TID-4500, UC-51
Geology and Mineralogy

LAWRENCE LIVERMORE LABORATORY
University of California, Livermore, California, 94550

UCRL-51193

**DESIGN BASIS EARTHQUAKES
FOR THE
LAWRENCE LIVERMORE LABORATORY SITE**

D. L. Bernreuter

F. J. Tokarz

MS. date: May 19, 1972

NOTICE

This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Atomic Energy Commission, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately owned rights.

MASTER

MASTER COPY OF THIS DOCUMENT IS DEPOSITED

fly

Contents

Abstract	1
Introduction	1
Geology, Seismicity, and Soil Conditions	2
Geology	2
Faulting and Seismicity	2
Site Soil Conditions	10
Design Basis Earthquake Location and Magnitude	11
Location	11
Magnitude	12
Design Basis Earthquake Maximum Ground Acceleration, Response Spectra, and Surface Faulting	15
Maximum Ground Acceleration	15
Response Spectra	23
Surface Faulting	25
Design Basis Earthquake Ground Motions	25
Application of Design Basis Earthquake to Structural Design	28
Conclusions	29
Acknowledgments	29
References	30

DESIGN BASIS EARTHQUAKES FOR THE LAWRENCE LIVERMORE LABORATORY SITE

Abstract

A thorough review of the geology and past seismic history of the area surrounding the Lawrence Livermore Laboratory site is given. This information is used to identify those active faults on which destructive earthquakes could occur. Earthquake magnitudes are assigned to these postulated earthquakes, and the approaches used to assign magnitudes are discussed.

Estimates of maximum possible ground

acceleration, response spectra, and duration of the strong shaking at the Laboratory site resulting from the postulated earthquakes are given. A discussion of the methods used to predict these quantities is also presented.

Using the foregoing information, design-basis earthquakes, which define the ground motion for Laboratory structural design purposes, are developed.

Introduction

This report will define the earthquake hazard to which the facilities at the Lawrence Livermore Laboratory in Livermore, California might be subjected. The location and magnitude of earthquakes that could cause damage to Laboratory facilities will be postulated and ground motions at the Laboratory site resulting from these postulated earthquakes developed. These site ground motions are described in terms of maximum ground acceleration (peak g level), acceleration response spectra, duration, and accelerograms.

Unfortunately, defining earthquake hazard for structural design calculations is not subject to the same degree of certainty or the same exercise of judgment as are methods of design analysis. For this

reason, such factors as risk evaluation, probability, economics, and good engineering judgment are essential elements in earthquake engineering design procedures. Definitive results cannot be given and considerable judgment must be used; however, this study will develop reasonable estimates of the maximum ground shaking to which the Laboratory facility could be subjected, an estimate of the possibility of such occurrences, and a design-basis earthquake (DBE) with general comments on its application to structural design. Considerable detail as to the methods used in the development of the estimates and the DBE will be given.

Although many investigators have studied the probability of occurrence of earthquakes, their studies are not yet

linked in a meaningful way to local geology and other local tectonic processes. It is therefore not possible to discuss quantitatively the probability of occurrence of

any given earthquake. However, should any probability exist, then it should be considered in the structural design process.

Geology, Seismicity, and Soil Conditions

The Laboratory is located in the south-east portion of the Livermore Valley. The geology, faulting, and seismicity of the area have been thoroughly reviewed. The review was based solely on a literature search, with the most recent review being that reported by John A. Blume and Associates, Engineers.¹ The Blume study was undertaken to establish seismic design criteria for a proposed plutonium facility at the Laboratory site. Other sources of information include Refs. 2-5.

GEOLOGY

The location and geological setting of the Laboratory site within the eastern portion of the Valley are shown in Fig. 1. The site rests on a gently sloping alluvial plain. Within a mile to the south are low hills called the Livermore Uplands. To the east and northeast are hills generally referred to as the Altamont Uplands.

Figure 2 shows two geological sections that are at right angles to each other and intersect at the Laboratory site. The locations of these sections are shown in Fig. 1. It may be observed that the site is blanked by unconsolidated alluvial deposits directly overlying the Livermore formation. These formations are of recent to Plio-Pleistocene origin and consist of an active deposit of gravels, sands, and clays. The thickness of the deposit varies along the sections. It is

estimated to be on the order of 400 ft at the site. Older Miocene deposits underlie the Livermore formation. A more detailed description of the general characteristics of the rock and soil deposits in the area is included in Fig. 1.

FAULTING AND SEISMICITY

The locations of the faults considered most pertinent to this study are shown in Fig. 3. These include a number of the major faults that transect the Livermore Valley in close proximity to the Laboratory, as well as the San Andreas, Hayward, and Calaveras faults to the west. The faults within the vicinity of the Laboratory include the Tesla, Corral Hollow, Carnegie, Greenville, Patterson Pass, and Mocho faults. The Tesla, Corral Hollow, and Carnegie faults pass through the Laboratory site and therefore are of particular importance. These faults appear to be branches of the complex Patterson Pass-Greenville-Marsh Creek-Riggs Canyon fault system.

All these faults are within the coastal portion of Central California, which is one of the most seismically active regions of the United States. Earthquake epicenters of $M \geq 4^*$ within a 60-mi radius of the Laboratory are also shown in Fig. 3.

*M is earthquake magnitude. All magnitudes in this report are based on the Richter scale.

Fig. 1. Plan view of site geology.

Geologic section B-B' (as shown in Fig. 1)

Geologic section A-A' (as shown in Fig. 1)

LEGEND

- — — — — PIEZOMETRIC SURFACE
- - - - - PIEZOMETRIC SURFACE NOT PRECISELY DEFINED
- ? - ? - CONTACT NOT PRECISELY DEFINED
- - - - - CONTACT APPROXIMATE
- // FAULT - DISPLACEMENT INDICATED BY ARROWS, DASHED WHERE INFERRRED

HORIZ. SCALE IN FEET
0 2000 4000 6000

Fig. 2. Geological sections through site.

Fig. 3. Locations of important faults and earthquake epicenters located within 60 mi of site.

Historical earthquake records indicate that several destructive earthquakes have occurred along the San Andreas fault. The largest had a magnitude of 8.3 and occurred in 1906; the most recent occurred in 1957, with a magnitude of 5.3. Along the Hayward fault destructive earthquakes occurred in 1836 and 1868. Modified Mercalli intensities for these earthquakes are estimated at VIII and X. Along the Calaveras fault it appears that in 1861 there was a major earthquake with intensity estimated between VIII and IV.

Closer to the Laboratory no earthquakes larger than 4.5 magnitude have been recorded since 1934. On April, 1943, an earthquake of magnitude 4.2 occurred in the vicinity of the Tesla fault near the intersection of East Avenue and South Vasco Road. In the same month, two seismic shocks, with magnitudes of 4.0 and 4.1, were recorded along the Mocho fault in the Livermore Valley.

San Andreas Fault

The San Andreas is the largest fault in California. It extends for more than 200 mi from San Juan Bautista in the south to Point Arena in the north. The fault is located approximately 30 mi west of the Laboratory. Maximum horizontal movement along the fault was 21 ft near Olema, some 26 mi northwest of San Francisco. For detailed discussion of the San Andreas fault zone and its branch faults (Hayward and Calaveras faults) see Ref. 6.

Hayward Fault

The Hayward fault is located approximately 15 mi west of the Laboratory. It has generally a N30W trend. To the north, the fault can be recognized in the Sonoma

Mountains near Petaluma. To the south, about 8 mi south of Irvington, the Hayward fault unites with the Sunol fault (an extension of the Calaveras fault) at Niles, where it traverses the low hills. Major earthquakes occurred on the Hayward fault in 1836 and 1868. The 1836 earthquake resulted in a 40-mi surface rupture between Mission San Jose and San Pablo, while a rupture of 20 mi between Warm Springs and San Leandro accompanied the 1868 earthquake. Right lateral movement accompanied both earthquakes with 3 ft of offset associated with the 1868 earthquake and an unknown amount associated with the 1836 earthquake. There is considerable evidence for creep along the Hayward fault.⁶

Calaveras Fault

The Calaveras fault lies along the base of Pleasanton Ridge and closely approximates the western boundary of Livermore Valley. This fault is one of the largest in California, extending to the north beyond Suisun Bay and to the south into the Gilroy-Hollister area. The Calaveras fault is primarily a right-lateral, strike-slip fault with a vertical component responsible for the upward movement on the west side. With the amount and direction of total displacement now known, its vertical component is estimated to be at least 300 ft. There is considerable evidence that creep is occurring along the Calaveras fault.⁶

Tesla Fault

The Tesla fault enters the Livermore Valley along the canyon of Arroyo Seco, continues northwesterly to North Livermore Boulevard and into the hills

to the west. Movement along the Tesla fault appears to be a left-lateral direction, and it appears to have caused the sharp jog in Collier Canyon. The fault zone can be identified along Greenville Road south of the Laboratory near the intersection of Grant Road. The inclination of the fault plane has been reported as ranging from 65° to vertical along its trace to the south of the Laboratory.

Between East Avenue and Highway 50, lateral movement along the Tesla fault has brought marine sediments into partial juxtaposition with those of the Livermore formation, the marine sediments being on the northeast side of the fault. Where marine sediments are not present, beds of the Livermore formation have been offset, creating a barrier to ground water. This barrier causes water levels to be about 30 ft lower on the northeastern side of the fault.

From Highway 50 northwest to North Livermore Boulevard, movement along the Tesla fault has brought the sediments of the Tassajara formation into contact with the alluvium. From there to the hill front, two portions of the Tassajara formation have been brought into contact, with only a thin veneer of alluvium overlying both portions. In the first section, the fault apparently serves as a barrier to ground water movement between the alluvium and the Tassajara formation. In the latter area, the fault apparently is a barrier to ground water movement between the two parts of the Tassajara formation; but ground water moves unimpeded in a southerly direction through the thin, overlying alluvium.

Based upon these water level differences, the fault can be traced with some confi-

dence across the Livermore Valley. The location of the fault was also established from a series of seismic surveys which were conducted in 1968 by the Department of Water Resources.⁴ A series of seismic lines were run along South Vasco Road from East Avenue to the Southern Pacific Railroad tracks to the north. These seismic surveys indicate that both the Tesla and Corral Hollow faults cross South Vasco Road. These points are shown in Fig. 4. A second series of seismic lines were run just east of the Greenville Road between East Avenue and Grant Road. This line also identifies the location of faulting associated with the Tesla fault in that area.

Corral Hollow Fault

The Corral Hollow fault is located southeast of the Laboratory. This fault branches at its east end from the Tesla fault and trends N75W toward the Livermore Valley, paralleling the Carnegie fault on the south. It has been observed to have a dip of 80° with the upthrow on the south at the point where it crosses Tesla Road.

Carnegie Fault

The Carnegie fault runs along the eastern edge of the Livermore Valley. This fault is a high-angle thrust fault with older rocks from the east being thrust over the younger rocks to the west. The fault is nowhere well exposed. However, its trace has been mapped from the south where it branches from the Patterson Pass fault northwestward until it disappears under the alluvium of the

Water level and stratigraphic data in

Fig. 4. Detailed map showing approximate location of faults in immediate vicinity of site.

the area from Greenville Road to Vasco Road indicate that the Carnegie fault is a barrier to the westward migration of ground water. This is indicated by a drop of some 150 ft in water levels across the fault.

It was reported¹ that field investigation uncovered some evidence of creep along the Tesla, Corral Hollow, and Carnegie faults. It was found that the concrete liner of the aqueduct cut by these faults (see Fig. 4) has zones of localized cracking. These zones coincide with the location of the projected traces of the Tesla, Corral Hollow, and Carnegie faults, as shown in Fig. 4. It must be made very clear, however, that the cracking and slumping of the aqueduct cannot at this time be positively attributed to fault activity. The cracking could, however, be considered as a possible indication of fault creep or stress adjustments since the aqueduct was constructed in the early 1960's.

Greenville Fault

Northeast of the Laboratory site is a fault which has been previously referred to as the Riggs Canyon fault by Vickery.⁵ Its extension into the Mt. Diablo quadrangle has also gone under several names (Marsh Creek fault, Mt. Diablo fault, Riggs Canyon fault). The fault trends approximately S40E. To the north, approximately 1 mi northwest of Greenville, the fault traces along a sag pond, called Fricks Lake. The southeast trace of the fault is lost at a point east of the Laboratory. The fault has a generally vertical attitude. Slickenside surfaces can be seen in the exposures. Numerous gouged and slickenside surfaces occur,

defining a zone of disturbance nearly 500 ft wide. No connection in the field is observed between the Greenville and Carnegie faults; however, the Greenville fault appears to join the Patterson Pass fault. The two have some characteristics in common, such as strong horizontal components of displacement and high angularity.

Patterson Pass Fault

The Patterson Pass fault is located east of the Greenville fault and more westerly in direction. To the northwest, the fault appears to join the Greenville fault. To the southeast, the fault is believed to be a northwesterly branch of the Tesla fault. The fault has been reported to be about 80° with a maximum vertical displacement estimated at 500 ft. The Patterson Pass fault is classified as a diagonal oblique-slip fault.

As noted above, to the northwest the fault apparently joins the Greenville fault and to the southeast it joins other faults, believed to be northwesterly diverging branches of the Tesla fault.

Mocho Fault

The Mocho fault is one of the major structural features of the region. This fault branches from the Madrone Springs fault in southern Santa Clara County, passes east of Mt. Hamilton, and runs the entire length of the Arroyo Mocho. North of the Livermore Valley, it trends westward and northwestward and apparently joins the Calaveras fault near the town of San Ramon. In the Livermore Valley, the Mocho fault passes directly beneath Livermore. The direction and magnitude of movement along the Mocho

fault in the Livermore Valley area is uncertain. However, along the hill front north of the Valley, the fault is identified by a line of depressed ridge tops. This may indicate vertical movement along this portion of the Mocho fault, with the south side of the fault being upthrown with respect to the north side.

Southeast of Marina Avenue, the Mocho fault apparently has little effect on ground water movement. Even though the alluvial materials may have been offset, the preponderance of coarse-grained materials allows ground water to move freely across the fault zone. From Marina Avenue to the mouth of Doolan Canyon, the Mocho fault appears to have some effect on ground water movement. This is indicated by water levels which are 30 to 50 ft lower on the northeastern side of the fault.

Other Faults

There are several other faults in the Livermore Valley of some importance, including the Livermore and Pleasanton faults. These faults do not influence the choice of the DBE and hence will not be discussed here.

SITE SOIL CONDITIONS

Although subsurface soil investigations have been conducted at many locations at the Laboratory, they were made to define the soil characteristics for foundation design. Such information is not sufficient to characterize the soil conditions for seismic studies. Therefore, the soils engineers of Shannon and Wilson, Inc. received a contract to provide a soil properties report that could be used for

Fig. 5. Soil properties used in site response analysis.

a seismic response study of the ground area under the Laboratory site.

Figure 5 summarizes most of the information provided by Shannon and Wilson⁷ in a form easily adapted to the computer program to be used to evaluate the ground response at the Laboratory site.

The soil conditions shown on the left side of Fig. 5 are based on a subsurface investigation carried out at the site of a proposed plutonium facility at the

Laboratory. Layers of stiff clays and dense sand were found to extend down to a depth of 90 ft, at which depth it is felt that the Livermore formation proper begins. There is no definite information concerning the depth to the ground water table at the site, but it was assumed that the water table is not shallower than 100 ft. The influences of the water table elevation on the ground response spectra are of minor importance in the present case.

Design Basis Earthquake Location and Magnitude

LOCATION

Although it is generally accepted that most earthquakes occur along active faults,⁸⁻¹¹ this is not incontrovertibly established as a law of nature, as pointed out by Richter.¹² Less than 50 earthquakes are known for which the evidence of faulting is individually clear; of these, half are incompletely known or inaccurately described. There is, however, much other evidence to support the argument that faulting is the immediate cause of earthquakes.^{8,12,13}

A fault is active if, because of its present tectonic setting, it can undergo movement from time to time in the immediate geological future. A number of characteristics have been used to identify active faults, such as historic seismicity or surface faulting, crustal strain, geologically-recent displacement inferred from topography or stratigraphy, or effects of faults on the movement of ground water or physical connection with a known active fault. Not enough is known, however, of the behavior of faults to assure

successful discrimination of all active faults by such characteristics.^{10,11} Wentworth *et al.*¹¹ concluded that the 1971 San Fernando earthquake data strengthen the conclusion that, in the absence of proof to the contrary, demonstrated late Quaternary movement should be considered evidence that a fault is probably active.

The seismic history of an area must be considered, as well as surface geological and geophysical data. Even when supplemented by subsurface geological data, this information often does not provide an adequate guide to the recent activity of the faults. Several authors^{9,10,14} point out two important facts that must be kept in mind when using the seismic history data of an area:

- (1) One cannot infer that the frequency of occurrence of small earthquakes in different areas varies with the incidence of great earthquakes so that the latter are to be expected especially in those areas where small shocks have been most frequent.

- (2) Except in areas of high seismicity, it is unlikely that the maximum intensity experienced at a given locality in so geologically short a time as two centuries represents the maximum to be expected in the future.

The preceding section on geology, seismicity, and soil conditions discussed evidence that the San Andreas, Hayward, Calaveras, and Mocho faults and the fault system under and to the east of the Laboratory site must be considered as active faults.

- (1) Earthquakes of $M > 4$ have occurred along them in the recent past.
- (2) There is considerable evidence of creep along the Hayward and Calaveras faults.
- (3) There is some evidence of creep along the Tesla, Corral Hollow and Carnegie faults.
- (4) There is a difference in ground water level on different sides of the faults.
- (5) Geological studies of the structural dynamics of the region indicate that the faults are stressed.

There is no doubt that San Andreas, Hayward, and Calaveras faults are very active, and the earthquake activity along the faults near the Laboratory site indicates that these faults have been very recently active. One should therefore expect future earthquakes to occur along these faults. For this reason these faults have been chosen as the locations for the DBEs.

MAGNITUDE

What now must be determined is the magnitude of the DBE. Seismic history is a good guide along the very active San Andreas, Hayward, and Calaveras faults; however, it is not so useful for the fault system near the Laboratory site. For this fault system other approaches must be used to estimate the magnitude of an earthquake that could occur.

Many authors have attempted to relate earthquake magnitude with ruptured fault length and fault displacement.^{9,10,15-18} Chinnery¹⁶ reviews some of the more complex relations between these parameters. However, when estimating earthquake magnitudes for a future earthquake, one does not have knowledge of such important parameters as fault displacement. Hence one must resort to the simpler approach of using fault length and recorded earthquake magnitude,^{9,15} despite the wide scatter in such data. For such correlations the type of fault does not appear to be an important parameter, and therefore all the data are considered together.

For engineering purposes, Housner's¹⁵ suggested relationship is useful, as shown in Fig. 6. It is seen from this figure that for

<u>Earthquake magnitude</u>	<u>Ruptured fault length (mi)</u>
5 - 7	2 - 25
7 - 7.5	25 - 70
>8	>190

By comparing these fault lengths with those shown in Fig. 3, it can be observed that the fault system near the Laboratory site is of sufficient length to have an earthquake of magnitude 5-7. The upper

Fig. 6. Idealized relation between length of slipped fault vs magnitude of earthquake. Information obtained from Ref. 15.

part of the fault system, north of the Laboratory site, may have already had earthquakes of magnitude greater than 5 (see Fig. 3).

From the above discussion, it is evident that the faults that run under the Laboratory site are potential locations for damaging earthquakes. The question arises—will a damaging earthquake occur along one of these faults?

The fact that earthquakes of $M > 4$ have occurred along these faults at the Laboratory site is extremely important. The reason for this is quite complex and is related to the strength of the local rocks in the fault zone, the state of stress causing rupture, and possible stress release via small earthquakes so that a larger earthquake will not occur.

It should be noted that estimates of the stress drop across a fault for even the largest earthquakes are very small compared to the strength of the earth's crust.^{16,17} Chinnery,¹⁹ for example, estimates that faulting occurs at a breaking stress on the order of 10 bar, as compared to an estimated strength of the earth's crust of 1500 bar. Most investigations agree that the stress drop is small, but some argue that the total stress level is much larger.²⁰⁻²² The role of friction is thought by some investigators²⁰⁻²² to be more important than the strength of the rocks in the genesis of an earthquake. It is safe to say at this time that it is not known what role either friction or the strength of the rocks in the fault zone enter into the determination of possible earthquake magnitude.

King and Knopoff¹⁷ have made estimates of the stress drop across a fault due to an earthquake. Figure 7, derived from their paper, shows the fractional

Fig. 7. Estimate of typical fractional stress drop vs earthquake magnitude.

stress drop (stress drop divided by initial stress level) of an earthquake as related to earthquake magnitude. It is seen from this figure that the fractional stress drop is very small for earthquake $M < 7$. Hence, the occurrence of earthquakes of small and intermediate size does not decrease the stress on a fault significantly. Since the rate of tectonic strain increase is also small (i.e., it cannot suddenly increase to a large value), the critical stress required to cause rupture is approximately constant for these shocks.¹⁷ Thus, there is little difference in the stress level required to initiate an M6 earthquake and an M4 earthquake. One can further conclude that because small earthquakes do not significantly release the stress, they do not appear to act as a safety valve to prevent the occurrence of larger earthquakes.

Clearly one of the most important factors in the genesis of a damaging earthquake is the continual buildup of stress along the fault. Thus, the possible creep along the local faults would indicate that stress is building up along the fault. As pointed out by Allen,²³ however, creep can also serve as a means of relieving the stress, so there is no way to know at the present time if the stress is being built up or decreased by fault creep. In view of the low stress difference required to initiate faulting and earthquakes, one must consider creep as definite evidence that the fault is active and potentially the source of a destructive earthquake.

One thing that must be kept in mind is that no clear relation exists between such important parameters as strong motion acceleration and earthquake magnitude.^{24,25} The magnitude is roughly defined²⁶ relative

to the maximum displacement on a standard torsion seismometer at a distance of 100 km. This is often from surface waves with 20-sec periods. The high-frequency (periods of 0.1-1 sec) waves which give rise to the important engineering effects close-in rapidly damp out and play no known role in the determination of the earthquake magnitude. Clearly there is a relation in that an earthquake of M7 will cause considerable damage whereas one of M4 will cause very little or no damage, but it is unlikely (except in very similar geologies) that two earthquakes of the same magnitude would have similar strong motion accelerograms. This is evidenced in part by the great variability of the accelerograms at different azimuths from a single underground nuclear explosion in alluvium.

The point of this discussion is that close-in the actual magnitude (in the range of $5 \leq M \leq 7$) of the earthquake is not so important from the engineering aspect since the maximum ground acceleration and response spectra will be much the same. The duration will be different. The larger the earthquake magnitude, the longer its duration. How these parameters will vary is related to the local geology and the complexity of the energy release pattern.²⁴ The local fault system is long enough that an earthquake of M7 could occur. Certainly it seems highly unlikely that the fault system near the Laboratory site would have an M7 earthquake; however, since the Laboratory site is at the epicenter, if the magnitude is in the range of $5 < M < 7$ it makes little difference except on duration. An upper limit of M6.5 is estimated as the largest earthquake that will occur

on the fault system under the Laboratory site.

As indicated above, the San Andreas, Hayward, and Calaveras faults are active enough that past seismicity should be a good guide to the future earthquake activity along these faults, particularly if it is in agreement with other

estimates arrived at by other approaches. Past seismicity would indicate that the largest earthquake to be expected on the Calaveras and Hayward faults is about $M < 7.5$ and on the San Andreas fault, about $M < 8.3$. These magnitudes are in agreement with other correlations.

Design Basis Earthquake Maximum Ground Acceleration, Response Spectra, and Surface Faulting

MAXIMUM GROUND ACCELERATION

There are three methods usually used to predict the maximum ground acceleration (peak g level) resulting from any given earthquake.^{14, 27-31} The first uses recorded surface motions from past earthquakes to extrapolate directly motions at some epicentral distance.²⁶⁻²⁸ The second also uses recorded motions of past earthquakes, but the records are modified by applying a local site amplification factor to account for differences between the site where the recording was made and the site where the estimate is desired.^{14, 30, 31} The third estimates the rock motion underlying the site of interest and then uses detailed site properties to compute the surface motion.²⁹

All three methods are applicable to studying ground motion from distant earthquakes (such as those along the San Andreas or Hayward faults). For two reasons, however, we chose to use only the first method for considering ground motion resulting from earthquakes in the local fault system and, to some extent, in the Calaveras fault.

First, the local fault system, and perhaps the Calaveras fault, are close

enough that one would expect a significant part of the wave energy to be derived from the superposition of many rays, some generated by reflections and refractions, some caused by scattering through the ground, and some emitted from different location along the fault surface.²⁴ The concept of wave superposition is in contrast to the assumptions made by Blume,¹⁴ Seed and Idriss,²⁹ and Kani;³¹ their approaches assume that ground motion is due to a vertically-propagating plane front of shear waves moving upward through uniformly stratified layers. This is a satisfactory assumption for estimating ground motions away from the epicentral region since waves at distant stations essentially propagate vertically because of the decreasing velocity of wave propagation toward the surface of the ground. However, we feel it is not applicable for close-in ground motion studies.

Trifunac²⁴ has investigated the ground motion in the epicentral region and found that the surface layer acts as a wave guide and tends to increase the amount of energy transferred to surface structures. Also, when the guided waves are propagated toward a decreasing layer thickness (as is the case at the Laboratory site), the

amplitude will increase. Although these results are only qualitative, they do indicate the complex pattern of waves that creates the important aspects of strong ground motion in the epicentral region. Hence, site properties are less important than wave activity in defining ground acceleration in the epicentral region.

Second, for uniform sources (e.g., underground nuclear explosions) experience indicates that using properly-correlated past data allows one to predict the dynamic environment from any new explosion.³³⁻³⁵ It is also shown³³ that there is much greater difference between the ground motion in the near field than the far field due to geology around the source. In the near field hard-rock cases give rise to much larger ground motions than deep dry alluvial fill. In the far field the experience is the opposite.

From the above discussion, it is clear that it is necessary to estimate the peak ground motion in the epicentral region using a proper correlation of data taken in the epicentral region of earthquakes. For earthquake centers farther away, other correlations are useful.

The major difficulty in estimating peak ground motion in epicentral regions is that only a few records exist, and proper correlation is not possible. The best solution is to consider all data together. While precision is lost, meaningful upper estimates can be reached. Gutenberg and Richter²⁶ also combine all data in arriving at their correlations for earthquake parameters; this is often done by many authors attempting to make similar correlations.

Peak g Level From Earthquakes on the Local Fault System

The method of Cloud and Perez,²⁸ which resembles that used for underground nuclear explosions,³³ was used for earthquake location on the local fault system. The peak g level at any site is plotted as a function of distance from the epicenter, using recorded surface motions from past earthquakes. No modification is made for local site properties.

Normally, one would scale for magnitude in applying this method; however, as can be seen in Fig. 8, earthquake magnitude does not appear to be significant in epicentral ground motion studies. There appear to be several possible reasons for this apparent lack of significance. First, since there is little difference in relieved stress relative to the magnitude of the earthquake, one might not expect to see too great a difference in peak acceleration near the causative fault.

Second, for close-in surface motion, the acceleration attenuates very rapidly with range. Hence, the energy release that effects the peak acceleration must be local.

Third, since it appears that the energy is released at many points along the fault for large earthquakes,^{25,36} only the local energy release is of concern. As far as the local acceleration is concerned, then, there is little difference between an M6 and an M8 earthquake.

We have modified the basic data of Cloud and Perez²⁸ to account for the Pacoima Dam record³⁶ from the 1971 San Fernando earthquake, for a new analysis of data from the 1966 Parkfield earthquake, and for the record from the Koyna earthquake³⁷ in India. Since

Fig. 8. Maximum accelerations recorded at various distances.

Pacoima Dam and Parkfield are the only true epicentral records existing, we have discussed them in some detail and have described our modification of the Cloud-Perez curve in light of these data.

Pacoima Dam Data

In applying the Pacoima Dam record (shown in Fig. 9) to the Laboratory situation, it must be noted that Pacoima Dam data were obtained on hard rock and the

earthquake was due to a thrust fault, whereas some of the local faults are strike-slip faults and the Laboratory site is overlaid by alluvial fill. One major difference is that earthquakes located on thrust faults generally produce more vertical motions than do earthquakes located on strike-slip faults. One also would expect that the waves would be more polarized for a strike-slip fault movement. Other possible differences are in the

frequency content and peak g level. The peak g level at the Pacoima Dam was at high frequency (0.05-0.10 sec). Rock tends to transmit high-frequency waves with less attenuation than alluvial fill; however, the reconstructed record from the Parkfield earthquake³⁸ on an alluvial fill shows high-frequency components,³⁸ indicating that close-in they are not filtered out.

Fig. 9. Pacoima Dam accelerogram, S74W component, San Fernando earthquake.

Some doubt is cast on the Pacoima Dam record because the accelerograph was located in the region where amplification could be expected. In addition, some cracking occurred in the mass of rock to which the accelerograph was mounted, making the records further subject to question. However, the only presently-published data are those of Trifunac and Hudson,³⁶ and they state the opinion that the Pacoima Dam record is an excellent example of a strong ground acceleration of short-to-moderately-long duration. Therefore, until other data become available, it is felt that this record should be considered for motion in epicentral regions.

Figure 8 indicates that the peak g level of 1.25 g from the Pacoima Dam is not unreasonable for a maximum peak g level

from an earthquake. However, it can be seen from the Pacoima Dam record, as shown in Fig. 9, that the peak is two short spikes. More important are the number of oscillations at 0.8 g. For earthquakes located on the local faults it is estimated that the peak g level will be 0.8-1.25 g. Certainly one could expect that 0.8 g level would create considerable energy, while the higher spikes would not greatly influence the spectra.

Parkfield Data

Several comments are in order regarding the Parkfield data recorded near the causative fault (see Fig. 10). First, the gage parallel to the fault (in the direction of the strike) failed to operate. Second, the epicenter was about 20 mi north of the recording site, which itself was near the far end of the ruptured fault where the peak displacement was the smallest. Third, the recording parallel to the fault has been partly reconstructed from a seismoscope record³⁸; however, only the first 3.8 sec could be reconstructed. The peak arrived at about 4 sec and was not reproduced. Other noteworthy features of the reconstructed record are the high frequency content of the record and the fact that the peak acceleration in the first 3.8 sec is apparently about 20-30% higher than the transverse component.

The fact that the recording station was near the far end of the rupturing fault may be important in two ways. First, the transverse component is likely to be higher relative to the parallel component than it might have been in the middle of the fault. How true this is can only be left to conjecture; however, the transverse component was quite large. It indicated

a peak dynamic displacement³⁹ of 38 cm transverse to the fault when it is estimated that the peak fault slip was in the order of 10-30 cm.⁴⁰ Second, the displacement at the far end (at the recording site) of the fault was smaller than at the other end (near the epicenter).

Fig. 10. Accelerogram recorded at station 2 near Cholame, N65E component, Parkfield earthquake.

The Parkfield instrumentation also included a string of accelerograph sites perpendicular to the fault (see Fig. 11). There are several interesting features of the motion recorded at the different stations. First, the acceleration wave quickly altered its shape from basically a single pulse to several pulses and then to an accelerogram of usual shape.⁴¹ All this occurred in several miles, indicating that the ground motion seen very close to the causative fault can be much different than that several miles away. Second, there was a station on hard rock at about the same distance from the fault as one on alluvial fill. There were only minor differences in the records and response spectra.⁴¹

These results indicate first, that there is considerable difference in motion near the fault and motion more distant, and second, that the difference in spectra on

rock and alluvial fill may not be large near the causative fault. This is generally not the case for locations farther from the causative fault.

Data point 1 in Fig. 8, which is from the station nearest to the Parkfield causative fault (station 2), was altered to account for the special features of the Parkfield records. First, it is assumed that the peak of the record parallel to the fault is 30% higher than that transverse to the fault. This seems reasonable from the reconstructed record, since the peaks are at high frequency and the method used to reconstruct the record tends to smooth them out.³⁸ In addition, one would expect the largest component of the motion to be in the strike direction at a higher frequency. Second, the peak g levels in the parallel and transverse directions were

Fig. 11. Strong motion array near Cholame which recorded Parkfield earthquake—5 accelerographs and 15 seismoscopes.

added vectorially. This appears reasonable since it can be seen from the reconstructed records that the peak transverse and peak parallel components occur at about the same time, and the transverse component does not show the high frequency content of the parallel record. This gives a peak value of around 0.87 g at station 2. The peak g level obtained at station 2 for the Parkfield earthquake appears to be in the range 0.7 to 0.9 g. Because station 2 was located near the end of the fault, and the center of energy release for the recorded pulse is not known, it is not possible to estimate what the peak g level was for a location near the middle of the fault. Wu²⁵ argues that the Parkfield earthquake was a multiple-source event, but he is unable to relate his argument to the strong motion records.

It should also be noted that relative to most correlations of displacement and earthquake magnitude, the Parkfield earthquake had initially very little displacement, but a very long fault rupture. The fact that there was initially very little fault displacement and the major amount of displacement occurred over a year⁴⁰ by creep could lead to the interpretation that the peak g level was lower than might be normally expected. There is then no way to correct the peak g level for possible attenuation and other factors to improve the correlation given in Fig. 8.

The Cloud and Perez correlation was modified in the epicentral region, as shown in Fig. 8, to account for the Pacoima Dam record and our interpolation of the Parkfield data. This raises the estimated g level in the epicentral region over past estimates; however, a recent study by Brune⁴² gives an estimate of 2 g as the

peak g level in the epicentral region of an earthquake. This is in agreement with our curve.

Peak g Level From Earthquakes on the San Andreas, Hayward, and Calaveras Faults

The San Andreas and Hayward faults are far enough away so that one can use the data in Fig. 8 or some of the other three methods of analysis discussed above. The Calaveras fault is close enough to the Laboratory site that some of the methods may not be applicable; however, all approaches were checked.

The application of the method using direct extrapolations from recorded surface motion was discussed in detail in the section on peak g levels from earthquakes on the local faults. The second method, which uses a local site amplification factor to modify the recorded motions, is based on work by Blume¹⁴ or Wiggins.³⁰

The site-factor is an empirical curve plotted against ρV_s (specific density times the shear velocity). The section on soil properties discusses the layering at the Laboratory site. It is seen that down to 90 ft, the shear velocity is about 1300 fps and below 90 ft, about 2700 fps, with a specific density of about 2. The site factor in these methods is so important that a degree of conservatism is required. Depending on how the weighing for the shear velocity is done, Blume's method gives values of acceleration at the Laboratory site in the range of 0.1-0.5 g for an M8.3 earthquake on the San Andreas fault (part of this wide range is because the estimated hypocenter plays an important role in the calculation). Wiggins'

method gives values that fall within this range.

Housner's²⁷ correlation is much easier to use and shows that from the DBE on the San Andreas fault the peak g level is about 0.35 g , from the DBE on the Calaveras fault, about 0.35-0.4 g and from the DBE on the Hayward fault, about 0.35 g . These results are consistent with the values obtained from Fig. 8; however, for the DBE on the Calaveras fault the estimated value is now about 0.5 g .

In all cases it is not clear how to handle the very large (M8.3) earthquake on the San Andreas fault, as no recordings have been made for such a large earthquake. Some data from South America⁴³ from very large earthquakes indicate that the g level can be quite large at long distances from the epicenter, as shown in points 17 and 20 on Fig. 8. It is suggested⁴³ that the actual fault was much closer (within 30-40 mi) of the recording site for point 17. This brings it into better agreement with the rest of the data, but still indicates a high g level. To account for all of these unknown factors, it is suggested that for a conservative upper limit one use 0.4 g for the DBE centered on the San Andreas fault and 0.5 g for the DBE on the Calaveras fault. It is reasonable to expect that the actual g level will be lower than this; however, so little data exists that one cannot know if a given record is abnormally low or high, particularly because local site factors are so important. Experience at Nevada Test Site indicates that the site factor is not only a function of the local geology under the site but also of the direction from which the waves arrive.

The third method, based on studies of rock motion underlying the site of interest,

was developed jointly by Idriss and Seed.^{29,44} It gave results similar to the other methods used. It uses a lumped-mass method and assumes that the ground motions developed near the surface of a soil deposit during an earthquake are attributed primarily to the upward propagation of shear waves from the underlying rock.

The method involves the determination of the type and extent of the various soil layers extending from the ground surface to the underlying rock at the site. These soil characteristics are incorporated in a lumped-mass model of the soil deposit assumed fixed at the base or rock level such as that shown in Fig. 12. The masses are interconnected by springs that resist lateral deformations. These springs represent stiffness (shear) properties between any two lumped masses. Damping in the system is assumed to be linearly viscous.

The response of the model is calculated to base motions estimated for the rock. Using the procedures described by Seed, *et al.*⁴⁵ and Housner and Jennings,⁴⁶ it is possible to describe the motion characteristics of rock underlying a site as induced by a particular earthquake, taking into account the magnitude and location of the earthquake.

Several computer runs were made to analyze the response of the soil deposit defined in Fig. 5. The calculations were made using a modified version of the computer program described by Idriss *et al.*⁴⁷ The modified version was provided by Professor H. B. Seed⁴⁸ and includes more recent thinking regarding the variation of shear modulus.⁴⁹ This modification consisted primarily of using a square root

Earthquake record	Base rock motion		Soil deposit		Surface motion			
	Maximum acceleration A_b (g)	Predominant period T_b (sec)	Fundamental period T_d (sec)	Fraction of critical damping β_d	Maximum acceleration A_s (g)	Predominant period T_s (sec)	Spectral values	
							Fraction of critical damping	Ratio S_a/A_s
Taft (1952)	0.2	0.35	1.39	0.108	0.24	0.35	0.02 0.05 0.10	4.6 3.0 2.0
	0.5	0.35	1.80	0.153	0.44	0.63/0.79	0.02 0.05 0.10	3.8 2.8 2.0
El Centro N/S (1940)	0.2	0.5	1.40	0.111	0.31	0.56	0.02 0.05 0.10	6.1 3.9 2.3
Pacoima Dam (1971) S74W	0.2	0.4	1.41	0.111	0.29	0.50	0.02 0.05 0.10	5.3 4.0 2.9

Fig. 12. Description of model used for site response analysis and some results.

variation of modulus with confining pressure instead of a cube root variation of modulus with overburden pressure.

The rock motions used in the computations were accelerograms of several earthquake records normalized to peak accelerations estimated for the underlying rock at the Laboratory site using curves suggested by Seed *et al.*⁴⁵ Table 1 shows the estimated peak values and the predominant period of the rock motions for the DBEs postulated along the San Andreas, Hayward, and Calaveras faults. The accelerograms used included the N21E component of the 1952 Taft, the NS component of the 1940 El Centro and the S74W component of the Pacoima Dam earthquake records. These were selected because their predominant period matched those estimated.

Some of the results obtained from the analysis are given in Figs. 12-14. A

comparison of these results with our DBE spectra show that maximum ground surface acceleration never exceeded those defined by the DBE spectra, and that the response spectra generated is in reasonable agreement with those established by the DBE spectra for fundamental periods less than 1.5 sec. It should be noted in Fig. 11 that although the maximum calculated accelerogram was 0.44 g (A_s), the response-spectra showed amplification as high as 6.1 (S_a/A_s).

RESPONSE SPECTRA

For reference, Fig. 15 shows the acceleration spectra from the Pacoima Dam record and from the Parkfield record normalized to a peak of 0.8 g to agree with the estimate made for the local fault DBE. The Pacoima Dam record was normalized by reducing the two spikes of over 1 g to 0.8 g. These spectra are representative

Fig. 13. Surface response spectra generated from accelerograms calculated from the site response analysis.

Table 1. Estimated rock motions underlying Laboratory site.^a

Earthquake location	Minimum epicenter distance (mi)	Magnitude	Predominant period (sec)	Maximum acceleration (g)
San Andreas fault	35	8.3	0.5	0.10-0.25
Hayward fault	17	7.0-7.5	0.3-0.35	0.12-0.35
Calaveras fault	10	7.0-7.5	0.3-0.35	0.15-0.30

^aBased on Ref. 45.

Fig. 14. Acceleration response spectra — 1952 Taft accelogram.

of what might be expected for earthquakes on the local fault system. Figure 16 shows the acceleration spectra for the Taft and El Centro earthquake normalized to 0.5 g to agree with the estimates made for a DBE along the Calaveras faults. For application it is suggested that in place of these spectra, composite spectra be used, modified to account for various factors. It is important to note that the accelerographs used in the field have a cut-off frequency of around 10-15 cps so that any spectra below periods of 0.1 sec are questionable and any very high frequency data are filtered out.

Fig. 15. Acceleration response spectra — Pacoima Dam and Parkfield components.

Fig. 16. Normalized acceleration response spectra—Taft and El Centro components.

SURFACE FAULTING

Surface faulting is an important design parameter; however, for the range of

earthquakes postulated on the faults that run through the Laboratory site, it is a very difficult parameter to estimate. As discussed in detail by Iida,⁵⁰ shallow earthquakes of magnitude $M < 7$ are not always accompanied by surface faulting, and surface faulting seldom occurs for earthquakes less than M_6 .

Unlike possible damage from the earthquake-induced ground motion, the damage from surface faulting is confined to a narrow region along the fault trace. For this reason one needs to know exactly where the faults are. It should be noted that the fault traces shown in Fig. 4 are only projections based on the two locations established by the seismic survey. In the near future a contract will be given to John A. Blume and Associates to locate the exact position of the faults and to establish by coring if surface faulting has occurred in the geological past. It is also hoped that their investigations will indicate the last time significant movement occurred along the faults near the Laboratory site. Their report should answer most of the questions relative to possible surface faulting.

Design Basis Earthquake Ground Motions

This section defines the maximum possible earthquake ground motion for the Laboratory site that should be considered in structural design. Such ground motions are considered to be induced by the DBE. The application of the DBE requires consideration of earthquake hazard, methods of analysis, factors of safety, and economics.

There are several ways to present the predicted DBE motions. The presentation of the data must accommodate the different methods of analysis used. The simplest way is to present the maximum horizontal ground accelerations or seismic factor. This seismic factor, when multiplied by the total imposed vertical loads, will indicate a lateral load for which the structure

need be designed. This method is applicable only to rigid structures that will move with the ground during the earthquake.

The predicted DBE motions can also be presented in the form of response spectra which indicate the estimated response of the structure subjected to the earthquake ground motions. The spectra represent the maximum amplitude of the motion over a range of frequencies corresponding to the natural frequencies of the structures or their various elements of interest, for various degrees of assumed damping. By using response spectra techniques, these maximum values can be used to arrive at design loads. This approach is applicable to both rigid and flexible structures since it considers possible dynamic amplification of the ground acceleration, depending on the fundamental frequency of the structure.

A more precise analysis procedure consists of determining the response of the structure to earthquake loading by subjecting a mathematical model of the structure to a digitized earthquake accelerogram. In this case, the predicted ground motion would consist of a suitable earthquake accelerogram to be used as input into the analysis, together with appropriate normalizing or scaling factors. This earthquake accelerogram should be based on a strong motion record of an earthquake which contains a similar time-history as the predicted ground motion for the structure.

It is recommended that the following be considered the maximum ground accelerations for the DBEs.

Fault	Maximum acceleration (g)	Duration of strong motions (sec)
Local fault system	0.8	2-14
Calaveras	0.5	24-30
Hayward	0.4	24-30
San Andreas	0.4	30-40

For the San Andreas, Hayward, and Calaveras faults the DBE accelerograms from the Taft or El Centro records are recommended. Both should be scaled upward to a maximum acceleration of 0.5 g. For the local fault system DBE acceleration should consist of the Pacoima Dam record, Fig. 9, with the two peaks over 1 g reduced to 0.8 g and the rest of the record unchanged. These accelerograms are available either on tape or punched cards. The Parkfield accelerogram is not used because it is a single pulse, and while such a pulse might cause damage, generally its duration is too short to cause catastrophic failure.⁴¹

Recommended DBE spectra are shown in Fig. 17. These spectra are the composite spectra of an envelope of the spectra generated by the Taft and El Centro accelerograms scaled to a 0.5 g maximum acceleration. It should also be noted that for the Pacoima Dam spectra the peak g level of 1.25 g hardly altered the spectra except at very high frequency.³⁶ This was reflected in the normalized spectra shown. Again this one spike in the accelerogram record should not cause damage problems except to very stiff nonductile structures.

It can be seen from the response spectra that considerable amplification of the

Fig. 17. Design basis earthquake acceleration spectra.

peak ground acceleration can occur with fundamental periods in the range of 0.2-1.0 sec. For other than very stiff

structures it is the acceleration obtained from the spectra that should be used for design.

Application of Design Basis Earthquake to Structural Design

In evaluating potential earthquake hazard in relation to structural design, such factors as safety, probability of damage, and economics must be considered. The margin of safety to be included in the design as a function of the DBE depends on the nature and importance of the structure and the probable results should the structure fail to survive. For example, a lower factor of safety might be permissible for a one-story residence or warehouse than for a multistory building. A much higher factor of safety would be required for a reactor facility or facility housing radioactive experiments where damage might involve the exposure of a large number of people to excessive radioactive hazard. In the former case probability of damage and economics are the more important factors; in the latter, safety is of paramount concern.

From the economic standpoint, the relative cost of designing against the earthquake ground motion should be compared to the cost of replacement or repair of the possible damage. It is usually possible to incorporate resistance to a minor ground shaking into the initial design of a structure without a significant increase in cost. For more severe ground shaking, it may be more economical to repair damage caused by the anticipated earthquake ground motions than to design the structure to resist these ground motions.

On the other hand, if the ground shaking is strong enough that severe deformations and even collapse of the structure might occur, the design must be different. The potential loss of life or excessive property damage then become the major considerations.

Another fundamental problem in earthquake design is the choice of analytical techniques used to determine the loads and forces for which the structure should be designed. For many structures the minimum seismic requirements set forth in the Uniform Building Code⁵¹ may be adequate; however, for more critical structures either a linear time-dependent dynamic analysis or a more refined method which accounts for energy dissipation through inelastic deformation ductility (a parameter ignored by linear dynamic analyses) may be in order.

The ability of a structure to withstand the predicted earthquake ground motion depends on many factors. These include the maximum ground acceleration (peak g level), the number of cycles of near peak g level, and the duration of the motion. The method of analysis used for design must properly account for these factors; for this reason all these factors have been considered in postulating a DBE for the Laboratory site.

For an initial or quick assessment of a design, a static method of analysis using response spectra or a linear dynamic analysis may be used. The peak

g level is the important parameter for such analyses. However, if the design is not refined to account for inelastic deformations, excessive overdesign may result. Furthermore, because the duration and

number of cycles near peak g level are extremely important as far as catastrophic failure or excessive damage is concerned, the analysis of more critical structures should consider these parameters.

Conclusions

This study shows that several important faults transect the Laboratory site and that both geological evidence and past seismic history indicate that they must be considered active. It is difficult to gauge precisely their degree of activity; however, there are enough indications of activity that they must be considered as possible locations of damaging earthquakes.

In addition to the local faults, the major faults west of the Laboratory must also be considered as much more likely sources

of damaging earthquakes. The actual intensity of ground shaking at the Laboratory site would be lower for earthquakes located on the San Andreas, Hayward, or Calaveras faults. However, earthquakes located on these faults are important because first, the duration of maximum shaking is much longer than that of earthquakes on the local faults and second, they are more likely to occur.

Peak design values based on appropriate spectra and other design information are summarized below.

Fault system in which earthquake occurs	Magnitude of earthquake	Maximum acceleration of b_z and $(\sim g)$	Duration of strong motions (sec)	Amplification of ground acceleration—ratio of peak spectra acceleration (5% damping) to peak ground acceleration
Local	≤ 6.5	0.8	2-14	2.8
Calaveras	≤ 7.5	0.5	24-30	3.3
Hayward	≤ 7.5	0.4	24-30	3.3
San Andreas	≤ 8.3	0.4	30-40	3.3

It was noted that the location of the local faults shown in Fig. 4 was only approximate. The location of these faults and possible verification of historic sur-

face faulting is now being studied. The precise location of these faults was not important for the conclusions reached in this report.

Acknowledgments

The authors express their appreciation to V. N. Karpenko and C. M. Bacigalupi for suggesting and supporting this study. Particular appreciation is also expressed

to S. Szybalski and C. Y. King, who provided us with continuous assistance and cooperation throughout the study.

References

1. Geologic, Seismologic, and Foundation Investigation, Plutonium Laboratory, Lawrence Livermore Laboratory, J. A. Blume & Associates, Engineers, San Francisco, Calif. (1971).
2. A. L. Huey, Geology of the Tesla Quadrangle California, Bull. 140, California Division of Mines and Geology (1948).
3. Livermore and Sunol Valleys—Evaluation of Ground Water Resources Bull. 112-2, App. A (Geology), California Department of Water Resources (1966).
4. Livermore and Sunol Valleys—Evaluation of Ground Water Resources Through 1968, unpublished memorandum, California Department of Water Resources (1970).
5. F. P. Vickery, The Structural Dynamics of the Livermore Region, Ph.D. Thesis, Stanford University, Stanford, Calif. (1925).
6. W. R. Dickinson and A. Grantz, Proceedings of Conference on Geological Problems of the San Andreas Fault System (Stanford University Publications, Stanford, Calif., 1968).
7. R. J. Dietrich, Shannon and Wilson, Inc., to S. Szybalski, Lawrence Livermore Laboratory (Nov. 24, 1971).
8. B. A. Bolt, "Causes of Earthquakes," in Earthquake Engineering, R. L. Wiegel, Ed. (Prentice-Hall Co., Englewood Cliffs, N. J., 1970), pp. 21-46.
9. M. G. Bonilla, "Surface Faulting and Related Effects," in Earthquake Engineering, R. L. Wiegel, Ed. (Prentice-Hall Co., Englewood Cliffs, N. J., 1970), pp. 47-74.
10. C. F. Richter, Bull. Seismo. Soc. Amer. 49 (2), 123-162 (1959).
11. C. M. Wentworth and R. F. Yerkes, "Geological Setting and Activity of Faults in the San Fernando Area, California" in San Fernando California Earthquake of February 9, 1971, Geology Survey Paper 733, (U.S. Geological Survey and National Oceanic and Atmospheric Administration, Washington, D. C., 1971) pp. 6-17.
12. C. F. Richter, Elementary Seismology (W. H. Freeman and Co., San Francisco and London, 1958), p. 89.
13. C. R. Allen, P. St. Amand, C. F. Richter, and S. M. Nordquist, Bull. Seismo. Soc. Amer. 55 (4), 753-797 (1965).
14. J. A. Blume, "Earthquake Ground Motion and Engineering Procedures for Important Installations near Active Faults," in Proc. World Conf. Earthquake Engineering, 3rd, New Zealand, 1965 (New Zealand National Committee on Earthquake Engineering, New Zealand, 1965), vol. IV, pp. 53-71.
15. G. W. Housner, "Engineering Estimates of Ground Shaking and Maximum Earthquake Magnitude," in Proc. World Conf. Earthquake Engineering, 4th, Santiago de Chile, 1969 (ACHISINA, Santiago de Chile, 1969), vol. I, pp. A-1-1-13.
16. M. A. Chinnery, Bull. Seismo. Soc. Amer. 59 (5), 1969-1982 (1969).
17. C. King and L. Knopoff, Bull. Seismo. Soc. Amer. 58 (1), 249-258 (1968).

18. D. Tocher, Bull. Seismo. Soc. Amer. 48 (2), 147-152 (1958).
19. M. A. Chinnery, J. Geophy. Res. 69, 2085-2089 (1964).
20. C. A. Berg, J. Geophy. Res. 73, 2217-2223 (1968).
21. J. C. Savage and M. D. Wood, Bull. Seismo. Soc. Amer. 61 (5), 1381-1388 (1971).
22. J. B. Walsh, J. Geophy. Res. 73, 761-776 (1968).
23. C. R. Allen, "The Tectonic Environment of Seismically Active and Inactive Areas along the San Andreas Fault System," in Proc. Conf. Geol. Problems, San Andreas Fault System, Stanford, 1967 (Stanford University Publications, Stanford, Calif., 1968), vol. XI, pp. 70-83.
24. M. D. Trifunac, Investigation of Strong Earthquake Ground Motion, Ph.D. thesis, California Institute of Technology, Pasadena, Calif. (1969).
25. F. T. Wu, Bull. Seismo. Soc. Amer. 58 (2), 689-711 (1968).
26. B. Gutenberg and C. F. Richter, Bull. Seismo. Soc. Amer. 46 (2), 105-146 (1956).
27. G. W. Housner, "Intensity of Earthquake Ground Shaking Near the Causative Fault," in Proc. World Conf. Earthquake Engineering, 3rd, New Zealand, 1965 (New Zealand National Committee on Earthquake Engineering, New Zealand, 1965), vol. III, pp. 94-109.
28. W. K. Cloud and V. Perez, "Strong Motion Records and Acceleration" in Proc. World Conf. Earthquake Engineering, 4th, Santiago de Chile, 1969 (ACHISINA, Santiago de Chile, 1969), vol. I, pp. A2-119-A2-132.
29. H. B. Seed and I. M. Idriss, J. Soil Mech. Found. Div., ASCE 95 (SM5), 1199-1218 (1969).
30. J. Wiggins, J. Struc. Div., ASCE 90 (ST2), 279-313 (1964).
31. K. Kani, Bull. Earthquake Res. Inst. 35, 309-326 (1957).
32. D. E. Hudson, "Strong Motion Records from the San Fernando Earthquake" in Engineering Features of the San Fernando Earthquake, P. C. Jennings, Ed., California Institute of Technology, Pasadena, Calif., Rept. EERL 71-67 (1971).
33. D. L. Bernreuter, E. C. Jackson, and A. B. Miller, "Control of the Dynamic Environment Produced by Underground Nuclear Explosives," in Proc. Symp. Eng. With Nuclear Explosives, Las Vegas, 1970 (U.S. Atomic Energy Commission, Oak Ridge, Tenn., 1970), vol. 2, pp. 979-993.
34. J. R. Murphy and J. A. Lahoud, Bull. Seismo. Soc. Amer. 59 (6), 2325-2341 (1969).
35. D. L. Bernreuter, D. M. Norris Jr., and F. J. Tokarz, "Shock Input for Earthquake Studies Using Ground Motions From Underground Nuclear Explosions" in Proc. Shock and Vibration Symp. 42nd, Key West, 1971 (Naval Research Laboratory, Washington, D. C., 1972) part 2, pp. 21-31.
36. M. D. Trifunac and D. E. Hudson, Bull. Seismo. Soc. Amer. 61 (5), 1393-1413 (1971).
37. J. Krishna, A. R. Chandrosekaran, and S. S. Saini, Bull. Seismo. Soc. Amer. 59 (4), 1719-1731 (1969).

38. M. D. Trifunac and D. E. Hudson, Bull. Seismo. Soc. Amer. 60 (3), 785-794 (1970).
39. K. Aki, J. Geophys. Res. 73, 5359-5376 (1968).
40. C. H. Scholz, M. Wyss, and S. W. Smith, J. Geophys. Res. 74 (8), 2049-2069 (1969).
41. W. K. Cloud and V. Perez, Bull. Seismo. Soc. Amer. 57 (6), 1179-1192 (1967).
42. J. N. Brune, J. Geophys. Res. 75 (26), 4997-5009 (1970).
43. W. K. Cloud and V. Perez, Bull. Seismo. Soc. Amer. 61 (3), 633-680 (1971).
44. I. M. Idriss and H. B. Seed, J. Soil Mech. and Found. Div., ASCE 94 (SM4), 1003-1031 (1968).
45. H. B. Seed, I. M. Idriss, and F. W. Kiefer, J. Soil Mech. and Found. Div., ASCE 95 (SM5), 1199-1218 (1969).
46. G. W. Housner and D. C. Jennings, J. Eng. Mech. Div., ASCE 90 (EM1), 113-150 (1964).
47. I. M. Idriss, H. Dezfulian, and H. B. Seed, Computer Programs for Evaluating the Seismic Response of Soil Deposits with Non-linear Characteristics Using Linear Procedures, University of California, Berkeley, Geotechnical Engineering, Department of Civil Engineering (1969).
48. H. B. Seed, University of California, Berkeley, Calif., private communication (February, 1972).
49. H. B. Seed and I. M. Idriss, Soil Moduli and Damping Factors for Dynamic Response, University of California, Berkeley, Rept. EERC-70-10 (1970).
50. K. Iida, J. Earth Sci. 13, 115-132 (1965).
51. International Conference of Building Officials, Uniform Building Code, 1967 edition, vol. I.

NOTICE

"This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Atomic Energy Commission, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately-owned rights."

Printed in USA. Available from the National Technical
Information Center, National Bureau of Standards,
U. S. Department of Commerce, Springfield, Virginia 22151
Price: Printed Copy \$3.00; Microfiche \$0.65.