# INTENSITY OF EARTHQUAKE GROUND SHAKING NEAR THE CAUSATIVE FAULT

by
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## Abstract

Data and analyses indicate an upper bound for intensity of ground shaking that is approximately 50% greater than at El Centro during the earthquake of 18 May 1940. Upper bounds of 50%g for maximum ground acceleration and 45 seconds for duration of strong shaking are indicated. The intensity immediately adjacent to a fault is not especially severe but is, in general, somewhat less than at a distance of several miles. The maximum intensity of shaking associated with a Magnitude 8.5 earthquake is less and that associated with a Magnitude 5 earthquake is greater than has been commonly supposed.

The strain energy that is released in the form of seismic waves during slip on a fault will affect most strongly a region in the general vicinity of the fault, whereas at greater distances the intensity of ground shaking will be attenuated. In the past, misunderstandings of the significance of the seismological terms "earthquake Magnitude" and "Modified Mercalli Intensity" have led to erroneous conclusions about the intensity of ground shaking. The only precise measure of the intensity of ground shaking is the spectrum intensity that has been calculated from instrumental recordings made on the spot, either from accelerograms or from readings of properly designed seismoscopes. For engineering purposes, a significant quantity is the maximum intensity of ground shaking that may be associated with an earthquake as this represents an upper bound for the forces that structures may be called upon to resist. The estimation of the maximum intensity must be based on ground motion records and observations of past earthquakes, and upon knowledge of the mechanics of fault slip and wave propagation.

Nature of Earthquake Faulting. In California, faults on which large earthquakes have occurred are well defined and the nature of the fault slip during the earthquakes is well understood. Since the most intense horizontal ground shaking is associated with horizontal (strike-slip) fault displacements, the San Andreas fault can be taken as the classical example of a strong-motion generating fault. The 1906 San Francisco earthquake resulted from horizontal slip over approximately 250 miles of this fault

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with a maximum relative displacement of the two sides of the fault of 21 feet (2). There was, of course, no recording of ground accelerations during this earthquake. The 18 May 1940 El Centro earthquake was the most severe so far recorded. This earthquake resulted from slip on a southern branch of the San Andreas fault system (Imperial fault). The slip extended over a length of approximately 50 miles of fault and with a maximum relative displacement of the two sides of the fault of 15 feet (3).

The El Centro, 1940 earthquake is a good illustrative example of a strong-motion earthquake in that it was a relatively large shock with well-defined faulting in a region having deep alluvium, and with ground motion recorded not far distant from the fault, and with a number of towns in the region of strong shaking. At El Centro there is more than 5000 feet of clay, loam, sand, and gravel underlaid by sandstone. The trace of the fault and the location of the adjacent towns are shown in Fig. 1. The maximum relative surface fault displacement occurred just east of Calexico. The southern extremity of the fault was not well defined. Presumably the maximum relative fault displacement in the rock beneath the alluvium was somewhat greater than 15 feet. The accelerometer that recorded the ground motion was located in the town of El Centro at a distance of approximately 4 miles from the fault trace. A Modified Mercalli Intensity of IX was assigned to all of the towns shown in Fig. 1 by Ulrich (3). In a later publication (4) the following MM intensities were assigned: Brawley and Imperial IX; El Centro and Holtville VIII; Calexico and Heber VII. A significant portion of the damage at Imperial and Brawley is reported to have occurred during a smaller aftershock, so that greater credence should be given to Ulrich's estimates of intensity which were made on the basis of personal inspection. It was noted that some rather poorly constructed farm buildings located within a few hundred feet of the fault trace suffered no damage.

The strongest component of horizontal ground acceleration recorded in El Centro (4) is shown in Fig. 2. This shows only the strong phase of shaking, following which there were several minutes of less strong shaking that gradually attenuated.

There are listed below the amplitude $A_1$ and duration t of some of the larger pulses of the El Centro ground acceleration. The values given will indicate the nature of the acceleration pulses during strong

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(2) Lawson, et. al., "Report of the State Earthquake Investigation Commission," Carnegie Institution of Washington, Vol. 1, 1908; Vol. 2, 1910.

(3) Ulrich, F. P., "The Imperial Valley Earthquakes of 1940," Bulletin of Seis. Soc. Am., Vol. 31, No. 1, 1941.

(4) U. S. Coast and Geodetic Survey, "U. S. Earthquakes - 1940," U.S. Government Printing Office, 1942.

ground motion. The area of each pulse (velocity increment) is also given. The size of a single acceleration pulse, however, is not a reliable indication of the intensity of shaking as regards its effect on structures for the intensity depends upon the cumulative effect of the sequence of pulses.

| $A_1$(%g) | $t_1$(secs.) | Velocity Increment (ft per sec.) |
|---|---|---|
| 33 | 0.23 | 1.6 |
| 27 | 0.14 | 0.8 |
| 31 | 0.10 | 0.6 |
| 23 | 0.29 | 1.4 |
| 30 | 0.18 | 1.1 |

Figure 3 shows the integrated velocity and displacement for both components of ground motion (5). The recording instrument was sufficiently close to the fault so that a permanent displacement is shown in Fig. 3. The resultant permanent displacement is approximately 12 inches in the northwest direction. The magnitude of surface slip at the adjacent part of the fault was reported to be approximately 4 feet. The maximum transient displacement in Fig. 3 is 20 inches, and this was attained at the end of the first 5 seconds of motion. A maximum velocity of 1.25 ft/sec was attained at the end of the first two seconds of motion in each component, it being the cumulative effect of the first 5 acceleration pulses. Assuming that the maximum velocities of the two components of ground motion are the components of a resultant vector ground velocity, there is obtained a value of 1.75 ft/sec for the peak ground velocity.

Figure 3 indicates a permanent EW displacement of 10 inches which would also be the approximate displacement of the underlying rock. It may be inferred that the transient displacement of 20 inches represents an amplification of about 2 at the surface of the alluvial layer. This would indicate a maximum velocity of the underlying rock of $1.75 \div 2 = 0.9$ ft/sec. If the underlying rock reached a peak velocity of 0.9 ft/sec and underwent a permanent displacement of $15 \div 2 = 7.5$ feet, the total duration of slipping at that point would be 8 seconds. Slipping progressed beyond this point some 15 miles south, and assuming that strong shaking would be produced by waves originating 15 miles away the total duration of strong shaking might be expected to be approximately $8 + 15 = 23$ secs. This is based on a velocity of propagation of slip along the fault of 2 miles per second and taking the same value for velocity of shear waves. The El Centro accelerogram shows 25 seconds of strong shaking.

Although no recordings of ground accelerations were made during the 1906 San Francisco shock, a very complete description of this earthquake has been given (2) which is in agreement with the characteristics

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(5) Berg, G.V. and Housner, G.W., "Integrated Velocity and Displacement of Strong Earthquake Ground Motion," Bulletin Seis. Soc. Am., Vol. 51, No. 2, 1961.

of the El Centro shock. The strongest ground shaking, as deduced from damage to buildings, was reported for the town of Santa Rosa which was located approximately 20 miles from the fault. An inspection of photographs of buildings indicates that the damage was similar to that observed in Santa Barbara (1925), in Long Beach (1933), and in El Centro (1940), and it is inferred that the intensity of shaking in Santa Rosa was not significantly greater than in the El Centro (1940) earthquake. Strong shaking was also reported for the northeastern part of San Francisco which was some 10 miles from the fault; this region of severe damage coincided approximately with the region of soft alluvium and the region of oldest commercial buildings. Photographs of damaged buildings indicate that the intensity of ground shaking was not more severe than has been experienced in subsequent California earthquakes. This conclusion has also been stated by Byerly (6) who thought that the 1906 shock, the El Centro, 1940, the Dixie Valley, Nevada, 1954, and the Kern County, 1952, all had approximately the same maximum intensity: "I feel that intensity 9 is as high as we should go in any of the shocks even if faults did break in some of them and even if incipient landslides were set off and loose earth disturbed by them."

It may also be seen that in 1906 the intensity of shaking immediately adjacent to the slipped portion of the fault was less severe than at greater distances, as evidenced by damage to structures (2).

The maximum permanent ground displacement in 1906 was 10.5 ft (on rock or shallow alluvium) some 10 miles north of San Francisco. This may be compared with the permanent displacement of 7.5 ft during the El Centro earthquake. Assuming a maximum ground velocity (rock) of 0.9 ft/sec, as during the El Centro shock, 11 seconds would be required to move through 10.5 feet. As strong shaking might be expected if the slipping portion of the fault was not more than about 25 miles distant, the total duration of strong shaking might be expected to be approximately 8 + 25 = 33 seconds. It would, of course, be followed by several minutes of less intense, gradually attenuating ground motion. This is in agreement with the description of ground motion during the 1906 shock: "What has been called the violent part of the shock did not last longer than 40 or 50 seconds, whereas the principal part certainly lasted many minutes." (2)(Vol. II, p. 114).

Properties of Strong Ground Motion. The properties of recorded strong ground motions are given in Table I, where there are listed the Magnitudes of the shocks, the spectrum intensities of the ground motion, the maximum recorded ground acceleration, and the duration of the strong phase of shaking. It should be noted that the maximum acceleration is not a good

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(6) Byerly, P., "Seismicity of Western United States," Proc. 1st World Conf. Earthquake Engineering, 1956.

measure of the intensity of shaking as regards effects on structures. The only precise measure of the effect of ground shaking is given by the spectrum (7) of the ground motion. The spectrum intensity $(SI)_n$ is defined (8) as the area under the Velocity Response Spectrum curve:

$$(SI)_n = \int_{0.1}^{2.5} S_v(n, T)dt \qquad (1)$$

where $S_v(n, T)$ is the velocity response spectrum, which is a function of natural period of vibration T and fraction of critical damping.

A properly designed seismoscope will give a point on the $S_v(n, T)$ curve for a particular set of values n and T and, hence, an estimate of $(SI)_n$ can be made (9).

The commonly used Modified Mercalli Intensity is a completely subjective description and hence is not suitable for engineering purposes. The defects of the Modified Mercalli Intensity are exhibited by comparing the Long Beach, California (10 March 1933) earthquake with the Helena, Montana (31 October 1935) shock. The Long Beach 'quake was recorded at Vernon which was approximately 15 miles horizontally (estimated) from the nearest point of the slipped fault. The recording at Helena is estimated to have been 5 to 10 miles horizontally from the nearest point of the slipped fault. From Table I the following comparison can be made.

| | Long Beach (Vernon) | Helena |
|---|---|---|
| Magnitude | 6.3 | 6.0 |
| Max. Acceleration | 0.19g | 0.16g |
| Duration | 6 secs | 4 secs |
| Spectrum Intensity: | | |
| 0.0 Damping $(SI)_0$ | 4.62 | 1.82 |
| 0.2 Damping $(SI)_{0.2}$ | 1.70 | 1.02 |
| Modified Mercalli (10) | VII | VIII |

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(7) Alford, J. L., Housner, G. W., and Martel, R. R., "Spectrum Analyses of Strong-Motion Earthquakes," Earthquake Research Laboratory Report, California Institute of Technology, 1951.

(8) Housner, G. W., "Spectrum Intensities of Strong-Motion Earthquakes," Proc. Symp. Earthquake and Blast Effects on Structures, Earthquake Engineering Research Institute, 1952.

(9) Cloud, W. K., and Hudson, D. E., "A Simplified Instrument for Recording Strong-Motion Earthquakes," Bulletin Seism. Soc. Am., Vol. 51, No. 2, 1961.

(10) U. S. Coast and Geodetic Survey, "U. S. Earthquakes 1933-1935."

It is seen that the ground motion at Helena was significantly less intense than at Vernon. The 20% damped Spectrum Intensity is a good measure of the amount of damage to be expected and the ratio of $(SI)_{0.2}$ shows that the Vernon ground motion was 70% more intense than the Helena ground motion. However, a Modified Mercalli Intensity of VIII was assigned to Helena and only VII to Vernon. This discrepancy indicates that a casual observation of damage, as is required to assign MMI numbers, is not a reliable method of estimating the intensity of ground shaking. The Modified Mercalli Intensity should not be used for engineering purposes.

Seismologists sometimes estimate the maximum ground acceleration from the Modified Mercalli Intensity by means of the following empirical formula, or its equivalent:

$$\log_{10}A = \frac{I}{3} - \frac{1}{2} \qquad (2)$$

where 'A' is the maximum ground acceleration in gals and I is the MMI number. This formula gives:

| MMI | Max. Accel. (%g) |
|---|---|
| VII | 7 |
| VIII | 15 |
| IX | 32 |

Equation (2) was adjusted to fit El Centro 1940 which had MMI = IX, max. accel. = 33%g, but it is approximately 200% in error in predicting the Vernon ground acceleration. It would be illogical, of course, to suppose that maximum ground accelerations can be calculated from MMI numbers that are assigned on the basis of casual observations of building damage. The use of Eq. (2) to calculate very high ground accelerations for MMI numbers X and XI is completely irrational as these larger MMI numbers are assigned on the basis of ground cracking, landslides, and other phenomena that are not associated with intensity of ground shaking.

It should also be noted that the Magnitude of an earthquake is not a direct indication of the intensity of ground shaking in the epicentral region. The numerical value of the Magnitude is defined as the logarithm of the maximum amplitude (in millimeters) of a 0.8 sec period instrument having 60% damping and 2800 magnification, the instrument to be located 100 kms from the epicenter. To calculate the Magnitude from the reading is to use the instrument as a seismoscope to give a measure of the intensity of ground shaking 100 kms from the epicenter. The frequency characteristics of the ground motion at this distance are quite different from those close to the epicenter. In the case of a very large shock, such as the Alaskan earthquake of 28 March 1964 whose slipped length of fault was approximately 1400 kms, the 'seismoscopes' upon whose readings the Magnitude was determined were several thousand miles away. The large Magnitude (M = 8.5) given by these instrumental readings is indicative of the large area of slipped fault but is not indicative of the shaking near the fault. It must be emphasized that the Magnitude is merely an estimate of the intensity of shaking at large distances from the epicenter. It can be used to estimate the size of the earthquake (length of fault), but is not of itself a good indication of the intensity of strong shaking near the fault.

Maximum Intensity of Shaking. A plot can be made of the $(SI)_{0.2}$ spectrum intensity versus Magnitude using the values given in Table I. This plot is shown in Fig. 4 with the dashed line indicating the upper bound $(SI)_{0.2}$ max. Points close to this line represent ground motions relatively close to the causative fault. Points farther from the line represent ground motions recorded at greater distances from the fault. It is seen that $(SI)_{0.2}$ max does not vary strongly with Magnitude, being equal 1.2 at M = 5 and 3.0 at M = 7.1. The dashed line extrapolates to $(SI)_{0.2}$ max equal to 4.25 at M = 8.5. This is approximately 50% greater than for El Centro, 1940. The ground motions of Table I were almost all recorded on relatively deep alluvium.

It is noteworthy that the Port Hueneme earthquake had $(SI)_{0.2}$ equal to 1.2 and M = 5. This earthquake consisted essentially of a single displacement pulse (11). The accelerogram was recorded close to the epicenter and the focus was relatively shallow. Using $(SI)_{0.2}$ as a measure of intensity of shaking, the El Centro 1940 ground shaking was only 2.5 times as intense as the Port Hueneme. This is consistent with the observation that the Agadir, Morocco earthquake of 29 February 1960, which produced such great damage, had a ground motion similar to the Port Hueneme shock (12).

The duration of the strong phase of ground shaking is closely correlated with the Magnitude of shock. Figure 5 is a plot of duration of strong phase versus Magnitude. Since the duration of the strong phase of shaking can be distinguished only for ground motions recorded relatively close to the causative fault, there are fewer data points in Fig. 5 than in Fig. 4. The dashed line in Fig. 5 indicates an upper bound and it shows a strong variation with Magnitude, extrapolating to 45 seconds at Magnitude 8.5 which is an upper bound. The 1906 San Francisco shock has an assigned Magnitude of 8.2 for which Fig. 5 indicates a duration of 43 seconds. This is not inconsistent with the estimate of 33 secs based on the time required to complete the slipping, and it is also consistent with the report of not more than 40 or 50 secs (2).

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(11) Housner, G. W. and Hudson, D. E., "The Port Hueneme Earthquake of March 18, 1957," Bulletin Seism. Soc. Am., Vol. 48, No. 2, 1958.

(12) Clough, R. W., "The Agadir Morocco Earthquake," Am. Iron and Steel Institute, New York, 1962.

The maximum recorded acceleration can also be plotted versus the Magnitude and this has been done in Fig. 6. The data points in this graph represent a more complete set of U. S. Coast and Geodetic Survey values (13). The dashed line indicates an upper bound. The points close to the line represent ground motions recorded relatively close to the causative fault, whereas those at greater distances from the line represent ground motions at greater distances from the fault. The line extrapolates to a maximum acceleration of 50%g for M = 8.5. This agrees with the estimate of 50%g made by Cloud (13) and with the estimate of 50%g made by H. Benioff as quoted by Cloud (13).

It is, of course, to be expected that the maximum acceleration and the maximum intensity of ground shaking should not be very much greater for a Magnitude 8.5 earthquake than for a Magnitude 7.0 shock. The M = 7 shock (El Centro 1940) might release strain energy over a length of fault of approximately 50 miles and the M = 8 shock might release energy over a 200-mile length of fault. Since the point of strongest ground shaking for the M = 7 shock would be approximately 25 miles from each end of the surface trace of the slip, the additional 150 miles of slipped fault would begin 25 miles away and, hence, its effect upon the maximum acceleration should not be large, particularly as the superposition of ground accelerations emanating from two points on the fault is as the square root of the sum of the squares.

The same data points plotted in Fig. 6 are used in Fig. 7 to plot Magnitude versus distance to epicenter (or fault). The dotted lines in Fig. 7 indicate approximately the variation of maximum acceleration with distance from epicenter.

Acceleration Adjacent to Fault Plane. The fact that the data in the preceding section indicated an upper bound (50%g) for the maximum ground acceleration is not surprising since the maximum acceleration reflects the magnitude of stress relief afforded by the fault slip. It is well known that the rock on the two sides of the San Andreas fault is being displaced in such a way as to build up shear stress on the fault plane. When this stress reaches a failing value there will be a slip whose extent will depend upon the state of stress on adjacent portions of the fault. The value of failing stress will be less than the strength of the rock since the fault has experienced many movements in the past and the material along the fault is weaker than the pristine rock.

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(13) Cloud, W. K., "Maximum Accelerations During Earthquakes," Proc. Chilean Conf. on Seism. and Earthquake Engineering," Univ. of Chile, 1963.

During a large earthquake, such as the 1906 San Francisco shock, there may be as much as 21 ft relative displacement of the two sides of the fault. An analysis will be made of the maximum ground acceleration that might be experienced by a point sufficiently close to the fault to participate in the 10.5 ft permanent displacement. An idealized situation will be analyzed in which the granitic basement rock extends to the surface of the ground, with no alluvium or sedimentary rock cover. It is supposed, also, that the slip extends over several hundred miles of fault.

An extreme case for the violence of motion associated with the fling of the rock on one side of the fault would be if the entire fault were to slip simultaneously with complete release of shear stress on the fault plane (lubricated slipping). In this case the movement of the rock would experience no restraint and would be completely free to move as strongly as possible. The acceleration in this case will consist of a single positive acceleration pulse of short duration and large amplitude, followed by a negative acceleration pulse of long duration and small amplitude which brings the movement to rest, as shown in Fig. 8.

Let the relative displacement across a fault be 2L ft so that the absolute displacement of one side of the fault is L ft. Suppose the acceleration, $\ddot{u}$, of a point adjacent to the fault, as shown in Fig. 8, is expressed by:

$$\begin{aligned} \ddot{u} &= A_1 \sin \frac{\pi t}{t_1} && (0 < t < t_1) \\ &= -A_2 \sin \frac{\pi}{t_2} t' && (0 < t' < t_2) \end{aligned} \qquad (3)$$

The velocity $\dot{u}$ is given by:

$$\begin{aligned} \dot{u} &= \frac{A_1 t_1}{\pi}\left(1 - \cos \frac{\pi t}{t_1}\right) && (0 < t < t_1) \\ &= \frac{2A_1 t_1}{\pi} - \frac{A_2 t_2}{\pi}\left(1 - \cos \frac{\pi t'}{t_2}\right) && (0 < t' < t_2) \end{aligned} \qquad (4)$$

At $t = t_o$ the velocity must be zero ($\dot{u} = 0$) which requires:

$$A_1 t_1 = A_2 t_2$$

The maximum velocity is given by:

$$\dot{u}_{max} = \frac{2A_1 t_1}{\pi} \qquad (5)$$

The displacement of the point is given by:

$$
\begin{aligned}
u &= \frac{A_1 t_1}{\pi}\left(t - \frac{t_1}{\pi}\sin\frac{\pi t}{t_1}\right) && (0 < t < t_1) \\
&= \frac{A_1 t_1^2}{\pi} + \frac{2A_1 t_1 t'}{\pi} - \frac{A_2 t_2}{\pi}\left(t' - \frac{t_2}{\pi}\sin\frac{\pi t'}{t_2}\right) && (0 < t' < t_2)
\end{aligned}
\qquad (6)
$$

At $t = t_o$ it is required that $u = L$, from which condition there is obtained:

$$A_1 t_1 = \frac{\pi L}{t_o} \qquad (7)$$

The quantities $\dot{u}_{max}$, $t_o$, and $(A_1 t_1)$ are unknowns and if one of them can be specified the other two can be determined from the preceding equations. An upper bound for $\dot{u}_{max}$ can be found as follows. The instantaneous release of stress on the fault will initiate a shear wave which propagates normal to the fault plane. A point on the surface of the ground near the fault will experience essentially a motion generated by the passage of a step-function, plane shear wave. If the change in shear strain is $\gamma$ and the velocity of propagation of a shear wave is $c$, the point will be given a step-function increase in velocity:

$$\dot{u}_s = \gamma c \qquad (8)$$

Substituting this value of maximum velocity in equations (3) and (5) gives:

$$A_1 t_1 = \frac{\pi}{2}\gamma c \qquad (9)$$

$$t_o = \frac{2L}{\gamma c} \qquad (10)$$

The velocity of propagation, c, of shear waves is known to be approximately 10,000 ft per sec and, hence, if $\gamma$ is known the acceleration pulse $A_1 t_1$ can be determined. The report on the 1906 earthquake states that the measurements after the earthquake indicated that, adjacent to the fault, there was $\gamma = 0.00015$ on the ocean side and $\gamma = 0.00025$ on the continental side (2)(Vol. 1, p. 134). The different values of $\gamma$ on the two sides were attributed to the fact that the ocean side of the fault was all granite whereas on the continental side the granite was overlaid by several thousand feet of sedimentary rock. This would indicate that a value $\gamma = 0.0002$ would be reasonable. The measurements required to determine the value of $\gamma$ adjacent to a fault are rather difficult and it appears that their accuracy is questionable. Various authors have made estimates and calculations (also of doubtful accuracy) and have come up with various values of $\gamma$. Equation (10) gives the following values of duration of slip $t_o$ for various values of $\gamma$:

| $\gamma$ | $t_o$(secs.) |
|---|---|
| 0.0001 | 20 |
| 0.0002 | 10 |
| 0.0003 | 6.7 |
| 0.0004 | 5 |

It is concluded from this that $\gamma = 0.0003$ gives too short a duration and $\gamma = 0.0001$ gives too long a duration and, hence, $\gamma = 0.0002$ is taken as a reasonable estimate for the maximum shear strain. This value would not be inconsistent with measurements made after the El Centro, 1940 earthquake (14)(15).

For $\gamma = 0.0002$ and $c = 10,000$ ft/sec there is obtained for the amplitude-duration product: $A_1 t_1 = 3.1$ ft/sec. Such a pulse would have an area equal to 2.0 ft/sec and would correspond to $A_1 = 50\%g$, $t_1 = 0.2$ secs; or $A_1 = 40\%g$, $t_1 = 0.25$ sec; or $A_1 = 65\%g$, $t_1 = 0.15$ sec. These may be compared with the El Centro, 1940 pulses. The maximum of these had $A_1 = 33\%g$, $t_1 = 0.23$ secs, with area of 1.55 ft/sec. Since the computed pulse was for granite adjacent to the fault, and the El Centro pulse was recorded on deep alluvium 4 miles from the face of the fault, the conditions are not the same and they cannot be compared directly. However, the computed pulse lends credence to the estimate of 50%g for the maximum acceleration that was deduced from Fig. 6. The foregoing analysis makes clear why there is an upper bound for the maximum acceleration.

Intensity of Motion Immediately Adjacent to a Fault. It was reported that the intensity of ground shaking immediately adjacent to the fault, during the El Centro earthquake, was very much less than at several miles distant from the fault. Similar reports have been made about other earthquakes and it has been attributed to the way shear waves propagate from the face of the fault, the amplitude being greatest along a ray perpendicular to the fault and being least along a ray that makes a small angle with the face of the fault (cosine law). Ground motions have been observed only on alluvium or sedimentary rock and never on granite that slips against granite; this means that the shear waves must travel directly upward from the point of origin some distance before reaching the surface of the ground adjacent to the fault.

The intensity of shaking in the immediate vicinity of a fault was discussed by Louderback (16) who stated:

"The occurrence of an observable fault trace, or shearing of the ground, does not necessarily indicate high intensity of earthquake action in the past or point to such action in the future.... . The idea held by many that moving the location of a proposed structure a thousand yards or even a few miles from the outcrop of a known active, strong-earthquake-generating fault will render the structure much less liable to earthquake

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(14) Whitten, C. A., "Horizontal Earth Movements in California," Journal of Coast and Geodetic Survey, No. 2, April 1949.

(15) Whitten, C. A., "Coastal Movements in California and Nevada," Trans. Am. Geophysical Union, Vol. 37, No. 4.

(16) Louderback, G. D., "Faults and Earthquakes," Bulletin of the Seism. Soc. Am., Vol. 32, No. 4, 1942.

damage, is not borne out by theory or experience."

Observations of large earthquakes having surface faulting agree that the intensity of shaking close to the fault was not particularly severe: 1906 San Francisco (2); 2 October 1915 Nevada (17); 16 December 1954, Nevada (18); 17 August 1959, Montana (19); 1 September 1962, Iran (20). These observations all indicate that the intensity of ground shaking at El Centro (4 miles from the fault) could not have been significantly less than at points closer to the fault.

Summary. Data and analyses indicate an upper bound for the intensity of ground shaking on reasonably firm deep alluvium that is 50% greater than that at El Centro during the earthquake of 18 May 1940.

An upper bound is indicated for the maximum acceleration during the ground motion on firm, deep alluvium of 50%g.

An upper bound is indicated for the duration of the strong phase of shaking during a Magnitude 8.5 earthquake of 45 seconds.

The intensity of ground shaking immediately adjacent to a fault is not especially severe but is, in general, somewhat less than at a distance of several miles from the fault.

The maximum intensity of shaking associated with a great earthquake of Magnitude 8.5 is only approximately 50% greater than for a Magnitude 7 earthquake, and there is less intense than has been sometimes supposed. The maximum intensity of ground shaking associated with a Magnitude 5 earthquake is 1/3 to 1/2 that of a Magnitude 7 earthquake and therefore is more severe than has been sometimes supposed.

The Modified Mercalli Intensity is not suitable for engineering purposes and in particular it should not be used to estimate maximum ground acceleration. The spectrum intensity is the best measure of the intensity of ground shaking and it should be used for engineering purposes.

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(17) Jones, J. C., "The Pleasant Valley, Nevada Earthquake of October 2, 1915," Bulletin Seism. Soc. Am., Vol. 5, No. 4, 1915.

(18) Tocher, Steinbrugge, et. al., "The Dixie Valley-Fairview Peak, Nevada Earthquakes of December 16, 1954," Bulletin Seism. Soc. Am., Vol. 47, No. 4, p. 335 et seq.

(19) Steinbrugge, K. and Cloud, W.K., "The Earthquake at Hebgen Lake, Montana, August 17, 1959 — Epicentral Intensities and Damage," Bulletin Seism. Soc. Am., Vol. 52, No. 2, 1962.

(20) Ambraseys, N., "The Buyin-Zara (Iran) Earthquake of September 1962, A Field Report," Bulletin Seism. Soc. Am., Vol. 53, No. 4, July 1963.

## TABLE I

## SPECTRUM INTENSITIES OF RECORDED GROUND MOTION

| No. | Location | D | h | Magnitude | Component | Spectrum Intensities<br>$SI_0$ | <br>$SI_0$ Aver. | <br>$SI_{0.2}$ Aver. | Max. Accel. (g) | Duration (sec) |
|---|---|---|---|---|---|---|---|---|---|---|
| 1a | El Centro, Cal. | 30 | 15 | 7.0 | NS | 8.94 | 8.35 | 2.71 | 0.33 | 24 |
| 1b | May 19, 1940 | | | | EW | 7.77 | | | 0.23 | |
| 2a | El Centro, Cal. | 25 | 15 | 6.5 | NS | 5.93 | 5.88 | 2.09 | 0.26 | 16 |
| 2b | Dec. 30, 1934 | | | | EW | 5.83 | | | 0.20 | |
| 3a | Olympia, Wash. | 25 | 45 | 7.1 | S80W | 6.05 | 5.82 | 2.21 | 0.31 | 23 |
| 3b | April 13, 1949 | | | | S10E | 5.59 | | | 0.18 | |
| 4a | Taft, Calif. | 40 | 15 | 7.7 | S69E | 4.84 | 4.69 | 1.91 | 0.18 | 17 |
| 4b | July 21, 1952 | | | | N21E | 4.53 | | | 0.17 | |
| 5a | Vernon, Calif. | 28 | 15 | 6.3 | S82E | 4.9 | 4.62 | 1.70 | 0.19 | 6 |
| 5b | March 10, 1933 | | | | N08E | 4.35 | | | 0.13 | |
| 6a | Santa Barbara, Cal. | 15 | 19 | 5.9 | S45E | 3.43 | 3.29 | 1.80 | 0.24 | 5 |
| 6b | June 30, 1941 | | | | N45W | 3.15 | | | 0.23 | |
| 7a | Ferndale, Calif. | 50 | 15 | 6.4 | N45E | 3.2 | 2.99 | 1.41 | 0.13 | 5 |
| 7b | October 3, 1941 | | | | S45E | 2.78 | | | 0.12 | |
| 8a | L. A. Subway Terminal | 33 | 15 | 6.3 | N51W | 3.21 | 2.94 | 0.82 | 0.065 | 6 |
| 8b | March 10, 1933 | | | | N39E | 2.67 | | | 0.04 | |
| 9a | Seattle, Wash. | 55 | 45 | 7.1 | N88W | 2.81 | 2.63 | 1.10 | 0.075 | 23 |
| 9b | April 13, 1949 | | | | S02W | 2.46 | | | 0.058 | |
| 10a | Hollister, Calif. | 10 | 15 | 5.3 | S01W | 2.44 | 2.36 | 1.27 | 0.23 | 5 |
| 10b | March 9, 1949 | | | | N89W | 2.29 | | | 0.11 | |
| 11a | Helena, Montana | 15 | 25 | 6.0 | EW | 2.49 | 1.82 | 1.02 | 0.16 | 4 |
| 11b | Oct. 31, 1935 | | | | NS | 1.16 | | | 0.14 | |

TABLE I (Continued)

| No. | Location | D | h | Magnitude | Component | Spectrum Intensities $SI_0$ | $SI_0$ Aver. | $SI_{0.2}$ Aver. | Max. Accel. (g) | Duration (sec) |
|---|---|---|---|---|---|---|---|---|---|---|
| 12a | Ferndale, Calif. | 35 | 10 | 5.5 | N45E | 1.64 | 1.45 | 0.64 | 0.082 | 5 |
| 12b | Sept. 11, 1938 | | | | S45E | 1.27 | | | 0.16 | |
| 13a | Vernon, Calif. | 17 | 15 | 5.3 | S82E | 1.65 | 1.32 | 0.69 | 0.12 | 4 |
| 13b | Oct. 2, 1933 | | | | N08E | 0.99 | | | 0.085 | |
| 14a | Ferndale, Calif. | 75 | 15 | 6.6 | N45E | 1.31 | 1.10 | 0.40 | 0.075 | - |
| 14b | Feb. 9, 1941 | | | | S45E | 0.88 | | | 0.04 | |
| 15a | L. A. Subway Terminal | 22 | 15 | 5.3 | N39E | 1.14 | 0.96 | 0.45 | 0.065 | 4 |
| 15b | Oct. 2, 1933 | | | | N51W | 0.78 | | | 0.060 | |
| 16a | Golden Gate Park | 8 | 7 | 5.3 | S80E | 1.04 | 0.84 | 0.49 | 0.13 | 3 |
| 16b | (S. F.)Mar. 22, 1957 | | | | N10E | 0.64 | | | 0.095 | |
| 17a | S. F. State Bldg. | 10 | 7 | 5.3 | S9E | 1.29 | 1.12 | 0.58 | 0.10 | - |
| 17b | March 22, 1957 | | | | S81W | 0.95 | | | 0.60 | |
| 18a | S.F. Alexander Bldg. | 11 | 7 | 5.3 | N81E | 0.50 | 0.48 | 0.28 | 0.05 | - |
| 18b | March 22, 1957 | | | | N9W | 0.45 | | | 0.05 | |
| 19a | So. Pacific Bldg. | 11 | 7 | 5.3 | N45E | 1.32 | 1.22 | 0.48 | 0.05 | - |
| 19b | (S.F. )Mar. 22,1957 | | | | N45W | 1.12 | | | 0.046 | |
| 20a | Oakland, Calif. | 17 | 7 | 5.3 | N26E | 0.46 | 0.38 | 0.2 | 0.05 | - |
| 20b | March 22,1957 | | | | S64E | 0.29 | | | 0.04 | |
| 21a | Port Hueneme, Cal. | $2^{\pm}$ | $5^{\pm}$ | 5.0 | NS | 2.55 | 2.05 | 1.27 | 0.17 | 1 |
| 21b | March 18, 1957 | | | | EW | 1.55 | | | 0.09 | |

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g = Acceleration of gravity

D = Estimated true epicentral distance in miles

h = Estimated depth of center of fault in miles

Duration is that of strong phase of ground shaking

Magnitude is that reported by the Seismological Laboratory of the Calif. Institute of Technology

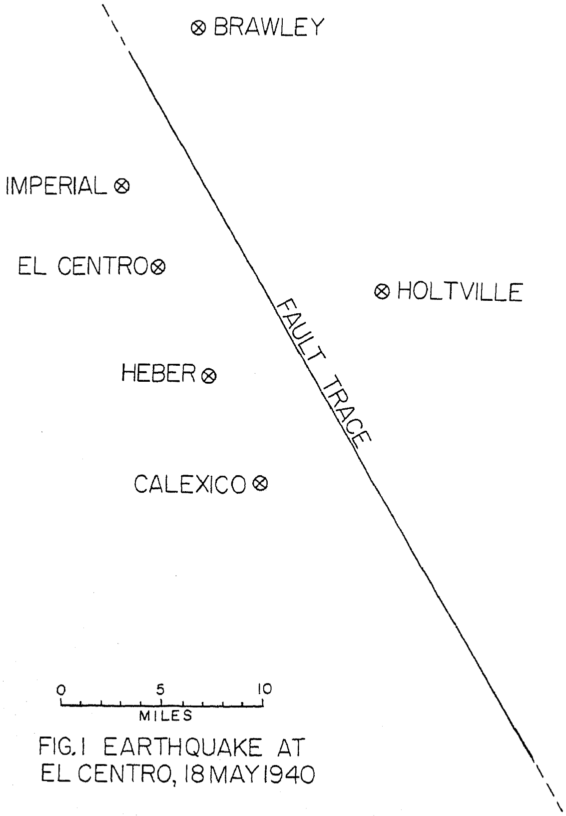

FIG. I EARTHQUAKE AT EL CENTRO, 18 MAY 1940

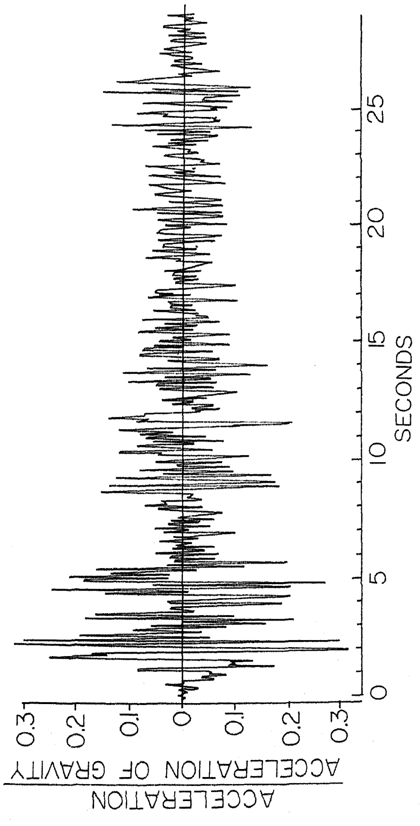

FIG. 2 ACCELEROGRAM - EL CENTRO 18 MAY 1940 COMPONENT N-S

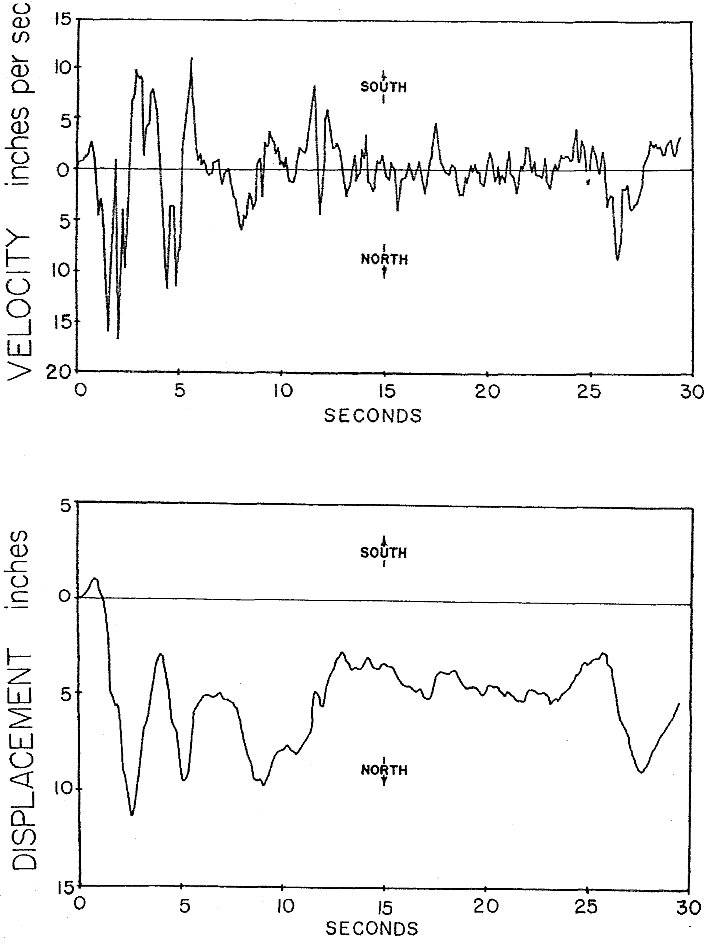

FIG. 3 EL CENTRO, 1940. N–S

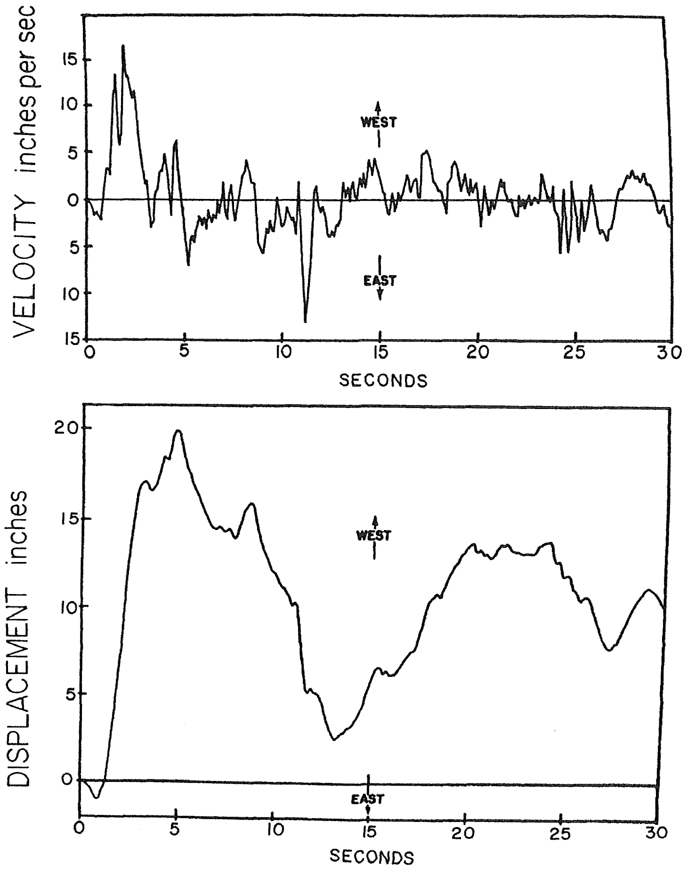

FIG. 3b EL CENTRO, 1940. E-W

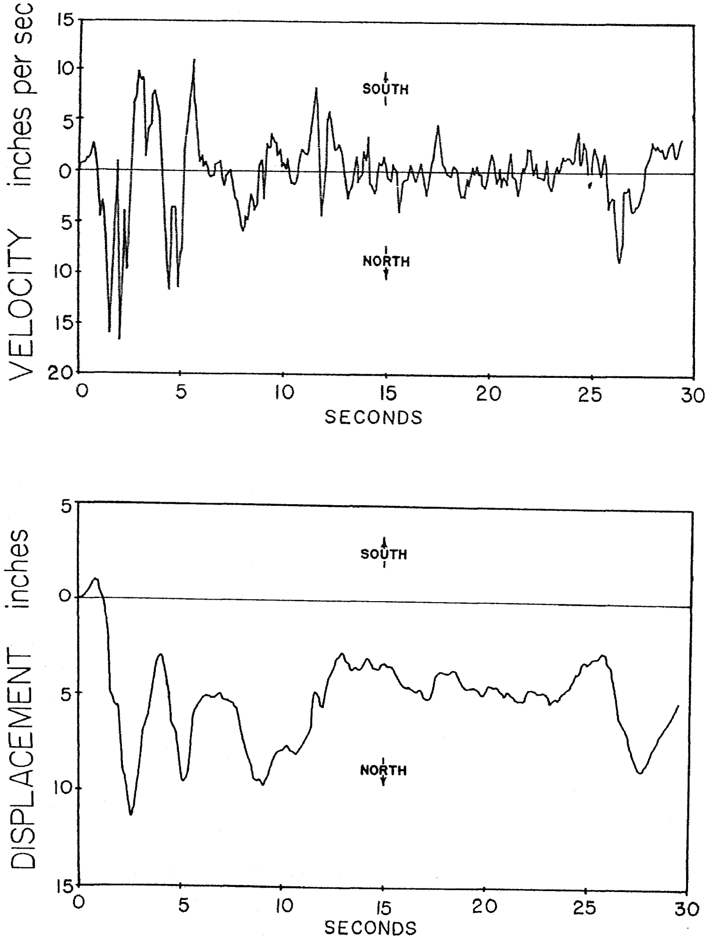

FIG. 3 EL CENTRO, 1940. N–S

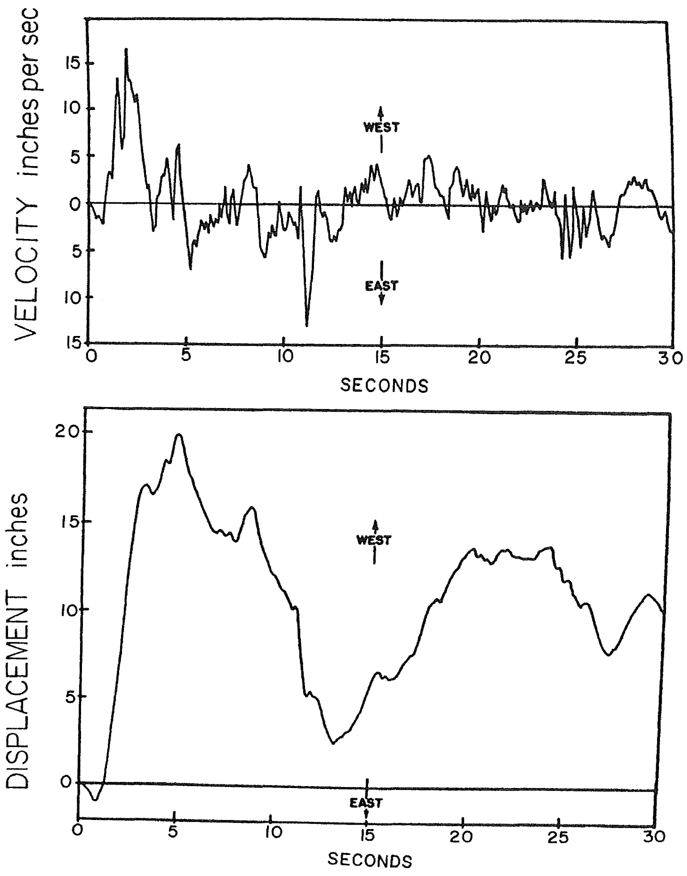

FIG. 3b EL CENTRO, 1940. E-W

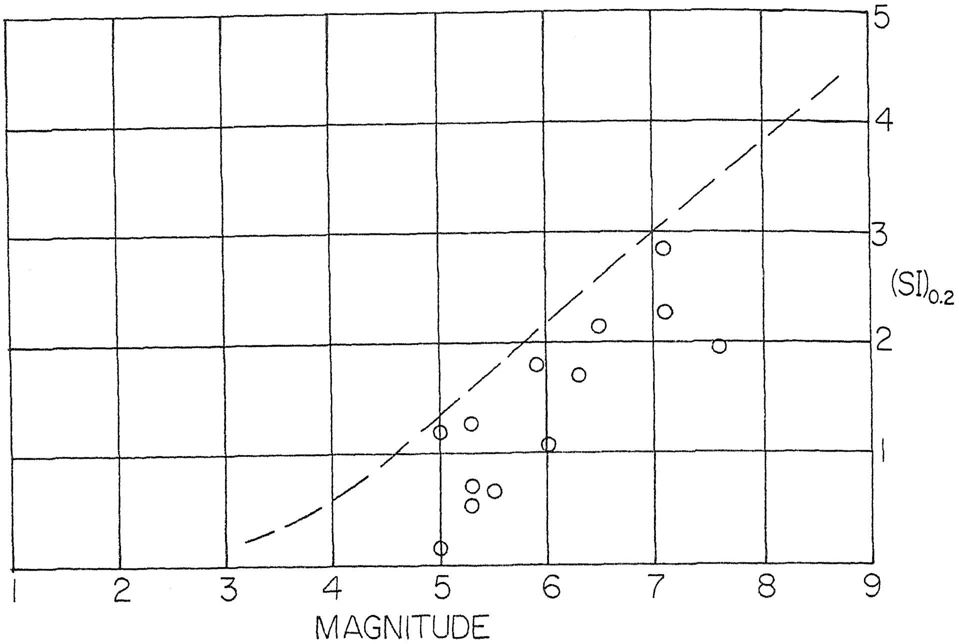

FIG. 4 SPECTRUM INTENSITY VS MAGNITUDE

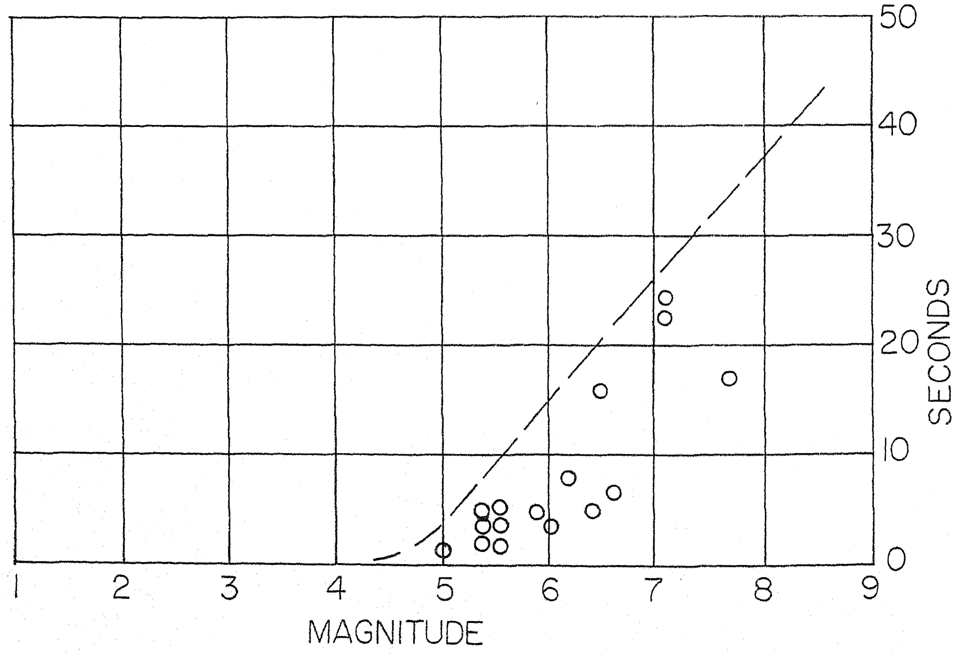

FIG. 5 DURATION OF STRONG SHAKING

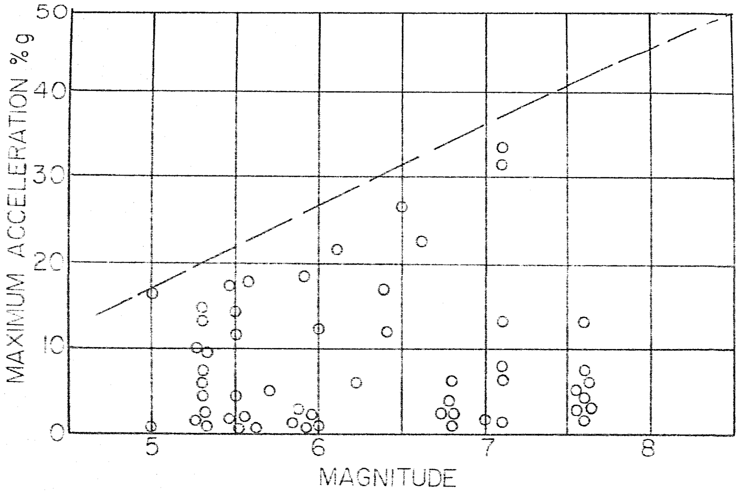

FIG. 6 MAXIMUM ACCELERATION VS MAGNITUDE

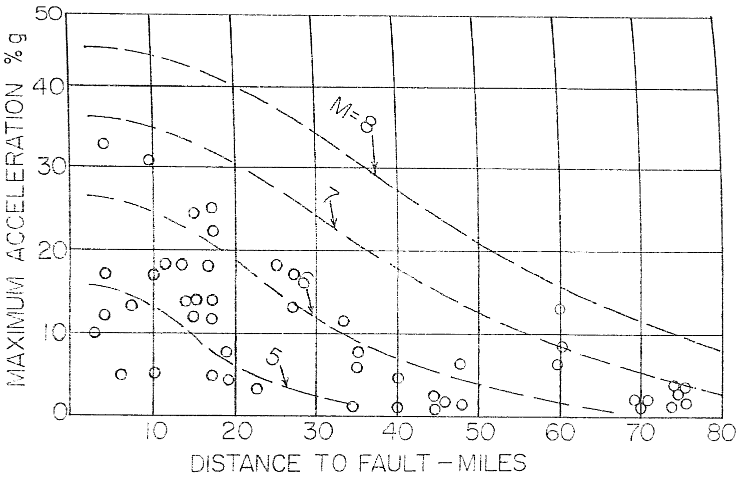

FIG. 7 MAXIMUM ACCELERATION VS DISTANCE

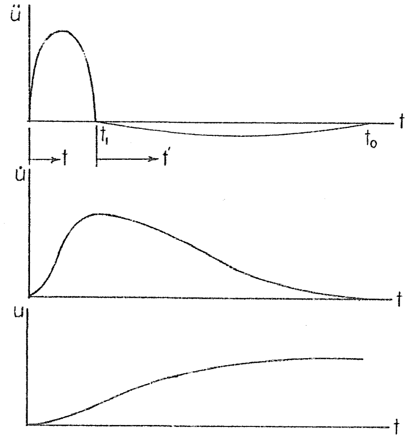

FIG. 8 MOTION NEAR IDEALIZED FAULT

# INTENSITY OF EARTHQUAKE GROUND SHAKING NEAR THE CAUSATIVE FAULT

## BY G. N. HOUSNER

QUESTION BY: R.J.P. GARDEN - NEW ZEALAND

In cases of compression failure of the rock, would the upper bound of acceleration exceed the figure of 0.5g given by the author for shear faulting?

AUTHOR'S REPLY: In California we have had no experience with the release of strain energy over large volumes of rock by compression failure, nor does it seem likely that this could occur. Special forms of localized failures of rock might lead to ground accelerations differing in frequency and amplitude characteristics from those observed during California earthquakes. It should be noted that the estimate of the maximum acceleration of 0.5g is associated with a pulse whose half wavelength is 0.2 secs. It is the area of the pulse that is significant, not the amplitude by itself.

QUESTION BY: F.F. MAUTZ - U.S.A.

The author and discussor were recently associated on a project for which the design contemplated safety against collapse for ground acceleration up to 1.0g, but the proposed project did not receive acceptance. Now it has been proposed to build a nuclear project in California with design criteria proposing 3g horizontal ground acceleration and a 2g vertical ground acceleration. Does the author consider it possible to justify this criteria, either engineering-wise or mathematically?

AUTHOR'S REPLY: A horizontal ground motion of 3g maximum acceleration and 2g vertical acceleration would correspond to ground motion ten times more intense than the strongest so far recorded. Neither theoretical analysis, instrumental measurements, nor observations of damage would indicate that ground motion of this intensity is possible.

QUESTION BY: J.A. FISCHER - U.S.A.

As I understand it, your maximum acceleration of 50%g is a special intensity occurring over a period of approximately 0.2 sec. Could you expect higher accelerations at shorter periods?

AUTHOR'S REPLY: The analysis given in the paper indicates an upper bound only for the area of the pulse, hence, if the pulse had a half wavelength less than 0.2 sec., an acceleration greater than 50%g would be indicated. The destructiveness of two pulses of equal area is essentially the same, although there would be a difference in the frequency characteristics of the spectra of the two ground motions. All of the recorded ground motions show the largest accelerations associated with pulses whose half wavelengths are in the range 0.2 to 0.25 sec. The spectra of all of the recorded strong ground motions also show clearly that the maximum energy in strong ground motions is not associated with half wavelengths less than 0.2 sec.

QUESTION BY: J.F. BORGES - PORTUGAL

I much appreciated Professor Housner's paper, and my only observation concerns the spectrum intensity. Although this is a good measure of the ground vibration, it seems for several engineering studies not to be the best. In many cases the acceleration power spectral density may be used with advantage.

AUTHOR'S REPLY: The average of power spectral density over the period range 0.1 to 2.5 sec. would give a measure of the intensity of ground shaking essentially the same as the spectrum intensity. The last conclusion in the paper would, perhaps, have been stated better by saying that a satisfactory method of measuring the intensity of ground motion, must be based upon the spectral characteristics of the ground motion, and this might equally well involve the response spectrum, the Fourier spectrum, or the power spectral density. The Modified-Mercalli system should not be used for engineering purposes.

# INTENSITY OF EARTHQUAKE GROUND SHAKING NEAR THE CAUSATIVE FAULT

## BY G.N. HOUSNER

## DISCUSSION

## BY E. ROSENBLUETH*

There are two means available for establishing the probability of occurrence of earthquakes of very high magnitudes. One is extrapolation from statistical data and the other rests on physical considerations. Ideally one should use both approaches, that is, all the information available to arrive at valid conclusions.

Certainly, the argument that earthquakes with magnitude greater than 8.5 are impossible because they have not been observed is not a valid one, and similar statements can be made about ground accelerations and the duration of strong motions. At present one can say, at least, that there is room for doubt concerning the earthquake releasing mechanism or mechanisms as well as the pertinent rock properties. Hence it would seem that considerably more weight should be laid on extrapolation from statistical data than on physical considerations, and in that light, no upper limit to earthquake magnitudes can be established or is even indicated by the data available.

The data derived by Gutenberg and Richter(1) from a half century of observations can be approximated by either of the following expressions:

$$N = 233097.3 \int_{\ln M}^{\infty} e^{-7.002\,(\ln m - 0.95)^2}\, d(\ln m) \qquad (1)$$

$$N = 35740.26 \int_{M}^{\infty} e^{-0.163\,(m - 0.33)^2}\, dm \qquad (2)$$

$$N = 41.906 \int_{M}^{\infty} e^{-1.08\,(m - 6.50)^2}\, dm \qquad (3)$$

(Fig. 1) where N(M) denotes the average yearly number of earthquakes whose magnitude exceeds M. Neither expression is adequate for earthquakes of low magnitudes; the three equations are limited respectively to $M \geq 2.0$, 4.9 and 6.0, and the goodness of their fit increases with the lower limit of M to which they are intended to apply. If we take N to measure the expected yearly number of earthquakes, extrapolation from Eq. 3 gives one earthquake

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* Director, Institute of Engineering, National University of Mexico, Mexico, D.F.

(1) Gutenberg, B. and Richter , C.F., "Seismicity of the earth (and associated phenomena)", Princeton University Press, Princeton, N.J., 1954, 2nd Edition.

per 635 years for magnitude 9.25 or greater, and this conclusion does not stand in contradiction with the fact that it is conceivable that the 1755 Lisbon earthquake had a magnitude of 9.25 nor with any other historic piece of information.

Clearly, extrapolation from statistical data will be untenable if some day upper limits of magnitude, acceleration, etc., are established on firm physical considerations. But, until then, the existence of serious doubts concerning the premises for establishing such limits favors the adoption of the statistical approach without appreciable modification.

## REPLY TO DISCUSSION BY G.W. HOUSNER.

It was not intended in the paper to imply that there could be no earthquake of magnitude greater than 8.5. The San Francisco earthquake of 1906 had a Magnitude of 8.2, and a slipped length of fault approximately 250 miles; the Alaskan earthquake of 1964 had a Magnitude of 8.4 and a slipped length of fault approximately 450 miles; the Chilean earthquake of 1960 had a Magnitude of 8.5 and a slipped length of fault of approximately 600 miles. Such data on past earthquakes are fitted well by the following expression for the natural logarithm of the length for $M > 7$: $\log L = 2M - 10.7$. This expression indicates that a Magnitude 9.25 earthquake would have a slipped length of fault of approximately 25,000 miles. This could certainly be taken as an upper bound. One of the points made in the paper is that the maximum intensity of ground shaking near the causative fault does not depend significantly upon the slipped length of fault when that is greater than perhaps 100 miles. Hence, the dotted line in Fig. 6 should properly be curved so as to become horizontal when it is extrapolated beyond $M = 7.5$ to $M = 9.25$.

The process of the straining of the earth's crust and the faulting during earthquakes is a completely deterministic process. In principle, if one knew the complete stress-strain history of the earth's crust, and knew all of the pertinent properties of the rocks, one could predict the location and magnitude of future earthquake faulting and the nature of the seismic waves and, indeed, a large-scale attack on precisely this problem is now being planned in the United States. It is only because the necessary data is not available and our computing machines are not sufficiently large that we are unable to make such predictions. In this case we must fall back on statistics to circumvent our ignorance. Statistical estimates of upper bounds require assumptions about the nature of the event, such as statistical independence, which is not true for any earthquakes, though it may be a reasonable assumption for the analysis of the seismicity of a region that is large compared to the area affected by strain release during faulting. For California, the occurrence of large earthquakes cannot be treated as statistically independent, neither in time nor in space.

Although we are forced to use statistical methods to analyse earthquake data, and derive much valuable information from them, it should be kept in mind that an earthquake is a completely deterministic event that falls within the scope of Newtonian mechanics, and that all of the significant characteristics of ground motion must have rational explanations. From the nature of the faulting process during California earthquakes it is clear that there must be an upper bound for acceleration pulses, spectral amplitudes, duration of strong shaking, and for wavelengths and energy released. For example, the strain energy released during the 1906 San Francisco earthquake was stored in a volume of rock approximately equal in length to the slipped fault (approximately 250 miles) and extending perhaps 15 miles on each side of the fault, and extending in depth approximately 15 miles. For the great Chilean earthquake of 1960 there was a similar elongated volume whose length was approximately 600 miles. For the same mechanism of slip and the same local geology there would be no reason to expect more intense ground shaking near the center of the 600-mile fault than near the center of the 250-mile fault, even though the Magnitude was 8.5 rather than 8.2. The only way to make a case for ground shaking more intense than indicated by California experience is to show that there is an energy release mechanism for which the energy density released in the rock is significantly greater than that which can be inferred from California experience.

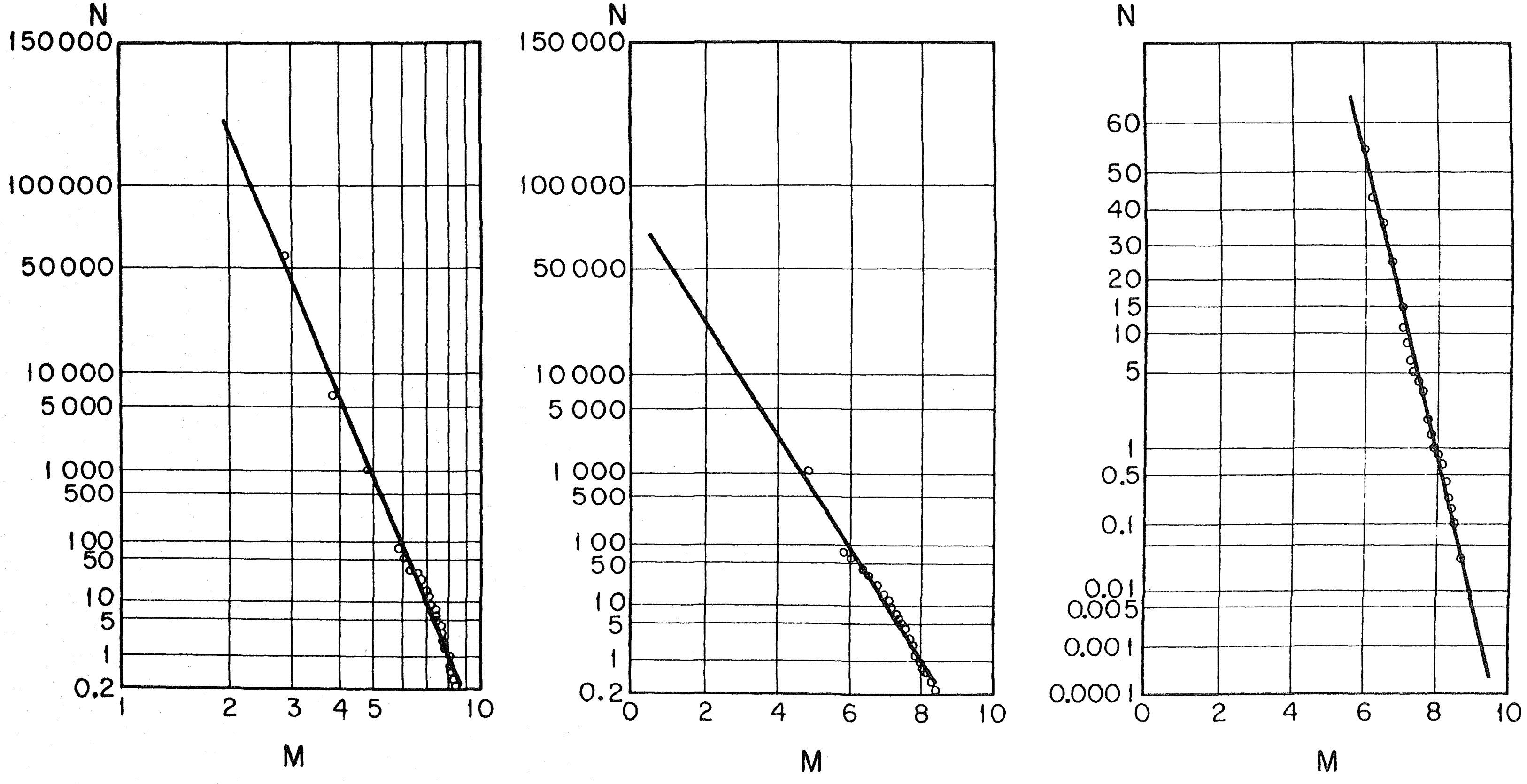

FIG. 1 YEARLY NUMBER OF EARTHQUAKES OF MAGNITUDE GRATER THAN M