Use of Seismic Intensity Data to Predict the Effects of Earthquakes and Underground Nuclear Explosions in Various Geologic Settings

GEOLOGICAL SURVEY BULLETIN 1279

Prepared on behalf of the
U.S. Atomic Energy Commission

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By PATRICK J. BAROSH

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A summary of the various factors that determine the effects of a seismic disturbance at a particular location and their utilization in predicting these effects

UNITED STATES GOVERNMENT PRINTING OFFICE, WASHINGTON : 1969

UNITED STATES DEPARTMENT OF THE INTERIOR

WALTER J. HICKEL, *Secretary*

GEOLOGICAL SURVEY

William T. Pecora, *Director*

Library of Congress catalog-card No. 77-601453

For sale by the Superintendent of Documents, U.S. Government Printing Office
Washington, D.C. 20402 - Price 45 cents (paper cover)

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USE OF SEISMIC INTENSITY DATA TO PREDICT THE EFFECTS OF EARTHQUAKES AND UNDERGROUND NUCLEAR EXPLOSIONS IN VARIOUS GEOLOGIC SETTINGS

By Patrick J. Barosh

ABSTRACT

A survey of the literature reveals the feasibility of using seismic intensity data to construct useful intensity-epicentral-distance curves for earthquakes of different magnitudes. To do this, variables other than epicentral intensity must be considered. The variable principally responsible for the range of intensities at any given epicentral distance is the geologic environment, and considerable work has been done, mainly by Russian and Japanese scientists, in evaluating relative intensity differences of different types of ground.

Microregionalization maps, which show relative intensities for different geologic settings, could be used with intensity-epicentral-distance curves for a particular geologic setting to predict the intensity, at a given point of known ground type, from an earthquake of given magnitude, epicentral distance, and focal depth. These maps and curves can also be used to estimate potential seismic effects on manmade structures from underground nuclear explosions. To make these estimates, the relationship between nuclear-explosion energy and earthquake magnitude and between intensity and focal depth must be sufficiently well known to permit extrapolation of earthquake data to the shallow depths and energy releases of nuclear explosions. Preliminary equations, showing these relations, exist.

INTRODUCTION AND DEFINITIONS

This report summarizes earthquake data that may be useful in predicting potential damage from earthquakes and from underground nuclear explosions. The problem of predicting damage from earthquakes has been studied for many years, but the subject is so complex that empirical data and judgment are still the principal bases for prediction. The ground motion produced by nuclear explosions is so similar to that produced by earthquakes that it is difficult or impossible to differentiate between the two. Possible damage due to ground motion caused by nuclear explosions should reasonably be of the same kind as that caused by earthquakes. The method of predicting potential damage is a problem common to both sources of motion.

The data and suggestions contained herein are not meant to be a substitute for measured or predicted ground motion parameters, but they do provide a basis for estimating intensity as a function of magnitude and epicentral distance. Intensity is a rather subjective measure of shaking, based upon real effects of shaking of things. Intensity scales, because they are based on real effects rather than on a predicted structural response to ground motion, may be temporarily of more practical use than ground motion measurements. If and when realistic structural responses in terms of ground motion are established for various types of ground and construction, intensity scales may decline in importance. However, as stated by Wood and Neumann (1931, p. 277), "we are not yet in position to correlate destructive effects with instrumental data so as to establish an adequate measure of intensity. Though the importance of the factor of acceleration is recognized, we have as yet no satisfactory definition of intensity, no formula expressing earthquake violence in terms of ground movement." Eiby (1965) pointed out that this still holds true. Furthermore, no significant progress in predicting potential damage from ground motion caused by earthquakes and nuclear explosions is likely until damage criteria are established; this will require rigorous scientific study by the combined community of seismologists, geologists, and structural engineers.

Two examples are cited to show what effects, in terms of perceptibility and potential damage, could have been predicted on the basis of a variety of compilations of observed earthquake, ground motion, and intensity data.

The great bulk of earthquakes occur around the Pacific basin and in the Mediterranean-Himalayan belt; and the pertinent literature on earthquake intensity comes from those countries in this seismically active area which have competent seismologists and adequate earthquake records, for example the United States, Japan, Russia, and New Zealand. The literature from many countries, such as those in Central and South America and India, in this seismically active area deals mainly with the descriptive aspects of earthquake damage and commonly does not deal with quantitative aspects of intensity. For the purposes of this report the United States literature published before 1968 was moderately well searched, and the Russian, Japanese, and New Zealand literature was scanned. Emphasis is on the foreign work, however, because it is poorly known and not readily available in the United States.

In the United States the groundwork for quantitative intensity studies was laid in the early 1930's by the systematic collection of data on earthquake intensity (by the U.S. Coast and Geodetic Survey), by the formulation of the Modified Mercalli intensity scale (Wood and Neumann, 1931), and by the definition and introduction of an instrumental earthquake magnitude scale (Richter, 1935). A large amount of qualitative information on intensity had previously been acquired by the classic studies of the 1906 San Francisco earthquake. Much information on intensities for southern California was presented by Gutenberg and Richter (1942, 1956). Intensity variations with epicentral distance for two different geologic conditions in western Washington and California were analyzed by Neumann (1954, 1959). The variation in ground motion due to different geologic conditions in southern California was demonstrated by Gutenberg (1956b, c, 1957), and the probable intensity variation due to geologic conditions for the Los Angeles basin and, in less detail, for all of California was shown by Richter (1959). The relation of intensity to ground motion has been considered by Benioff (1934), Neumann (1954, 1959), and many later authors.

In Japan, intensity studies were begun at about the same time they were begun in the United States. The relation of acceleration to the Japanese intensity scale was studied by Ishimoto (1932). Intensity–epicentral-distance curves for a great many earthquakes were drawn by Hirosi Kawasumi and others about 1939 and by Hirono (1948) and Sato (1948). An equation for a mean curve relating these parameters was formulated by Kawasumi (1951). The relation between intensity, epicentral distance, and acceleration was investigated by Hirono (1958) and Hirono and Hisamoto (1963). The relations between variations in damage and geologic conditions was studied by Kanai (1947, 1949, 1951), Kanai and Tanaka (1950), Kanai and Yoshizawa (1951), Omote (1946, 1949), Omote and Miyamura (1951), Takahasi (1950), and many others. Ground-motion variations due to geologic conditions, particularly the effect of the surface layer, were studied by Minakami (1944), Minakami and Utibori (1946), Minakami and Sakuma (1948), Sakuma (1948), Hayashi (1950), Kanai (1952), Kanai and Yoshizawa (1956), Kanai, Tanaka, and Yoshizawa (1959), Kanai, Tanaka, Yoshizawa, Morishita, Osada, and Suzuki (1966), Omote, Komaki, and Kobayashi (1956), and many others.

In Russia, intensity studies were begun in the late 1940's and have progressed rapidly. A new intensity scale was adopted in 1953 (Medvedev, 1953); and since then much work has been done on the relationship of intensity to geologic conditions (Gorshkov and others, 1947, 1949; Gubin, 1954, 1955, 1960; Belousov, 1954; Nazarov, 1954; Petrushevsky, 1955; Safaryan, 1954, 1957; Popov, 1959; Kats, 1960; Medve-

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dev, 1952a, b, 1958, 1961; Medvedev and others, 1961, 1962; Kuliev, 1962; Fedotov, 1961; and Goryachev and others, 1963). Studies have also been made relating intensity to magnitude (Shebalin, 1955, 1957a, b, c, 1959b), to focal depth (Medvedev, 1959; Shebalin, 1955, 1959a, 1960, 1961), and to ground motion (Medvedev, 1961, 1963a, b).

In New Zealand there has been more emphasis on aspects of seismology other than quantitative intensity relations, but the relation between magnitude, epicentral intensity, focal depth, and mean radius of felt area has been studied (Hayes, 1953, p. 634–635).

Information available in the literature is presented in many different ways and recompilation and correlation of most of the data are required to put it in a form that allows it to be readily compared.

No attempt has been made to include earthquake-engineering aspects of construction that are important in determining the response of stuctures to ground motion.

Most of the terms used in the seismic literature that are pertinent to this report are well enough known that an extensive glossary is not needed here. Two very important concepts, magnitude and intensity, have been defined in various ways, however, and some discussion of them is necessary to avoid confusion in later parts of this report.

The following symbols for terms used in formulas are introduced where the terms are first discussed and are not generally defined after each formula:

Δ=epicentral distance (in kilometers)
h=focal depth (in kilometers)
I=intensity
I_0=epicentral intensity
M=Richter, or local magnitude
M_k=Kawasumi magnitude
m=unified magnitude
r=radius of perceptibility (in kilometers)

MAGNITUDE

Earthquake magnitude is a measure of the size of an earthquake and is related to the energy released in the form of seismic waves. The concept was developed initially by Richter (1935) for use with normal-depth local earthquakes in southern California. By definition, an earthquake's magnitude (M) is equal to the common logarithm of the maximum trace amplitude (expressed in microns) written by a standard torsion seismometer (free period 0.8 sec, damping ratio about 50:1, and static magnification of 2,800) at an epicentral distance (Δ) of 100 km (kilometers). Tables for adjusting amplitudes of earthquakes recorded at other distances to those expected at 100 km were developed empirically.

On the basis of simple auxiliary definitions and some theoretical considerations, the concept of magnitude was extended to cover large shallow earthquakes recorded at great distances (from amplitudes of surface waves with periods near 20 sec) and earthquakes with arbitrary focal depth (from amplitude: period ratios of P, S, and PP body waves) (Gutenberg and Richter, 1936, 1942, 1956; Gutenberg 1956a). Calculation of magnitudes according to the extended definition was implemented by additional tables and charts, also determined empirically, that were constructed so that magnitudes of a given earthquake computed from different types of observations (maximum recorded amplitudes at small distances, surface waves with periods near 20 sec, and various types of body waves) were the same numerically.

Magnitudes of large shallow earthquakes computed from surface-wave amplitudes have since been found to differ systematically, as a function of magnitude, from those computed from body-wave amplitude: period ratios. Gutenberg (1956a) regarded the body-wave magnitudes as the most reliable and elevated them to the status of "unified magnitude" (m).

The unified magnitude is found from

$$m = \log(A/T) + B + C,$$

where A is the maximum ground amplitude, in microns, of body waves (the vertical components, Z, as well as the horizontal, H, of P and PP, but only the horizontal component, SH, for S waves), and T, the corresponding period, in seconds. C is an empirically determined station constant which rarely exceeds 0.2. B, the value of which is given in tables and graphs, depends mainly on the phase and component, the epicentral distance, and, to a lesser degree, the focal depth. B depends on the local structure up to an epicentral distance of about 20° (Gutenberg, 1956a, p. 5).

The two magnitude scales, one (M) based on maximum trace amplitudes of local earthquakes or on 20-second-period surface waves of distant earthquakes, and the other (m) based on amplitude: period ratios of body waves of distant earthquakes, are related by

$$m = 2.5 + 0.63M, \text{ or } M = 1.59m - 3.97$$

(Richter 1958, p. 348). The scales match at a magnitude of approximately 6.75. Above this, the Richter scale gives a higher magnitude; below it, a lower magnitude (fig. 1). An earlier correlation by Gutenberg (1956a, p. 5) showed closer agreement between the two scales.

From the definition of magnitude, an increase of one unit in magnitude corresponds to a tenfold increase in amplitude (or amplitude: period), focal depth and epicentral distance remaining unchanged, of the ground motion produced at a given location. The largest recorded earthquakes had magnitudes M of 8.9 (or m of 8.0), and earthquakes with magnitudes less than zero are recorded at small epicentral distances by very sensitive seismographs.

The Gutenberg-Richter magnitude is used in its original or slightly modified form by seismologists throughout the world. In some places (for example, in Russia), the empirical interpretive material needed for computing magnitudes has been recompiled from domestic stations.

In Japan, the magnitude used previous to the adoption of the Richter scale, the Kawasumi scale (M_k), is based on the average intensity on the Japanese intensity scale, at an epicentral distance of 100 km (Kawasumi, 1943). The relation of the Kawasumi scale (1951, p. 472) to the Richter scale is

$$M = 4.85 + 0.5M_k, \text{ or } M_k = 2M - 9.70.$$

INTENSITY

Intensity is the effect of an earthquake at a particular place. The effects generally considered in determining earthquake intensity are those on man, on construction, and on the earth's surface, but certain instrumentally measured parameters of ground motion have at times been included. A great number of intensity scales have been devised and revised to describe the varying degrees of sensation and damage caused by earthquakes. Forty-four of these scales were correlated by Gorshkov and Shenkarev (1958) and discussed briefly by them and by Medvedev (1961).

In the United States the Modified Mercalli scale (M.M. or M.M. 1931) of 12 units is in general use (Wood and Neumann, 1931; table 1 of present report). Richter (1958, p. 136–139) suggested some slight changes for clarification of this scale. In New Zealand the Modified Mercalli scale is also used, but before 1943 the Rossi-Forel scale was used there (Eiby, 1966, p. 123). Recently the definitions of the Modified Mercalli scale units were revised slightly to better fit the construc-

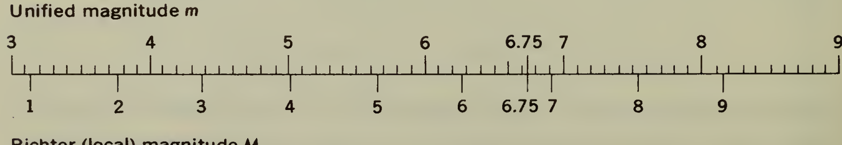

FIGURE 1.—Relationship between the Richter (local) magnitude M and the unified magnitude m, according to Richter's formula $m=2.5+0.63M$ (1958, p. 348).

tion characteristics of New Zealand (Eiby, 1966; table 2 of present report). In Japan, the 8-unit Japanese Seismic Intensity Scale, a modification of an earlier scale (Omori, 1920), is in use (Kawasumi, 1951, p. 481; table 3 of present report). In Russia the GEOFIAN scale (abbreviation of Geophysics Institute of the Academy of Sciences) of 12 units was used until recently (Medvedev, 1953; table 4 of present report).

The GEOFIAN scale is very similar to the Modified Mercalli scale, both having been developed from the same earlier scales. The GEOFIAN scale, however, incorporates some quantitative evaluation of ground motion in addition to sensation and structural response.

The MSK 1964 scale, which is very similar to the GEOFIAN scale, was proposed by Medvedev, Sponheuer, and Kárník (1963, 1964; in Sponheuer, 1965) as an international intensity scale (table 5). It is now being tried experimentally in Japan (T. Hirono, oral commun., 1967) and apparently in use in Russia.

The relation of the M.M. 1931, GEOFIAN, and Japanese scales is shown in figure 2. The correlation is based on comparison and evaluation of the data shown in tables 1, 3, and 4 and on some slight additional information (Richter, 1958, p. 138–139; Collins and Foster, 1949, p. 25; and Stechschulte, 1932, p. 87). This correlation is different from that of Gorshkov and Shenkarev (1958, table 4) in that the Modified Mercalli and GEOFIAN scales are shown to be less equivalent at the low end of the scale and much more equivalent in the area of intensities VIII, IX, and X.

It is doubtful that more than 12 intensity units can be adequately defined, and when employing these scales whole units are used (Eiby, 1966, p. 128). When uncertainties exist as to which of two intensity units to assign, the higher unit is used. The intensity is customarily written in Roman numerals, which helps prevent it from becoming confused with magnitude.

The value of the intensity concept and the general problems encountered in assigning intensity ratings were discussed by Eiby (1965). He (1965, p. III–66 to III–67) pointed out that a single international intensity scale is undesirable because the intensity criteria, to be most applicable, should be in terms that fit local construction characteristics, and these vary greatly throughout the world.

The intensity of an earthquake at any specific point depends on a great many variables, including earthquake magnitude; epicentral distance; acceleration, period, duration, and amplitude of seismic waves; type of ground; geologic structure; slope of ground; ground water; type of construction; quality of workmanship; and the natural period of buildings and sites. Fortunately, some of the variables are

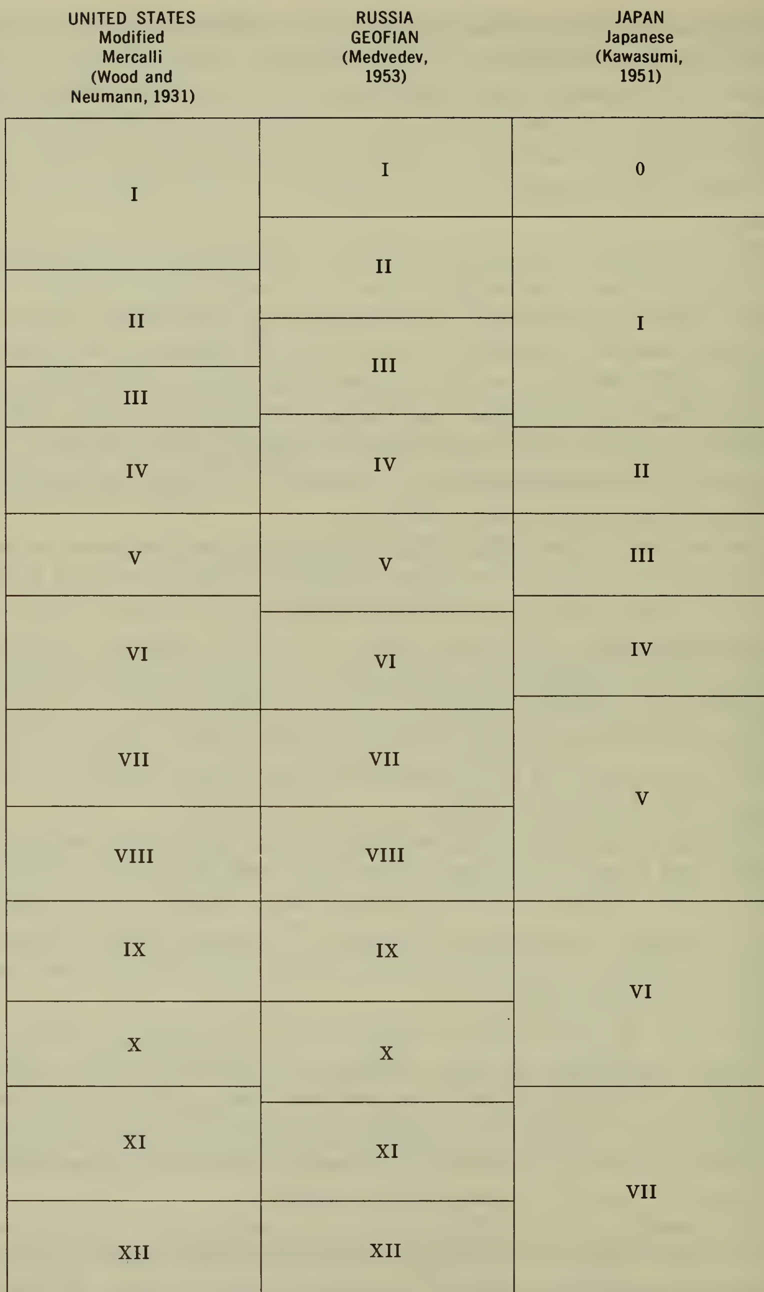

FIGURE 2.—Correlation of intensity scales.

not independent and some others can be evaluated separately. Intensity scales recognize the different types of construction, and usually the effects of poor workmanship are taken into consideration when assigning intensity ratings. Intensity scales are most successfully used where there is a general uniformity in type and quality of construction as in central Asia and Japan.

In the United States, information on intensities is gathered by the U.S. Coast and Geodetic Survey, which, after an earthquake, obtains reports of damage and other effects from the disturbed region (Scott, 1965). From this information, intensities are assigned to the reporting localities and are plotted on a map. Between areas of predominantly one intensity rating, boundaries are drawn to form an isoseismal map (fig. 3). The smooth symmetrical appearance of many isoseismal maps may be a reflection of the lack of data rather than uniformity of intensity variation with epicentral distance. This information on intensities, along with the location of the epicenter, time of occurrence, the extent of the area over which the earthquake was felt, and generally the magnitude, is published in an annual bulletin, "U.S. Earthquakes" by the U.S. Coast and Geodetic Survey.

In Japan, weather stations routinely report intensities and, for large earthquakes, the Earthquake Research Institute of the University of Tokyo gathers supplemental information. In New Zealand, permanent reporters send in intensity information; and for earthquakes of special interest or of Richter magnitude greater than 6, special questionnaires are also issued (Eiby, 1965, p. III–68). In Russia, strong earthquakes are described in the annual publication "Proceedings of Earth Physics Institute of the Academy of Sciences"; it contains information on intensities (GEOFIAN).

A factor that affects the assignment of intensity in seismically active regions is accumulated damage—damage which either had not been previously noticed or had been inadequately repaired after a previous shock.

When intensity values are employed in equations, the simplifying assumption is made that the intensity degrees represent equal steps in a scale. It is doubtful that the intensity degrees of a scale represent equal steps, but how much the scales differ from this approximation is not known.

INTENSITY AS A FUNCTION OF GROUND MOTION

Intensity is the effects of ground motion on humans, on construction, and on the earth's surface. The exact relations between instrumentally recorded components of ground motion and intensity are difficult to obtain due to the complex motion of the ground during an earthquake.

The relative importance of different components of ground motion may also vary with epicentral distance and cause a variation in the type of structural damage.

A number of attempts have been made to correlate intensity with acceleration alone. Several of the earlier seismic scales listed acceleration values, and Ishimoto (1932) presented acceleration values for the

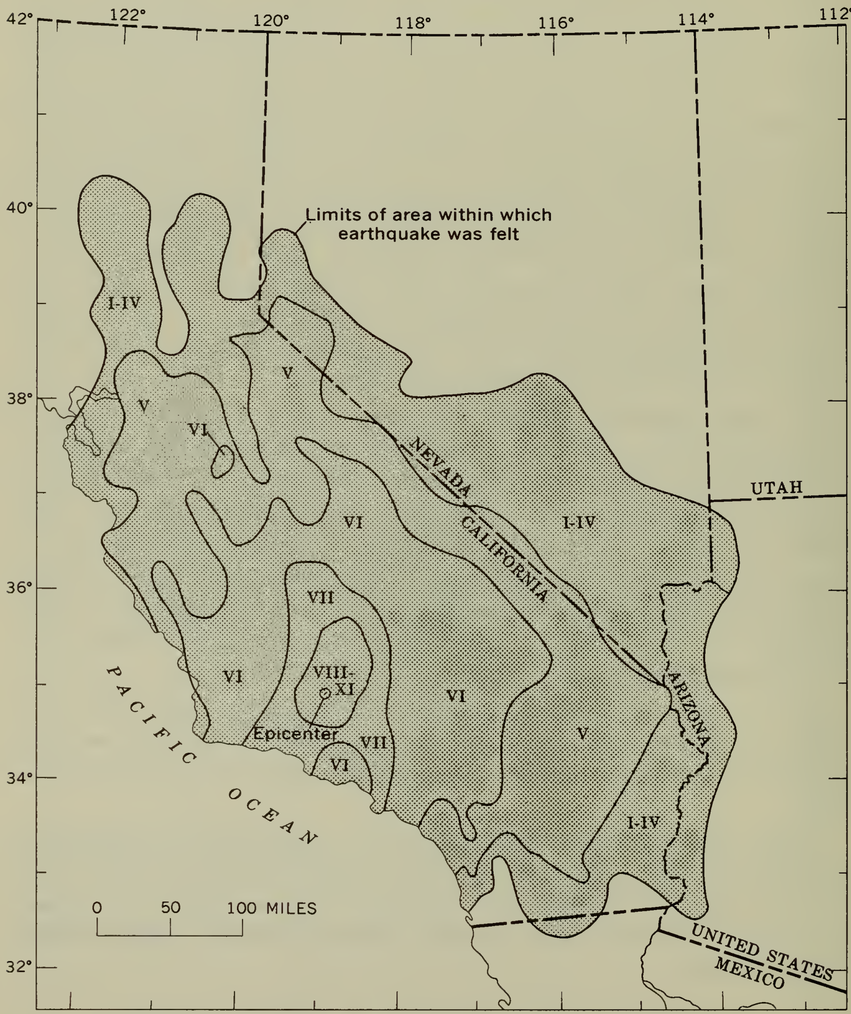

FIGURE 3.—Isoseismal map of the Arvin-Tehachapi earthquake area, 1952, in Modified Mercalli scale. Magnitude: 7.7. Maximum intensity: XI (Bealville). Total area within which earthquake was felt: 160,000 sq mi (414,000 sq km). Modified from Murphy and Cloud (1954, p. 16). July 21, 1952, 04 : 05 : 31 P.s.t. (main shock). Epicenter: lat 35.0° N., long 119.0° W., near Wheeler Ridge, Calif.

Japanese scale. Kawasumi (1951, p. 472) considered the relation between intensity I (Japanese) and the maximum acceleration a to be closely approximated by

$$\bar{a}=0.45\times10^{0.5I},$$

where $\bar{a}$, in gals, is the geometrical mean value of a as observed at Hongo, Tokyo, by means of the Ishimoto acceleration seismograph. Gutenberg and Richter (1942, p. 171; 1956, p. 131) reported acceleration values for the Modified Mercalli scale and found the relation to be approximately

$$\log a=I/3-0.5$$

except for high intensities. Hershberger (1956), however, considered that, with abundant data, the overlap is too great to permit working out a significant relation, and Housner (1965, p. III–105) stated that the Modified Mercalli intensity should not be used to estimate maximum ground acceleration. The scatter between several suggested relationships between acceleration and intensity is shown by Eiby (1965, fig. 1) (fig. 4). Neumann (1954, p. 6) believed, however, that the accelerations now being registered on strong-motion seismographs for the various grades of the M.M. intensity scale showed a remarkable consistency.

There is a strong suggestion that when acceleration is much higher than the observed intensity would indicate, the duration of shaking was relatively brief (Ikegami and Kishinouye, 1950, p. 126) and "the more violent shaking may have subsided before there was time to produce generally the effects usually characteristic of the force experienced (Gutenberg and others, 1932, p. 143)." According to Ikegami and Kishinouye (1950, p. 127), "To estimate the intensity of an earthquake, the amplitude (or the period) of the ground motion and the duration of the acceleration as well as the value of the acceleration must be taken into account at any place."

A relation of intensity to both acceleration and period was shown by Neumann (1959, figs. 5 and 7), Medvedev (1960a; 1961, p. 123; 1963a, p. 15, 25; 1963b), and Shaginyan (1963; fig. 5 of present report). The overlap of acceleration values is reduced by consideration of the period, but the accelerations recorded for a particular intensity still overlap the restricted ranges given for the intensities above and below (fig. 5). Both Neumann and Medvedev showed an increase in intensity with increasing acceleration and, to a much lesser extent, with increasing period. Earlier, however, the value of acceleration at the limit of perception (boundary between I and II GEOFIAN or 0 and I Japanese scale) was found to increase with increasing period (Suye-

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hiro, 1929, p. 411; Ishimoto, 1932, p. 621), which means a slight decrease in intensity, at these low levels, with increasing period. Neumann (1954, p. 64; 1959, p. 219) and Medvedev (1963a, table 1; 1963b, table 5) both found that in the central areas of strong earth-

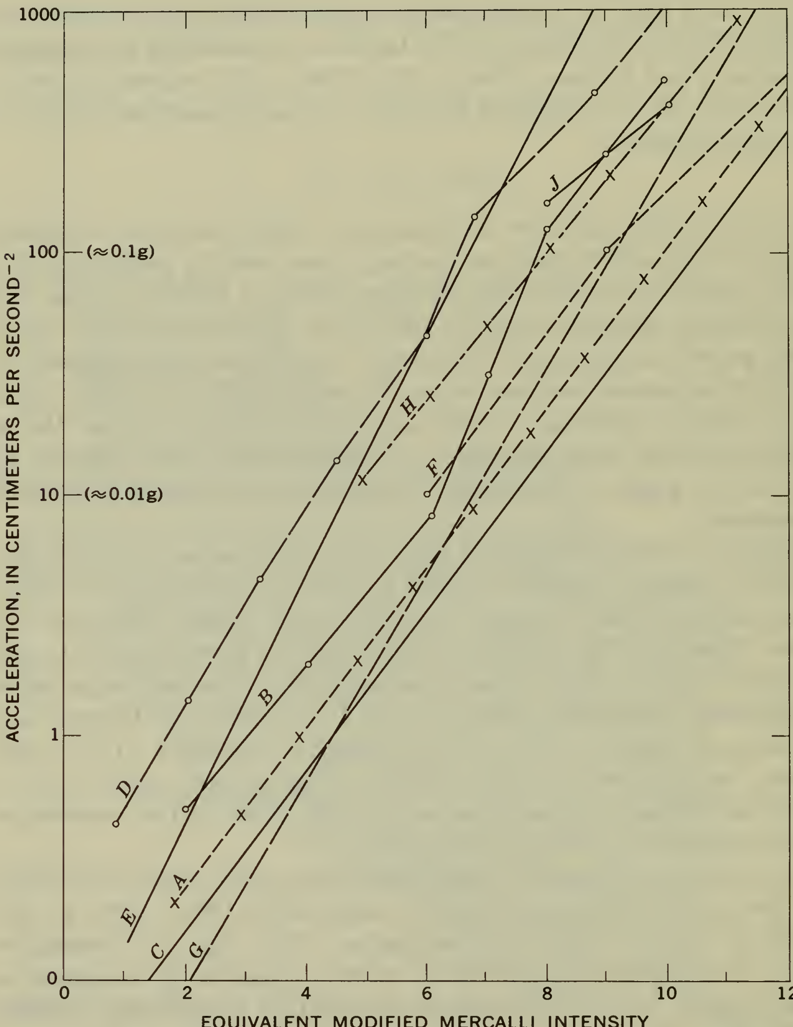


FIGURE 4.—Suggested relationships between ground acceleration and intensity (Eiby, 1965, fig. 1). Reproduced by permission of the New Zealand National Committee on Earthquake Engineering. *A*, Cancani (1904); *B*, Ishimoto (1932); *C*, Gutenberg and Richter (1942); *D*, Kawasumi (1951); *E*, Peterschmitt (1952); *F*, Savarensky and Kirnos (1955); *G*, Hershberger (1956); *H*, Medvedev, Sponheuer, and Kárník (1963); *J*, New Zealand draft by-law D–7547.

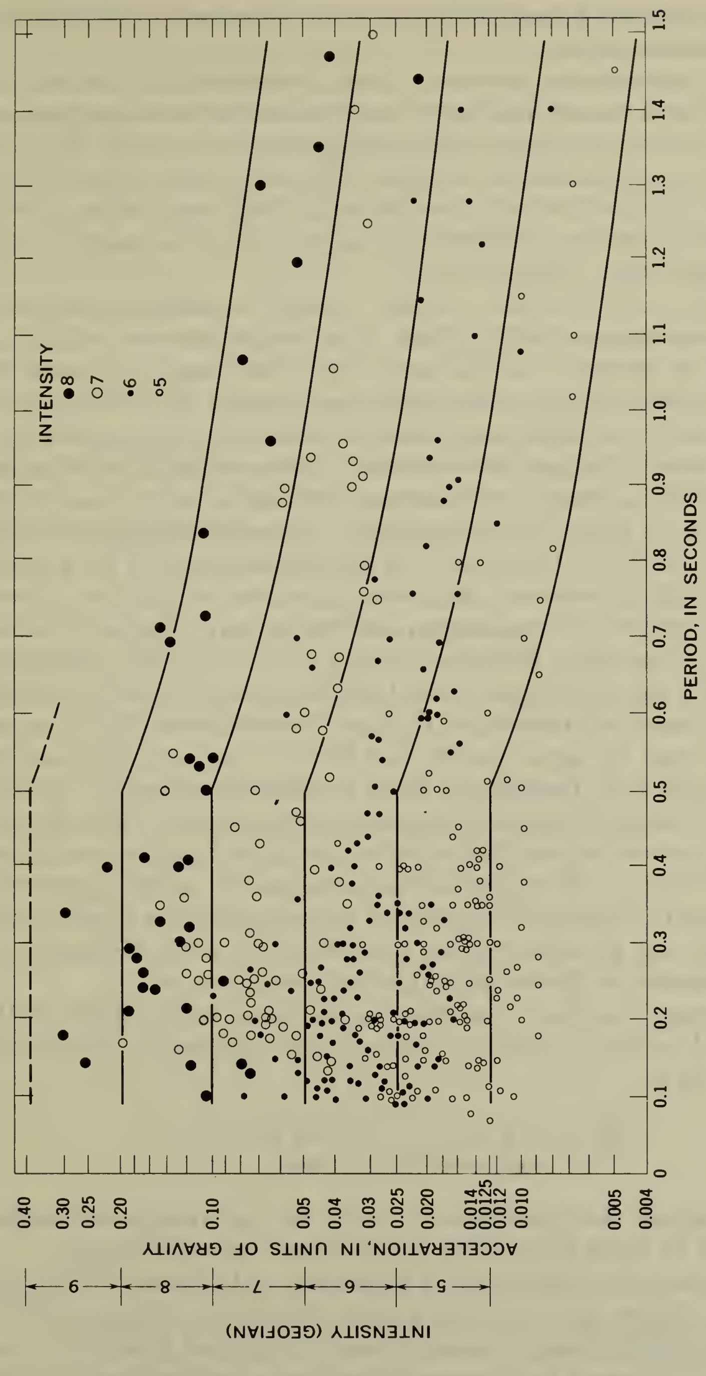


FIGURE 5.—Correlation of acceleration, a_0, and period of ground motion, T, for earthquake intensities 5–8 (Medvedev, 1963a, fig. 1).

quakes a one-grade increase in intensity corresponded to a doubling of the acceleration (table 6).

Specific earthquakes produce a peak acceleration at a period of about one-third second, with lower accelerations for lesser and greater periods, at short epicentral distances (Neumann, 1954, p. 22), although, as a generalization, changes of period in the range 0.1–0.5 second has negligible effect on acceleration (Medvedev, 1963a, p. 16). Acceleration, however, is dependent on period for the range 0.5–1.5 seconds (Medvedev, 1963a, p. 16).

Neumann (1954) further clarified intensity-acceleration relationships by consideration of the effects of epicentral distance and variations due to geologic environments. He (1954, figs. 6, 8, table 3) developed provisional acceleration-period graphs, for two types of basement rock, that relate maximum acceleration at various periods to specific intensity values, for epicentral distances less than 25 miles (40 km). The geologic environments considered were those interpreted to be for granitic rock and highly compacted sedimentary rock. Beyond this epicentral distance the maximum acceleration for a given intensity (M.M.) decreases with increasing epicentral distance, whereas both the period of the maximum acceleration wave and the duration of the record increase (Neumann, 1954, p. 1, 21, 26, 27, 72). Neumann (1954, p. 27) reached the provisional conclusion that for each 100-mile (160.9 km) increase of epicentral distance the acceleration, for the same intensity, drops the equivalent of four-thirds of an intensity grade in the epicentral area. Because the lower acceleration values for specific intensities outside the epicentral area are not included in the graphs, Neumann's values for specific intensities are higher than the mean given for acceleration at all epicentral distances and lie at the upper end of the range of acceleration values for various intensities given by the U.S. Coast and Geodetic Survey and above the restricted range of values presented by Medvedev (table 6 of present report).

The average maximum acceleration associated with a given M.M. intensity, I, at short epicentral distances was expressed by Neumann (1954, p. 69) as:

$$\log a_I = \log 1.85 + (I-1) \log 2.031, \text{ or}$$
$$\log a_I = 0.308\, I - 0.041.$$

These equations are provisionally valid for an average epicentral distance of 15 miles and require modifications beyond 25 miles.

The acceleration values given by Gutenberg and Richter (1956, table 16) fall within or very close to the restricted ranges of those given by Medvedev (1963b, table 5; see also table 6 of present report) for the periods 0.1–0.5 second for the same intensities on the Modified Mercalli and GEOFIAN scales. The values derived from Kawasumi's formula (table 6, No. 4) correspond very well to those of the other two scales as correlated in figure 2.

Intensity varies with displacement amplitude, or, in other words, with the Richter magnitude, *M*. As shown in figure 6, with an increase of intensity of one unit (GEOFIAN) the probable amplitude increases twice (according to Medvedev, 1963a, p. 18 and fig. 3). For any specific intensity the amplitude is greater the longer the period (fig. 6). Also the predominant period rises with an increase of intensity (Medvedev, 1963a, p. 18).

The particle velocity (table 6, No. 7), which is derived from acceleration or displacement, is also considered to increase two times for an increase of one intensity unit (Medvedev, 1963b, table 5).

Combined theoretical and empirical studies of the effects of earthquakes on structures have led Russian workers to introduce a function which they call the "spectrum of the effect of seismic oscillations on

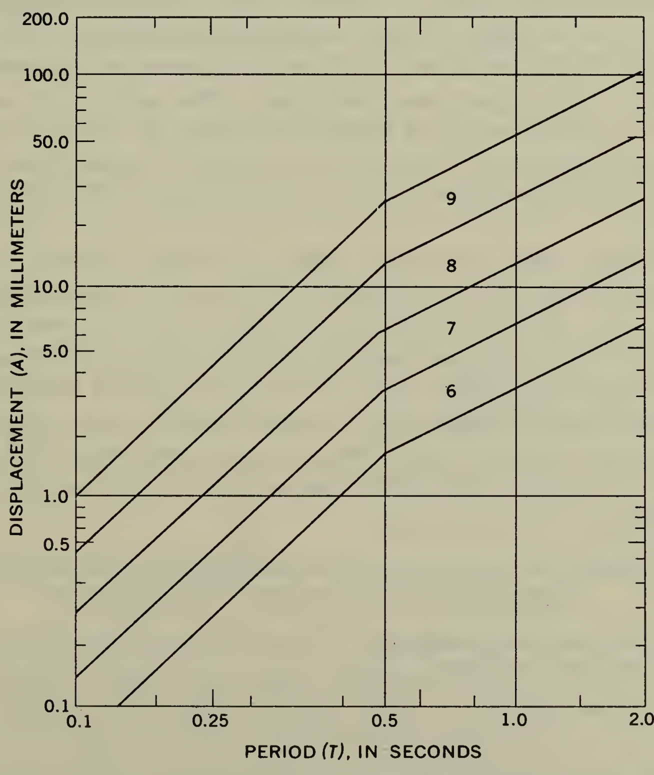


FIGURE 6.—Correlation of amplitude of displacement for ground motion, *A*, and period, *T*, during earthquakes of intensities 6–9 (Medvedev, 1963a, fig. 3).

structures," or the seismic effect spectrum. By means of this function they seek to describe the effects of irregular earthquake-induced ground motion, corresponding to various GEOFIAN intensity levels, on simplified mathematical modes of buildings. The seismic effect spectrum itself represents the maximum amplitude of displacement X (T,λ) induced in a simple pendulum of free period T and logarithmic decrement (damping) λ by the ground motion produced by an earthquake. For convenience, this function is represented by the product of three factors $[X(T,\lambda) = X_0 \cdot {}_0\psi(T) \cdot E(\lambda)]$ where X_0 refers to the seismic effect at standard period T_0 and damping λ_0, and $\psi \cdot (T)$ and $E(\lambda)$ indicate the dependence of X on period and damping, respectively.

The seismoscope adopted for general use in the U.S.S.R. was designed to have a response similar to that of dwellings and public buildings of only a few stories' height that are of most widespread occurrence in the country. It has a free period T_0 of 0.25 second and a logarithmic decrement λ_0 of 0.50; and its maximum displacement X_0 during an earthquake is one of the principal criteria used in assigning GEOFIAN intensities as well as the reference amplitude level of the seismic effect spectrum (Medvedev, 1953; table 4 of present report). The displacement is mainly a function of maximum acceleration, although other factors, such as period of predominant strong ground motion and duration, must contribute also (Steinbrugge, 1960, p. 150).

Medvedev (1961, p. 125; 1963a, p. 21–26; 1963b) presented graphs showing X as a function of T, for $\lambda = 0.5$, for earthquakes of intensity 6–9 on the GEOFIAN scale. He also presented graphs of maximum velocity and acceleration corresponding to X (maximum displacement) for the same value of λ and for the same intensity range. The ground motion data used in the derivations of the seismic effects spectra were obtained from strong motion seismograms and accelerograms of strong earthquakes as well as from large industrial explosions.

INTENSITY VARIATION AS A FUNCTION OF EPICENTRAL DISTANCE FOR DIFFERENT MAGNITUDES

The decrease in intensity with increasing epicentral distance for an earthquake of a given magnitude does not produce a simple curve, owing to the number of other variables that affect intensity. At a given epicentral distance, it is common to find a range of four or five intensities, and intensities at sensitive spots 100 miles from the epicenter may equal the intensity at the epicenter without any error in intensity rating (Neumann and Cloud, 1955, p. 207).

Partly owing to this wide range of intensities, information pertaining to intensity variation with epicentral distance is presented in a variety of ways. Curves are drawn for average intensities, minimum intensities, maximum intensities, and predominant maximum intensities. Also information is presented for epicentral intensities (where the epicentral distance equals zero), and radius of perceptibility, which is the maximum epicentral distance that an earthquake is felt, for different magnitudes. In addition, variations exist within the above types of curves.

EPICENTRAL INTENSITY (I_0)

Epicentral intensity is the intensity reported in the epicentral area. Plots showing the variation of the epicentral intensity with differing magnitudes are useful in evaluating the probable maximum damage. An epicentral-intensity curve for southern California, for a general focal depth of about 16 km, is shown in figure 7.

The curve indicates, for example, that to produce damage ($I \geqq 5$ M.M.) a magnitude-4 earthquake must be directly under the area and structure. The epicentral intensity in southern California varies with magnitude such that, as a generalization (Gutenberg and Richter, 1956, p. 131):

$$M = 1 + 2/3 I_0 \text{ (} I \text{ is in M.M.).}$$

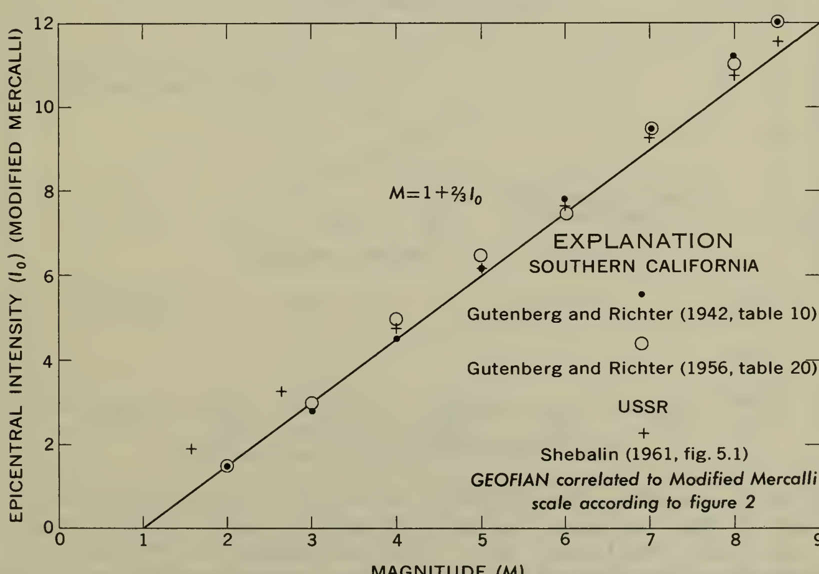


FIGURE 7.—Epicentral intensity as a function of magnitude for southern Californian and Russian earthquakes. Focal depths approximately 16 km (those for southern California from Gutenberg and Richter, 1956, p. 106–107).

A curve, based on only seven earthquakes, appears to indicate slightly lower epicentral intensities for magnitudes below 6 for western Nevada than for southern California. This may be due to a greater average focal depth for earthquakes in the western Nevada region.

AVERAGE-INTENSITY CURVES

Average-intensity curves are constructed by plotting the average intensities for epicentral distance intervals and drawing a smoothed curve through the resulting scatter of points (fig. 8). Average intensity decreases fairly regularly with increasing epicentral distance beyond an epicentral distance of 20–100 km; at lesser distances the intensity increases greatly with decreasing epicentral distance. In some earthquakes the decrease of intensity with epicentral distance beyond 100 km is approximately linear, whereas in others the amount

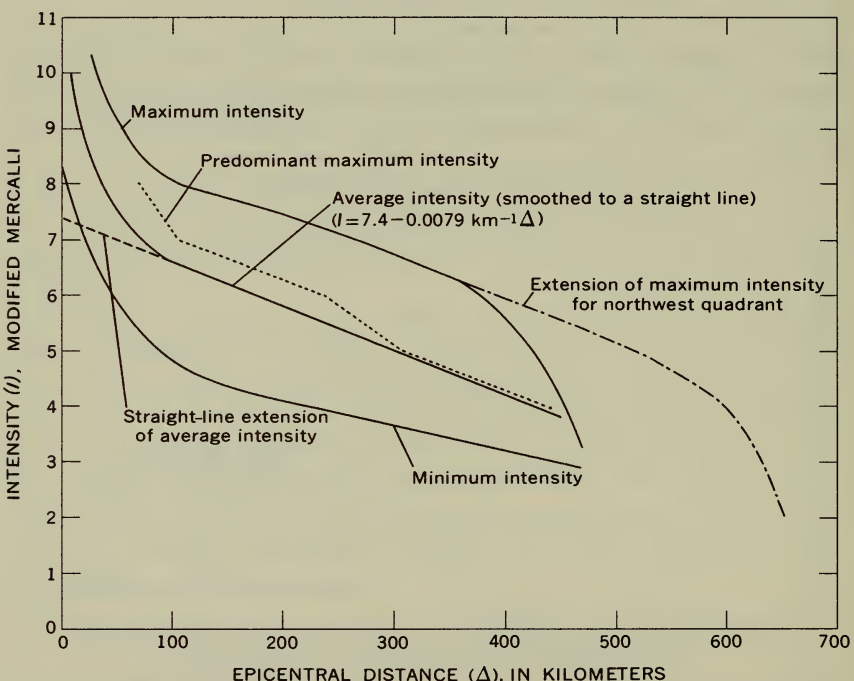
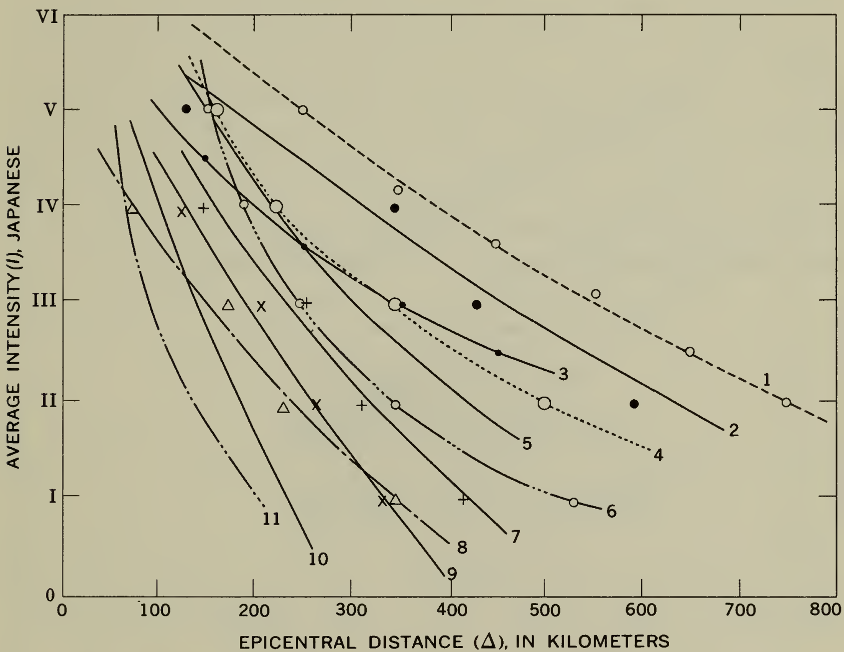


FIGURE 8.—Intensity–epicentral-distance curves for Arvin-Tehachapi earthquake, July 21, 1952; northwest quadrant from epicenter. Area: California. Magnitude: 7.6–7.7. Focal depth: 16 km. Epicentral intensity: XI. Total area felt: 160,000 sq mi (414,000 sq km) (derived from data in Neumann and Cloud, 1955, p. 208).

of decrease per unit distance diminishes slightly with increasing epicentral distance (fig. 9).

Average-intensity curves have been used to assign magnitude and to characterize earthquakes in Japan (fig. 9). The Kawasumi magnitude equates magnitude and average intensity (Japanese) at an epicentral distance of 100 km (Kawasumi, 1951, p. 472; 1952). The average-intensity–epicentral-distance relationships for many earthquakes have been studied by Kawasumi (1951) and Sato (1948).

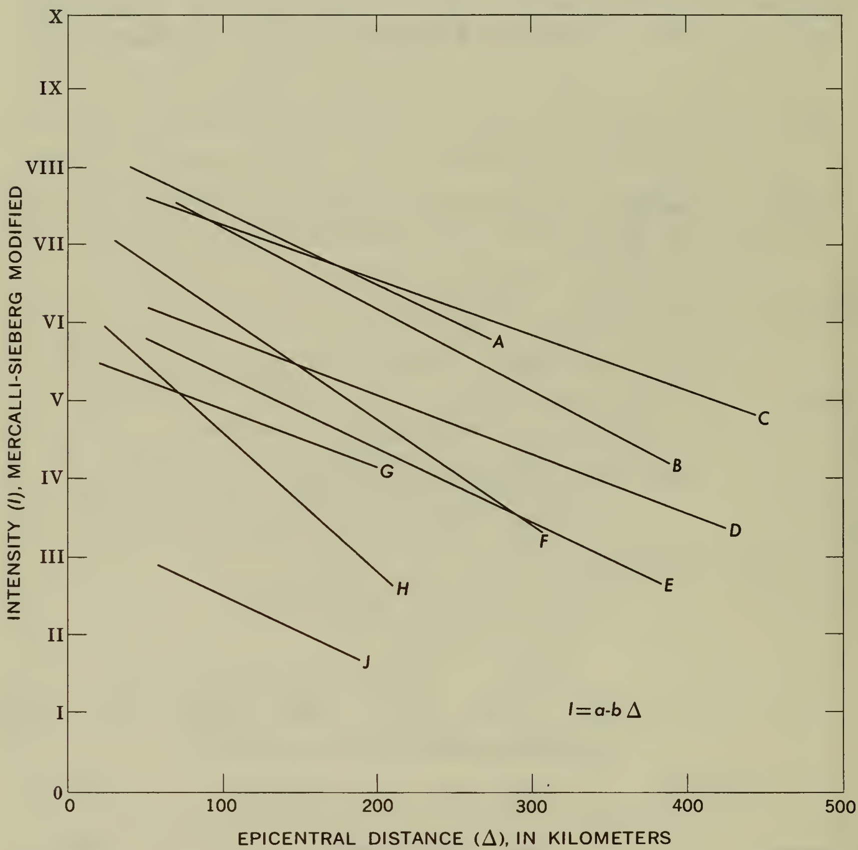


Earthquake	Date	M	Earthquake	Date	M
1. Sanriku	1933	8.3	7. Tottori	1943 (Sept.)	7.4
2. Nankaido	1946	8.1	8. Mikawa	1945	7.1
3. Kwanto	1923	7.9	9. Fukui	1948	7.3
4. Tonankai	1944	8.0	10. Tottori	1943 (Mar.)	6.1
5. Hyuganada	1941	7.4	11. Nagano	1941	6.2
6. Tango	1927	7.5			

All focal depths ≤30 km

FIGURE 9.—Average-intensity–epicentral-distance curves of some major earthquakes in Japan since 1923 (Collins and Foster, 1949, p. 24; and Kawasumi, 1950a, p. 9, after Hirono, 1948; *M* and focal-depth data from Japan Meteorological Agency, 1958).

These authors present the intensity in terms of a modification of the 12-unit Mercalli-Sieberg scale, which is the forerunner of, and similar to, the Modified Mercalli scale. The intensity–epicentral-distance plots are averaged to a straight line, beyond an epicentral distance of about 50 km, which is described simply by $I=a-b\Delta$ (Sato, 1948, p. 91; fig.



	Earthquake	Date	a	b	M
A	Mino-Owari	1891	8.4	0.0094	----
B	Tonankai	1944	8.3	.0104	8.0
C	Nankaido	1946	8.0	.0071	8.1
D	Hatinohe-Oki	1945	6.6	.0075	7.3
E	Tottori	1943 (Sept.)	6.3	.0094	7.4
F	Fukui	1948	7.5	.0135	7.3
G	Mikawa	1945	5.7	.0076	7.1
H	Imaichi	1949	6.4	.0178	6.7
J	Noziriko	1943	3.5	.0095	6.1

FIGURE 10.—Average-intensity–epicentral-distance curves of selected Japanese earthquakes (compiled from Kawasumi, 1950a, b, 1951; and Sato, 1948; *M* data from Japan Meteorological Agency, 1958).

10 of present report). An equation describing the average-intensity–epicentral-distance curves for the Japanese scale was also developed (Kawasumi, 1952; 1953, p. 639). Data presented by Gutenberg and Richter (1942, table 10; 1956, table 20) on epicentral distance versus average intensity for earthquakes of different magnitudes in southern California are shown in figure 11.

MINIMUM-INTENSITY CURVES

Smooth curves drawn through the plots of minimum intensities recorded at any epicentral distance (fig. 8) have been referred to as basement-rock attenuation curves and infer that the intensities are at a minimum on a granitic basement rock or, where granite is absent, on highly compacted sedimentary rock (Neumann, 1954, p. 5, 16). According to Neumann and Cloud (1955, p. 207), "localities which are resting for all practical purposes on outcrops of basement rock, the intensities are minimum * * * and that at such localities the decrease in intensity with increase of epicentral distance is surprisingly uniform and generally the same for all shocks." The minimum intensity

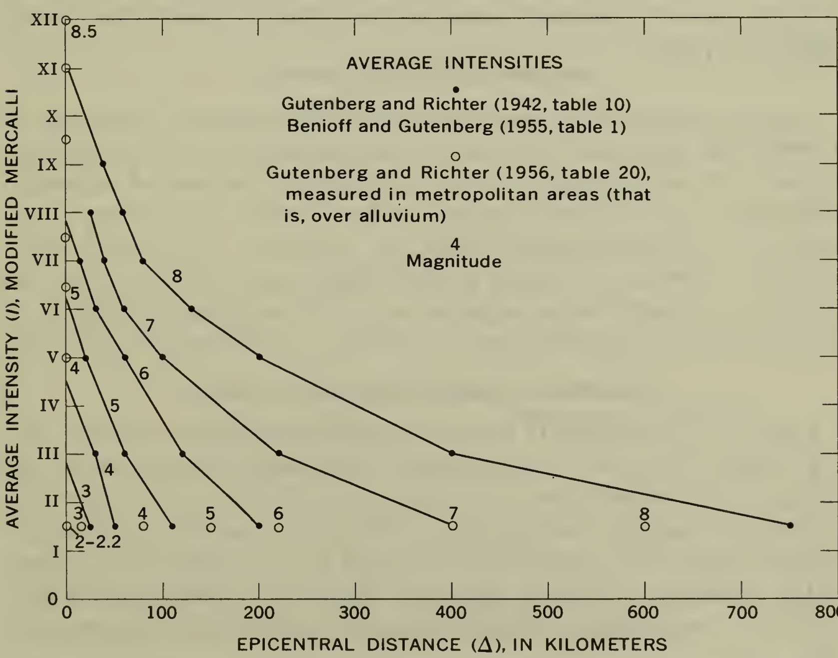


FIGURE 11.—Average-intensity–epicentral-distance curves for earthquakes of different magnitudes in southern California. Focal depth=16 km. Richter (1958, p. 140) considered $I=1\frac{1}{2}$ as the limit of perceptibility.

decreases approximately exponentially with increasing epicentral distance (Neumann, 1954; 1959, p. 214).

Neumann (1954, p. 12) believed that smoothed basement-rock–epicentral-distance curves can give the basement-rock intensity at a specific epicentral distance more accurately than intensity assignments based on observed effects on a specific basement-rock outcrop at that distance. He (1954, p. 43) found good agreement between minimum intensity, obtained from minimum-intensity curves for a site at a short epicentral distance, and acceleration-period charts.

For western Washington, Neumann (1954, p. 12; 1959, p. 214) generalized that the attenuation of intensity with epicentral distance is of such form that each time the epicentral distance is doubled the minimum intensity (M.M.) drops one unit. For the Puget Sound earthquake of 1949 he found the minimum-intensity curve to be approximated by:

$\log \Delta \text{ (mi)} = \log 0.68 + (9.7 - I) \log 2.193$ (Neumann, 1959, fig. 1), or

$$\log \Delta \text{ (km)} = \log 0.68 + (9.7 - I) \log 2.193 + \log 1.609.$$

Difficulties in undertaking minimum-intensity studies may be encountered in other regions owing to different types of basement rock, complex tectonic features, and limited intensity data (Neumann, 1959, p. 217, 218).

MAXIMUM-INTENSITY CURVES

Maximum intensity as used here refers to the maximum intensity at a particular epicentral distance as distinguished from the maximum intensity of an earthquake, which is usually the epicentral intensity. Smoothed curves drawn through points plotted for maximum intensity at various epicentral distances represent the intensity produced over the more unstable ground. These curves (fig. 8) show the maximum intensity to be expected at a given epicentral distance or the maximum epicentral distance to which a specific intensity extends.

PREDOMINANT MAXIMUM-INTENSITY CURVES

Isoseismal lines separate bands of predominantly one intensity rating (fig. 3). A point on an isoseismal line, therefore, represents the maximum epicentral distance in that particular direction for which a particular intensity rating is the predominant one. The average epicentral distance to a particular isoseismal line represents the average of the maximum epicentral distances, in all directions from the epicenter, for which the particular intensity rating is the predominant one.

Predominant maximum-intensity curves are constructed from the plots of average epicentral distances, obtained from isoseismal maps, for the various isoseismal lines of an earthquake (fig. 3). These curves generally lie between the average and maximum intensity curves and show the average extent of predominant intensity bands of an earthquake (fig. 8).

Data from predominant maximum-intensity curves for seven earthquakes in western Nevada and adjacent California illustrate the variation of predominant maximum intensity with magnitude (fig. 12). The variation, particularly of the lower intensities, appears to be fairly regular, and it probably indicates that predominant maximum-intensity curves are a valid way to compare earthquakes and that the focal depth of these earthquakes is similar. The higher intensities are more scattered, which is probably mainly due to poor control for these intensities in areas of sparse population. The lower intensities are felt over a much greater area and are consequently better controlled. Figure 12 shows that in western Nevada an earthquake of magnitude 6 would be expected to have a band of intensity 5 that would extend about 118 km, or 73 miles, from the epicenter.

RADIUS OF PERCEPTIBILITY (*r*)

The radius of perceptibility is the average radius, from the epicenter, of the total area over which an earthquake is felt. It has importance as an additional control point for intensity curves and has been described as a function of both magnitude and epicentral intensity. Richter (1958, p. 140) considered the lower limit of perceptibility

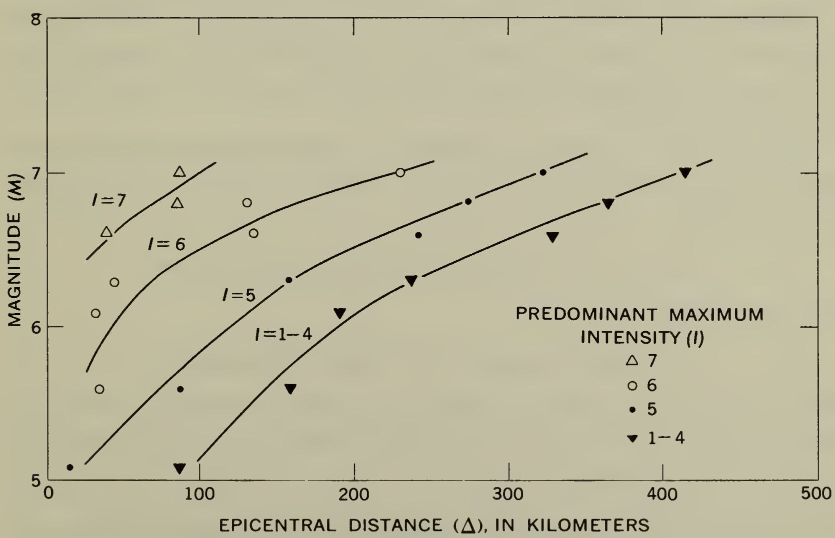


FIGURE 12.—Predominant maximum intensity (M.M.) as a function of magnitude and epicentral distance for seven earthquakes in western Nevada and adjacent California. Derived from data in "U.S. Earthquakes 1954, 1959, and 1962" (U.S. Coast and Geodetic Survey), Murphy and Cloud (1956), Eppley and Cloud (1961), and Lander and Cloud (1964).

equivalent to a Modified Mercalli intensity of 1½ in accordance with the definition of the scale. Shebalin (1959a, p. 103) considered this unrealistic to use in dealing with isoseismal maps as information on intensities less than 3 is, for practical purposes, generally not available, which is in agreement with Neumann (1954, p. 10 and 11; 1959, p. 214), as intensity 3 is sometimes reported as not felt. (See table 1.) Gutenberg and Richter (1956, p. 131–133) gave the radius of perceptibility, in kilometers, in southern California as equal to:

$r=0.5I_0^3-1.7$ (I is in M.M.), and

$r=1.4(M-0.614)^3$ for a curve, or

$M=-3.0+3.8\log r$ for a linear approximation.

INTENSITY VARIATION AS A FUNCTION OF FOCAL DEPTH

Focal depth is a major variable affecting intensity distribution, but unfortunately accurate information on focal depths is not available for most earthquakes within the earth's crust, and studies relating focal depth to intensity have been adequately documented only for quakes beneath the crust. However, in some local areas most of the earthquakes are considered to originate at about the same level; for example, 16 km in southern California (Gutenberg and Richter, 1956, p. 106, 107), and the variation of intensity caused by different focal depths in such an area may be small. Information on the variation caused by different focal depths is important in attempting to compare the distribution of effects of earthquakes of different focal depths and to extrapolate earthquake effects to the shallow depths in which nuclear testing is conducted.

The epicentral intensity increases with decreasing focal depth. The relationship was shown by Shebalin (1957b; 1959a, p. 101; 1959b; 1961, p. 127) as

$$I_0=1.5M-3.5\log h+3.0 \text{ (normal earthquakes)}$$

if $0<h<H_a$ and

$$I_0=1.5M-3.4\log h+5.4 \text{ (deep earthquakes)}$$

if $H_a<h<640$ km, where $H_a\approx80$ km, the upper boundary of the low-velocity layer, and I is in the GEOFIAN scale (fig. 13). For example, an earthquake of magnitude 5 at 10-km focal depth would produce an epicentral intensity of 7, whereas the intensity would be 10½ if the focal depth were 1 km. This relationship for normal earthquakes served as the basis for a generalized table which shows epicentral intensities for earthquakes of different magnitudes at three focal depths (table 7).

Epicentral intensities derived from Shebalin's (1961) nomogram (fig. 13) for a focal depth of 16 km agree very closely with the epicen-

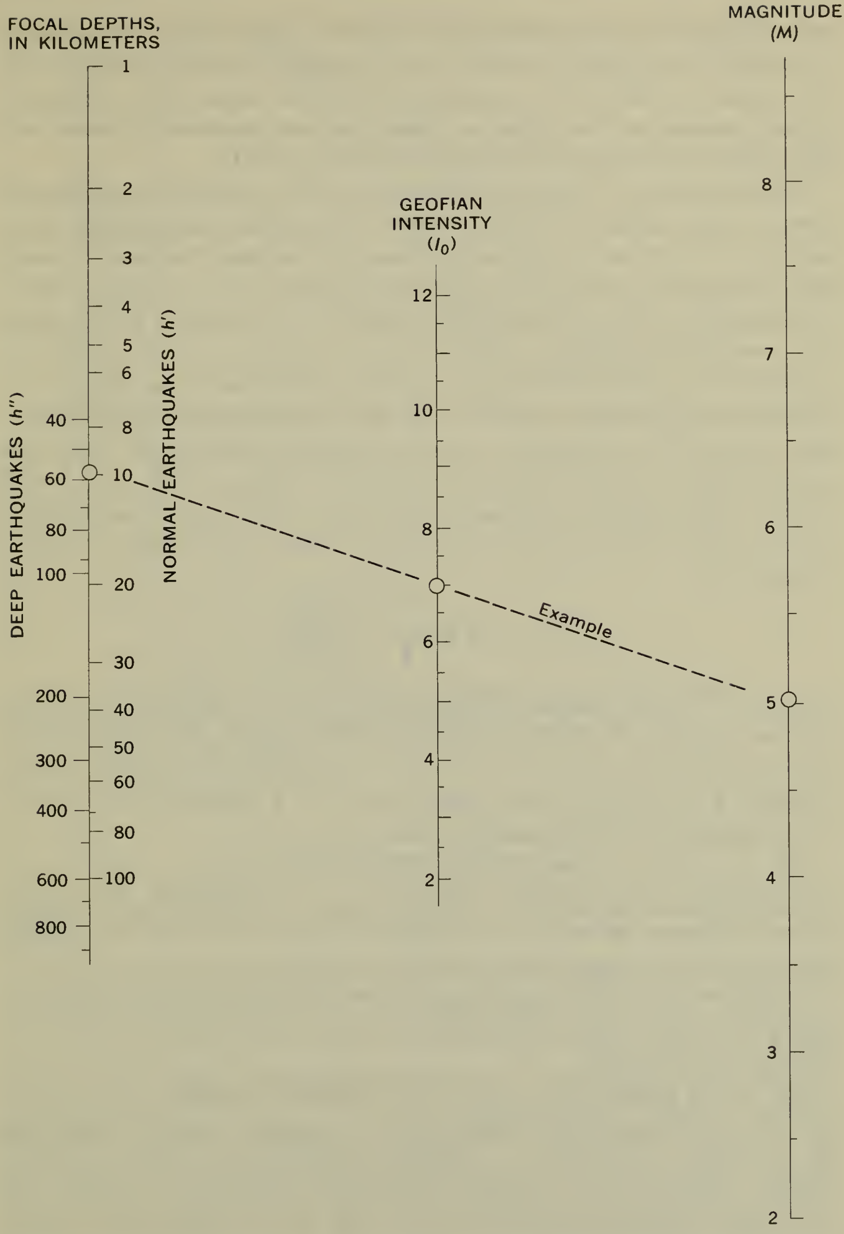


FIGURE 13.—Nomogram for determination of one of the values epicentral intensity (I_0), magnitude (M), or focal depth (h) if the other two are known. From Shebalin (1961, fig. 5.1).

tral intensities of Gutenberg and Richter (1942, 1956) for southern California, except for the very low intensities, where the control is poor (fig. 7). Shebalin's nomogram has been used in New Zealand to help determine focal depths where the instrumentally determined focal depths were apparently erroneous (Eiby, 1964).

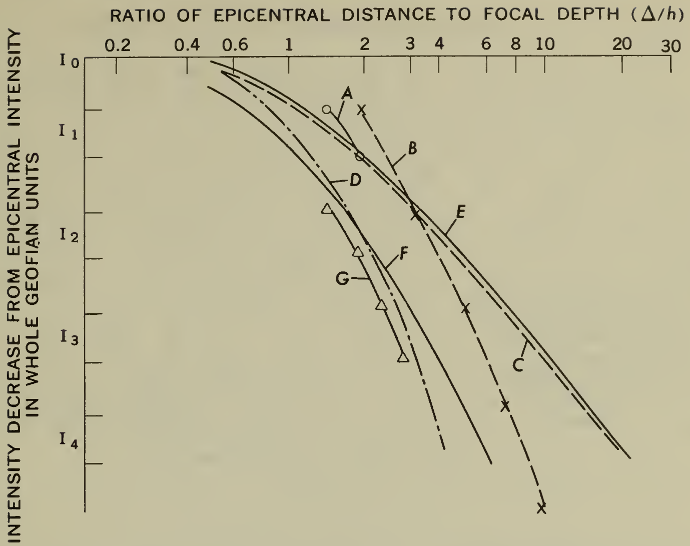
The character of intensity attenuation with increasing epicentral distance also varies with focal depth. A discussion and graphic comparison of different formulas proposed by various workers (Blake, 1941; Gassmann, 1925; Gutenberg and Richter, 1942; Inglada, 1924; Kovesligethy, 1907; and Medvedev, 1959) to express this relationship was presented by Shebalin (1959a; fig. 14 of present report). Shebalin considered the chief difficulty with these formulas to be the lack of discrimination between normal and deep earthquakes, which apparently differ in the character of their intensity attenuation. With due consideration for this difference, Shebalin (1959a, p. 109–110) found that the relationship of intensity attenuation with epicentral distance to focal depth obtained from earthquake data approximates a curve of the form

$$I_0 - I_i = k \log \sqrt{1 + \left(\frac{\Delta_i}{h}\right)^2},$$

where $I_0 - I_i$ is the intensity difference between the epicentral intensity and the intensity, I_i, at some epicentral distance, Δ_i. The coefficient of intensity attenuation, k, was found to range from 2.8 to 4.5 and to average 3.6 for normal earthquakes. The value k ranges from 4.5 to 7.5 and averages 6.0 for deep earthquakes.

The accuracy of determining focal depths depends basically on how precisely the epicentral intensity, I_0, is determined. The value of the difference between the epicentral intensity and the first isoseismal probably averages about one-half an intensity unit, but it is likely to be higher for shallow earthquakes because the epicentral intensity occurs over a comparatively small area and may be missed (Shebalin, 1959a, p. 102, 103, 112).

The above relationship was used by Shebalin (1959a, fig. 4; 1961, fig. 5.3) as the basis for construction of a graph (fig. 15) depicting the changing character of intensity attenuation with epicentral distance occasioned by varying focal depth. The graph indicates that the higher epicentral intensity occasioned by a shallow focal depth is somewhat compensated for by the higher rate at which intensities decrease with epicentral distance. For example, the intensity drops 1 unit from the epicentral intensity within 3 km for a focal depth of 2 km, whereas this does not occur until 17–30 km for a focal depth of 20 km (fig. 15). The difference in intensity attenuation for an earth-



$I_0 - I_i = f\left(\frac{\Delta_i}{h}\right)$ according to different formula.

A, Inglada (1924), estimated;
B, Gutenberg and Richter (1942);
C, Koveslígethy (1907) and Gassmann (1925), without consideration of absorption ($p=0.00$);
D, Same as *C* but with consideration of absorption ($p=0.06$);
E, Blake (1941) for $k=3$;
F, Same as *E* for $k=6$;
G, Medvedev (1959).

FIGURE 14.—Graphic presentation of the function of intensity attenuation (Shebalin, 1959a, fig. 1).

quake of magnitude 6 at focal depths of 10 and 20 km is shown in figure 16.

In using the graph (fig. 15), individual points at which intensities were observed are plotted and the focal depth curve that fits best is used. Thus, essentially average intensities are used, but it also may be possible to use the average isoseismal radii (predominant maximum intensities) (Shebalin, 1959a, p. 111). Apparently Shebalin believed that the accuracy of the chart is such that the difference between average intensity radii and isoseismal radii is not critical. The relative error of the derived focal depth does not exceed a factor of about 1.5 or 2 (Shebalin, 1959a, p. 112; 1961, p. 134). Instrumentally determined depths for earthquakes at a depth of 16 km may well be in error of ±6 km in favorable circumstances, and at a depth of 50 km the error may be as high as ±20 km (Benioff and Gutenberg, 1955, p. 134).

The graph (fig. 15) has been used to help determine focal depths

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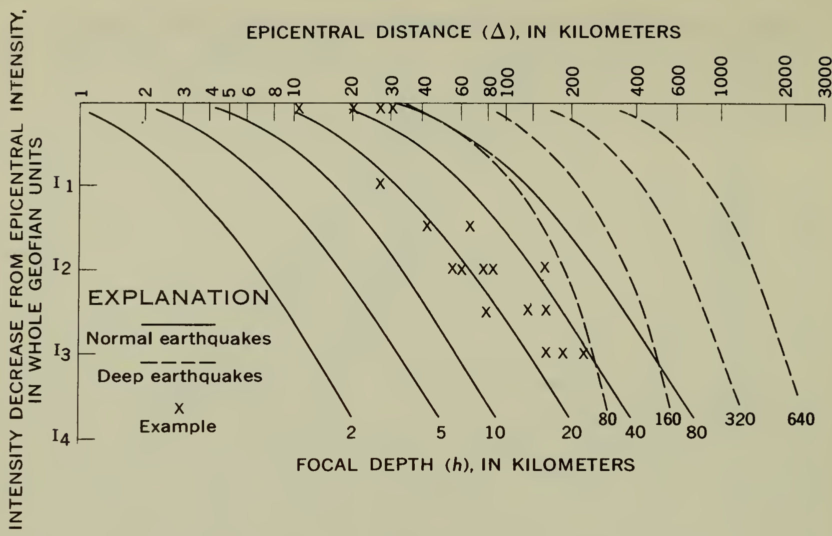


FIGURE 15.—Universal chart for determining focal depth according to macroseismic data and an example of such a determination (Gudamakarsk earthquake, Aug. 15, 1947); focus of normal and deep earthquakes and example. (Shebalin, 1959a, fig. 4.)

in Russia (Gubin, 1960, p. 277). The data in figure 12 for western Nevada indicate a general focal depth of 20–40 km, when plotted in figure 15, for that region. Starting with a known focal depth one can use the graph to help determine intensity distribution.

Gutenberg and Richter (1942, p. 174, 175) had previously proposed a formula relating epicentral intensity, focal depth, and radius of perceptibility:

$$I_0 = 1.5 + 3 \log\left(\frac{r^2}{h^2} + 1\right).$$

Shebalin (1959a, p. 103, 104) considered this formula to be useful provided there is a significant epicentral intensity, a sufficiently populated area, and a utilization of the more practical perceptibility boundary of intensity 3, rather than 1½.

Data on the Tesikaga earthquakes in eastern Hokkaido are given (fig. 17) to illustrate the relationship of intensity with focal depth and magnitude and the use of Shebalin's nomogram and chart. The difference between the extent of intensity distribution from the 5.7-magnitude earthquake, *A*, and the two 6.2-magnitude earthquakes, *B* and *C*, is clearly shown (fig. 17). Also, of the two 6.2-magnitude earthquakes, earthquake *B* shows a greater intensity decrease with epicentral distance (fig. 17*D*). Focal depths, derived from Shebalin's chart, indicate that earthquake *B* may have been shallower (table 8).

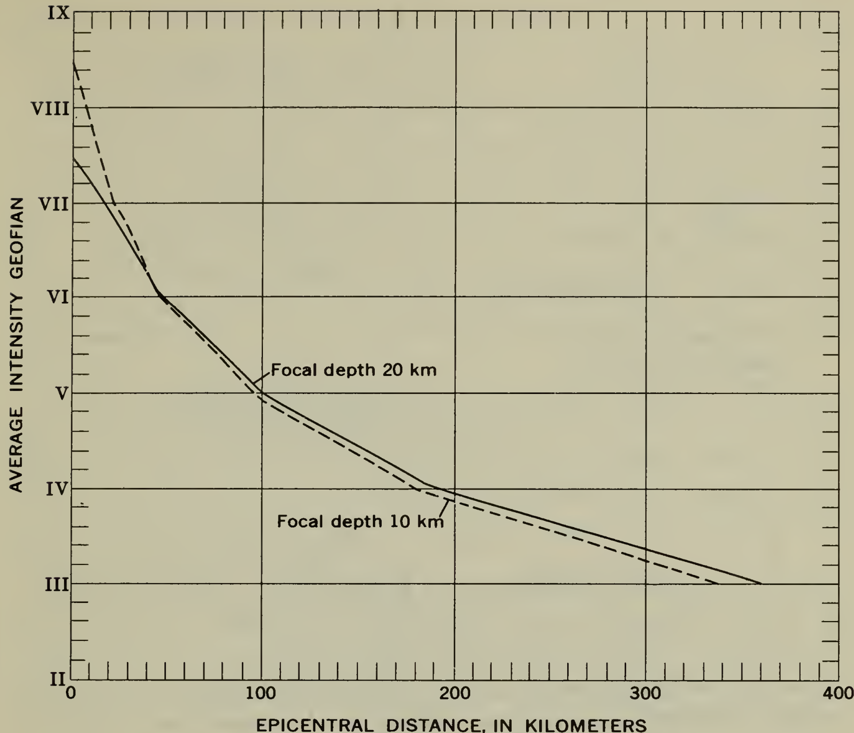


FIGURE 16.—Average-intensity–epicentral-distance curves for earthquakes of magnitude 6 at focal depths of 10 and 20 km (derived from Shebalin, 1959a, p. 109).

A comparison of the focal depths derived from Shebalin's nomogram and chart with those given for the earthquakes (Matumoto, 1959) shows fair agreement for earthquakes *A* and *B* and a difference of about 15 km for *C* (table 8).

INTENSITY VARIATION AS A FUNCTION OF GEOLOGIC CONDITIONS

The principal geologic elements that affect intensity are structure, the physical properties of the underlying material, ground water, slope, thickness of material, and, perhaps, type of material at the focus.

GEOLOGIC STRUCTURE

Geologic structure at and near the surface causes variations in intensity. This is easily seen on isoseismal maps of most California earthquakes (fig. 3). The major structures in California trend northwest, and the isoseismal maps reflect this trend. It is necessary to divide the disturbed area of many California earthquakes into northwest-southeast and northeast-southwest segments (fig. 8) in

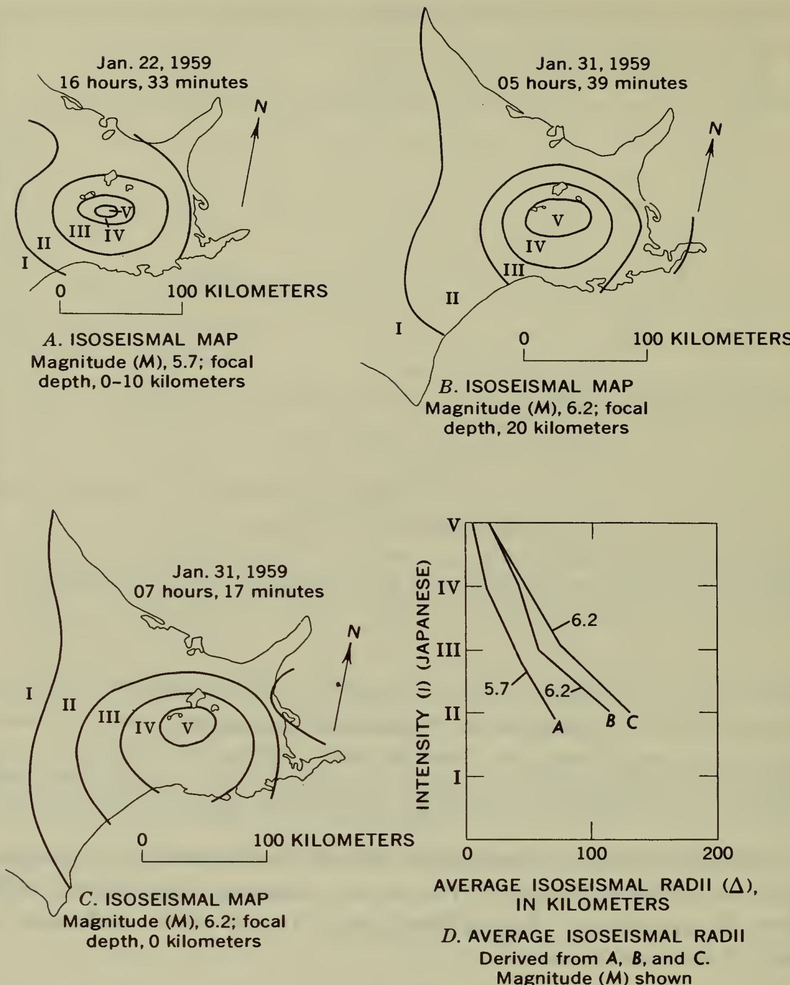


FIGURE 17.—Isoseismal data from the Tesikaga earthquakes of January 1959. Intensities shown in Japanese scale. (*A*, *B*, and *C* from Matumoto, 1959.)

studying the intensities, as the relation of intensity with epicentral distance varies considerably between these segments. Part of this variation in intensity could possibly be due to trend of a linear source, which most likely parallels regional structure. However, for the Arvin-Tehachapi earthquake of 1952 the presumable linear source, the White Wolf fault, trends northeastward perpendicular to the regional structure, whereas the isoseismals are elongated in a northwesterly direction (fig. 3). Also, Neumann (1954, p. 13) found, from his minimum intensity studies, indications of radial distribution of intensity from a point source rather than from a long stretch of a fault. Thus, it appears that the regional structure and not a linear source is responsible for elongated isoseismals.

Possibly the structures themselves, such as faults and folds, are not as important in affecting intensities as the resultant distribution of rock types caused by the structures. Where structure causes changes in a rock by crushing or shearing, it also affects the intensity over the rock (Popov, 1959). However, some variation in seismic wave characteristics along different paths results directly from structure (Hankins, 1964, p. 197). In central Asia, Vvedenskaya (1961) found that the distribution of isoseismals is partly dependent on the regional structure.

In New Zealand the regional trends of geologic structure is a major factor causing asymmetry in isoseismals, as is shown by isoseismal maps for major historic earthquakes (Clark and others, 1965, p. 120). The northeast axes of the isoseismals, paralleling the regional structural trends, are greater than the northwest axes. This is also true for some earthquakes in Japan.

Ikegami (1948, p. 88) believed that either the influence of the geologic structures along the travel path of the earthquake waves or the differences in the mechanism of earthquake origin are responsible for anomalous maximum amplitudes recorded at some stations in central Honshu. The anomaly at a specific station is positive for seismic waves arriving from one direction and negative for those arriving from another direction.

GROUND TYPES

It has long been recognized that similar structures in proximity and built on different types of ground may suffer vastly different effects from an earthquake (Duke, 1958) (figs. 18, 19). This variation, due to different responses of the underlying material, is generally the principal factor causing the range of intensities at any given epicentral distance. The minimum and maximum intensity curves of Neumann (1954, 1959) for the Puget Sound earthquake of 1949 were ascribed to differences in type of ground; the minimum to "granitic rock equivalent" material and the maximum to the more unstable "light formation."

Many studies have shown a correlation of damage to alluvium thickness (figs. 20, 21). However, some studies show that for certain types of more rigid buildings the damage is greater on firmer ground and the damage decreases with increasing alluvium thickness (Kanai, 1949; Kanai and Tanaka, 1950; Kanai and Yoshizawa, 1951). Kanai (1949) attributed the greater overall damage to all types of buildings on soft ground possibly to a secondary process such as unequal settling of the ground.

The type of damage sustained differs with ground type. In severe earthquakes in Japan, wooden buildings are more likely to be partially destroyed if on alluvium and totally destroyed if on other geologic formations (Kanai, 1951). This suggests that buildings on firm or rigid

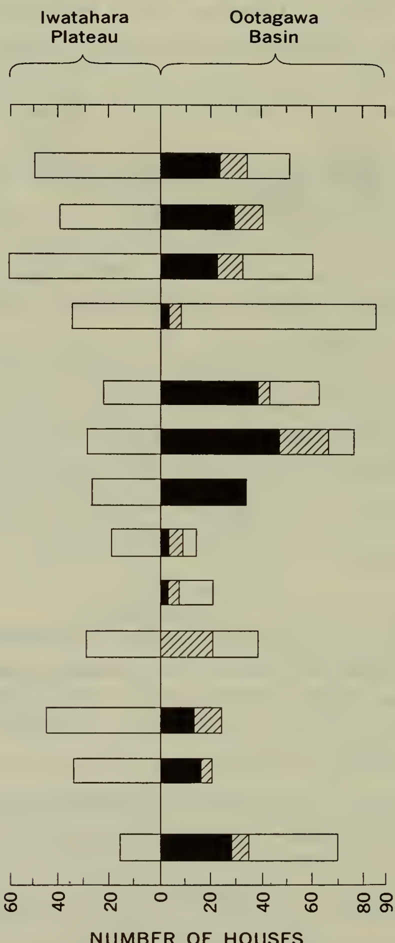


FIGURE 18.—Contrast of damage from the Tōnankai earthquake of December 7, 1944, M: 8.0, to houses on the Iwatahara Plateau, underlain by diluvium, and in the Ootagawa Basin, underlain by clayey material, within the same hamlets; Shizuoka Prefecture, Japan. Totally collapsed houses, black; half-collapsed houses, hatched; undamaged houses, white (Ooba, 1957, figs. 6 and 2). Each horizontal bar represents a different hamlet.

ground are mainly subjected to pure vibrational forces which cause either little or no damage or total destruction, whereas buildings on soft ground are, as mentioned before, affected mainly by secondary factors, especially unequal settling of the ground, which result in partial destruction (Kanai, 1947, 1951). In Japan, ferroconcrete, brick, and other types of relatively rigid buildings on firm ground are most severely damaged on first floors, whereas those on soft ground are most severely damaged on the higher floors or upper parts (Kanai, 1949; Kanai and Yoshizawa, 1951; Kanai and Tanaka, 1950).

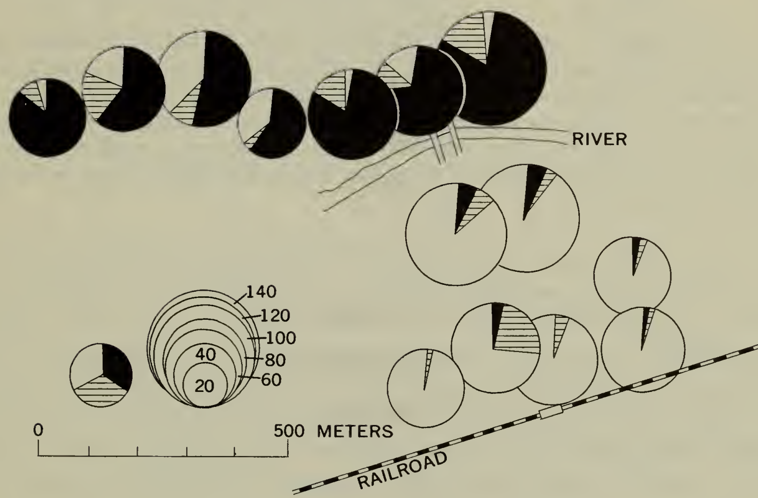


FIGURE 19.— Damage from the Tōnankai earthquake of December 7, 1944, M: 8.0, to houses in Fukuroi, Shizuoka Prefecture, Japan. Black, hatched, and white areas of a circle represent the numbers of collapsed, half-collapsed, and undamaged houses of a single hamlet. Hamlets north of river were on a clayey foundation; those to south, on rock foundation (Ooba, 1957, figs. 7 and 2).

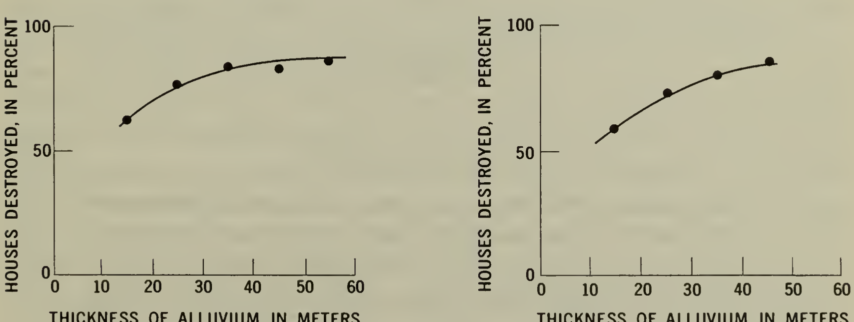


FIGURE 20.—Relation between thickness of alluvium and damage from the 1923 Kwanto earthquake for two parts of Yokohama (Omote, 1949, figs. 4 and 5).

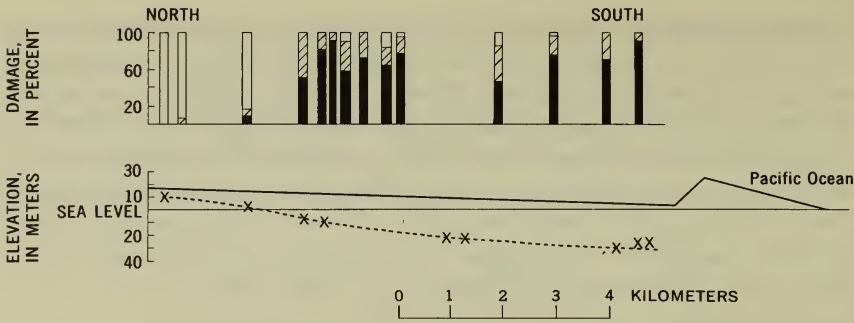
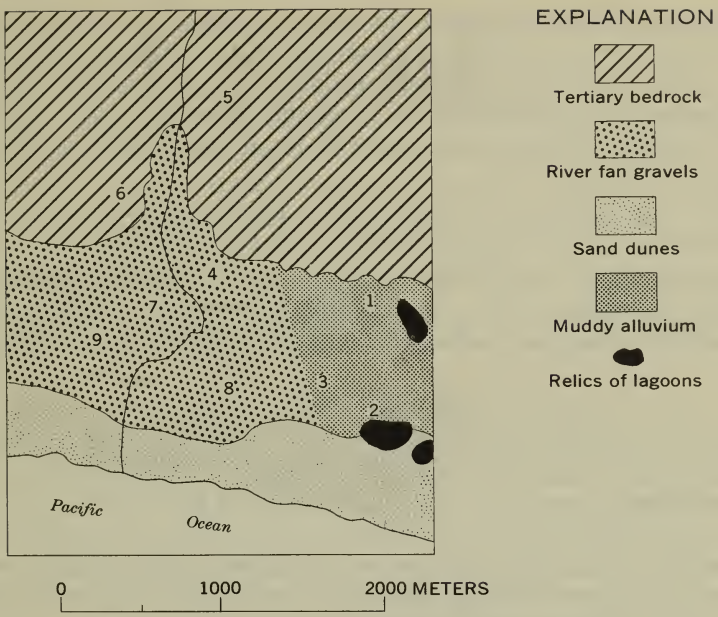


FIGURE 21.—Relation between the thickness of clayey overburden and the damage percentage of houses in hamlets in the Kikugawa basin. Damage from the Tōnankai earthquake of December 7, 1944, M : 8.0. Solid line and dotted line, respectively, denote the surface profile and the lower boundary of the clayey overburden. Black, hatched, and white areas represent, respectively, the percentage of collapsed, partially collapsed, and undamaged houses of hamlets (Ooba, 1957, fig. 10).

Two distinct types of damage involved here are (1) damage resulting primarily from seismic vibration and (2) damage resulting primarily from foundation failures. Under category 1 the most critical aspect depends upon the coincidence of the fundamental period of the structure with that of the ground motion; for example, low rigid short-period structures are more heavily damaged on firm ground, and tall flexible long-period structures are more heavily damaged on soft ground (and at greater epicentral distances where the predominant period is longer). Under category 2 any structure, regardless of its inherent characteristics, is subject to damage if the materials supporting the foundation undergo appreciable deformation.

Miyamura (1953, p. 654) and Ooba (1957) studied the effects of some earthquakes on the southeast side of central Honshu and found that whereas damage was limited to flat alluvial plains the distribution of damage on the plains was not uniform. All severely damaged localities were confined to mud plains, such as deltas, drowned valleys, reclaimed lagoons, and other lowlands of muddy alluvium and artificially made land. Gravel plains, on the contrary, received only slight damage or none (fig. 22). On coastal beaches the villages and towns were partly damaged. At these localities the damaged parts were on recently deposited loose-packed sand and, at places, had mud layers beneath. The nondamaged parts were on older close-packed sand with, at many places, stone or gravel layers underneath (Miyamura, 1953, p. 657).

Intensities over highly compacted sedimentary rock outcrops were consistently about 1 intensity (M.M.) grade higher than those over granitic outcrops at all epicentral distances (Neumann, 1954, p. 72).



Locality	*Village subdivision*	*Damage percentage*
1	Noga	2.7
2	Arai	5.3
3	Naka Arai	15.5
4	Okahara	1.2
5	Higasi Oya	.0
6	Nonaka	.0
7	Huzizuka	.8
8	Hama	.7
9	Udari	.0
	Total for village	10.8

FIGURE 22.—Variation of earthquake damage with geologic conditions in Obuti Village, Sizuoka Prefecture, from the Tokaido (Tōnankai) earthquake of December 7, 1944 (Miyamura, 1953, fig. 5). Damage percentage equals percentage of destroyed houses plus one-half the percentage of partially destroyed houses.

Medvedev (1952 a, b, 1961), Popov (1959), and others have listed quantitative intensity differences for various ground types. Medvedev chose granite as a standard and listed intensity differences to be added for other materials, whereas Popov listed the intensity differences both as variations from the standard granite and as variations to be added to or subtracted from the average intensity. Intensities for granite could be correlated with minimum intensity curves. In general, at a given epicentral distance, the relative range in intensity given by these and other workers is 4 units from granite outcrops to thick water-saturated alluvium.

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Puckhov (1965) devised a theoretical method for estimating the maximum particle velocity on bedrock during violent earthquakes. His (1965, p. III–248) results, correlated to intensity, indicated that for destructive earthquakes the maximum intensity would be about 7 on bedrock, whereas it may be 9 or 10 on loose sandy argillaceous ground.

Medvedev (1961, p. 115–116) used the product of the velocity of the longitudinal wave (v) and the density (ρ) of the material, the impedance, as a basis for estimating the relative differences in intensity, although he realized that a considerable influence on intensity is also rendered by the water content of the ground. He determined that

$$n = 1.67\,[\log\,(v_s\rho_s) - \log\,(v_n\rho_n)] + e^{-0.04h^2},$$

where n is the increase in intensity on the GEOFIAN scale, for ground with characteristic v_n and ρ_n, with respect to standard ground, with characteristic v_s and ρ_s, and h equals depth of ground-water level, in kilometers. The increase, n, is given to 0.1 intensity unit to differentiate the various types of ground in seismic response, as the intensity change in general is not particularly great. In practice, the increase is rounded off to whole intensity units (table 9).

A plot (fig. 23) of the data presented by Medvedev (1961) shows that the average intensity increase, n, over granite of different types

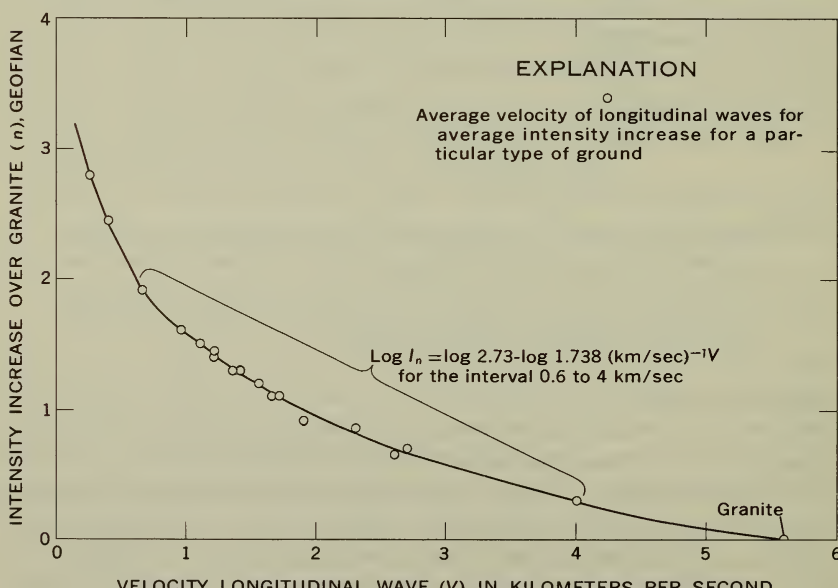

FIGURE 23.—Increase of intensity of different types of ground over that of granite as a function of seismic-wave velocity. Data from Medvedev (1961. table 4.2).

of ground has a smooth inverse relationship with the average velocity of the longitudinal wave through the materials.

Popov (1959), in addition, took into account geologic factors such as slope, thickness of layers, structure, and degree of weathering in assigning relative intensity differences for general examples (table 10). Tables 11 and 12 show the results of determining seismic-intensity differences for various ground conditions at specific areas.

The effect of ground type on intensity appears to lessen with decreasing epicentral distance near the epicenter, and in the immediate epicentral area the intensity apparently remains practically the same regardless of the geologic character of the overburden (Neumann, 1954, p. 39, 59).

Intensity, of course, is directly dependent on ground motion, and ground motion studies are useful in evaluating intensity differences over different ground types even though a practical description of intensity in terms of ground-motion components has yet to be made.

Differences in ground motion over various types of materials were instrumentally measured in southern California by Gutenberg (1957); in Japan by Minakami (1944, 1950), Minakami and Sakuma (1948), Sakuma (1948), Omote, Komaki, and Kobayashi (1956), and others; and in Russia by Lyamzina (1960, 1962), Puchkov (1959, 1962), Shteinberg (1964), Skorik (1964), and others.

Ground motion varies greatly over different ground types. A basement-rock outcrop and an adjoining area of unconsolidated soil may have as much as a 15-fold difference in acceleration (Neumann and Cloud, 1955, p. 205), and, with certain assumptions, possibly as much as a 22-fold difference (Neumann, 1954, p. 58). The amplitudes recorded over water-saturated soft ground may be 10 times those over bedrock (Minakami and Sakuma, 1948, p. 64; Gutenberg, 1957, p. 221). Different ground types were considered by Neumann (1954, 1959) to be responsible for irregularities in acceleration-period curves of earthquakes. Also, Neumann (1954, p. 21, 61) considered the slope of acceleration-period curves for the longer periods of earthquakes to be a function of the particular type of basement rock in which the earthquake originated.

The studies have shown greater amplitude, duration, and mean period over alluvium than over harder rock (fig. 24).

Medvedev (1963a, p. 18, 19) used ground-motion data to calculate the stress and relative deformation resulting from the ground motion of various ground types for different intensities. He concluded that for the same intensity, deformation in firm ground is approximately 15 times less than in unconsolidated material (fig. 25).

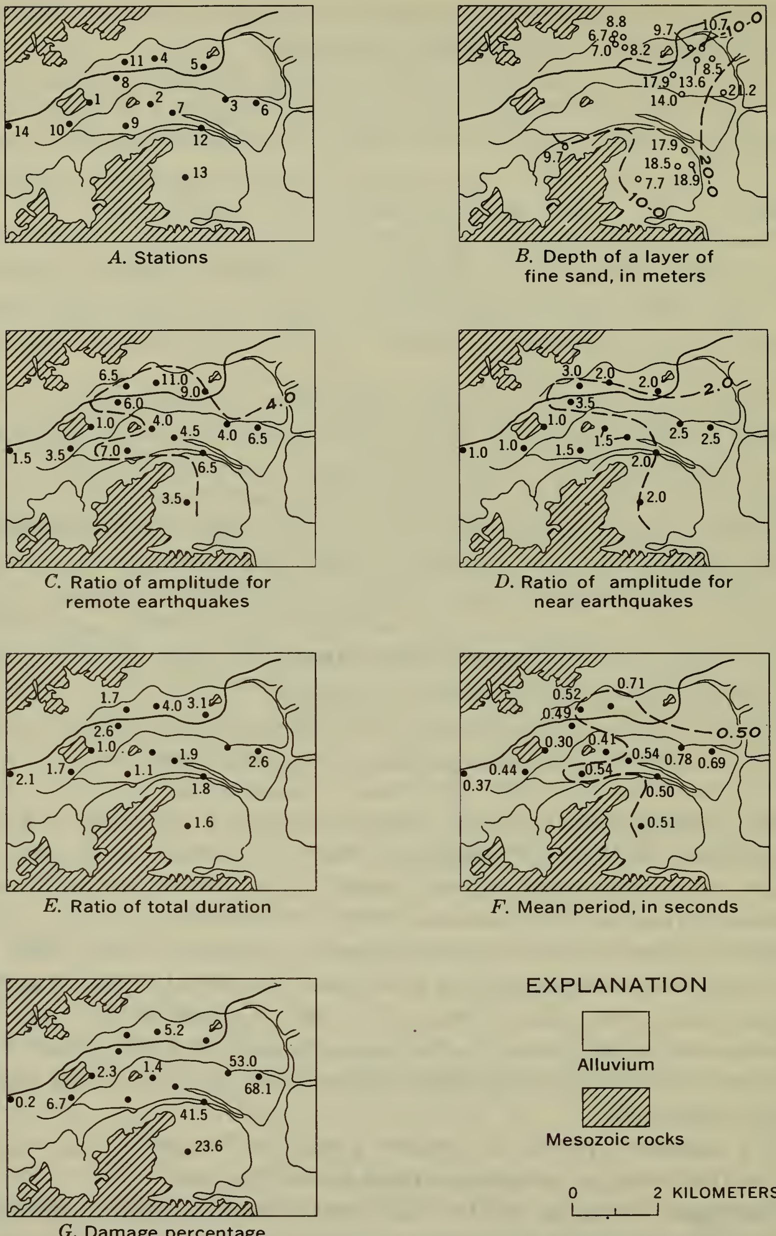

FIGURE 24.—Ground-motion variation over different ground types at Koti, Japan (Minakami and Sakuma, 1948, figs. 1–7). Ground motions, *C–F*, recorded from aftershocks of Nankai earthquake, 1946. *B* represents approximately the character of the alluvium thickness variation. *G* from Nankai earthquake, 1946.

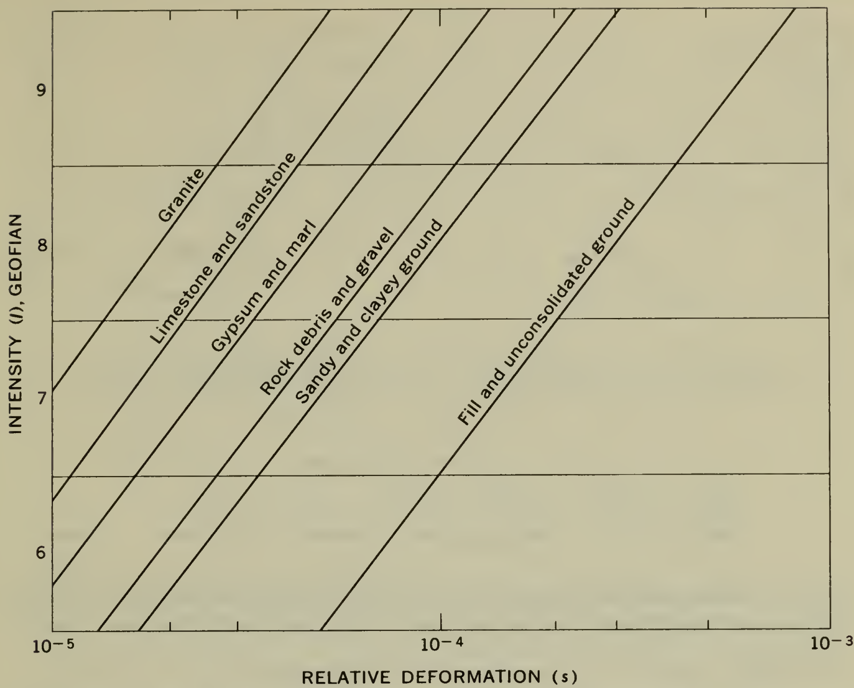

FIGURE 25.—Relative deformation (s) in different types of ground for earthquake intensities (I) from 6 to 9. $s=V0/C$; $V0$ is the particle velocity, and C is the velocity of seismic-wave propagation (Medvedev, 1963a, fig. 4).

The ratio of the maximum particle velocity expected at one site compared with that at another was found by Wiggins (1964, p. 311) to be very nearly equal to the inverse of the square root of the impedance ratios if all other factors are equal or scaled.

Microtremors, which are small ground motions caused chiefly by artificial disturbances such as traffic and industrial machines, vary with ground type and may be useful in ground classification (fig. 26). The results of microtremor studies in several Japanese towns were summarized by Kanai, Kawasumi, Tanaka, and Osada (1957), Kanai and Tanaka (1961), and Kanai, Tanaka, Osada, Suzuki, Morishita, and Yoshizawa (1966). It was found that the distribution of periods of microtremors, which have a close relation to the dominant period of earthquake motion, shows a different form for different kinds of subsoil. The characteristic forms are determined not only by the thickness of the alluvium, but also by the impedance ratio of neighboring layers and the thickness of each layer. All the layers between the surface and the bedrock appear to play a part in determining the largest period. The distribution curves are flat on bedrock, and the amplitudes

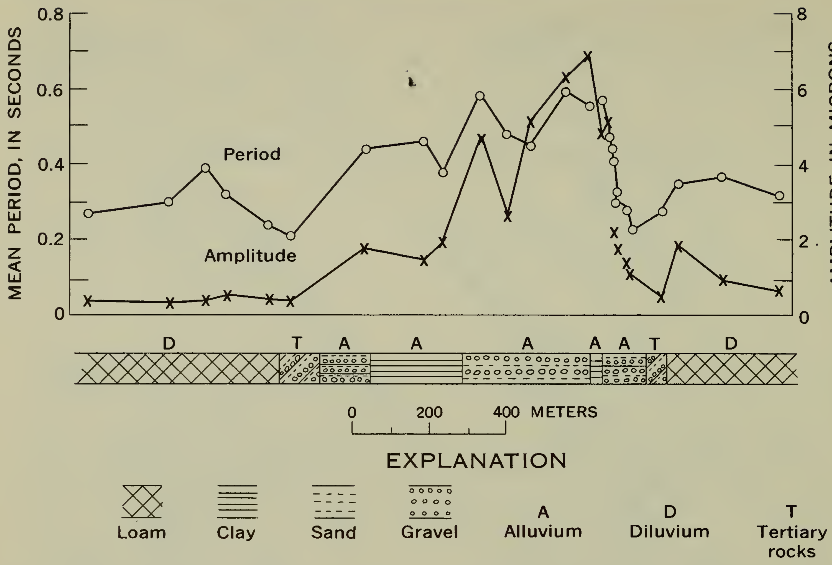

FIGURE 26.—Relation of the mean period and largest amplitude of microtremors to geologic formations in the Misaki area, Tokyo (Kanai, Tanaka, and Osada, 1957, fig. 67).

at the surface become relatively large at such periods as are synchronous with the natural period of the subsoil due to a selective resonance effect.

As the predominant, mean, and largest periods of microtremors vary greatly as a function of the vibrational characteristics of the subsoil, it is thought that the largest and mean periods can be used in a practical classification of the ground even though their physical meaning is not yet clear (Kanai and Tanaka, 1961, p. 101, 110). The ground classification consists of four divisions corresponding to those used in the building code of Japan (Kanai and Tanaka, 1961, p. 112–113) (fig. 27):

Type I: Ground consisting of rock, hard sandy gravel, and the like, classified as Tertiary or older strata over a considerable area around the structure.

Type II: Ground consisting of sandy gravel, sandy hard clay, loam, and the like, classified as diluvial, or gravelly alluvium, about 5 meters or more in thickness, over a considerable area around the structure.

Type III: Ground consisting of alluvium 5 meters or more in thickness, which can be distinguished from type II by bluff formation.

Type IV: Alluvium consisting of soft delta deposits, topsoil, mud, or the like, which is about 30 meters or more in thickness. Land obtained by the reclamation of a marsh, muddy sea bottom, and the like; the depth of the reclaimed ground is about 3 meters or more and 30 years have not yet elapsed since the time of reclamation.

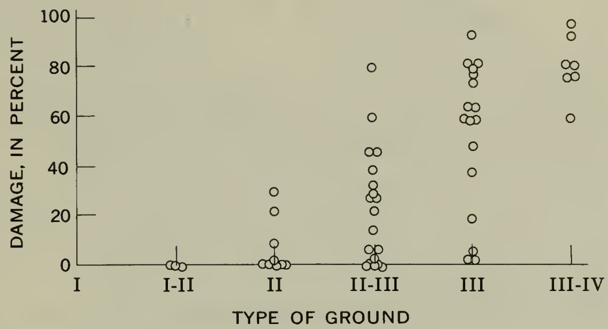

FIGURE 27.—Relation between earthquake damage to Japanese-style wooden houses in the Kikugawa district from the 1944 Tōnankai earthquake and type of ground as classified by microtremor measurements. The four types of ground correspond to those designated in the "Building Code of Japan" (Kanai and Tanaka, 1961, fig. 23).

Very thick soft ground, bedrock, and sand were not classified well, and an auxiliary classification using the relationship of the largest amplitude and predominant period was also adopted (Kanai and Tanaka, 1961, p. 110–111). Ground types, as classified by microtremors, show a relationship to earthquake damage (fig. 27).

The amplitudes of earthquake motions on the surface are larger than those underground, according to studies made by Kanai and Tanaka (1951), Kanai, Tanaka, and Yoshizawa (1959), Shima (1962), and Kanai, Tanaka, Yoshizawa, Morishita, Osada, and Suzuki (1966). The results of these and the microtremor studies showed that the surface layers greatly modified the seismic waves passing up through them and that, as earlier stated by Takahasi and Hirano (1941), the seismic waves at depth in bedrock could be thought of as having a constant form which is modified during passage through the surface layers. This is virtually the same conclusion reached by Neumann (1954, 1959). Thus, the ground motion at the surface can be described as the motion at depth in bedrock plus the modifications due to the vibrational characteristics of the particular surface layers. A set of empirical formulas was devised to describe the displacement amplitude, velocity, and acceleration at depth for an epicentral distance, Δ, in kilometers, and a magnitude, M (Kanai, 1958, 1961; Kanai and

Yoshizawa, 1958; Kanai, Tanaka, Yoshizawa, and others, 1966). A semiempirical formula describing modification of the seismic waves in the surface layer of the ground was also devised (Kanai and others, 1956; Kanai, 1957, 1961; Kanai, Tanaka, Yoshizawa, and others, 1966):

$$G(T)=1+\frac{1}{\sqrt{\left[\frac{1+\alpha}{1-\alpha}\left\{1-\left(\frac{T}{T_G}\right)^2\right\}\right]^2+\left\{\frac{0.3}{\sqrt{T_G}}\left(\frac{T}{T_G}\right)\right\}^2}},$$

in which T and T_G represent, respectively, in seconds, the period of seismic waves and the predominant period of the ground, and α represents the impedance ratio of the ground to the bedrock $(\rho_1 V_1/\rho_2 V_2)$ (Kanai, Tanaka, Yoshizawa, and others, 1966, p. 624). This formula when combined with the empirical formulas gives the ground motion at the surface (Kanai, 1961, p. 88; Kanai, Tanaka, Yoshizawa, and others, 1966, p. 624).

Ratios of the calculated acceleration values on bedrock and observed values on the surface were found by Kanai, Yoshizawa, and Suzuki (1963, p. 262) to be constant for different earthquakes and thus correspond to magnification constants. The ratios are normally 2 to 5 and rarely are more than 10. They (1963, p. 264) concluded that the destructiveness of earthquake motions depends mostly on the seismic characteristics of the prism of deposits overlying bedrock.

SEISMIC MICROREGIONALIZATION MAPS

The quantitative evaluation of intensity differences of ground types allows maps to be made which show the geology in terms of potential relative intensities. Data from such maps combined with data on the seismicity of a region are used to construct seismic microregionalization maps, which show earthquake risk in terms of the maximum intensity expected. The data on the seismicity of a region are usually taken from seismic regionalization maps, which are small-scale maps presenting the data as the maximum intensities to be expected on average ground for large regions (Medvedev, 1965, p. III–178) (fig. 28). Richter (1959) presented a general discussion of both regionalization and microregionalization maps. The problems of seismic regionalization were discussed by Medvedev (1960b, 1965) and Bune (1965), and instructions for the construction of seismic regionalization maps were promulgated by Medvedev and others (1961).

Microregionalization maps have been made for many parts of Russia (Puchkov, 1959; Kats, 1960; Kuliev, 1962; Goryachev and others, 1963), and instructions on the construction of these maps have

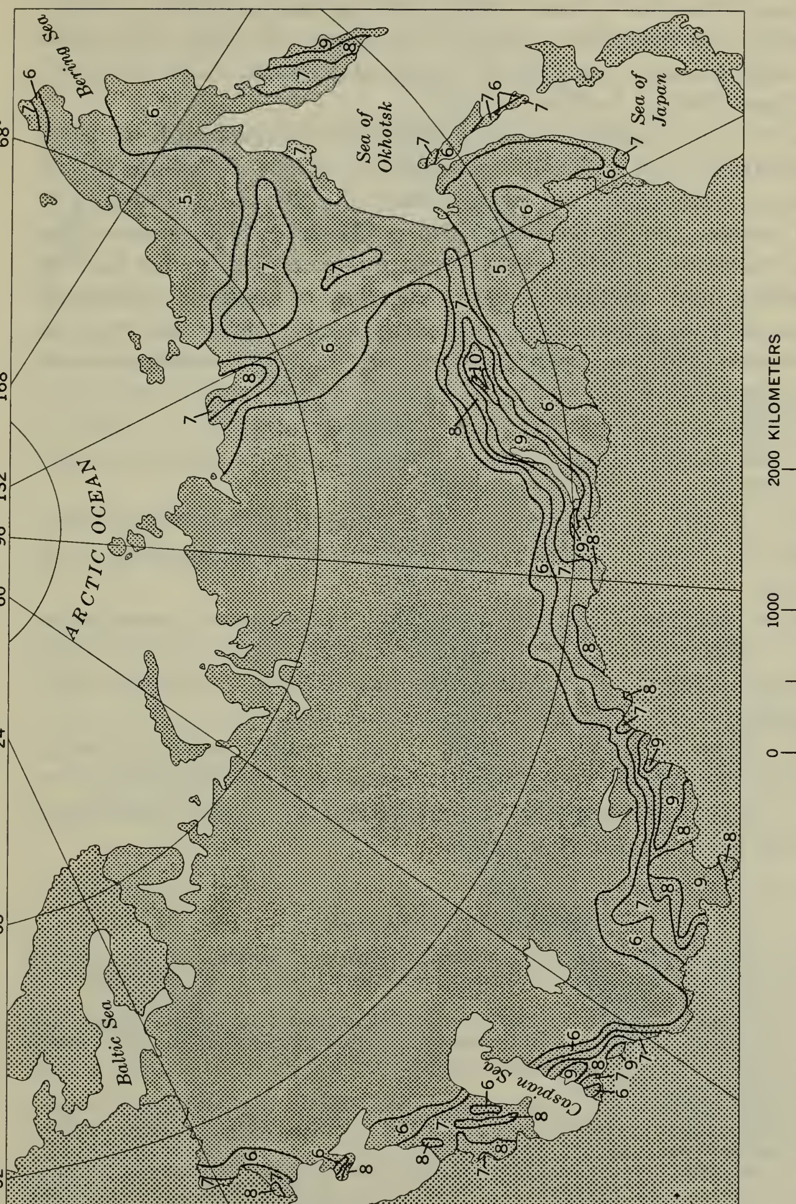

FIGURE 28.—Seismic regionalization map of the U.S.S.R. The figures show intensity according to the GEOFIAN seismic scale (Medvedev, 1965, fig. 1). Reproduced by permission of the New Zealand National Committee on Earthquake Engineering.

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been presented (Kats, 1961; Medvedev and others, 1962). Problems and methods involved have been discussed by Medvedev (1952a), Safaryan (1954, 1957), Kats (1958, 1959), Lyamzina (1962), Yershov, Lyamzina, and Shteinberg (1965), and others. In Japan, maps have been made showing the ground classification based on microtremor data (Nasu, 1965, p. I–152 to I–153).

A microregionalization map of Petropavlovsk in eastern Kamchatka was constructed by Goryachev and others (1963) following the instructions of Medvedev and others (1962) (fig. 29). According to Yershov, Lyamzina, and Shteinberg (1965, p. III–227), "The scheme of the seismic microzoning of Petropavlovsk was compiled on the basis of engineering and geological data, analyses of seismic oscillations brought about by sufficiently strong earthquakes and the data from the measurements of the microtremors and the data from the measurements of the velocities of propagation of waves." The average intensity differences due to ground conditions in this area are shown in table 11. These differences were added or subtracted from the general intensity 8 (GEOFIAN) given for the region.

Richter (1959, fig. 2) constructed a generalized microregionalization map of the Los Angeles area (fig. 30) as an illustration of the procedure.

Seismic microregionalization maps show the expected variations of intensity within an area, and the vulnerability of any particular spot to damage in relative terms, or in absolute terms if an absolute value is assumed to apply to a particular area of the map.

Such maps, based on ground types, coupled with intensity-epicentral-distance curves could serve as the basis for predicting intensities at specific locations for an earthquake of a given magnitude, epicentral distance, and focal depth.

EXPLANATION TO FIGURE 29

Zone of intensity 7.—on the gentle mountain slopes with outcrops of rocky ground or with thin layers of unconsolidated ground (provided that the authorized building foundation extends to bedrock).

Zone of intensity 8.—within the limits of non-water-saturated stony-sandy loam and loam on the gentle mountain slopes; placed here also are the thick waterless sandy gravelly ground of the high terrace, the pyroclastic ground of the north region, and the narrow ridge of Nikolsk Mountain.

Zone of intensity 9.—pebbly sandy loam and loam that is water-saturated at shallow depth; sandy gravelly ground of stream and river bottoms, marshy I terrace of the Kirpich River; filled and alluvial ground.

Area recommended for exclusion from building.—marshy river bottoms, flood plains of the Kirpich River, beaches, and parts of rocky scarps and steep mountain slopes; building in these areas requires land reclamation measures and complex engineering experience in these conditions in regions of abnormal seismic activity.

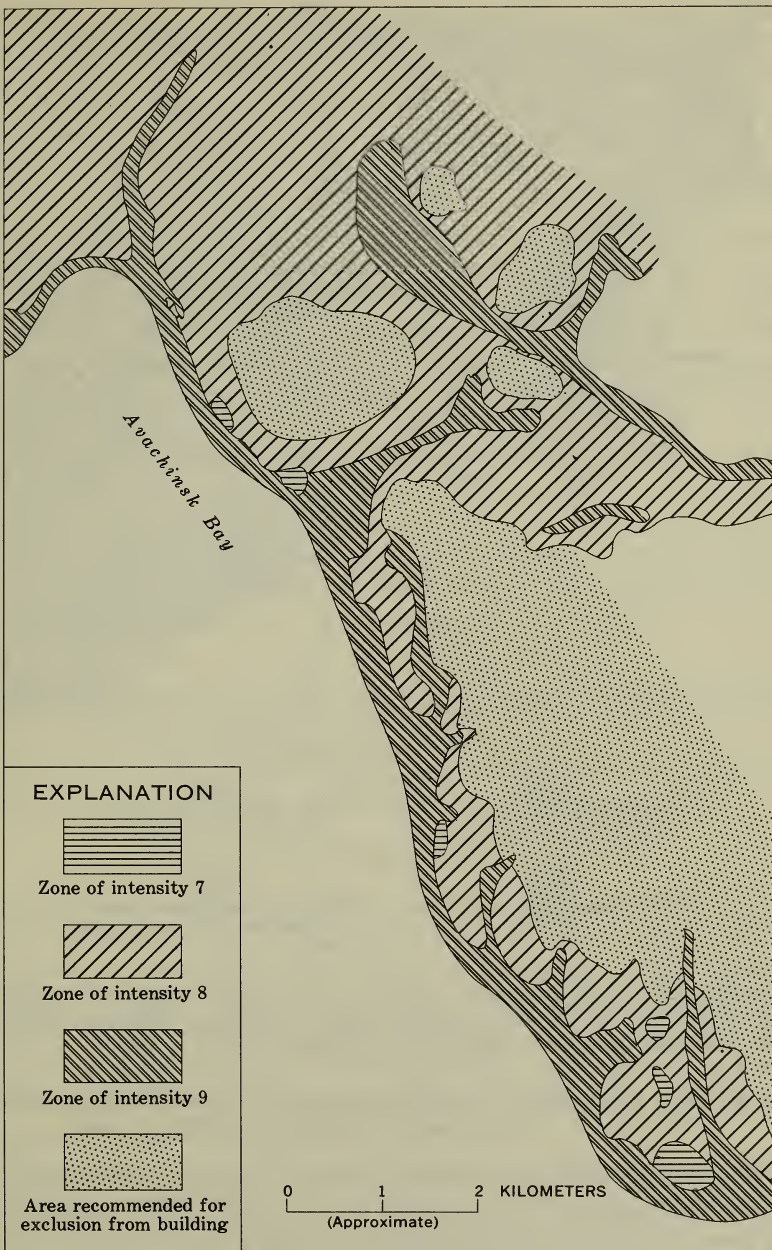

FIGURE 29.—Seismic microregionalization map of Petropavlovsk, Kamchatka, and vicinity (Goryachev and others, 1963, fig. 21 and p. 50).

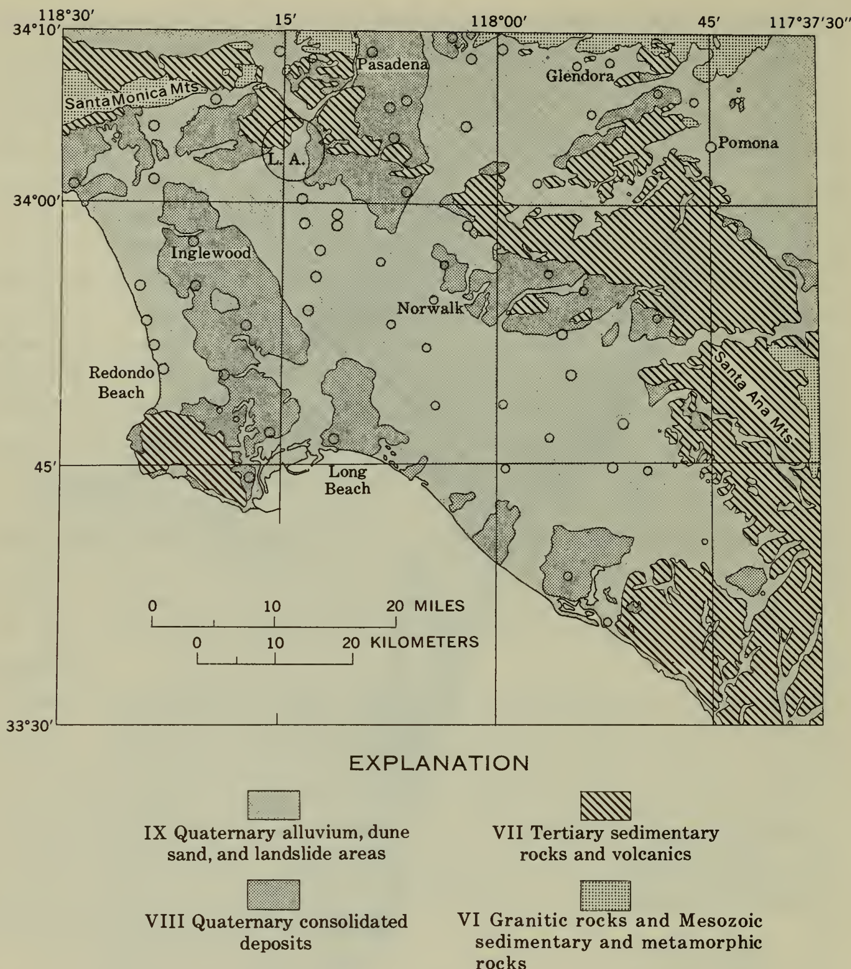

FIGURE 30.—Microregionalization map of Los Angeles basin and vicinity, southern California, showing probable maximum intensity (Modified Mercalli) and prevailing geological character (from Richter, 1959, p. 129).

RELATION BETWEEN EARTHQUAKE MAGNITUDE AND NUCLEAR EXPLOSION ENERGY RELEASE

Underground nuclear explosions produce seismic effects similar to those of earthquakes (Evison, 1963, p. 887; Bath, 1962), so much so that great effort has been expended in trying to find a means of distinguishing the two. Intensity data from earthquakes are thus applicable to underground nuclear explosions; but to use these data for prediction purposes, the yield of a nuclear explosion must be adequately equated to earthquake magnitude. This problem has been studied.

Shallow earthquakes, except those related to volcanism, are considered to be related to fault movement and, therefore, to originate along a line and not at a point. The computed epicenters represent the location of the first recorded movements and probably present too limited a representation of the energy source area. Chemical and nuclear explosions are different from most earthquakes in that they are point sources of energy. The explosions may, however, be similar in source configuration to some very shallow earthquakes related to volcanism. The differences in source configuration between explosions and most earthquakes might be expected to produce differences in recorded magnitudes and intensity in the epicentral area, but as the epicentral distance increases, the difference may become insignificant. As implied previously, a linear source may not be an important factor in affecting intensity distribution.

A large number of chemical explosions have resulted in ground amplitudes that varied as the ½–1 power of the explosives charge (Carder and Cloud, 1959, p. 1474). As the magnitude of an earthquake is proportional to the logarithm of the amplitude, a general relationship of magnitude to yield, Y, for chemical and nuclear explosions may be expressed by

$$M = C + n \log Y$$

(Romney, 1959a, b, p. 1498; Riznichenko, 1960, p. 75), where $n = 0.5–1.0$ and C is a constant.

Romney (1959b, p. 1498), using data available from underground nuclear explosions in tuff, considered $n = 1$ and determined that

$$M = 3.65 + \log Y,$$

where Y is the explosive yield expressed in kilotons of TNT equivalent. This relationship may not apply for explosions in other localities, or in other media (Romney, 1959a). In formulating this expression Romney averaged together magnitudes on the Richter scale and those of the unified magnitude scale. However, these magnitude scales should not have matched in the magnitude range of the explosions used, but should have disagreed by nearly one magnitude unit (Romney, 1959b, p. 1497; Riznichenko, 1960, p. 60).

Riznichenko (1960, p. 76) considered that in different ranges of yield the value of n may change. A theoretical consideration lead him to conclude that when Y is small n should be near 1, but when Y is large n should approach a value of two-thirds and even as little as one-half. Riznichenko (1960, p. 76) kept the two magnitude scales separate and arrived at the following equations, using more complete data than

Romney (1959a, b) used for the Rainier, Logan, and Blanca nuclear explosions:

$$m = 4.6 \pm 0.1 + (0.50 \pm 0.06) \log Y$$

for the unified magnitude scale or

$$M = 3.9 + 0.7 \log Y$$

on the Richter scale at lesser distances (fig. 31) for the approximate range from 1 to 25 kt (kilotons). Thus a detonation of 5-kt yield would approximately equal an earthquake of magnitude 4.4 on the Richter scale according to the equations of both Romney and Riznichenko. At higher yields, Romney's equation gives progressively higher magnitudes than Riznichenko's. Since the promulgation of these equations, considerably more data concerning magnitudes of nuclear explosions have accumulated, allowing the equations to be improved.

The recent 80-kt Longshot nuclear explosion under Amchitka Island in the Aleutian Islands (DeNoyer and Frosch, 1966) produced a magnitude $m=6.1$ and a surface-wave magnitude of at least 1½–2 less (Liebermann and others, 1966). Riznichenko's equations give for an 80-kt explosion, a maximum m about 0.5 lower and a M about 0.5–1.0 higher than the magnitudes recorded.

Surface waves from explosions generally have shorter periods than those from earthquakes (Pasechnik and others, 1960, p. 50; Keilis-

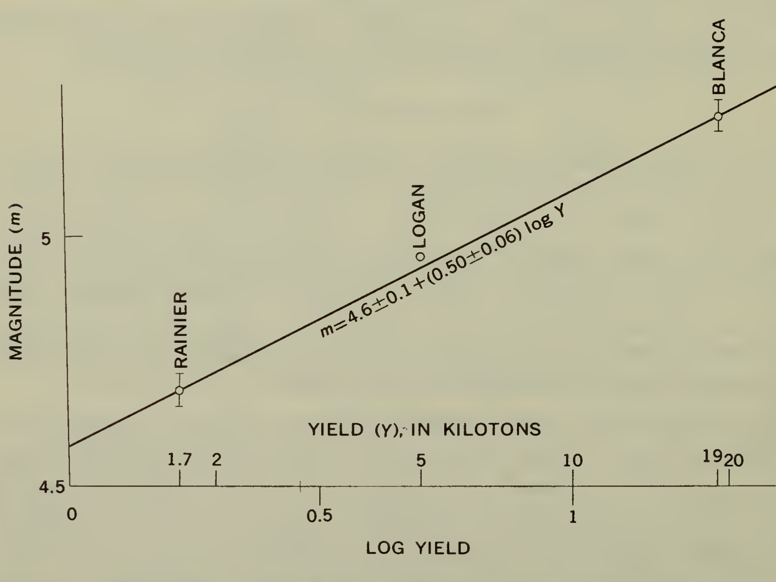

FIGURE 31.—Relationship between yield (Y, in kilotons) and magnitude (m) from three underground nuclear explosions (from Riznichenko, 1960, fig. 6).

Borok, 1960, p. 98; Willis, 1963, p. 967). This is thought to be principally due to the smaller size of the source area in explosions (Keilis-Borok, 1960, p. 98). The effects of this difference are not properly taken into account when computing magnitude by ordinary methods, nor are the different damping characteristics of seismic waves with epicentral distance (Riznichenko, 1960, p. 55). Also, earthquakes in general generate larger shear-surface waves than the underground explosions (Willis and others, 1963, p. 979). Of the earthquakes studied by Willis, DeNoyer, and Wilson (1963, p. 986), 78 percent had amplitude ratios of shear surface to compressional waves larger than those of nuclear explosions, except the Gnome explosion, which generated large-amplitude short-period waves larger than those generated by the earthquakes they studied.

Some of the slight variance in ground motion may be due to other variables, such as very shallow focal depth and the travel path, rather than to any intrinsic difference in underground nuclear explosions. For example, the test media will influence the magnitude of the seismic signals (Hankins, 1964). "Evidence has been obtained which shows that firing underground nuclear shots in various media such as granite, tuff, salt, and alluvium affect the amplitude and frequency content of the seismic waves" (Willis, 1963, p. 975). A further complication is that of a possible seismic-energy contribution from tectonic strain release triggered by an underground nuclear explosion.

PREDICTION OF SEISMIC INTENSITY FOR NUCLEAR EXPLOSION

The following two examples serve merely to illustrate how the aforementioned data might be applied to predict intensities at various distances from underground nuclear explosions and do not utilize all the available information. No discussion of accuracy is attempted.

An underground nuclear explosion of 1,000-kt yield would approximately equal an earthquake of magnitude, M, 6 following Riznichenko's equation and 6.65 following Romney's.

An earthquake of magnitude 6 in southern California, focal depth approximately 16 km, would have the following average epicentral distances for *average intensities* (fig. 11):

I (M.M.)	1½	3	5	6	7
Δ (km)	220	120	60	30	15

with an epicentral intensity, I_0, of 7–8, averaging 7.8, and an average epicentral acceleration a_0 of 130 cm/sec^2 (Gutenberg and Richter, 1942, 1956, p. 141; Benioff and Gutenberg, 1955, table 1; Richter, 1958, p. 353).

Predominant maximum intensity radii (isoseismals) for western Nevada and adjacent California for an earthquake of magnitude 6 are (fig. 12):

I (M.M.)	1–4 (generally 4)	3	6
Δ (km)	190	118	40

The epicentral intensity would be approximately 7.1, and the total area over which the shock is felt would equal about 32,000 square miles (83,000 sq km).

An earthquake of magniture 6.1 in western Nevada, June 23, 1959 (Eppley and Cloud, 1961, p. 51), had the following *maximum intensity* radii:

I (M.M.)	4	5	6
Δ (km)	265	201	82

The shallow focal depth of nuclear detonations would cause both greater epicentral intensities and a greater attenuation rate of intensity with epicentral distance than earthquakes of equivalent magnitude at greater focal depth. The variation of the epicentral intensity with focal depth is given as

h (km)	5	15	45
I_0 (GEOFIAN)	9–10	7–8	5–7

for an earthquake with a magnitude of 5 1/4 $<M<$ 6 1/2, and as

h (km)	1	2	5	10	16	20	30	45
I_0 (GEOFIAN)	12	11	9.6	8.5	7.8	7.5	6.8	6.2

for an earthquake with a magnitude of 6 by Shebalin (1961, table 5.1 and fig. 5.1) (fig. 13).

By combining the above epicentral intensity values of Shebalin with his intensity-attenuation–epicentral-distance relationships (1959a, p. 109, fig. 15), the following intensity radii were calculated, rounding off to two places, for an earthquake of magnitude 6:

h (km)	Radii of *I* (GEOFIAN) (km)									
	12	11	10	9	8	7	6	5	4	3
1 (I_0=12)	0.1	1.6	3.4	6.7	13	24	46	88	170	320
2 (I_0=11)	-----	0.1	3.2	6.9	14	26	49	93	180	330
10 (I_0=8.5)	-----	-----	-----	-----	9.4	23	48	93	180	340
20 (I_0=7.5)	-----	-----	-----	-----	-----	19	48	97	190	360

Approximately equivalent *I* (M.M.)	12	11	10	9	8	7	6	5	4	3	2

For any site the intensity at a given epicentral distance, for an earthquake of a particular magnitude, is highly dependent on the geologic environment, as pointed out by Popov (1959) and summarized in table 10. As an example of how the intensity might vary, dependent on the geologic environment of a site, an earthquake of magnitude, M, 6 in southern California can be expected to produce at an epicentral distance of 60 km an average intensity of 5 (fig. 11). Thus, where the average intensity is assumed to occur over "thick layers of dry argillaceous rocks, gently dipping or folded" (type geologic section 3, table 10), the anticipated average intensity can be corrected for the particular geologic environment; decreased by one to two scale units for massive compact rocks such as granite, or increased by one to two scale units for unstable, wet, or unconsolidated materials.

Thus, for an underground blast of magnitude 6 at 1 km depth in northern Yucca Flat, Nevada Test Site, an epicentral intensity of 12 (M.M.) might be expected. At the Control Point, about 26 km south, the average intensity would be about 6. At Mercury, 56 km south, it would be approximately 5. The predominant maximum intensity 5 radii would perhaps be 70–90 km, extending to the vicinity of Indian Springs, and with unfavorable ground conditions the maximum intensity 5 might extend to 120–140 km, about the edge of Las Vegas.

An underground explosion of 5-kt yield would have a magnitude, M, of about 4.4 according to the equations of Romney (1959b) and Riznichenko (1960).

Variation of the epicentral intensity with focal depth is given as

h (km)	5	15	45
I_0 (GEOFIAN)	7–8	5–7	4–5

for an earthquake with a magnitude $4\frac{1}{4} < M < 5\frac{1}{4}$ by Shebalin (1961, table 5.1), and as

h (km)	0.82	1	2	5	10
I_0 (GEOFIAN)	10 (est.)	9.6	8.6	7.2	6.0

for an earthquake with a magnitude of 4.4 by Shebalin (1961) (fig. 13).

Intensity–epicentral-distance values, for epicentral intensities of 9.6 and 8.6 at focal depths of 1 and 2 km, respectively, were calculated from the intensity-attenuation–epicentral-distance equation of Shebalin (1959a, p. 109). They are:

h (km)	Radii of I (GEOFIAN) (km)					
	9	8	7	6	5	4
1 (I_0=9.6)	1. 1	2. 6	5. 2	10	18	36
2 (I_0=8.6)	--------	2. 1	5. 2	10	20	39

The increase in intensity attenuation with epicentral distance for decreasing focal depth is such that for an earthquake at 0.82-km focal depth, the epicentral distance radii for intensity 4 would probably be similar to or slightly smaller than that for a focal depth of 1 km, although the shallower earthquake would have a higher epicentral intensity.

Thus, if an underground nuclear device at 5-kt yield was detonated at a depth of 0.82 km, the average intensity at a distance of 32 km (the distance from Hattiesburg, Miss., to the Salmon explosion locality) would be on the low side of 4, or 3–4 (GEOFIAN or M.M.). If the location at that distance is underlain by thick water-saturated unconsolidated clays and sands the intensity could be increased to 5 or 6 (Popov, 1959; Medvedev, 1961, p. 115; table 10 of present report), which was the approximate intensity level at Hattiesburg from the Salmon explosion.

SUMMARY AND CONCLUSIONS

Much is known about the various parameters affecting intensity, and several preliminary relationships have been worked out. It seems that a combination of these relationships would enable the prediction of intensity at a particular spot for an earthquake of a given magnitude, epicenter, and focal depth. An adequate equation of magnitude to yield would allow intensity predictions to be made for underground nuclear explosions also.

It appears that some type of reasonable intensity–epicentral-distance curves for different magnitudes and focal depths could be drawn after due consideration of the other variables affecting intensity. Also, by application of some of the work on relative intensities of ground types, useful microregionalization maps could be constructed for areas, southern Nevada for example. If the intensity–epicentral-distance curves were drawn for a particular type of ground on the microregionalization map, then a basis would be established for predicting the intensity at a given spot caused by a given earthquake or explosion. For example, minimum-intensity–epicentral-distance curves might be chosen and considered to represent the intensity on granite. Then, if the microregionalization were done in terms of relative intensity differences from granite, the relative intensity difference from granite of a particular spot would be added to that derived from the intensity–epicentral-distance curve, for the proper epicentral distance, to arrive at the predicted intensity for that spot for an earthquake of a given magnitude and location. For both the intensity–epicentral-distance curves and microregionalization map, the probable limits of accuracy would have to be carefully considered.

Neumann (1954, 1959) presents convincing evidence that useful minimum-intensity–epicentral-distance curves can be constructed.

Comparison of records of nearby seismic recording stations on different ground types within the area of the microregionalization map would be useful in understanding the different responses of the materials and in assigning relative intensity differences. Also, thorough analyses of well-documented earthquakes, including a survey of the ground types of the localities reporting intensities, would be a good check on the curves and values chosen for use and would contribute additional information.

Well-constructed microregionalization maps could also be utilized in evaluating reactor and other types of sites in active seismic regions.

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TABLES 1–12

TABLE 1.—*Modified Mercalli intensity scale of 1931*

[Adapted from Sieberg's (1923) Mercalli-Cancani scale, modified and condensed. Quoted from Wood and Neumann (1931)]

I. Not felt—or, except rarely under especially favorable circumstances. Under certain conditions, at and outside the boundary of the area in which a great shock is felt:
 sometimes birds, animals, reported uneasy or disturbed;
 sometimes dizziness or nausea experienced;
 sometimes trees, structures, liquids, bodies of water, may sway—doors may swing, very slowly.

II. Felt indoors by few, especially on upper floors, or by sensitive or nervous persons.
 Also, as in grade I, but often more noticeably:
 sometimes hanging objects may swing, especially when delicately suspended;
 sometimes trees, structures, liquids, bodies of water, may sway, doors may swing, very slowly;
 sometimes birds, animals, reported uneasy or disturbed;
 sometimes dizziness or nausea experienced.

III. Felt indoors by several, motion usually rapid vibration.
 Sometimes not recognized to be an earthquake at first.
 Duration estimated in some cases.
 Vibration like that due to passing of light, or lightly loaded trucks, or heavy trucks some distance away.
 Hanging objects may swing slightly.
 Movements may be appreciable on upper levels of tall structures.
 Rocked standing motor cars slightly.

IV. Felt indoors by many, outdoors by few.
 Awakened few, expecially light sleepers.
 Frightened no one, unless apprehensive from previous experience.
 Vibration like that due to passing of heavy, or heavily loaded trucks.
 Sensation like heavy body striking building, or falling of heavy objects inside.
 Rattling of dishes, windows, doors; glassware and crockery clink and clash.
 Creaking of walls, frame, especially in the upper range of this grade.
 Hanging objects swung, in numerous instances.
 Disturbed liquids in open vessels slightly.
 Rocked standing motor cars noticeably.

V. Felt indoors by practically all, outdoors by many or most: outdoors direction estimated.
 Awakened many, or most.
 Frightened few—slight excitement, a few ran outdoors.
 Buildings trembled throughout.
 Broke dishes, glassware, to some extent.
 Cracked windows—in some cases, but not generally.

TABLE 1.—*Modified Mercalli intensity scale of 1931*—Continued

Overturned vases, small or unstable objects, in many instances, with occasional fall.
Hanging objects, doors, swing generally or considerably.
Knocked pictures against walls, or swung them out of place.
Opened, or closed, doors, shutters, abruptly.
Pendulum clocks stopped, started, or ran fast, or slow.
Moved small objects, furnishings, the latter to slight extent.
Spilled liquids in small amounts from well-filled open containers.
Trees, bushes, shaken slightly.

VI. Felt by all, indoors and outdoors.
Frightened many, excitement general, some alarm, many ran outdoors.
Awakened all.
Persons made to move unsteadily.
Trees, bushes, shaken slightly to moderately.
Liquid set in strong motion.
Small bells rang—church, chapel, school, etc.
Damage slight in poorly built buildings.
Fall of plaster in small amount.
Cracked plaster somewhat, especially fine cracks chimneys in some instances.
Broke dishes, glassware, in considerable quantity, also some windows.
Fall of knick-knacks, books, pictures.
Overturned furniture in many instances.
Moved furnishings of moderately heavy kind.

VII. Frightened all—general alarm, all ran outdoors.
Some, or many, found it difficult to stand.
Noticed by persons driving motor cars.
Trees and bushes shaken moderately to strongly.
Waves on ponds, lakes, and running water.
Water turbid from mud stirred up.
Incaving to some extent of sand or gravel stream banks.
Rang large church bells, etc.
Suspended objects made to quiver.
Damage negligible in buildings of good design and construction, slight to moderate in well-built ordinary buildings, considerable in poorly built or badly designed buildings, adobe houses, old walls (especially where laid up without mortar), spires, etc.
Cracked chimneys to considerable extent, walls to some extent.
Fall of plaster in considerable to large amount, also some stucco.
Broke numerous windows, furniture to some extent.
Shook down loosened brickwork and tiles.
Broke weak chimneys at the roofline (sometimes damaging roofs).
Fall of cornices from towers and high buildings.
Dislodged bricks and stones.
Overturned heavy furniture, with damage from breaking.
Damage considerable to concrete irrigation ditches.

TABLE 1.—*Modified Mercalli intensity scale of 1931*—Continued

VIII. Fright general—alarm approaches panic.
Disturbed persons driving motor cars.
Trees shaken strongly—branches, trunks, broken off, especially palm trees.
Ejected sand and mud in small amounts.
Changes: temporary, permanent; in flow of springs and wells; dry wells renewed flow; in temperature of spring and well waters.
Damage slight in structures (brick) built especially to withstand earthquakes.
Considerable in ordinary substantial buildings, partial collapse: racked, tumbled down, wooden houses in some cases; threw out panel walls in frame structures, broke off decayed piling.
Fall of walls.
Cracked, broke, solid stone walls seriously.
Wet ground to some extent, also ground on steep slopes.
Twisting, fall, of chimneys, columns, monuments, also factory stacks, towers.
Moved conspicuously, overturned, very heavy furniture.

IX. Panic general.
Cracked ground conspicuously.
Damage considerable in (masonry) structures built especially to withstand earthquakes:
threw out of plumb some wood-frame houses built especially to withstand earthquakes;
great in substantial (masonry) buildings, some collapse in large part; or wholly shifted frame buildings off foundations, racked frames;
serious to reservoirs; underground pipes sometimes broken.

X. Cracked ground, especially when loose and wet, up to widths of several inches; fissures up to a yard in width ran parallel to canal and stream banks.
Landslides considerable from river banks and steep coasts.
Shifted sand and mud horizontally on beaches and flat land.
Changed level of water in wells.
Threw water on banks of canals, lakes, rivers, etc.
Damage serious to dams, dikes, embankments.
Damage severe to well-built wooden structures and bridges, some destroyed.
Developed dangerous cracks in excellent brick walls.
Destroyed most masonry and frame structures, also their foundations.
Bent railroad rails slightly.
Tore apart, or crushed endwise, pipe lines buried in earth.
Open cracks and broad wavy folds in cement pavements and asphalt road surfaces.

XI. Disturbances in ground many and widespread, varying with ground material.
Broad fissures, earth slumps, and land slips in soft, wet ground.
Ejected water in large amount charged with sand and mud.
Caused sea-waves (tidal waves) of significant magnitude.
Damage severe to wood-frame structures, especially near shock centers.

TABLE 1.—*Modified Mercalli intensity scale of 1931*—Continued

Great to dams, dikes, embankments, often for long distances.
Few, if any (masonry), structures remained standing.
Destroyed large well-built bridges by the wrecking of supporting piers, or pillars.
Affected yielding wooden bridges less.
Bent railroad rails greatly, and thrust them endwise.
Put pipe lines buried in earth completely out of service.

XII. Damage total—practically all works of construction damaged greatly or destroyed.
Disturbances in ground great and varied, numerous shearing cracks.
Landslides, falls of rock of significant character, slumping of river banks, etc., numerous and extensive.
Wrenched loose, tore off, large rock masses.
Fault slips in firm rock, with notable horizontal and vertical offset displacements.
Water channels, surface and underground, disturbed and modified greatly.
Dammed lakes, produced waterfalls, deflected rivers, etc.
Waves seen on ground surfaces (actually seen, probably, in some cases).
Distorted lines of sight and level.
Threw objects upward into the air.

MODIFIED MERCALLI INTENSITY SCALE OF 1931

(Abridged)

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 made 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. Disturbance 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 struc-

TABLE 1.—*Modified Mercalli intensity scale of 1931*—Continued

tures. 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. Disturbed persons driving motor cars.

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 pipe lines completely out of service. Earth slumps and land slips in soft ground. Rails bent greatly.

XII. Damage total. Waves seen on ground surfaces. Lines of sight and level distorted. Objects thrown upward into the air.

TABLE 2.—*Modified Mercalli scale* (*New Zealand version, 1965*)

[Quoted from Eiby (1966, p. 124–128). Reproduced by permission of the New Zealand Journal of Geology and Geophysics]

M.M. 1. Not felt by humans, except in especially favourable circumstances, but birds and animals may be disturbed.
Reported mainly from the upper floors of buildings more than 10 storeys high.
Dizziness or nausea may be experienced.
Branches of trees, chandeliers, doors, and other suspended systems of long natural period may be seen to move slowly. Water in ponds, lakes, reservoirs, etc., may be set into seiche oscillation.

M.M. 2. Felt by a few persons at rest indoors, especially by those on upper floors or otherwise favourably placed.
The long-period effects listed under M.M. 1 may be more noticeable.

M.M. 3. Felt indoors, but not identified as an earthquake by everyone. Vibration may be likened to the passing of light traffic.
It may be possible to estimate the duration, but not the direction.
Hanging objects may swing slightly.
Standing motorcars may rock slightly.

M.M. 4. Generally noticed indoors, but not outside.
Very light sleepers may be wakened.
Vibration may be likened to the passing of heavy traffic, or to the jolt of a heavy object falling or striking the building.
Walls and frame of buildings are heard to creak.
Doors and windows rattle.
Glassware and crockery rattles.
Liquids in open vessels may be slightly disturbed.
Standing motorcars may rock, and the shock can be felt by their occupants.

TABLE 2.—*Modified Mercalli scale (New Zealand version, 1965)*—Continued

M.M. 5.	Generally felt outside and by almost everyone indoors. Most sleepers awakened. A few people frightened. Direction of motion can be estimated. Small unstable objects are displaced or upset. Some glassware and crockery may be broken. Some windows cracked. A few earthenware toilet fixtures cracked. Hanging pictures move. Doors and shutters may swing. Pendulum clocks stop, start, or change rate.
M.M. 6.	Felt by all. People and animals alarmed. Many run outside. Difficulty experienced in walking steadily. Slight damage to Masonry D. Some plaster cracks or falls. Isolated cases of chimney damage. Windows, glassware, and crockery broken. Objects fall from shelves, and pictures from walls. Heavy furniture moved. Unstable furniture overturned. Small church and school bells ring. Trees and bushes shake, or are heard to rustle. Loose material may be dislodged from existing slips, talus slopes, or shingle slides.
M.M. 7.	General alarm. Difficulty experienced in standing. Noticed by drivers of motorcars. Trees and bushes strongly shaken. Large bells ring. Masonry D cracked and damaged. A few instances of damage to Masonry C. Loose brickwork and tiles dislodged. Unbraced parapets and architectural ornaments may fall. Stone walls cracked. Weak chimneys broken, usually at the roof-line. Domestic water tanks burst. Concrete irrigation ditches damaged. Waves seen on ponds and lakes. Water made turbid by stirred-up mud. Small slips, and caving-in of sand and gravel banks.
M.M. 8.	Alarm may approach panic. Steering of motorcars affected. Masonry C damaged, with partial collapse. Masonry B damaged in some cases. Masonry A undamaged. Chimneys, factory stacks, monuments, towers, and elevated tanks twisted or brought down.

TABLE 2.—*Modified Mercalli scale (New Zealand version, 1965)*—Continued

	Panel walls thrown out of frame structures.
	Some brick veneers damaged.
	Decayed wooden piles broken.
	Frame houses not secured to the foundation may move.
	Cracks appear on steep slopes and in wet ground.
	Landslips in roadside cuttings and unsupported excavations.
	Some tree branches may be broken off.
	Changes in the flow or temperature of springs and wells may occur.
	Small earthquake fountains.
M.M. 9.	General panic.
	Masonry D destroyed.
	Masonry C heavily damaged, sometimes collapsing completely.
	Masonry B seriously damaged.
	Frame structures racked and distorted.
	Damage to foundations general.
	Frame houses not secured to the foundations shifted off.
	Brick veneers fall and expose frames.
	Cracking of the ground conspicuous.
	Minor damage to paths and roadways.
	Sand and mud ejected in alluviated areas, with the formation of earthquake fountains and sand craters.
	Underground pipes broken.
	Serious damage to reservoirs.
M.M. 10.	Most masonry structures destroyed, together with their foundations.
	Some well built wooden buildings and bridges seriously damaged.
	Dams, dykes, and embankments seriously damaged.
	Railway lines slightly bent.
	Cement and asphalt roads and pavements badly cracked or thrown into waves.
	Large landslides on river banks and steep coasts.
	Sand and mud on beaches and flat land moved horizontally.
	Large and spectacular sand and mud fountains.
	Water from rivers, lakes, and canals thrown up on the banks.
M.M. 11.	Wooden frame structures destroyed.
	Great damage to railway lines.
	Great damage to underground pipes.
M.M. 12.	Damage virtually total. Practically all works of construction destroyed or greatly damaged.
	Large rock masses displaced.
	Lines of sight and level distorted.
	Visible wave-motion of the ground surface reported.
	Objects thrown upwards into the air.

Categories of nonwooden construction:

Masonry A. Structures designed to resist lateral forces of about 9.1 [percent] g, such as those satisfying the New Zealand Model Building Bylaw, 1955. Typical buildings of this kind are well reinforced by means of steel or ferro-concrete bands, or are wholly of ferro-concrete

TABLE 2.—*Modified Mercalli scale (New Zealand version, 1965)*—Continued

construction. All mortar is of good quality and the design and workmanship is good. Few buildings erected prior to 1935 can be regarded as in category A.

Masonry B. Reinforced buildings of good workmanship and with sound mortar, but not designed in detail to resist lateral forces.

Masonry C. Buildings of ordinary workmanship, with mortar of average quality. No extreme weakness, such as inadequate bonding of the corners, but neither designed nor reinforced to resist lateral forces.

Masonry D. Buildings with low standards of workmanship, poor mortar, or constructed of weak materials like mud brick and rammed earth. Weak horizontally.

Windows:

Window breakage depends greatly upon the nature of the frame and its orientation with respect to the earthquake source. Windows cracked at M.M. 5 are usually either large display windows, or windows tightly fitted to metal frames.

Chimneys:

The "weak chimneys" listed under M.M. 7 are unreinforced domestic chimneys of brick, concrete block, or poured concrete.

Water tanks:

The "domestic water tanks" listed under M.M. 7 are of the cylindrical corrugated-iron type common in New Zealand rural areas. If these are only partly full, movement of the water may burst soldered and riveted seams.

Hot-water cylinders constrained only by supply and delivery pipes may move sufficiently to break the pipes at about the same intensity.

TABLE 3.—*Japanese seismic intensity scale*

[Adapted from Kawasumi (1951, p. 481) with minor additions from the unpublished version used by the Central Meteorological Observatory]

0. Not felt: too weak to be felt by humans; registered only by seismographs.

I. Slight: felt only feebly by persons at rest or by those who are especially observant of earthquakes.

II. Weak: felt by most persons; slight shaking of windows and Japanese latticed sliding doors (Shōji).

III. Moderately strong: shaking of houses and buildings, heavy rattling of windows and Japanese latticed sliding doors, swinging of hanging objects, stopping of some pendulum clocks, and moving of liquids in vessels; some people are so frightened that they run out of doors.

IV. Strong: strong shaking of houses and buildings, overturning of unstable objects, and spilling of liquids out of vessels.

V. Very strong: cracking brick and plaster walls, overturning stone lanterns and gravestones, and similar objects, damaging chimneys and mud-and-plaster warehouses, and causing landslides in steep mountains.

VI. Disastrous: causing destruction of 1–30 percent of Japanese wooden houses; causing large landslides; fissures in flat ground and some in low fields, accompanied by mud and waterspouts.

VII. Ruinous: causing destruction of more than 30 percent of the houses; causing large landslides, fissures and faults.

TABLE 4.—*GEOFIAN scale; seismic scale of the Earth Physics Institute of the U.S.S.R. Academy of Sciences, and description of aftereffects of earthquakes*

[Slightly modified quotation from translation by Akademii Nauk SSSR (1961, p. 129–134) of Medvedev (1961). The intensity representing the earthquake force is determined by the quantity X_0, which represents the largest displacement of the spherical pendulum of a seismometer with a natural period of 0.25 sec, a logarithmic damping decrement of 0.50, and a static magnification of 1]

Intensity	X_0 (mm)	Brief description of earthquake
1	------------	Oscillations of the ground are detected with instruments.
2	------------	In individual cases felt by very sensitive persons at rest.
3	------------	Oscillations felt by few persons.
4	<0. 5	Noted by many persons. Windows or doors may rattle.
5	0. 5–1. 0	Objects swing, floors squeak, glasses jar, outer plaster crumbles.
6	1. 1–2. 0	Light damage to buildings: thin cracks in plaster, cracks in tile furnaces, etc.
7	2. 1–4. 0	Considerable damage to buildings: thin cracks in plaster and stripping of individual pieces, thin cracks in walls.
8	4. 1–8. 0	Destruction in buildings: large cracks in walls, falling of cornices or chimneys.
9	8. 1–16. 0	Collapse in some buildings; destruction of walls, roofs, floors.
10	16. 1–32. 0	Collapse of many buildings; fissures in ground about 1 meter wide.
11	>32. 0	Numerous fissures on the surface of the earth, large landslides in mountains.
12	------------	Large scale change in the relief.

DESCRIPTION OF AFTEREFFECTS OF EARTHQUAKES

The force of the earthquake at points where there are no seismometers is determined from the aftereffects of the earthquake, as described below for:

1. Buildings and structures.
2. Residual phenomena in ground and change in the state of the ground and surface water.
3. Other symptoms.

The degree of damage and destruction resulting from an earthquake in buildings constructed without the necessary earthquake countermeasures is established in accordance with the following subdivisions:

I. By groups of buildings.

Group A—Single story buildings with walls of unfinished stone, raw brick, adobe, etc.

Group B—Brick and stone houses.

Group C—Frame houses.

II. By degree of damage.

Light damage—Thin cracks in plaster and in tile furnaces, crumbling of outer plaster, etc.

Considerable damage—Cracks in plaster, falling of pieces of plaster, thin cracks in the walls, cracks in partitions, damage to chimneys, furnaces, etc.

Destruction—Large cracks in walls, splitting of masonry, destruction of individual parts of walls, falling of cornices and parapets, collapse of plaster, falling of chimneys, furnaces, etc.

Collapses—Destruction of walls, roofs, and floors of the entire building or of considerable parts of the building and large deformation of the walls.

TABLE 4.—*GEOFIAN scale; seismic scale of the Earth Physics Institute of the U.S.S.R. Academy of Sciences, and description of aftereffects of earthquakes*—Continued

DESCRIPTION OF AFTEREFFECTS OF EARTHQUAKES—Continued

III. By the number of buildings.
Majority.
Many.
Individual.

Buildings and structures

Intensity:

I. No damage.

II. No damage.

III. No damage.

IV. No damage.

V. Light squeaking of floors and partitions. Jarring of glasses. Crumbling of outer plaster. Movement of unclosed doors and windows. Slight damage in individual buildings.

VI. Light damage in many buildings. In individual buildings of Groups A and B—considerable damage. In rare cases, in the case of wet ground—thin cracks on the roads.

VII. In most buildings of Group A considerable damage and in individual cases destruction. In most buildings of Group B—light damage, and in many, considerable damage. In many buildings of Group C light damage, with considerable damage in individual buildings.
In some cases, landslides on steep slopes of road embankments, cracks in roads, and dislocations in joints of pipelines. Stone walls damaged.

VIII. In many buildings of Group A there is destruction and individual buildings collapse. In most buildings of Group B there is considerable damage, and destruction in individual ones. In most buildings of Group C light damage and in many of them considerable damage.
Small slides on steep banks of cuts or embankments of roads. In individual cases piping joints break. Statues and tombstones shift. Stone walls are destroyed.

IX. In many buildings of Group A—collapse. In many buildings of Group B—destruction and individual ones collapse. Many buildings of Group C are considerably damaged and some are destroyed.
In individual cases, railroad tracks are twisted and embankments damaged. Many cracks in roads. Breaking and damaging of pipelines. Monuments and statues overturned. Most stacks and towers destroyed.

X. In many buildings of Group B—collapse. In many buildings of Group C—destruction and in some cases collapse.
Considerable damage to embankments and dams. Local bending of rails. Breaks in pipelines. Roads crack in many places and are deformed; smokestacks, towers, and monuments, stone walls collapse.

XI. Total destruction of buildings.
Destruction of embankments over great lengths. Pipelines become completely useless. Railroad tracks bent over great lengths.

XII. Total destruction of buildings and structures.

TABLE 4.—*GEOFIAN scale; seismic scale of the Earth Physics Institute of the U.S.S.R Academy of Sciences, and description of aftereffects of earthquakes*—Continued

DESCRIPTION OF AFTEREFFECTS OF EARTHQUAKES—Continued

Residual phenomena in ground with change in status of ground and surface waters

Intensity:

I. No damage.

II. No damage.

III. No damage.

IV. No damage.

V. Small waves in unstable water reservoirs. In some cases the spring flow is changed.

VI. Cracks in wet ground with widths up to 1 cm. In mountainous regions there are sporadic cases of slides and crumbling of ground. Small changes in the spring flow and the water level in wells.

VII. Thin cracks in dry ground. Large numbers of cracks in wet ground. Individual cases of slides on river banks. Small slides in mountainous regions and crumbling of ground. Possible landslides in the mountains.

In individual cases the water becomes muddy in reservoirs and in rivers. The spring flow and the water level are changed. In some cases new springs appear or existing ones are lost.

VIII. Cracks in ground reach several centimeters. Many cracks on slopes of mountains and in wet ground. Extensive crumbling of ground, slides, and mountain landslides. Water in the reservoirs becomes turbid. New water reservoirs are produced. New springs of water appear and existing ones are lost. In many cases the spring flow and the water level in wells change.

IX. Fissures in ground reach widths of 10 cm, and more than 10 cm on slopes and river banks. Large number of thin fissures in ground. Mountain landslides. Many slides and crumbling of ground. Small mud eruptions. Pronounced waves on water reservoirs. New water springs frequently arise or old ones disappear.

X. Fissures in ground with widths of several decimeters and in individual cases reaching 1 m. Rock slides in mountainous regions and at the seashore. Large mudflows of sand and clay. Surf and splashing of water in reservoirs and rivers. New lakes are produced.

XI. Numerous fissures are produced on the surface of the earth. Vertical displacement of strata. Large landslides and earth slips. Water-saturated friable sediments come out of the fissures. The conditions in the springs and water reservoirs change strongly, as well as the ground-water level.

XII. Large scale change in the relief. Tremendous landslides and earth-slides. Considerable vertical and horizontal faulting and displacement. Large changes in the state of the ground and surface waters. Waterfalls are produced. Lakes are produced. River beds change.

TABLE 4.—*GEOFIAN scale; seismic scale of the Earth Physics Institute of the U.S.S.R. Academy of Sciences, and description of aftereffects of earthquakes*—Continued

DESCRIPTION OF AFTEREFFECTS OF EARTHQUAKES—Continued

Other symptoms

Intensity:

I. Earthquakes not felt by persons. The oscillations of the earth are registered with instruments.

II. Noticed by individual persons who are very sensitive and who are perfectly at rest.

III. Oscillations noted by a few persons who are at rest inside buildings. Careful observers note only a slight swinging of hanging objects.

IV. Light swaying of hanging objects and of standing automobiles. Slight vibration of liquids in vessels. Slight ringing of densely stacked unstable dishes.

Earthquake perceived by most people located indoors. In rare cases sleepers are awakened. Felt by individual people outdoors.

V. Hanging objects swing noticeably. In rare cases pendulums of wall clocks stop. Water splashes sometimes from filled vessels. Unstable dishes and ornaments on shelves sometimes topple over.

Felt by all persons inside buildings and by majority of persons in the outdoors; all wake up. Animals are restless.

VI. Hanging objects swing. Sometimes books fall off shelves and pictures shift. Many pendulums of wall clocks stop. Light furniture shifts. Dishes fall.

Many persons run out of the houses. Movement of persons unstable. Animals run out of shelter.

VII. Chandeliers swing strongly. Light furniture shifts. Books, vessels, and vases fall down.

All persons run out of the buildings and in individual cases jump out of windows. It is difficult to move without support.

VIII. Some hanging lamps are damaged. Furniture shifts and frequently tilts over. Light objects jump and tilt over. Persons can stand on their feet with difficulty. All run out of buildings.

IX. Furniture topples over and breaks. Animals very panicky.

X. Numerous damages to household goods. Animals cry and howl.

XI. Loss of life, animals, and property under fragments from buildings.

XII. Great catastrophe. A considerable part of the population is killed by collapse of the buildings. Vegetation and animals destroyed by avalanches and landslides in mountainous regions.

TABLE 5.—*MSK 1964 intensity scale*

[Quoted from Sponheuer (1965). Reproduced by permission of Wilhelm Sponheuer, Institut für Geodynamik, Jena]

CLASSIFICATION OF THE SCALE

1. *Types of structures (buildings not antiseismic):*
   Structure A: Buildings in field-stone, rural structures, adobe houses, clay houses.
   B: Ordinary brick buildings, buildings of the large block and prefabricated type, half timbered structures, buildings in natural hewn stone.
   C: Reinforced buildings, well-built wooden structures.
2. *Definition of quantity:*
   Single, few: about 5 percent
   Many: about 50 percent
   Most: about 75 percent
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 larger pieces of plaster; pantiles slip off; cracks in chimneys; parts of chimneys fall down.
   Grade 3—Heavy damage: Large and deep 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 and filled-in walls of the frame collapse.
   Grade 5—Total damage: Total collapse of buildings.
4. *Arrangement of the Scale:*
   a. Persons and surroundings.
   b. Structures of all kinds.
   c. Nature.

INTENSITY SCALE

I. *Not noticeable:*
   a. The intensity of the vibration is below the limit of sensibility; 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 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, somewhat more heavily on upper floors.

IV. *Largely observed:*
   a. The earthquake is felt indoors by many people, outdoors by few. Here and there people awaken, 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. Furniture begins to shake. Hanging objects swing slightly. Liquids in open vessels are slightly disturbed. In standing motor cars the shock is noticeable.

TABLE 5.—*MSK 1964 intensity scale*—Continued

V. *Awakening:*

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

b. Slight damages of grade 1 in buildings of type A are possible.

c. Sometimes change in flow of springs.

VI. *Frightening:*

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

b. Damage of grade 1 is sustained in single buildings of type B and in many of type A. Damage in few buildings of type A is of grade 2.

c. In few cases cracks up to widths of 1 cm possible in wet ground; in mountains occasional landslips; changes in flow of springs and in level of well water are observed.

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 many buildings of type B damage is of grade 2. Many buildings of type A suffer damage of grade 3, few of grade 4. In single instances landslips of roadway on steep slopes; cracks in roads; seams of pipelines damaged; cracks in stone walls.

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

VIII. *Destruction of buildings:*

a. Fright and panic; also 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. Many buildings of type C suffer damage of grade 2, few of grade 3. Many buildings of type B suffer damage of grade 3, and many buildings of type A suffer damage of grade 4. Occasional breakage of pipe seams. Memorials and monuments move and twist. Tombstones overturn. Stone walls collapse.

c. Small landslips in hollows and on banked roads on steep slopes; cracks in ground up to widths of several centimeters. Water in

TABLE 5.—*MSK 1964 intensity scale*—Continued

in lakes becomes turbid. New reservoirs come into existence. Dry wells refill and existing wells become dry. In many cases change in flow and level of water.

IX. *General damage to buildings:*

a. General panic; considerable damage to furniture. Animals run to and fro in confusion and cry.

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

c. On flat land overflow of water, sand and mud is often observed. Ground cracks to widths of up to 10 cm, on slopes and river banks more than 10 cm. furthermore a large number of slight cracks in ground; falls of rock, many landslides and earthflows; large waves 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, a few of grade 5. Many buildings of type B show damage of grade 5; most of type A have destruction category 5; 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 show waves.

c. In ground, cracks up to widths of several decimeters, sometimes up to 1 meter. Parallel to water courses occur broad fissures. Loose ground slides from steep slopes. From river banks and steep coasts considerable landslides are possible. In coastal areas displacement of sand and mud; change of water level in wells; water from canals, lakes, rivers, etc., thrown on land. New lakes occur.

XI. *Catastrophe:*

b. Severe damage even to well-built buildings, bridges, water dams, and railway lines; highways become useless; underground pipes destroyed.

c. Ground considerably distorted by broad cracks and fissures, as well as by movement in horizontal and vertical directions; numerous landslips and falls of rock.

The intensity of the earthquake requires to be investigated specially.

XII. *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 over wide areas; lakes are dammed; waterfalls appear, and rivers are deflected.

The intensity of the earthquake requires to be investigated specially.

TABLE 5.—*MSK 1964 intensity scale*—Continued

Table 1: Magnitudes of the oscillations of earthquakes of different intensities

I (grade)	α (cm sec^{-2})	v (cm sec^{-1})	x_0 (mm)
5	12–25	1. 0– 2. 0	0. 5– 1. 0
6	25–50	2. 1– 4. 0	1. 1– 2. 0
7	50–100	4. 1– 8. 0	2. 1– 4. 0
8	100–200	8. 1–16. 0	4. 1– 8. 0
9	200–400	16. 1–32. 0	8. 1–16. 0
10	400–800	32. 1–64. 0	16. 1–32. 0

I = Intensity of earthquakes
α = Ground acceleration in cm sec^{-2} for periods between 0.1 sec and 0.5 sec.
v = Velocity of ground oscillation in cm sec^{-1} for periods between 0.5 sec and 2.0 sec.
x_0 = Amplitude of movement of centre of gravity of the pendulum mass in mm. The natural period of the pendulum is 0.25 sec, the logarithmic decrement is 0.5.

Table 2: Types of structures, number and classification of damage to buildings

Intensity grade	Types of structures		
	A	B	C
5	Single–1		
6	Single–2	Single–1	
	Many–1		
7	Single–4		
	Many–3	Many–2	Many–1
8			Single–3
	Many–4	Many–3	Many–2
9		Single–5	Single–4
	Many–5	Many–4	Many–3
10			Single–5
		Many–5	Many–4
	Most–5		

1, 2, 3, 4, 5 = Classification of damage.

Table 3: Short characterization of the earthquakes

Intensity (grade)	*Effects*
1	Only recorded by seismographs.
2	Only felt by individual people at rest.
3	Only felt by a few people.
4	Felt by many people. Dishes and doors rattle.
5	Hanging objects swing, many sleeping people awaken.
6	Slight damage in buildings and small cracks in plaster.
7	Cracks in plaster, gaps in walls and chimneys.
8	Wide gaps in masonry, parts of gables and cornices fall down.
9	In some buildings walls and roofs collapse, landslips.
10	Collapse of many buildings, cracks in ground up to widths of 1 m.
11	Many cracks in ground, landslips and falls of rocks.
12	Strong changes in the surface of the ground.

Table 5.—*MSK 1964 intensity scale*—Continued

Table 4: Converting table for seismic scales

Seismic Scale MSK 1964	Scale of the Inst. of Physics of the Earth, Sov. Acad. of Sciences 1952	American modified Mercalli Scale (M.M.) 1931	Japanese Scale 1950	Rossi-Forel Scale 1873	European Mercalli-Cancani-Sieberg Scale 1917
1	1	1	0	1	1
2	2	2	1	2	2
3	3	3	2	3	3
4	4	4	2, 3	4	4
5	5	5	3	5, 6	5
6	6	6	4	7	6
7	7	7	4, 5	8	7
8	8	8	5	9	8
9	9	9	5, 6	10	9
10	10	10	6	10	10
11	11	11	7	10	11
12	12	12	7	10	12

Table 6.—*Maximum acceleration and velocity values of different intensities*

Intensity	Acceleration						Velocity value range (cm per sec)
	Average (in gals)				Range		
					units of 10^{-3} g, ≈ gals	gals	
	Scale used [1]						
	1	2	3	4	5	6	7
	(M.M.)	(M.M.)	(M.M.)	(Japanese)	(GEOFIAN)	(M.M.)	(GEOFIAN)
I			2	1.4			
II	1.0	2.3	4	4.5		1–5	
III	1.6	3.1	8	14		1–8	
IV	3.2	9.3	16	45		2–46	
V	10	13.3	31	140	12–25	2–75	1.0– 2.0
VI	32	40	64	450	25–50	5–175	2.1– 4.0
VII	79	67	130	1,400	50–100	18–140	4.1– 8.0
VIII	200	172	264		100–200	51–350	8.1–16.0
IX	316	(250)	537		200–400		16.1–32.0
X	398		1,090		400–800		32.1–64.0

[1] Refer to fig. 2 to correlate columns.

1. California data derived from Gutenberg and Richter (1956, table 16).
2. U.S. Coast and Geodetic Survey (1948) strong motion stations. Parentheses indicate estimated acceleration.
3. U.S. Coast and Geodetic Survey strong motion stations for period of 0.33 sec and epicentral distances less than 25 miles (Neumann, 1954, table 3).
4. Japan data (derived from Kawasumi, 1951, p. 476).
5. Restricted range for periods of 0.1 to 0.5 sec (Medvedev, 1963b, table 5).
6. U.S. Coast and Geodetic Survey (1948) strong motion stations.
7. For periods of 0.5 to 2.0 sec (Medvedev, 1963b, table 5).

TABLE 7.—*Correspondence between magnitude, epicentral intensity (GEOFIAN), and focal depth*

[From Shebalin (1961, table 5.1)]

Magnitude (*M*)	Intensity at epicenter		
	h=5 km	h=15 km	h=45 km
>7½		10	9–10
6½–7½	10	9–10	7–8
5¼–6½	9–10	7–8	5–7
4¼–5¼	7–8	5–7	4–5
<4¼	<7	<5	<3

TABLE 8.—*Focal depth determination of Tesikaga earthquakes based on intensity data*

Earthquakes (fig. 17)	From Matumoto (1959)			From Shebalin (1961) and fig. 2			h[4]
	M[1]	I_0 (Japanese)	h[1]	I_0 (Japanese)[1]	h[2]	h[3]	
A	5. 7	V	0–10	VI–VII (h=0–5) V (h=6–10)	6–20	7–10	6–10
B	6. 2	V	20	V	9–30	10–15	10–20
C	6. 2	V	0	VII	9–30	14–16	12–22

[1] Shown in fig. 13; based on Matumoto's M and h.
[2] Shown in fig. 13; based on Matumoto's M and I_0.
[3] Shown in fig. 15; based on Matumoto's intensity data (fig. 14). Range denotes spread of plotted points, not accuracy.
[4] h estimate based on foregoing data.

TABLE 9.—*Increase in seismic intensity from the ground*

[Translated by P. J. Barosh from Medvedev (1961, table 4.2)]

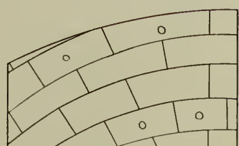
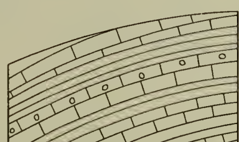
Ground	v (km per sec)	n (intensity increase)
Stable rock:		
Granites	5. 6	
Dense limestones, schists, gneisses	3. 5–4. 5	0. 2–0. 4
Dense sandstones	2. 2–3. 0	. 5–0. 8
Disturbed limestones, shales, sandstones	1. 5–2. 3	. 7–1. 1
Semistable rock:		
Gypsums	2. 4–3. 0	0. 6–0. 8
Marls	2. 0–2. 6	. 7–1. 0
Cemented sands	1. 4–1. 9	1. 0–1. 2
Coarse debris:		
Rubble and pebbles	1. 3–2. 1	0. 9–1. 3
Gravels (from crystalline rock)	1. 2–1. 9	1. 0–1. 4
Gravels (from sedimentary rock)	1. 1–1. 7	1. 1–1. 5
Sandy:		
Grit and coarse sands	1. 1–1. 6	1. 2–1. 4
Sands of average coarseness	1. 0–1. 4	1. 3–1. 6
Fine and silty sands	. 7–1. 2	1. 4–1. 8

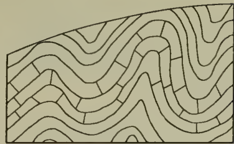
TABLE 9.—*Increase in seismic intensity from the ground*—Continued

Ground	v (km per sec)	n (intensity increase)
Clayey:		
Clays	0. 9–1. 5	1. 2–1. 6
Loams	. 8–1. 4	1. 3–1. 7
Sandy loams	. 7–1. 2	1. 4–1. 8
Loams (E=1.0) and sandy loams (E=0.7)	. 5–0. 8	1. 7–2. 1
Fill and soils:		
Filled ground	0. 3–0. 5	2. 3–2. 6
Soils	. 2–0. 3	2. 6–3. 0
Water saturated:		
Gravel (pebbly)		1. 6–2. 0
Sandy		2. 0–2. 4
Clayey (sandy loams, loams)		2. 4–2. 9
Fill and soils		3. 3–3. 9

TABLE 10.—*Typical engineering-geologic conditions that determine the size of the correction to seismic intensity*

[From data of investigations of the consequences of earthquakes in Gori in 1920 and 1940, the Crimea in 1927, Ashkhabad in 1948, and others. Quoted from Popov (1959) as translated by G. P. Eaton (unpub., 1965). In the column "Increase in the seismic intensity," granite was taken as the standard rock (0), and the amount of increase was obtained by Popov or by him from Medvedev (1952a, b)]

Type geologic section	Engineering-geologic condition	Degree of seismic hazard		
		General appraisal	Increase in the seismic intensity	Deviation from the average intensity
1  	Massively crystalline and the most compact schistose and layered, hard and semihard rocks of great thickness, unweathered and unfractured, magmatic crystalline and compact structures—for example, granite and basalt; sedimentary rocks, thickly layered—for example, conglomerate, sandstone, and limestone; metamorphic rocks—for example, gneiss and quartzite.	The safest in seismic behavior; not subjected to permanent deformation (except for earthquakes above intensity 10–11).	0 0.2–0.8	Decreased by 1–2 units.
2 	Less compact layered and schistose and also porous hard and semihard rocks of great thickness, gently lying or contorted by shallow folds, without signs of fault dislocations, unweathered and unfractured: volcanic tuffs and tuffaceous sandstones; micaceous and argillaceous schists; thin-bedded sandstones; marls; porous rocks—such as calcareous tufa, chalk, tripolite; soft rocks such as gypsum.	Also safe in seismic behavior, but less so than case 1; these rocks, now subject to permanent deformation, can develop fissures.	0.7–1.1	Decreased by 1 unit.



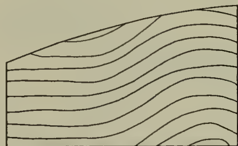
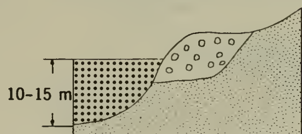
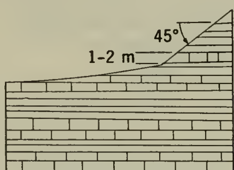
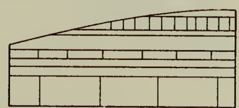
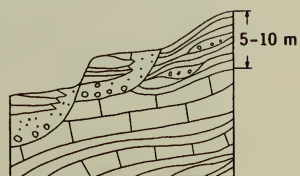
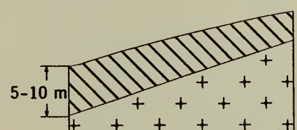
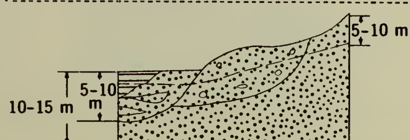
3. 	Thick (not less than 10 m) layers of dry argillaceous rocks, gently dipping or folded.	Safe under dry conditions; but when wet the rocks become dangerous and are subject tɔ permanent dislocation in proportion to the degree of wetness.	1.2–1.6	Unchanged.
4. 	Thick (not less than 10–15 m) layers of compactly deposited granular rocks: sandstone, gritstone, and boulder gravel.	Can be seismically hazardous because of low seismic stability; subject to compaction and unequal settling; sudden sags on saturated, weakly compacted sands are possible.	1.2–1.8	Unchanged or increased by 1 unit on layered strata.
5. 	Interbedded layers (1–2 m thick) of unconsolidated (argillaceous or sandy) and hard or semihard rocks—alternating bands of clay or sand with sandstone, limestone, or other sedimentary rock; total thickness of the series is large.	Seismic hazard not great; behavior is worse on steep slopes (steeper than 45°), where local reflected waves can arise; respond more strongly to shaking than layered, massive, homogeneous rocks.	1.0–2.0	Unchanged or increased by 1 unit on layered strata.

TABLE 10.—*Typical engineering-geologic conditions that determine the size of the correction to seismic intensity*—Continued

Type geologic section	Engineering-geologic condition	Degree of seismic hazard		
		General appraisal	Increase in the seismic intensity	Deviation from the average intensity
6.   	Layers 5–10 m thick of dry homogeneous argillaceous or sandy gravelly formations of various origins (marine, lacustrine, glacial, alluvial, proluvial, deluvial), with or without thin (less than 1 m) bands of hard or semihard rock (sandstones, limestones); also similar rocks with sharp facies variations.	Not strongly hazardous seismically; the greater the difference in physical properties of contiguous layers, the greater the hazard.	1. 0–2. 0	Unchanged or increased by 1 unit when the rocks are saturated at a depth not greater than 5 m.
7. 	Rather thick unconsolidated formations (clay, sand, gravel) saturated at depths greater than 5 m.	Not strongly hazardous seismically, since saturation at depths greater than 5 m does not strengthen seismic effects.	2. 0–2. 5	Unchanged or increased by 1 unit when the rocks are saturated at a depth of 5 m.

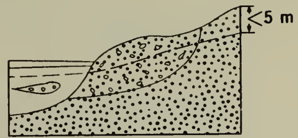
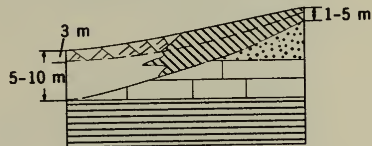
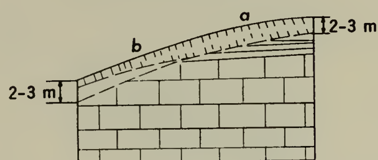
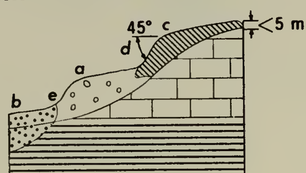
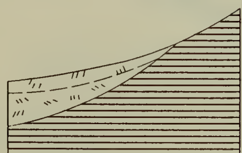
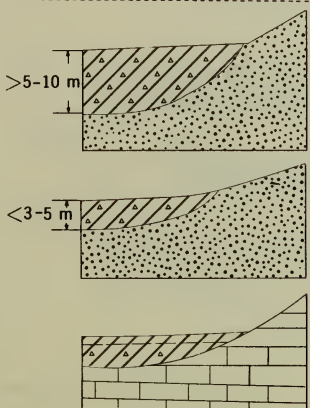
8		Rather thick unconsolidated formations (clay, sand, gravel), but saturated at depths shallower than 5 m (in some places saturated to depths of only 1–3 m).	Argillaceous types and peat bogs are seismically more hazardous than sands, grits, and bouldery gravels; seismic stability of rewetted argillaceous rock types (including loess) is greatly reduced.	1.6–2.4	Increased by 1 unit.
9		Less thick unconsolidated formations (5–10 m) (clay, sand, gravel) saturated almost to the surface of the earth (1–3 m).	More hazardous seismically than section 8	1.6–2.8	Increased by 1–2 units.
10		Eluviated hard, semihard, or argillaceous rocks in the dry (*a*) or saturated (*b*) state, converted into rubbly or disintegrated loamy formations.	Just as hazardous seismically as section 9, particularly in loosely bedded large fragments.	1.6–2.9	Increased by 1–2 units.
11		Layers (less than 5 m thick) of unconsolidated formations (diluvial and alluvial argillaceous loams, sandy loams, sands, gravels) lying on compact rock (*a*, *b*, *c*). Also contacts of diluvial, alluvial (*d*, *e*) and other types of Quaternary formations.	Just as hazardous seismically as section 10, particularly on steep slopes; the seismic effect becomes stronger the larger the difference in physical properties of the overlying formations and the underlying rocks that are in contact.	2.3–3.0	Increased by 1–2 units.

TABLE 10.—*Typical engineering-geologic conditions that determine the size of the correction to seismic intensity*—Continued

Type geologic section	Engineering-geologic condition	Degree of seismic hazard		
		General appraisal	Increase in the seismic intensity	Deviation from the average intensity
12 	Continually wet or swampy argillaceous formations; such as muddy, sandy, or coarsely broken accumulations on seashores, lake and river banks, river courses, low islands, and turfs that are saturated to the surface of the earth.	Very hazardous seismically, not only on slopes but also on level parts of the region; dilute argillaceous rocks and swamp rocks have a very low seismic stability and may flatten.	2. 3–3. 9	Increased by 1–2 units (on saturated peat soils).
13 	Layers of filled mineral ground and various manmade materials, such as structural debris, that are either (*a*) thicker than 5–10 m; (*b*) thinner than 3–5 m; or (*c*) saturated.	Very hazardous seismically, especially on slopes and in fills that are loosely bedded and may undergo strong, unequal settling (sections *b* and *c* are always hazardous).	2. 3–3. 9	Increased by 1–2 units.

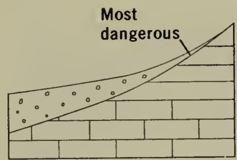
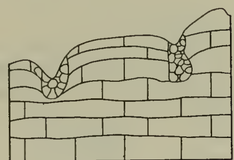
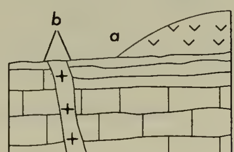
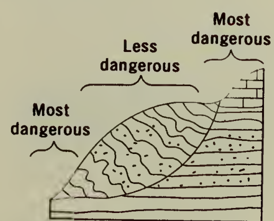
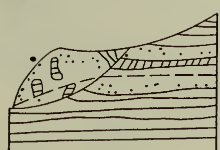
14 	Unstably bedded gravitating formations; hillside waste (talus) of finely broken material and large angular fragments of different thicknesses.	Very hazardous seismically, especially on steep slopes and also in regions undergoing solufluction.	2.0–3.9	Increased by 1–2 units.
15 	Karst carbonate, hard and semihard rocks, strongly deformed but with the phenomena of settling and caving-in not yet completed; here also can be classified rocks that have been disrupted by mining.	Very hazardous seismically on active karst because of unequal settling; on old karst seismic "islands" can occur.	2.0–4.0	Intensity unchanged or increased by 1–2 units.
16 	Contacts of intrusive and extrusive rocks with metamorphic or sedimentary rocks; for example, contacts of basaltic lava flows with clays (*a*) and other rocks, and contacts of intrusive rocks with their enclosing rocks (*b*).	Sometimes very hazardous seismically, especially at contacts between rocks with sharply different physical properties.	1.0–4.0	Intensity unchanged or increased by 1 unit.

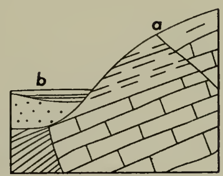
TABLE 10.—*Typical engineering-geologic conditions that determine the size of the correction to seismic intensity*—Continued

Type geologic section	Engineering-geologic condition	Degree of seismic hazard		
		General appraisal	Increase in the seismic intensity	Deviation from the average intensity
17	Old, dry, arrested landslides and earthflows of diverse rocks (*a*); active earthflows of various types, with different thicknesses of the sliding material, and saturated (*b*).	Old, dry, large earthflows are relatively safe; but active, wet earthflows are very hazardous, for earthquakes can cause them to move; the breakaway line and sectors located on it are the most hazardous.	1.0–4.0	Intensity unchanged (on old earthflows) or increased by 1–2 units (on active earthflows).





18	Hard (stony), semihard, or soft (nonstony) rocks broken by fissures due to faults and offsets, or a whole zone of fractures, cropping out at the earth's surface (*a*) or covered by unconsolidated formations (*b*, saturated; *c*, dry).	Extremely hazardous seismically, but deep zones of fractures and faults, can decrease the seismic effect on the other side of these disturbances in relation to the direction of arrival of the seismic shock (*c*). Thick, uncompacted mantling formations are capable of mitigating the seismic effect on faults; but thin, especially saturated, mantling formations increase the seismic effect, being badly cracked, and having settled.	3.0–4.0	Increased by 2 units.



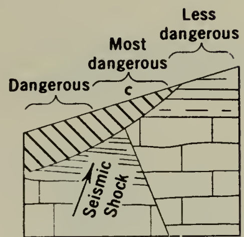


TABLE 11.—*Intensity increase from ground conditions of the Apsheronsk Peninsula*

[Quoted from Kuliev, 1962, p. 78]

Depth of ground-water level, in meters	≤10	4	1
Limestone (Tertiary and Quaternary)	−1.2	−0.7	−0.4
Sandstone (Tertiary and Quaternary)	−.8	−.3	+.0
Clay (Tertiary)	−.6	−.1	+.2
Sandy-argillaceous ground (Tertiary)	−.2	+.3	+.6
Clay (Quaternary)	−.2	+.3	+.6
Sand (Tertiary)	−.1	+.4	+.7
Sandy-argillaceous ground (Quaternary, second category)	.0	+.5	+.8
Loams (Tertiary and Quaternary)	+.2	+.7	+1.0
Filled ground (Recent)	+.3	+.8	+1.1
Eolian-diluvial ground (Recent)	+.4	+.9	+1.2

TABLE 12.—*Engineering-geologic divisions of the Petropavlovsk area, Kamchatka*

[From Goryachev and others (1963, table 3)]

Engineering-geologic region	Geomorphic conditions	Ground thickness layer H, m	Depth ground water level	Seismic intensity increase $\pm\Delta n$, intensity units	Seismic intensity (GEOFIAN)
1	Summits and steep mountain slopes (steeper than 20–30 percent); separate outcrops of rocky ground in lower parts of slopes.	Rocky ground; phyllitic schists, sandstones, siliceous schists, gabbro-diabase, andesite; weathered in upper parts; $H>100$.	Water in fractures, variable depth	−1	7
2	Lower parts of mountain slopes (gentler than 20–30 percent).	Eluvial-diluvial stoney-pebbly ground; sandy loams, loams, angular pebbles; $H=1$–3 (in middle parts of slopes) up to 5–10 (in lower parts of slopes).	In middle parts of slopes ground water less, in lower parts of slopes depth variable.	0	8
3	Weakly broken up hilly plain proluvial train (inclination <10 percent).	Pyroclastic ground; ash, sand with coarse lava, tuff; $H>50$–100.	Great	0	8
4	Eroded high deltaic-marine terrace (inclination <5–10 percent).	Sand, gravels, pebbles; $H>50$–80	Great	0	8
5	Gentle slopes (<5 percent) in foothills and plains between them.	Eluvial-diluvial angular-pebbly loam; $H=$ 3–5.	Small	+1	9
6	Level stream and river bottoms with fall from 10–15 to <5 percent in estuaries; marine beaches.	Sands with gravel, pebbles; silty sands in estuary parts; $H>10$.	Small	+1–+2	9–10
7	Level flood plain surfaces and I terrace in river valleys.	Marshy peaty sandy-argillaceous ground, lower gritty-angular-pebbly sands; $H>$ 10–15.	Small	+1–+2	9–10
8	Level stream bottoms (flood plain inclination <5–10 percent).	Argillaceous gritty sands with parts peaty sandy-loam; $H>10$.	Small	+1	9
9	Filled territory (inclination <3 percent)	Filled ground—stoney sands with gravel and pebbles; alluvium—argillaceous and silty sands; $H=3$–4 (up to 5).	Small	+1–+2	9
10	Parts of abrupt scarps with height from 10 up to 20–30 m; possible talus and landslides.	Rocky ground—siliceous schist; weathered from the surface; $H>100$.	Drained	+1	9

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