floor and to the equipment.

FIGURE 5

FLOOR OR ROOF MOUNTED EQUIPMENT W/ VIBRATION ISOLATION

NOTE: THE FOLLOWING DETAILS REPRESENT SPECIFIC INSTALLATIONS. HOWEVER, EQUIVALENT DETAILS WOULD BE ACCEPTABLE.



(1) RESTRAINING DEVICES FOR LATERAL AND VERTICAL LOADS

NOTES:

1. — DESIGN RESTRAINING DEVICES (ANGLES & BOLTS) TO WITHSTAND 1.0g (0.4g)* LATERAL AND VERTICAL LOADS.
2. — INSTALL LATERAL RESTRAINING DEVICES ON ALL SIDES OF EQUIPMENT BASE.
3. - *THE FIRST g FORCE IS FOR ESSENTIAL BLDGS OR LIFE SAFETY EQUIPMENT. THE g FORCE IN PARENTHESIS IS FOR OTHER BLDGS.

6. Pipelines should be tied only to one structural system. Where structural systems change, or seismic joints are provided and relative deflections are anticipated, movable joints should be installed in the piping to allow for the same amount of anticipated movement.

7. The standards of the NFPA for earthquake protection to fire-sprinkler systems should be referred to for successful, field-tested installation details that are applicable to any piping system.

8. Supports for tanks and heavy equipment, whether factory supplied or field installed, should be designed to withstand earthquake forces.

9. Suspended tanks should be tightly strapped to their hanger system and provided with lateral bracing.

10. All suspended equipment should have lateral bracing. If the equipment must be allowed to move, damping elements or restraints should be built into the hanger system to restrict the amount of movement.

11. Long hanger supports for ductwork should be provided with lateral bracing.

12. Flexible duct connections should be installed with enough material to allow for the expected differential deflection between the fans and the ductwork.

13. Pipe sleeves or duct openings through walls or floors should be sized large enough to allow for the anticipated movement of the pipes and ducts.

14. All masonry chimneys and stacks should be subjected to earthquake-resistive design.

15. Lightweight double-wall sheet metal flues should be used where possible. Prefabricated stacks or chimneys with heavy refractory liners should be avoided, or used with great care.

16. Domestic hot water heaters should be provided with legs that can withstand earthquake forces, and they should be anchored to the floor and/or strapped to a structurally sound wall.

17. Earthquake-sensitive shutoff valves on gas service lines should be provided where maximum protection from gas leaks is required.

Considerations in the seismic design of lighting fixtures are:[(2)]

1. Support systems for all pendant, recessed, and surface-mounted fixtures, including the various fixture/ceiling combinations, should be subject to engineering analysis and/or laboratory tested designed to simulate actual earthquake conditions.

2. Commercially available pendant fluorescent fixtures should be redesigned to include:

   (a) Provisions for dampened flexibility in stem materials and/or at swivel joints and housing connections.

   (b) Ball joint swivels that have holddown devices to eliminate pounding at sockets due to horizontal and vertical forces.

   (c) Stems that have a minimum wall thickness equal to that of rigid conduit (0.109 inch).

   (d) Fixture assemblies that are supported directly from the structure and not from any part of the ceiling system.

   (e) Secondary support cables that are carried through each stem and base plate to the supporting structure.

3. Recessed fluorescent fixtures should be mechanically attached to main support elements of ceiling systems that are structurally designed to carry the weight of the ceiling and the fixtures. Independent support wires should be provided to the supporting structure at diagonal corners of each fixture.

4. Surface fixtures should be mechanically attached to ceilings using fixture studs, through bolts, or positive clamping devices.

5. Chains for fixture supports should be solid link type with safety latch hooks.

6. Detachable fixture accessories such as louvers, diffusers, or lenses should be attached to the fixture body with locking catches or screws and provided with safety chains.

The Sheet Metal Air Conditioning Contractors National Association has presented additional guidelines for the seismic restraint of mechanical systems.[7] They consist of specifications for lateral bracing of duct work and piping, anchor details for concrete, wood, and steel, and additional support for vibration isolation mounted equipment (Figure 5).

The Uniform Building Code[9] specifies common building practices for structures and equipment. The lateral load which equipment must be designed to resist is given as

$$F_p = ZIC_pSW_p$$

where W_p is the weight of the equipment

Z is a coefficient depending on the seismic geographical zone in which the plant is located (Z = 3/16 for zone 1, such as much of the east coast, and Z = 1 for zone 4, such as much of Southern California).

I is the occupancy importance factor (1.50 for essential facilities such as hospitals, 1.25 for areas assembling more than 300 persons, 1.00 for all others).

C_p is the horizontal force factor which depends on the type of equipment (for example, parapets use $C_p = 1.0$, while towers, tanks, chimneys, storage racks, and non-safety related equipment and machinery use $C_p = 0.2$; safety related machinery uses $C_p = 0.5$).

S is a factor to account for amplification of the ground motion by building vibration. For one or two story structures, S will equal about 1.0. S usually does not exceed 1.5.

Putting all these factors together indicates that plant equipment may have to withstand up to 0.2 to 2.0 times its weight in lateral loads. Note that these Uniform Building Code requirements are designed chiefly to assure the safety of personnel and may not assure survival of the equipment.

IV. Summary

Plant equipment has suffered considerable damage from earthquakes. Good seismic design and retrofitting can be guided by common sense if one realizes that during a major earthquake, plant equipment may have to support lateral loads one or two times its own wieght. Clearly it is necessary to tie down equipment, provide lateral bracing, reduce the height or amount of tall unsupported masses, and follow the recommendations in the previous sections of this paper, of design guides,(7) of the Uniform Building Code,(9) and from the earthquake engineering field.(8)

Based on these guidelines and recommendations, the plant engineer can perform some of the retrofit work himself. Every facility has glaring examples of equipment which is ill suited for surviving an earthquake. If extensive modifications are planned, however, an engineer familiar with seismic design should be consulted. His review of your plant would consist of a walk-through "seismic audit", followed by recommended retrofit procedures for critical equipment.

Such an audit and retrofit program can save you tens of thousands of dollars in damage and prevent days or weeks of downtime in your plant. "Is your plant prepared?" Ask this question <u>before</u> the next earthquake and take appropriate action.

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APPENDIX A

EARTHQUAKE MAGNITUDE AND INTENSITY

EARTHQUAKE MAGNITUDE AND INTENSITY

Vibrations produced by earthquakes are detected, recorded and measured by instruments called *seismographs.* The zig-zag trace recorded by a seismograph - called a "seismogram" - reflects the varying amplitude of the vibrations by responding to the motion of the ground beneath the instrument. From the data expressed in seismograms, the time, epicenter, and focal depth of an earthquake can be determined, and estimates can be made of the amount of energy that was released.

The severity of an earthquake can be expressed in several ways. The *magnitude* of an earthquake, as expressed by the *Richter magnitude scale,* is a measure of the amplitude of the seismic waves. The amplitude is measured on seismograph recordings. When the earth quakes, the amplitude of the wave recorded on the seismograph is measured and is then corrected mathematically to what the amplitude would have been if it had been recorded at a distance of 100 kilometers from the epicenter. The Richter magnitude derived from these corrected seismograph recordings indicates the amount of energy released as if it had been recorded at this standard 100-kilometer distance from the epicenter of the quake. The *intensity* as expressed by the *Modified Mercalli intensity scale,* is a partly subjective measure which depends on the effects of a quake such as damage at a particular location.

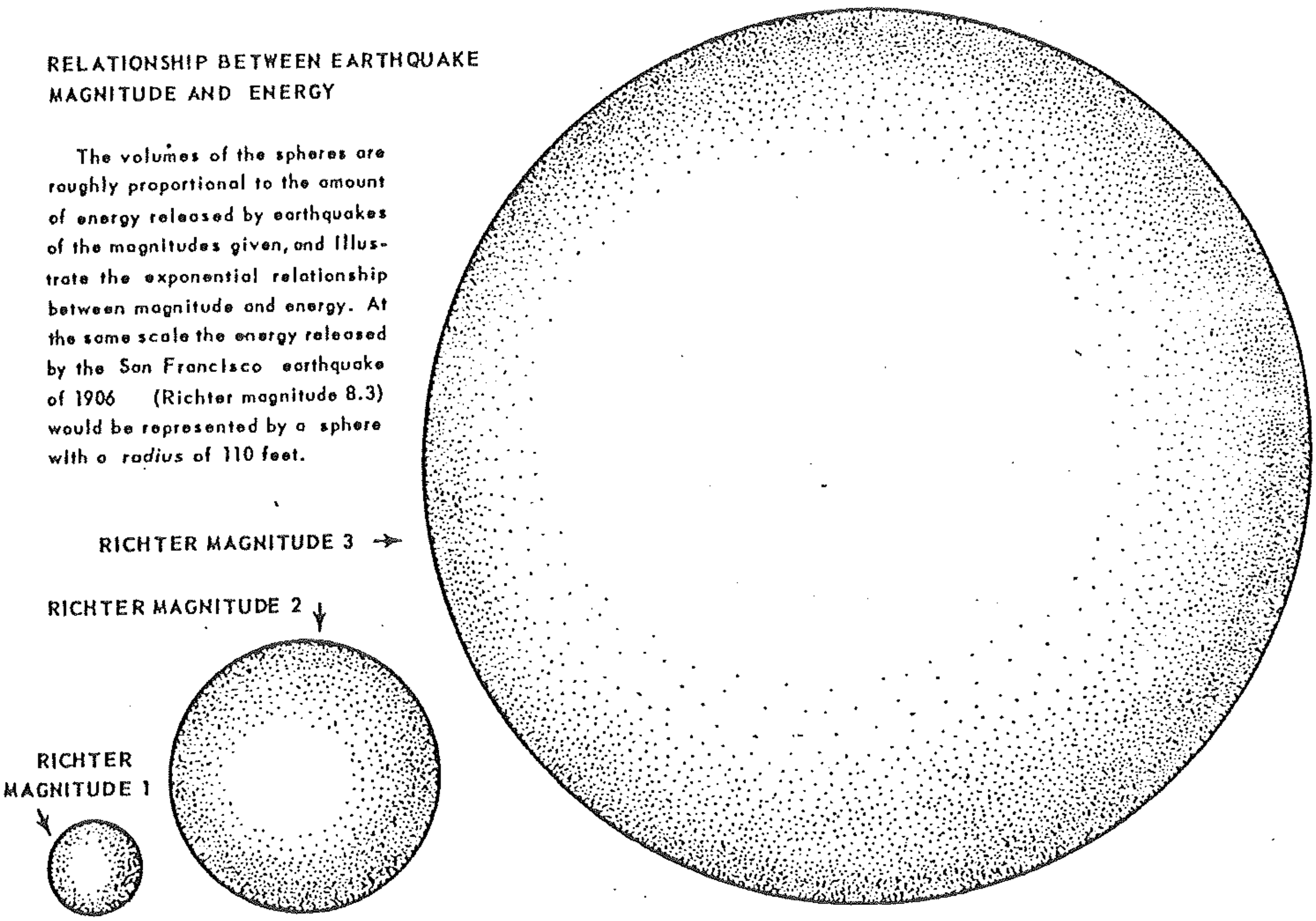
RICHTER MAGNITUDE SCALE

The Richter magnitude scale, named after Dr. Charles F. Richter, Professor Emeritus of the California Institute of Technology, measures the energy of an earthquake at its source, and is the scale most commonly used, but often misunderstood. On this scale, the earthquake's magnitude is expressed in whole numbers and decimals. However, Richter magnitudes can be confusing and misleading unless the mathematical basis for the scale is understood. It is important to recognize that magnitude varies logarithmically with the wave amplitude of the quake recorded by the seismograph. Each whole number step of magnitude on the scale represents an increase of *10 times* in the measured wave amplitude of an earthquake, and an increase of *31 times* in the amount of energy released by the quake. Thus, the amplitude of an 8.3 magnitude earthquake is not twice as large as a shock of magnitude 4.3, but 10,000 times as large. Correspondingly, a magnitude 8.3 earthquake releases almost one million times more energy than one of magnitude 4.3.

A quake of magnitude 2 on the Richter scale is the smallest quake normally felt by humans. Earthquakes with a Richter magnitude of 7 or more are commonly considered to be major. The Richter magnitude scale has no fixed maximum or minimum; observations have placed the largest

RELATIONSHIP BETWEEN EARTHQUAKE MAGNITUDE AND ENERGY

The volumes of the spheres are roughly proportional to the amount of energy released by earthquakes of the magnitudes given, and illustrate the exponential relationship between magnitude and energy. At the same scale the energy released by the San Francisco earthquake of 1906 (Richter magnitude 8.3) would be represented by a sphere with a *radius* of 110 feet.



recorded earthquakes in the world at about 8.9, and the smallest at about -3. Earthquakes with magnitudes smaller than 2 are called "micro-earthquakes." Richter magnitudes are not used to estimate damage. An earthquake in a densely populated area, which results in many deaths and considerable damage, may have the same magnitude as an earthquake that occurs in a barren, remote area, that may do nothing more than frighten the wildlife.

MODIFIED MERCALLI INTENSITY SCALE OF 1931

The first scale to reflect earthquake intensities was developed by de Rossi of Italy, and Forel of Switzerland, in the 1880 s. This scale, with values from I to X, was used for about two decades. A need for a more refined scale increased with the advancement of the science of seismology, and in 1902, the Italian seismologist, Mercalli, devised a new scale on a I to XII range. The Mercalli Scale was modified in 1931 by American seismologists Harry O. Wood and Frank Neumann to take into account modern structural features:

I. Not felt except by a very few under especially favorable circumstances.

II. Felt only by a few persons at rest, especially on upper floors of buildings. Delicately suspended objects may swing.

III. Felt quite noticeably indoors, especially on upper floors of buildings, but many people do not recognize it as an earthquake. Standing motor cars may rock slightly. Vibration like passing of truck. Duration estimated.

IV. During the day felt indoors by many, outdoors by few. At night some awakened. Dishes, windows, doors disturbed; walls make cracking sound. Sensation like heavy truck striking building. Standing motor cars rocked noticeably.

V. Felt by nearly everyone, many awakened. Some dishes, windows, etc., broken; a few instances of cracked plaster; unstable objects overturned. Disturbances of trees, poles, and other tall objects sometimes noticed. Pendulum clocks may stop.

VI. Felt by all, many frightened and run outdoors. Some heavy furniture moved; a few instances of fallen plaster or damaged chimneys. Damage slight.

VII. Everybody runs outdoors. Damage negligible in buildings of good design and construction; slight to moderate in well-built ordinary structures; considerable in poorly built or badly designed structures; some chimneys broken. Noticed by persons driving motor cars.

VIII. Damage slight in specially designed structures; considerable in ordinary substantial buildings, with partial collapse; great in poorly built structures. Panel walls thrown out of frame structures. Fall of chimneys, factory stacks, columns, monuments, walls. Heavy furniture overturned. Sand and mud ejected in small amounts. Changes in well water. Persons driving motor cars disturbed.

IX. Damage considerable in specially designed structures; well-designed frame structures thrown out of plumb; great in substantial buildings, with partial collapse. Buildings shifted off foundations. Ground cracked conspicuously. Underground pipes broken.

X. Some well-built wooden structures destroyed; most masonry and frame structures destroyed with foundations; ground badly cracked. Rails bent. Landslides considerable from river banks and steep slopes. Shifted sand and mud. Water splashed (slopped) over banks.

XI. Few, if any, (masonry) structures remain standing. Bridges destroyed. Broad fissures in ground. Underground pipelines completely out of service. Earth slumps and land slips in soft ground. Rails bent greatly.

XII. Damage total. Practically all works of construction are damaged greatly or destroyed. Waves seen on ground surface. Lines of sight and level are distorted. Objects are thrown upward into the air.

The Modified Mercalli intensity scale measures the intensity of an earthquake's effects in a given locality, and is perhaps much more meaningful to the layman because it is based on actual observations of earthquake effects at specific places. It should be noted that because the data used for assigning intensities can be obtained only from direct firsthand reports, considerable time -- weeks or months -- is sometimes needed before an intensity map can be assembled for a particular earthquake. On the Modified Mercalli intensity scale, values range from I to XII. The most commonly used adaptation covers the range of intensity from the conditions of "I - not felt except by very few, favorable situated," to "XII - damage total, lines of sight disturbed, objects thrown into the air." While an earthquake has only one magnitude, it can have many intensities, which decrease with distance from the epicenter.

COMPARISON OF MAGNITUDE AND INTENSITY

It is difficult to compare magnitude and intensity because intensity is linked with the particular ground and structural conditions of a given area, as well as distance from the earthquake epicenter, while magnitude is a measure of the energy released at the focus of the earthquake.

Richter Magnitude	Expected Modified Mercalli Maximum Intensity (at epicenter)	
2	I - II	Usually detected only by instruments
3	III	Felt indoors
4	V	Felt by most people; slight damage
5	VI - VII	Felt by all; many frightened and run outdoors; damage minor to moderate
6	VII - VIII	Everybody runs outdoors; damage moderate to major
7	IX - X	Major damage
8	X - XII	Total and major damages

After Charles F. Richter, 1958, *Elementary Seismology.*