UNITED STATES DEPARTMENT OF THE INTERIOR

GEOLOGICAL SURVEY

# Scenarios of Possible Earthquakes Affecting Major California Population Centers, with Estimates of Intensity and Ground Shaking

by

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This report is preliminary and has not been reviewed for conformity with U.S. Geological Survey editorial standards

## Preface

Following the President's trip to review the destruction caused by the eruption of Mount St. Helens on May 18, 1980, he directed that an immediate assessment be undertaken of the consequences of, and state of preparedness for, a major earthquake in California. The review was conducted by an *ad hoc* committee of the National Security Council chaired by Frank Press, the President's Science Advisor.

This report was compiled by the staff of the U.S. Geological Survey Office of Earthquake Studies for use by government agencies in estimating casualties, economic losses, and overall disaster preparedness. The basic charge to the Office of Earthquake Studies was to develop scenarios of credible earthquakes that would severely affect major California population centers, to estimate intensities for these events, and to indicate the approximate level of strong ground motion in the affected regions. This report presents estimates of ground motion based on current data and methods and is thought to be accurate. Nevertheless, the information in this report was prepared in an extremely short period of time, solely for the purposes of the National Security Council review. This report should not be taken to represent either a comprehensive statement of earthquake hazard throughout California, or a definitive statement regarding the effects of any specific earthquake.

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## INTRODUCTION

When great California earthquakes like those of 1857 and 1906 recur, the effects will be devastating. Magnitude 8+ events such as these are of staggering dimension. Events of similar size in China killed an estimated 830,000 people in 1556, primarily from the collapse of poorly built houses and cliff dwellings, and in 1976 at Tangshan, the official casualty count was 240,000. Depending upon the time of day the earthquake occurs and the number of dam failures, a repeat of the 1906 San Francisco earthquake could result in tens of thousands of deaths. Damage estimates in the Los Angeles area from a repeat of the 1857 earthquake are as high as $60 billion.

In this brief report, geologic scenarios are presented for recurrence of 1857 and 1906 magnitude* 8+ earthquakes, as well as for five other credible events; a magnitude 7.4 event on the Hayward fault in the eastern San Francisco Bay area, a magnitude 7.5 earthquake on the Newport-Inglewood fault in the western Los Angeles-Long Beach area, a magnitude 6.7 event on the Santa Monica fault bordering the northern Los Angeles basin, a magnitude 6.8 earthquake along the Cucamonga fault east of Los Angeles, and a magnitude 7.0 event on the Rose Canyon fault in the San Diego area.

In addition to the geologic scenarios of these events presented in Section I, detailed intensity maps are presented for each scenario in Section II, and data are presented in Section III for making quantitative strong-motion estimates. Strong-motion data recently recorded from the Imperial Valley earthquake (M 6.9) of October 1979 are presented for illustrative purposes. To assist other agencies in the assessment of earthquake damage, an annotated bibliography on the subject is provided in Section IV.

*In this report, surface-wave magnitudes are used unless otherwise noted.

# I. SCENARIOS OF CREDIBLE EARTHQUAKES

In this section, geologic scenarios are presented for seven postulated large earthquakes in California, and the locations of the seven associated faults are shown in figure 1. The earthquakes were selected to include some of the most damaging earthquakes that are likely to shake California's three major population centers—the Los Angeles, San Francisco, and San Diego metropolitan regions.

All the postulated earthquakes are thought to be credible events, but they are judged to have different probabilities of occurrence. (Earthquake probabilities are discussed later in this section.) Some of the earthquakes are repeat occurrences of large historical events, such as the magnitude 8+ earthquakes on the San Andreas fault in 1857 and 1906. Others are larger than any historic earthquake that has occurred on a particular fault; geologic evidence suggests that they are possible. In no case can it be rigorously demonstrated that a larger earthquake physically cannot occur on a particular fault. Thus, the postulated events are <u>not</u> the largest events that can possibly be imagined.

The number of postulated events is limited. Accordingly, there are many equally probable destructive earthquakes for which scenarios are not presented in this report. For example, the extended Los Angeles metropolitan area is traversed or bordered by many active faults other than those considered here: it is entirely possible that the next California earthquake that causes more than $100 million of damage to structures is not included in this report. This report, therefore, contains a sample rather than a complete catalog of potentially destructive California earthquakes. A brief review of damaging earthquakes that have occurred in California and the Western United States in historic time concludes this section.


Figure 1

Map of California showing the locations of the seven faults discussed in this report.

## Magnitude 8+ Earthquake on the San Andreas Fault, Southern California

### Characteristics of earthquake to be expected

Repetition of a great earthquake (M 8+) similar to that of 1857 would be accompanied by horizontal slip of as much as 10 m along a 320 km-length of the San Andreas fault from near Cholame (35.8$^{\circ}$N.Lat) in central California to near San Bernadino (34.3$^{\circ}$N.Lat) in southern California. As in 1857, modified Mercalli intensities of IX near the fault and VI to VIII in the broad Los Angeles metropolitan area can be expected. Accompanying maps (fig. 4) show the distribution of expected shaking intensities.

The earthquake shaking can be expected to cause differential settlement of local areas in the San Joaquin Valley; thousands of rock falls and landslides in the Transverse Ranges; many landslides in the Los Angeles basin, especially if the earthquake occurs during a very wet period; and local ground failure resulting from liquefaction. Warping and tilting of ground surfaces may be sufficient to affect water flow in canals and irrigation in fields.

Slip on the fault during the earthquake of 1857 was confined to a zone generally less than 100 m wide and in many places less than 10 m wide. The fracture was not continuous along the entire 320-km length but was, in segments, generally less than 9 km long. Some segments overlapped; others were separated by gaps in the surface breakage. This pattern can be expected to be repeated.

In 1857, two shocks in the magnitude range $5 \leq M \leq 6$ that occurred near the northern end of the 1857 break may have been foreshocks. They preceded the main shock by 1 to 9 hours. Many aftershocks occurred. Although many of the aftershocks may have been small, two that occurred within several days of the main January 9 event were large enough to be widely felt and recorded, and were probably in the magnitude 6 range. Worldwide seismicity records indicate that it would not be unusual for a magnitude 7 aftershock to follow a magnitude 8+ main shock.

### Recent seismicity

Current seismicity is extremely low along the segment of the San Andreas fault that broke in 1857, with the exception of considerable activity at either end of the segment, and a small swarm of activity in 1976-77 near Palmdale. No evidence of creep on this segment of the fault has been noted, and some fences more than 50 years old show no distortion where they cross the fault. The "locked" character of this part of the San Andreas fault permits strain to accumulate in preparation for another great earthquake.

At the northern end of this fault segment, a series of earthquakes of $5 \leq M \leq 6$ shook the Parkfield area in 1901, 1922, 1934, and 1966, and seismic activity continues there unabated. In crustal blocks adjacent to or near the southern end at Cajon Pass, hundreds of earthquakes have occurred within the last 20 years; one of magnitude 5 occurred in 1979. Other recent earthquakes that must have at least an indirect relation to the 1857 segment of the San Andreas fault include the Arvin-Tehachapi earthquake of 1952 (M=7.7); the San Fernando earthquake of 1971 (M=6.4); and the Imperial Valley earthquakes of 1940 (M=7.1) and 1979 (M=6.9).

### Evidence of previous great events

At least nine large fault-offset events have occurred in the past 1500 years along the southern half of the 1857 break, and presumably, they were accompanied by large earthquakes. This history is derived from fault offsets and sand boils in an ancient peat bog at Pallett Creek near Palmdale where sediments datable by radiocarbon techniques can calibrate the history. The calculated average recurrence interval of faulting at the site is 140 $\pm$ 30 years. On the northern half of the 1857 break, offset of the stream channel at Wallace Creek provides an interpreted slip rate of 3 to 4 cm/yr or an average recurrence of 250 to 330 years for slip events in the range of 10 m.

Two statistical questions can be addressed at this point: "What is the cumulative probability that an earthquake will occur by a certain date?" and "What is the annual probability of occurrence?". The results of such a statistical analysis are presented in figures 2 and 3. We see that the probability that the earthquake will have occurred by the year 2000 is about 50 percent (figure 2). As shown in figure 3 the current annual probability of occurrence is about 1 percent and increases to a little more than 2 percent by the year 2000. These probabilities are based purely on the occurrence times of past events. The numerous geophysical anomalies that have been occurring in southern California in the past few years (uplift and subsequent subsidence over a 10,000-km$^2$ area, marked increases in seismicity, and abnormal patterns of tectonic strain accumulation) lead us to estimate that the annual probability of occurrence should be raised to about 5 percent. Should the geophysical anomalies in southern California abate or intensify, this probability will be altered accordingly.

Other possible earthquakes on the southern part of the San Andreas fault

Instead of an exact duplication of the 1857 event, only the southern half or the northern half of the segment that broke in 1857 may break next, or the segment of the San Andreas fault betwen San Bernardino and the Salton Sea may break next. Almost nothing is yet known about long-term recurrence intervals for the segment of the fault between San Bernardino and the Salton Sea, but no large historic event has occurred there. A more complex pattern of fault breakage including part of the San Bernardino-Salton Sea segment and part of the 1857 segment of the San Andreas fault, plus reactivation of thrust faults along adjacent parts of the Transverse Ranges, is conceivable. Each combination would produce a major earthquake but would affect a different region.

## Magnitude 8.3 Earthquake on the San Andreas Fault, Northern California

Characteristics of earthquake to be expected

An earthquake M 8.3, similar to that in 1906, accompanied by surface faulting on the same segment of the San Andreas fault between San Juan Bautista and Cape Mendocino is postulated. As in 1906, fault slip would be expected to be horizontal on a nearly vertical fault, and the block northeast of the fault would move toward the southeast. The zone of surface faulting would vary in width from 10 to 300 m; several surface breaks would be parallel or en echelon, and in some segments, the fault would branch and then rejoin, producing the wider zones. Cumulative displacement across the fault zone would average about 4 m, but might be as much as 6 m in the central part of the 430-km-long surface break. Accompanying maps (fig. 5) show the distribution of shaking intensities that would be produced by this earthquake.

Numerous aftershocks are to be expected for many days or weeks. Little is known in detail about the 1906 aftershock sequence as a guide to what may be expected in the future. Some M 6 aftershocks are likely, and perhaps a M 7 event is possible, but aftershock activity should subside within several weeks.

Figure 2

Cumulative probability (relative to 1857) of the recurrence of a major earthquake on the southern San Andreas fault.

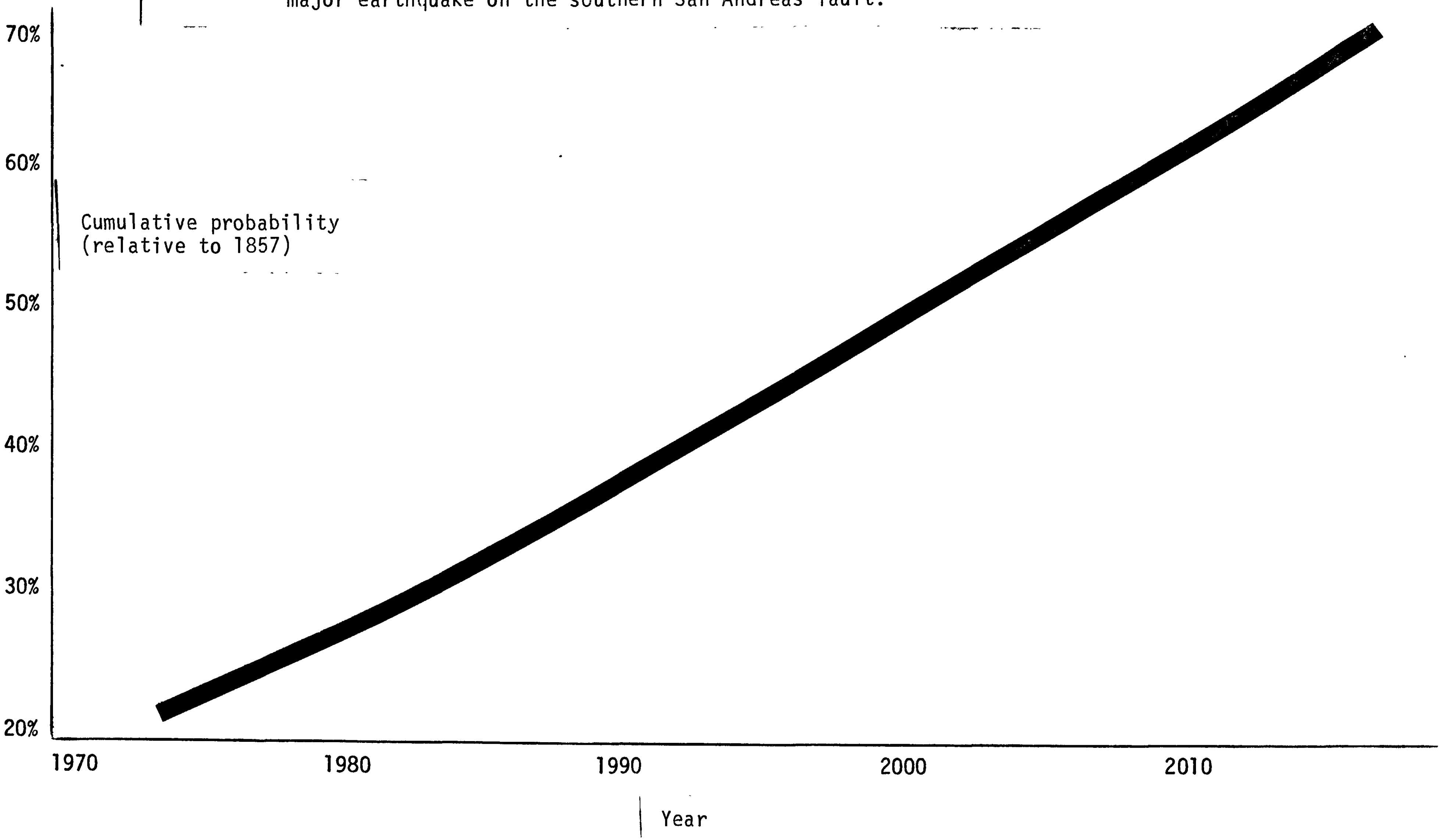
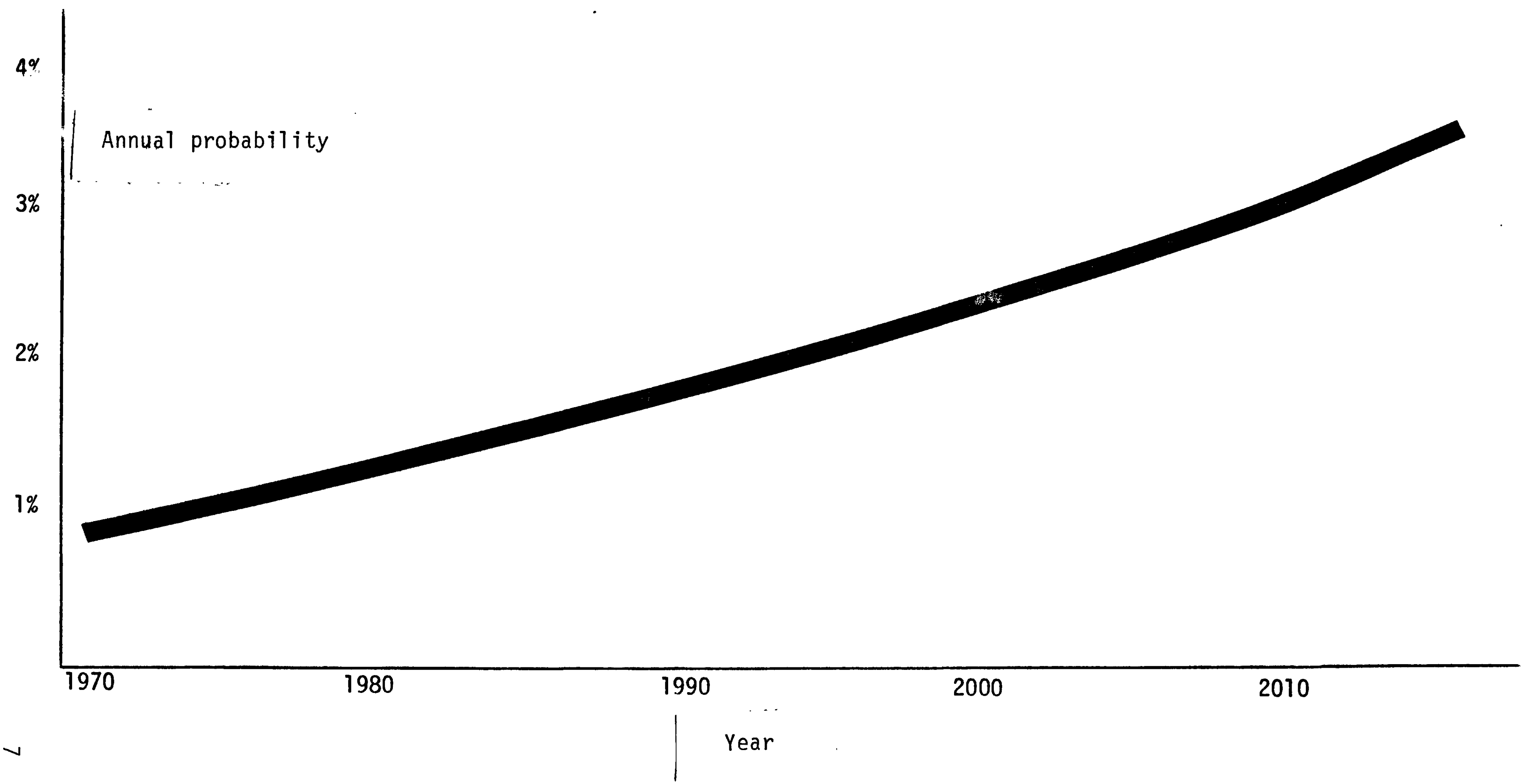


Figure 3

Annual probability of recurrence of a major earthquake on the southern San Andreas fault.



Coastal bluffs within a few kilometers of the San Andreas fault are retreating inland at rates of about a meter per year; many of these bluffs are barely stable under static load and are likely to fail during strong ground motion. Much of the Santa Cruz mountains, west of San Francisco Bay, and much of the northern Coast Ranges, north of San Francisco, are susceptible to slope failure, especially during the wet season (November to April). Earthquake-induced landslides would be widespread if, as happened in 1906, the earthquake follows a period of heavy rainfall.

Natural and reclaimed marshlands bordering San Francisco Bay and along several smaller coastal bays locally contain layers of liquefiable sand; strong shaking may liquefy these sand layers and cause lateral spreading, ground failure, and settlement of manmade structures. Problems related to liquefaction are addressed elsewhere in this report.

## Recent seismicity

This segment of the San Andreas fault is currently very quiet, compared to the creeping segment to the southeast. It is also quieter than the Hayward and Calaveras faults to the east. This fault segment is considered to be "locked" and thus in a state of strain accumulation preparatory to another great earthquake like that in 1906.

Three moderate to large earthquakes, accompanied by surface faulting, occurred on this fault segment in 1957 near Daly City.

## Evidence of previous great events

The segment that broke in 1906, like other parts of this fault, has scarps, linear undrained depressions, offset stream channels, tilted trees, and other evidence of repeated large displacements. Geologic evidence shows that the fault has moved episodically many times in the last 10,000 years and that similar fault movements along this trend have persisted for about 20 million years. Because the San Andreas fault accommodates most of the slip between the North American plate and the Pacific plate, it has produced more and larger earthquakes than other faults in the conterminous United States.

Earthquakes comparable with that in 1906 are estimated to recur on this segment of the fault about every 150 years, on the average.

# Magnitude 7.4 Earthquake on the Hayward Fault, Northern California

## Characteristics of earthquake to be expected

We postulate a M 7.4 earthquake on the Hayward fault that would be accompanied by surface faulting extending for 100 km, from San Pablo Bay to a point about 25 km south of San Jose, integrating the Hayward fault and part of the Calaveras fault. Fault slip would be horizontal on a nearly vertical fault, and the block northeast of the fault would move towards the southeast. The zone of surface faulting would vary in width from about 10 m to 100 m, and locally would widen where secondary or branch faults would depart from the main zone. Cumulative displacement across the surface-fault zone might locally be 2 to 3 m but would decrease near both ends of the zone. Accompanying maps (fig. 6) show the expected distribution of intensities that would be produced.

Aftershocks would follow the main earthquake but would diminish in number with time. For the 30-day period following the main earthquake, we estimate one or two aftershocks $M \sim 6$, and several aftershocks in the range $M \sim 5$.

Natural and reclaimed marshlands along the east side of San Francisco Bay are within a few kilometers of the Hayward fault and parts of these marshlands are underlain by liquefiable sand layers; such areas might show lateral spreading, ground failure, and settlement of manmade structures.

Hill slopes northeast of the fault, in the Berkeley Hills and the Diablo Range, are highly susceptible to failure and have extensive landslide areas. If the postulated earthquake occurs during the seasonal period of high ground-water levels, earthquake-induced landslides will contribute a significant added hazard.

Recent seismicity

A moderate level of seismicity combined with fault creep has characterized the Hayward fault in the past several decades. Most earthquakes have been less than 4 in magnitude. The magnitude of the Coyote Lake earthquake of 1979 on the Calaveras fault (possibly continuous with the Hayward fault) was 5.9. In January 1980, two earthquakes of M~5 occurred 18 km east of the Hayward fault near Livermore.

Evidence of previous great events

Historic, damaging earthquakes on the Hayward fault having estimated magnitudes of about 7 occurred in 1836 and 1868. Surface faulting of more than 30 km, from Oakland to Warm Springs, accompanied the 1868 earthquake.

Scarps, offset stream courses, and linear depressions delineate the fault and show that sudden movement during earthquakes has been commonplace during the last 10,000 years and probably for a much longer period. From the evidence, geologists and seismologists estimate that major earthquakes on this fault recur, on the average, about every 150 years.

Much of the fault is gradually creeping at rates of 5 to 10 mm/yr, and streets, curbs, and buildings record horizontal displacements of several centimeters.

## Magnitude 7.5 Earthquake on the Newport-Inglewood Fault Zone, Southern California

Characteristics of earthquake to be expected

An earthquake of M 7.5 can be expected to be produced by a 110-km-long rupture along the Newport-Inglewood fault zone. The 110-km length would integrate both onshore and offshore reaches of the fault zone. Horizontal slip of approximately 3 m can be expected to be distributed over an area as wide as 3 km. The postulated break on the fault zone would be at least twice that of the 1933 rupture. Accompanying maps (fig. 7) show the expected distribution of intensities that would be produced.

The 1933 Long Beach earthquake (M 6.3) was followed by numerous aftershocks in the several days after the main earthquake, the largest being M 5.5. Accordingly, aftershocks perhaps as large as M 6 are expected to follow the postulated event.

Permanent ground deformation, including that due to liquefaction, lateral spreading, and differential subsidence is to be expected in addition to surface faulting. In the 1933 earthquake, similar ground damage extended for 50 km along the trend of the zone and 15 km to either side. Surface effects of the 1933 Long Beach earthquake included lurching and settling due to lateral spreading, mud and sand craters over saturated ground, landslides and rock falls along nearby sea cliffs and roadcuts, differential elevation changes both positive and negative, and changes in water level in wells. Similar effects are to be expected in the next earthquake.

## Recent seismicity

At least three moderate earthquakes have been associated with the zone: 1812, San Juan Capistrano, M 6?; 1920, Inglewood, M about 5; and 1933 Long Beach, M 6.3, mainshock 5 1/2 km offshore of Newport Beach on trend with the onshore zone. Numerous small earthquakes, instrumentally well mapped, indicate dominantly right-lateral strike-slip displacement on a fault dipping steeply to the southwest. The seismic rupture during the 1933 earthquake propagated northwestward from the main shock a distance of about 43 km, of which about 29 km were onshore, passing directly beneath the Long Beach oil field and within 10 km of Los Angeles harbor.

## Evidence of past activity

No Holocene tectonic rupture is documented for faults of the zone, although most are well expressed physiographically and cut to the surface in pre-Holocene deposits.

The Newport-Inglewood zone of faults and folds is the surface expression of the westernmost onshore element of the San Andreas system south of the Transverse Ranges. At depth, it forms the eastern boundary of the Catalina Schist (Franciscan) basement that underlies the continental borderland west of the Los Angeles basin. The zone traverses the entire western part of the Los Angeles urban area, including many oil fields. The en echelon arrangement of the structural uplifts along the zone, combined with evidence of right-lateral separation along some of the faults, leads to the widely accepted hypothesis that the surface deformation is the result of right-lateral strike slip along the buried basement fault.

# Magnitude 7.0 Earthquake on the Rose Canyon Fault, San Diego Region, Southern California

## Characteristics of earthquake to be expected

An earthquake of about M 7.0 is postulated for the Rose Canyon fault zone. The event would be accompanied by a surface rupture of nearly 50 km and averaging 1 m of horizontal displacement.

The earthquake shaking can be expected to produce rockfalls and landslides (especially if the event occurs during unusually wet periods) along the sea cliff and steeper slopes of inland valleys. Liquefaction of soils locally around and within San Diego Bay and Mission Bay is likely. Submarine slumps and landslides are expected within La Jolla submarine canyon and along the steep slopes offshore of La Jolla to Point Loma. A zone of unstable sea floor 18 $km^2$ or more in area and located 15 km west-southwest of Point La Jolla could be destabilized by the postulated event. This and other rapid sliding of the sea floor sediments could produce locally generated tsunamis like the one in the San Diego region in 1968 that was associated with the more distant Borrego Mountain earthquake of M 6.5. Differential settlement of local lowland and bay areas (San Diego and Mission Bays) and possible disruption of fresh-water aquifers would be expected. Accompanying maps (fig. 8) show the distribution of expected shaking intensities.

## Recent seismicity

The general area of the Rose Canyon fault zone has been seismically active throughout historic time. Several strong earthquakes have shaken the San Diego and adjacent regions in the past. An earthquake on or near the Rose Canyon fault zone in

1862 was described as violent in San Diego. Also, seismic activity in northern Baja California, along the postulated southern extension of the Rose Canyon fault zone, occurred in 1949 (M 5.7) and 1956 ( M 6.8, and three aftershocks of M~6) and was felt in the San Diego region. Damaging earthquakes of unknown intensity and possibly associated with movement along the Rose Canyon fault zone also occurred in 1852, 1856, 1892, and 1894. More than 30 earthquakes between M 1.5 and M 5.9 were recorded in the general vicinity of the Rose Canyon fault zone between 1932 and 1976.

### Geologic evidence of previous activity

The Rose Canyon fault zone is a discontinuous, generally northwest-trending zone of en echelon faults and folds that connects with the Newport-Inglewood fault zone to the north. The fault is postulated also to extend to the south to connect with the Vallecitos-San Miguel fault zone in Baja California, giving it an overall length of at least 240 km. Both these fault zones, north and south, are presently seismically active. These connections with the known active fault zones, onland displacement of Pleistocene marine terrace sediments (about 85,000 years old) and possibly sediments of Holocene age (sediments deposited within the last 10,000 ± years), and offshore displacement of recent sediments and the sea floor (8,000 years?) all indicate that the zone is active. Folding and other disruption of recently deposited sediments within the offshore part of the fault zone, and apparently associated landslides, all detected by marine geophysical techniques, also indicate that the zone is active.

## Magnitude 6.8 Earthquake on the Cucamonga Fault Zone, San Bernardino Region, Southern California

### Characteristics of earthquake to be expected

We postulate a M 6.8 earthquake being produced by a 25-km-long break on the Cucamonga fault between San Antonio Canyon and Lytle Creek. Surface ruptures on a north- dipping fault would form scarps as much as 2 m high across the fans at the canyon mouths over a zone as wide as 2 km; maximum displacement would be about 2 m on any single rupture. Accompanying maps (fig. 9) show the distribution of expected shaking intensities.

Liquefaction or lateral spreading would be localized where fan and stream deposits are saturated. Numerous landslides, rockfalls, and debris slides along mountain-front slopes would occur.

### Recent seismicity

No major earthquakes have occurred in historic time (the past 200 years) on the fault. The largest, M 3.3, was nearby but not on the range-front fault. Fault-plane solutions indicate north-south regional compression across the fault.

### Evidence of past activity

Basement rocks are thrust over Pleistocene stream-terrace deposits. Young fault scarps in older alluvium are as much as 5 km long and 7 m high. Evidence observed in trenches indicates seven or eight displacement events of 2-m vertical separation each in the last 10,000 ± years, giving an average recurrence interval of about 1500 ± 500 years.

## Magnitude 6.7 Earthquake on the Santa Monica Fault, Los Angeles Region, Southern California

### Characteristics of earthquake to be expected

An earthquake of M 6.7 is postulated in the vicinity of Beverly Hills on the Santa Monica fault near its junction with the Newport-Inglewood fault. Fault displacement of at least 2 m left-lateral, 1.5 m vertical, and 0.5 m horizontal shortening can be expected along a 30-km-long rupture. Surface ruptures may be distributed over a zone several hundred meters wide, as is characteristic of thrust faults.

Ground failure resulting from liquefaction will be localized where ground is saturated, and rock falls and landslides will be abundant in steeper terrain, especially if the season is wet. Accompanying maps (fig. 10) show the distribution of expected shaking intensities.

This earthquake, similar to that of 1971 at San Fernando, would be typical of any of a number that could take place along the south flank of the Transverse Ranges.

### Recent seismicity

The Point Mugu earthquake of M 6 on the westward continuation of this fault zone was 40 km west of the fault break postulated here. Sparse small earthquakes have occurred along the fault segment postulated, and fault-plane solutions indicate reverse faulting of left-oblique sense.

### Evidence of past activity

West of the Newport-Inglewood zone, the Santa Monica zone forms an important basement-rock boundary, the contact between continental granitic and metamorphic rocks on the upthrown block to the north, and buried Catalina Schist (Franciscan) terrane on the south. The history of displacement on the boundary is speculative, but reverse separation of at least 4 km is measured at the basement surface. No evidence of Holocene displacement has been documented along the zone. Long-term north-south compression across the Transverse Ranges implies probable future displacement on this and related fault zones.

## Probability of Earthquake Occurrence

Geologic scenarios have been presented for seven postulated earthquakes in California: we now consider their likelihood. Assigning probabilities of occurrence to these events is a speculative exercise, involving large extrapolations and broad interpretations of a meager set of data. Nevertheless, the exercise is motivated by the needs of planners and engineers for quantitative estimates of probabilities of occurrence. The estimates presented cannot be rigorously defended on scientific grounds; however, they represent our collective professional judgment at this time.

The past is the best guide for judging future earthquake occurrence, given the present state of knowledge. Because the historic record of seismicity in California is too short to confidently determine the repeat time of large earthquakes, information on past earthquakes must be gleaned from the geologic record. Current knowledge about the recurrence of large earthquakes on specific faults is rudimentary; nonetheless, order-of-magnitude distinctions can be made of the estimated annual probabilities of occurrence for the seven postulated earthquakes.

| Fault | Earthquake Magnitude | Annual probability of occurrence |
|---|---|---|
| Southern San Andreas | 8+ | 0.05 |
| Northern San Andreas | 8.3 | 0.01 |
| Hayward | 7.4 | 0.01 |
| Newport-Inglewood | 7.5 | 0.001 |
| Cucamonga | 6.8 | 0.001 |
| Rose Canyon | 7.0 | 0.0001 |
| Santa Monica | 6.7 | 0.0001 |

Only three individual prehistoric earthquakes comparable in size and location to the postulated events have been recognized and dated: the two San Andreas shocks and the Cucamonga earthquake. For the other earthquakes postulated, estimates of probabilities are based on more general considerations, such as the long-term average rate of fault slip and the relation of these faults to others nearby and to regional rates of deformation.

Substantial uncertainties are involved in all our probability estimates, and the degree of uncertainty is larger for the less probable events. A fault that is very active leaves abundant clear evidence in the geologic and historic record of its degree of activity; the evidence left by a relatively inactive fault tends to be scanty and equivocal. Thus, less historic and geologic information is available for judging the seismic potential of a less active fault. Of the seven postulated events, the Rose Canyon and Santa Monica shocks have the most uncertain probability estimates that are most subject to change as new geologic information is obtained.

The most likely of the postulated earthquakes is the M 8+ shock on the southern San Andreas fault. The current annual probability for a M 8+ event that would rupture that segment of the fault closest to the Los Angeles-San Bernardino megalopolis is judged to be as large as 0.05. As discussed above (Section I), this estimate is based on: 1) an average recurrence interval of about 140 years (within a range of about 100-230 years) for large earthquakes on that segment of the fault as determined from detailed geologic investigations; and 2) passage of nearly 125 years since the last large earthquaked in 1857. The estimate is conditioned by recent observations of several geophysical phenomena that could be related to an impending large earthquake (regional crustal uplift and its partial collapse, an episode of relaxation of normal stress across the fault, changes in radon emanation in deep wells, and a general increase in seismicity throughout the State). The data relating to prehistoric earthquake episodes on the segment of the southern San Andreas that ruptured in 1857 are more abundant and precise than those that exist for other segments of the San Andreas fault and for other faults.

Our estimate of the current annual probability for the M 8.3 shock on the northern San Andreas fault, 0.01, is less than that for the southern San Andreas event. Earthquake recurrence data for the northern fault segment come from earthquake-disturbed trees and are relatively sparse and less reliable than the data from southern California, which are from extensive trench investigations. Estimates of average recurrence interval for M 8+ shocks are the same for the northern and southern parts of the San Andreas fault: the difference in estimated probabilities for the two fault segments largely reflects the fact that only about 75 years have elapsed since the 1906 earthquake on the northern part of the fault, whereas nearly 125 years have elapsed since the 1857 rupture on the southern part.

Unlike the postulated earthquakes for the San Andreas fault, the M 7.4 shock on the Hayward fault probably would exceed the largest historic event on that fault. Damaging earthquakes having estimated magnitudes of about 7 occurred on the Hayward fault in 1836 and 1868. Neither the fault rupture length nor the magnitude is known for either event. The average recurrence interval for the postulated M 7.4 earthquake is judged to be similar to that for the M 8.3 on the nearby northern segment of the San Andreas fault. The estimated current annual probability, 0.01, is also the same as that for the northern San Andreas earthquake.

The postulated earthquakes on the Newport-Inglewood and Cucamonga faults are thought to be an order of magnitude less probable than the events on the San Andreas and Hayward faults in northern California. The M 7.5 Newport-Inglewood shock would exceed by a full magnitude unit the largest historic earthquake on that fault. Unlike the San Andreas and Hayward faults, the Newport-Inglewood fault is not characterized by Holocene (approximately the last 10,000 years) surface fault displacement. The absence of documented Holocene fault offset and the lack of an historic earthquake comparable in magnitude with the postulated shock suggest that the recurrence interval for earthquakes of about magnitude 7.5 is substantially greater on the Newport-Inglewood fault than it is on the Hayward fault. Accordingly, the estimated annual probability of the Newport-Inglewood shock, 0.001, is correspondingly less.

The M 6.8 earthquake postulated for the Cucamonga fault is more than two magnitude units larger than the largest historic earthquake associated with the fault. The geologic record indicates that the lack of large historic earthquakes is not characteristic of the long-term behavior of the fault. Evidence from trench investigations suggests that an average recurrence interval of about 1500 $\pm$ 500 years is reasonable for M 6.8 events on the Cucamonga fault. This interval is about a factor of 10 larger than those associated with the events postulated on the San Andreas and Hayward faults. Thus, we conclude that the Cucamonga event is significantly less probable than the San Andreas and Hayward earthquakes, and that its annual probability is 0.001.

We regard the Rose Canyon and Santa Monica earthquakes as the least likely of the seven postulated shocks. Less is known about the seismic potential of the Rose Canyon fault than for the Newport-Inglewood fault, with which it appears to connect to the north. No historic earthquake as large as magnitude 6 has been linked to the Rose Canyon fault; however, many small earthquakes have occurred near it. Geologic evidence of fault displacement within the last 10,000 years is equivocal. The Rose Canyon fault zone is marked by a discontinuous set of en echelon faults and folds. We assume, but do not know, that a 50-km-long segment of the fault could rupture in a single M 7.0 event. We consider the annual probability of such an event to be an order of magnitude less likely, at 0.0001, than a comparably sized shock on the Newport-Inglewood fault.

The seismic potential of the Santa Monica fault is as poorly known as that of the Rose Canyon fault. Small shocks occur along the Santa Monica fault, but no damaging historic earthquakes have taken place along the postulated fault break. No evidence for fault displacement during the last 10,000 years has yet been found, but intensive urban development along the Santa Monica fault has obliterated surficial geologic features that might have provided such evidence. Many other reverse faults along the southern front of the Transverse Ranges—for example, the Cucamonga fault—appear to be more active today than the Santa Monica fault. The estimated annual probability, 0.0001, of a M 6.7 earthquake on the Santa Monica fault is substantially smaller than that for the Cucamonga shock.

One way to summarize the preceding discussion is to describe the likelihood that a particular event will occur in the next 20 years as high, moderate, or low.

| Earthquake | Likelihood of occurrence in next 20 years |
|---|---|
| Southern San Andreas | High |
| Northern San Andreas | Moderate |
| Hayward | Moderate |
| Newport-Inglewood "type" | Moderate-low |
| Cucamonga/Santa Monica "type" | Moderate-low |
| Rose Canyon | Very Low |

In conclusion, a note of perspective is offered in regard to the estimated probabilities of occurrence. These probabilities are for the occurrence of a single event on a particular fault. If one is interested in estimating annualized losses in a particular region, it is necessary to add the cumulative effects from all possible earthquakes. Thus, for any large urban area traversed or bordered by numerous active faults, the annual probability of a destructive earthquake will be the sum of the probabilities of all damaging shocks, of whatever magnitude, on all faults that are close enough to cause damage. For example, we estimate that the annual probability of a destructive earthquake in the Los Angeles area, is a factor of 10 or more greater than the annual probability of the postulated earthquakes on either the Newport-Inglewood or the Cucamonga fault.

## Damaging Earthquakes in California

In 1812, southern California was rocked by a series of earthquakes, which resulted in 40 deaths at the mission at San Juan Capistrano. Since 1812, the loss of lives in California earthquakes has climbed to more than 1,000, and property-damage losses are estimated to be in excess of 10 billion 1980 dollars. The 32 most damaging California earthquakes are listed in table 1.

Estimates of losses from a repeat of the 1906 earthquake suggest that loss of life in a single major earthquake in a populated part of the State could exceed the total loss to date by as much as an order of magnitude. Nearly 20 million Californians live in zones of major earthquake risk. Major secondary sources of damage associated with California earthquakes are landslides and dam failures (primarily in winter or spring) and uncontrolled fires (primarily in summer and fall).

Not included in table 1 are the losses associated with a tsunami produced by the great Alaskan earthquake of 1964. The 11 deaths at Crescent City and damage in excess of $13 million along the California coast represented a small fraction of the total losses from the earthquake: 125 dead, $310 million in damage.

Table 1 Destructive California Earthquakes, 1812-1980

| Date | Location | Lives Lost | Dollar Loss at the time of the quake |
|---|---|---|---|
| 1812 | San Juan Capistrano | 40 | -- |
| 1857 | Fort Tejon | -- | -- |
| 1865 | San Francisco | -- | 500,000 |
| 1868 | Hayward | 30 | 350,000 |
| 1872 | Owens Valley | 27 | 250,000 |
| 1892 | Vacaville | -- | 225,000 |
| 1898 | Mare Island | -- | 1,400,000 |
| 1899 | San Jacinto | 6 | -- |
| 1906 | San Francisco | 700 | 500,000,000 |
| 1915 | Imperial Valley | 6 | 900,000 |
| 1918 | San Jacinto and Hemet | -- | 200,000 |
| 1925 | Santa Barbara | 13 | 8,000,000 |
| 1926 | Santa Barbara | 1 | -- |
| 1932 | Humboldt County | 1 | -- |
| 1933 | Long Beach | 115 | 40,000,000 |
| 1940 | Imperial Valley | 9 | 6,000,000 |
| 1941 | Santa Barbara | -- | 100,000 |
| 1941 | Torrance-Gardena | -- | 1,100,000 |
| 1949 | Terminal Island | -- | 9,000,000 |
| 1951 | Terminal Island | -- | 3,000,000 |
| 1952 | Kern County | 14 | 60,000,000 |
| 1954 | Eureka-Arcata | 1 | 2,000,000 |
| 1955 | Terminal Island | -- | 3,000,000 |
| 1955 | Oakland-Walnut Creek | 1 | 1,000,000 |
| 1957 | San Francisco | -- | 1,000,000 |
| 1961 | Terminal Island | -- | 4,500,000 |
| 1969 | Santa Rosa | -- | 8,350,000 |
| 1971 | San Fernando | 65 | 504,950,000 |
| 1975 | Oroville | -- | 2,500,000 |
| 1978 | Santa Barbara | -- | 12,000,000 |
| 1979 | Imperial Valley | -- | 30,000,000 |
| 1980 | Mammoth Lakes | -- | 1,500,000 |
| | Totals | 1,029 | $1,201,825,000 |

## II. PREDICTED INTENSITY MAPS

For each earthquake scenario presented in the previous section, maps of predicted intensity have been prepared at a scale of 1:750,000. These maps are shown in figures 4-10. The mathematical details of the method are summarized at the end of this section. The model considered horizontal propagation of seismic waves through basement having a prescribed attenuation factor (k). Site conditions are considered on the basis of data taken from geologic maps that were digitized at 0.5-minute increments in terms of 10 different ground conditions. Alluvium can be considered either saturated (the "J" condition) or unsaturated (the "J-1" condition) in the analysis. Intensity values for saturated alluvium (a water table within 10 m of the surface) are one Rossi-Forel intensity unit higher than values for unsaturated alluvium. For the analysis presented here, a constant water-table condition was chosen for each earthquake—saturated for the Cucamonga earthquake and unsaturated for the others. The effect of simply digitizing geology from maps results in isolated areas of overestimated intensity where a thin alluvial cover overlies bedrock.

The Rossi-Forel (R/F) intensity scale was chosen for this analysis because an increase of one R/F intensity unit corresponds to about doubling the peak acceleration. Thus, the R/F scale better correlates with other physical measurements. As confusion may arise between the R/F scale and the modified Mercalli (MM) intensity scale, both are given below. To convert from R/F to MM, the following table may be useful.

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| R/F | 1 | 3 | 5 | 7.75 | 8.75 | 9.5 | 10.0 |
| MM | 1 | 3 | 4.5 | 7.0 | 8.0 | 9.0 | 10.0 |

The scheme used here for calculating intensities has been successfully checked against available observations for the 1906 and 1857 earthquakes, 1971 San Fernando earthquake, the 1952 Kern County earthquake, and other events.

## Mathematical Details of Model for Predicting Intensities

The model assumes a fault to be a series of equal and uniformly spaced point sources as closely spaced as desired. The formulas used are

$$a = A \left[ \frac{10^{11.8+1.5M}}{n} \right]^{1/\gamma} \left[ \sum_{i=1}^{n} (R_i + C)^{-k\gamma} \right]^{1/\gamma} \tag{1}$$

(effectively, equation (7) of Evernden et al. (1973) with $\gamma = 4$ and the coefficient of M = 0.864 rather than 0.80) and

$$I = 3(0.5 + \log a) \qquad \text{(Richter, 1958)} \tag{2}$$

where

$a$ = "acceleration"

$I$ = intensity (Rossi-Forel) = I(R/F)

$M$ = local magnitude = $M_L \cong M_S$

$n$ = number of equally spaced subevents used in the model to achieve nearly uniform release of energy along the fault break

$\varepsilon = 10^{11.8+1.5M}$ = energy (ergs) released by earthquake of magnitude M (Richter, 1958, p. 366).

$R_i$ = distance, in kilometers, from point i of n points on fault to point of observation

$C$ = pseudo-depth term so set as to give proper near-range die-off of intensities.

= 25 for earthquakes of western California.

$k$ = term controlling rate of die-off of a ($a \propto \Delta^{-k}$) and thus effectively of I

= 1.75 for western California.

$\gamma$ = log [energy arriving at point]/a or a = [energy arriving at point]$^{1/\gamma}$

=4

A = 0.779 = arbitrary leading coefficient so selected as to give correct intensity values at a uniform ground condition for a particular earthquake. Once set for the normalizing earthquake (San Francisco 1906), it cannot be changed.

It appears from empirical California data that there is a general correlation between length of break (2L) and local magnitude.

Using

$$M = (3.2667 + \log 2L)/0.711,$$

and

$$\varepsilon_D = \frac{10^{11.8 + 1.5\,M}}{2L} \quad \text{(ergs per kilometer of break)},$$

we have Table 2.

TABLE 2

MAGNITUDE (M) RELATIVE TO LENGTH OF BREAK (2L) AND ENERGY DENSITY ($\varepsilon_D$)

| M | 2L | $\log\varepsilon_D$ | M | 2L | $\log\varepsilon_D$ | M | 2L | $\log\varepsilon_D$ |
|---|---|---|---|---|---|---|---|---|
| 4 | 0.4 | 18.2 | 6 | 10 | 19.8 | 8 | 265 | 21.4 |
| 4½ | 0.9 | 18.6 | 6½ | 23 | 20.2 | 8¼ | 400 | 21.6 |
| 5 | 2 | 19.0 | 7 | 50 | 20.6 | 8½ | 600 | 21.8 |
| 5½ | 4.5 | 19.4 | 7½ | 116 | 21.0 | 9 | 1350 | 22.2 |

For long fault breaks such as produced by the San Francisco earthquake of 1906, the summation used considers only energy arriving in a twenty second time window extending from 10 seconds before to 10 seconds after the energy from the closest sub-source.

## Rossi-Forel Intensity Scale

1. Microseismic shock. Recorded by seismographs and felt by some experienced observers.

2. Extremely feeble shock. Felt by a small number of persons at rest.

3. Very feeble shock. Felt by several persons at rest; strong enough for the direction or duration to be appreciable.

4. Feeble shock. Felt by persons in motion; disturbance of movable objects, doors, windows; cracking of ceilings.

5. Shock of moderate intensity. Felt generally by everyone, disturbance of furniture, beds, etc.; ringing of some bells.

6. Fairly strong shock. General awakening of those asleep; general ringing of bells; oscillation of chandeliers; stopping of clocks; visible agitating of trees and shrubs; some startled persons leaving their dwellings.

7. Strong shock. Overthrow of movable objects; fall of plaster; ringing of church bells; general panic, without damage to buildings.

8. Very strong shock. Fall of chimneys; cracks in the walls of buildings.

9. Extremely strong shock. Partial or total destruction of some buildings.

10. Shock of extreme intensity. Great disaster; ruins, disturbance of the strata, fissures in the ground, rock falls from mountains.

## Modified Mercalli Intensity Scale

I. Not felt. Marginal and long-period effects of large earthquakes.

II. Felt by persons at rest, on upper floors, or favorably placed.

III. Felt indoors. Hanging objects swing. Vibration like passing of light trucks. Duration estimated. May not be recognized as an earthquake.

IV. Hanging objects swing. Vibration like passing of heavy trucks; or sensation of a jolt like a heavy ball striking the walls. Standing motor cars rock. Windows, dishes, doors rattle. Glasses clink. Crockery clashes. In the upper range of IV, wooden walls and frame creak.

VI. Felt by all. Many frightened and run outdoors. Persons walk unsteadily. Windows, dishes, glassware broken. Knicknacks, books, etc., off shelves. Pictures off walls. Furniture moved or overturned. Weak plaster and masonry D cracked. Small bells ring (church, school). Trees, bushes shaken.

VII. Difficult to stand. Noticed by drivers of motor cars. Hanging objects quiver. Furniture broken. Damage to masonry D, including cracks. Weak chimneys broken at roof line. Fall of plaster, loose bricks, stones, tiles, cornices. Some cracks in masonry C. Waves on ponds; water turbid with mud. Small slides and caving in along sand or gravel banks. Large bells ring. Concrete irrigation ditches damaged.

VIII. Steering of motor cars affected. Damage to masonry C; partial collapse. Some damage to masonry B; none to masonry A. Fall of stucco and some masonry walls. Twisting, fall of chimneys, factory stacks, monuments, towers, elevated tanks. Frame houses moved on foundations if not bolted down; loose panel walls thrown out. Decayed piling broken off. Branches broken from trees. Changes in flow or temperature of springs and wells. Cracks in wet ground and on steep slopes.

IX. General panic. Masonry D destroyed; masonry C heavily damaged, sometimes with complete collapse; masonry B seriously damaged. Frame structures, if not bolted, shifted off foundations. Frames racked. Serious damage to reservoirs. Underground pipes broken. Conspicuous cracks in ground. In alluviated areas, sand and mud ejected, earthquake fountains, sand craters.

X. Most masonry and frame structures destroyed with their foundations. Some well-built wooden structures and bridges destroyed. Serious damage to dams, dikes, embankments. Large landslides. Water thrown on banks of canals, rivers, lakes, etc. Sand and mud shifted horizontally on beaches and flat land. Rails bent slightly.

XI. Rails bent greatly. Underground pipelines completely out of service.

XII. Damage nearly total. Large rock masses displaced. Lines of sight and level distorted. Objects thrown into the air.

## III. QUANTITATIVE GROUND MOTIONS

All earthquake damage except that induced by tectonic movement is caused by strong earthquake ground motions, either directly or indirectly through shaking-induced ground or structural failures. Data on the nature of strong ground shaking induced by earthquakes are of two basic types—intensity data and quantitative recordings of ground movement obtained from strong-motion accelerographs.

Earthquake intensity is a noninstrumental measure of the effects of ground shaking upon natural objects, structures, and people. Because the definition of higher levels of intensity is based to a large degree upon the effects and damage to structures, intensity data from past earthquakes provide an invaluable basis for deriving statistical estimates of earthquake losses to common traditional structures during postulated earthquakes. For evaluating the earthquake behavior of individual engineered structures, however, intensity does not provide a sufficiently quantitative and precise measure of ground shaking.

In analyzing the response of individual structures to earthquakes, engineers typically characterize ground shaking in terms of peak recorded motions or of response spectra, either scaled from peak-motion parameters or calculated directly from ground-motion records. Instrumental strong-motion records have now been obtained from many earthquakes. Most of the records, however, are from M 5 and M 6 earthquakes and at distances beyond which shaking causes significant damage to structures. Thus, the exisiting instrumental data provide limited guidance in assessing the level, nature, and variability of damaging ground shaking that might be expected close to the fault in a M 7 or M 8 earthquake.

Instrumental records obtained from earthquakes smaller than M 7 during the last decade demonstrate that ground motion close to a fault that slips during an earthquake is more severe than had been generally assumed. Four earthquake sequences in California during the past year have nearly doubled the data base for M 5 and M 6 earthquakes. Accordingly, it has been necessary to revise peak ground-motion estimates as a function of distance and corresponding estimates of the procedures for designing earthquake-resistant structures.

On the basis of data collected from the recent California earthquakes, the next section presents new empirical relations for quantitative ground-motion estimates as a function of distance, a map showing estimated peak horizontal ground velocity for a repeat of the great California earthquake of April 18, 1906, and a map showing ground velocities recorded from the Imperial Valley, California, earthquake of October 15, 1979.

### Empirical Strong-motion Relations

Preliminary attenuation relationships were derived by analysis of the strong-motion data in U.S. Geological Survey Circular 795 (Boore and others, 1978) combined with data from the recent Coyote Lake and Imperial Valley earthquakes. The relationships are given by the equation:

$$\log Y = a + bM_L + f \log \sqrt{D^2 + c^2} + s + e \qquad (3)$$

$$5.0 \leq M_L \leq 7.2$$

where Y represents either peak horizontal acceleration (g) or velocity (cm/s), $M_L$ is the Richter local magnitude, and D is the shortest distance to the rupture surface (km). For acceleration

$a = -1.10$
$b = 0.38$
$c = 10.0$
$f = -1.49$
$s = 0.0$
$e = 0.0$ for 50 percent exceedance
$= 0.33$ for 84 percent exceedance

and for velocity

$a = -1.60$
$b = 0.68$
$c = 4.6$
$f = -1.19$
$s = 0.0$ for rock sites
$0.10$ for soil sites
$e = 0.0$ for 50 percent exceedance
$= 0.37$ for 84 percent exceedance

Figures 11 through 16 show the relationships graphically and figures 17 through 20 give comparisons with the data for the 1979 Imperial Valley and the 1952 Kern County earthquakes.

The relationships were derived in terms of Richter local magnitude instead of the surface-wave magnitude ($M_S$), because $M_L$ is measured on waves in the period range of engineering significance, whereas $M_S$ is measured on waves of much larger periods.

We have data for a complete range of distances for the $M_L$ 6.6 Imperial Valley earthquake of 1979. For distances less than 40 km and $M_L$ greater than 6.6, equation (3) represents an extrapolation, and the results should be treated with caution. The extrapolation is based on the assumption that the attenuation curves for higher $M_L$ have the same shape as the curve for $M_L$ 6.6. We believe this to be a reasonable assumption.

Equation (3) predicts peak ground velocities greater than 200 cm/s. No values that high have ever been observed, but we know of no physical reason why they could not occur. At soil sites in earthquakes of $M_L$ greater than 6.6, the finite strength of the soil might limit the peak acceleration to values less than given by equation (3), but determining what the limit would be would require dynamic, insitu measurements of soil properties.

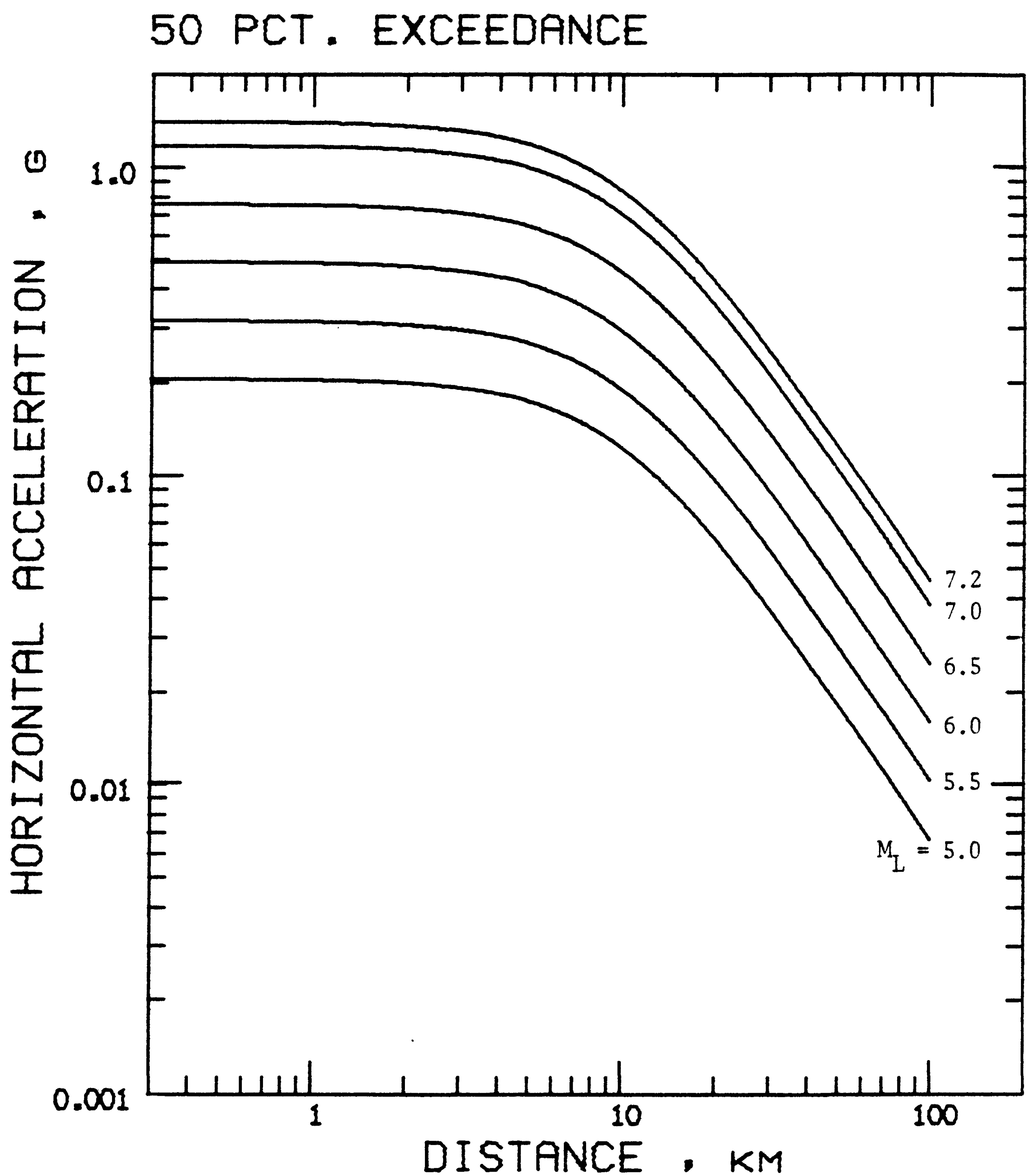



Figure 11: Peak horizontal acceleration for a 50 percent exceedance probability.

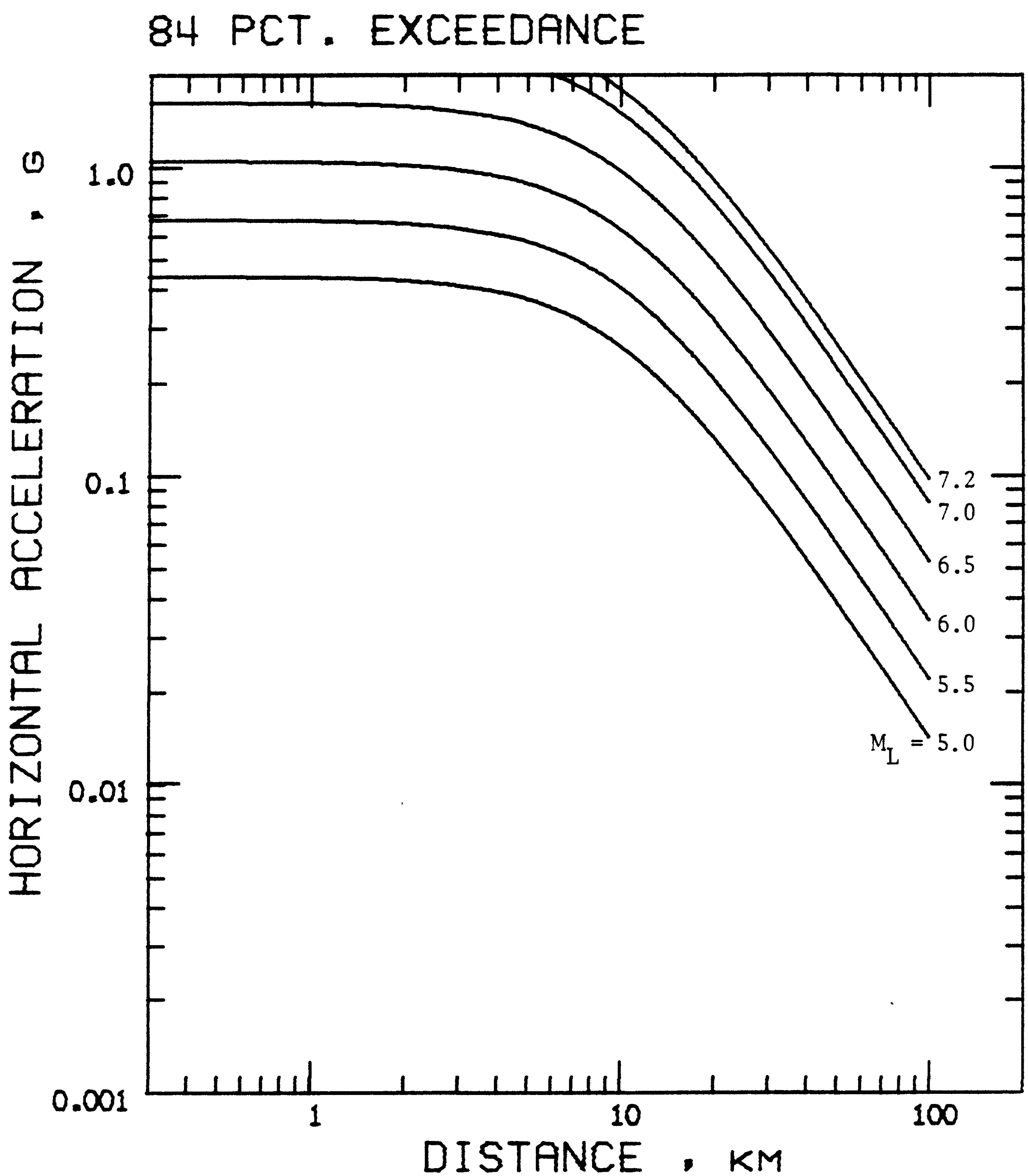



Figure 12: Peak horizontal acceleration for an 84 percent exceedance probability.

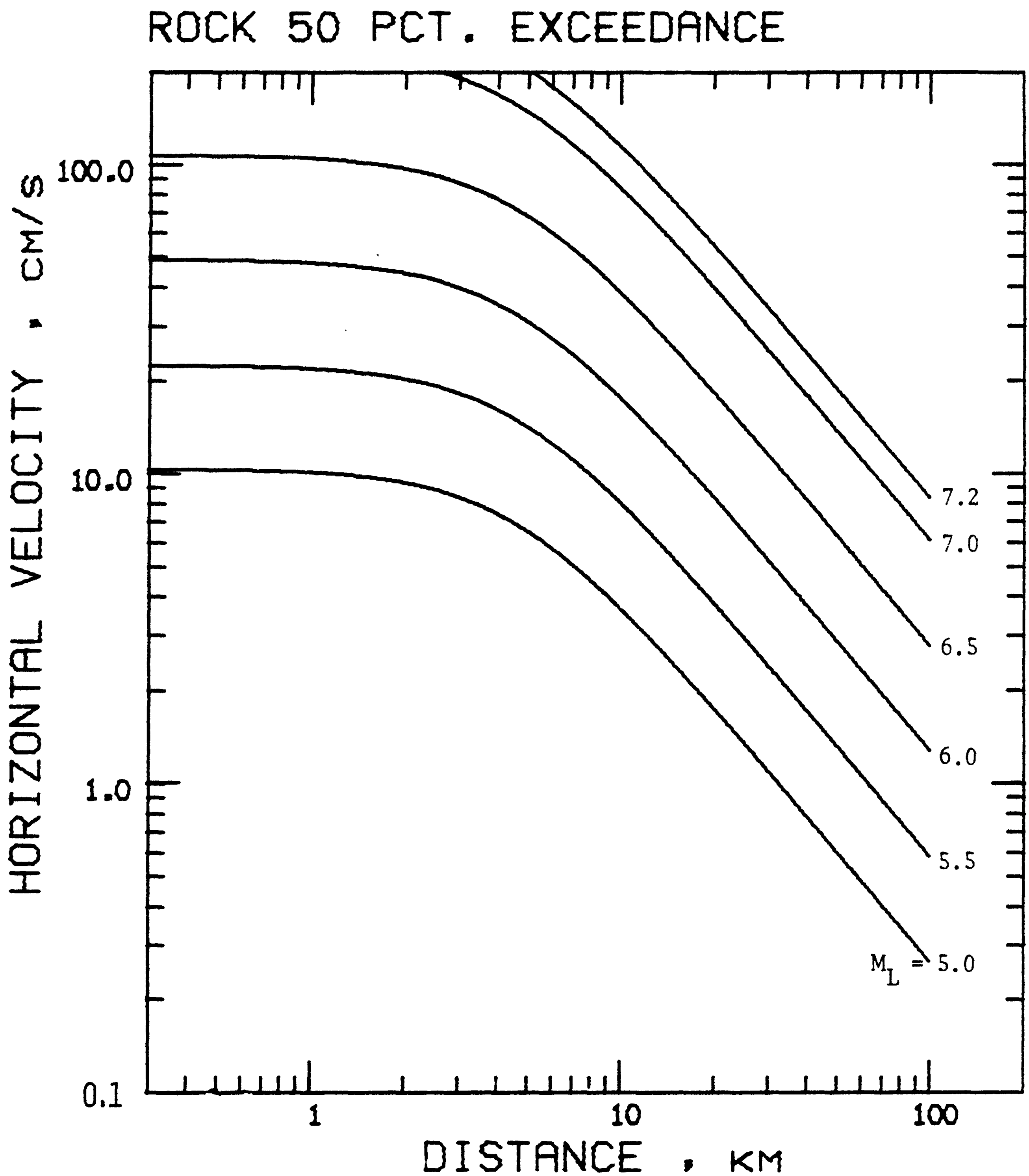



Figure 13: Peak horizontal velocity at rock sites for a 50 percent exceedance probability.

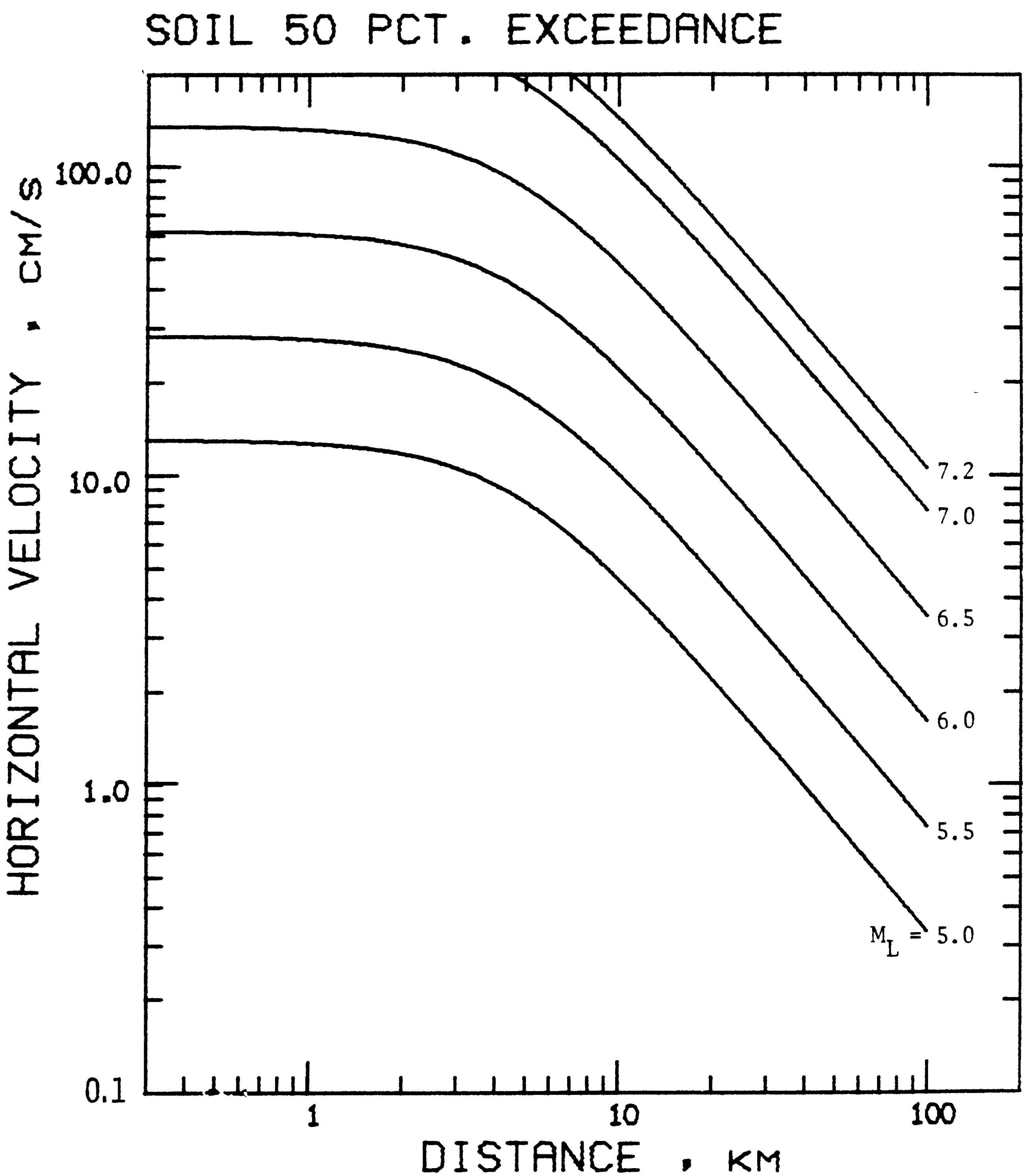



Figure 14: Peak horizontal velocity at soil sites for a 50 percent exceedance probability.

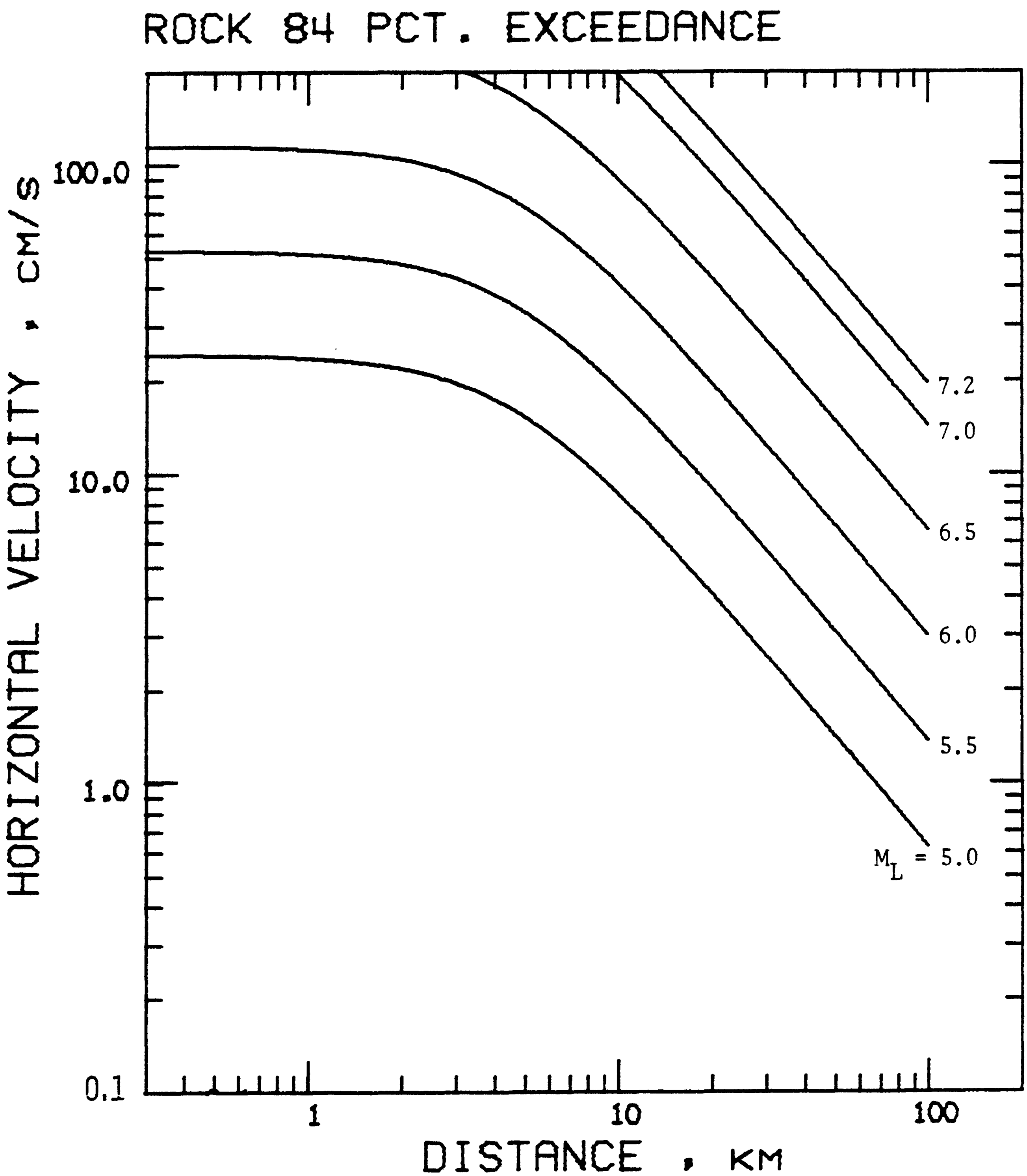



Figure 15: Peak horizontal velocity at rock sites for an 84 percent exceedance probability.

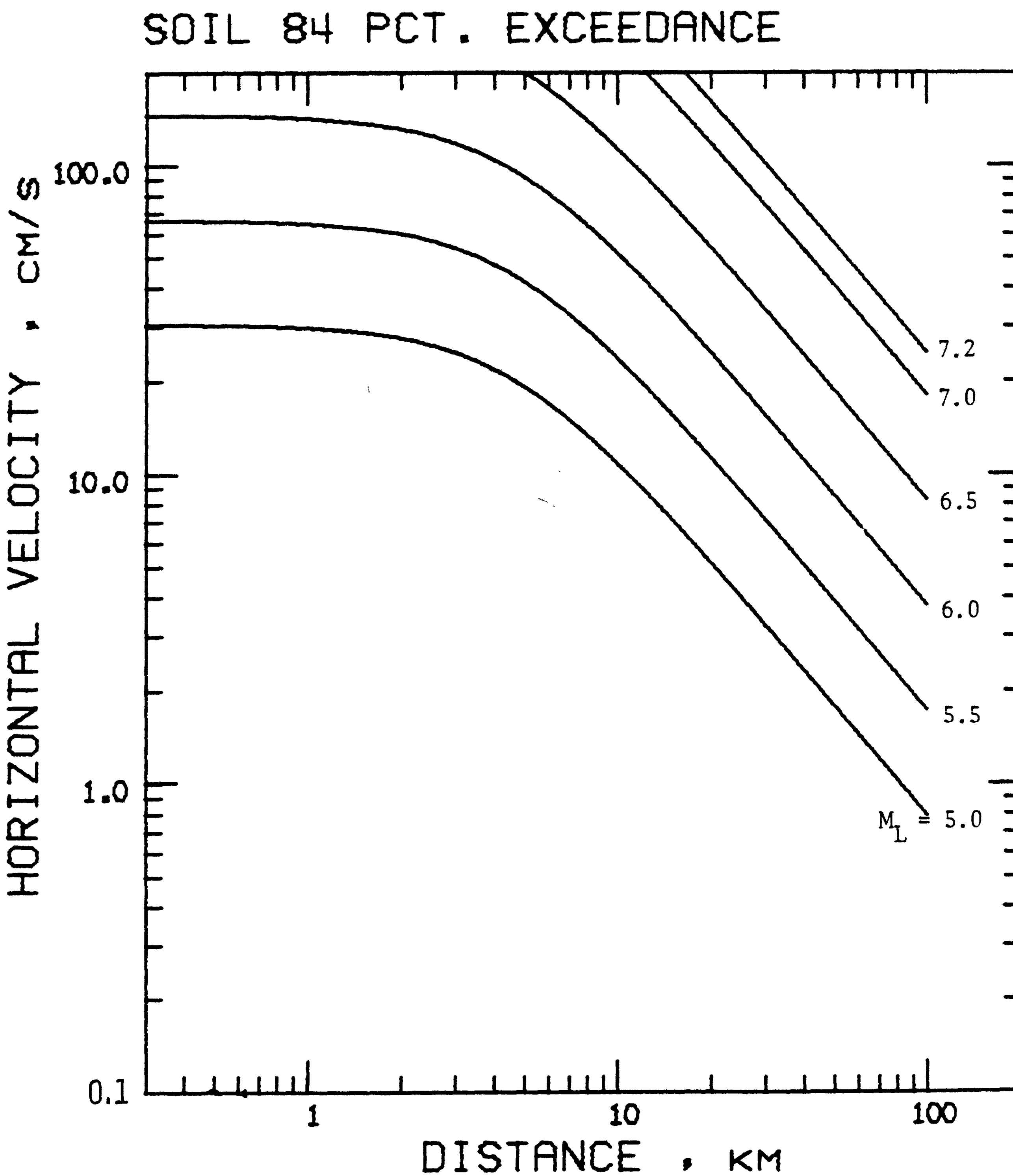



Figure 16: Peak horizontal velocity at soil sites for an 84 percent exceedance probability.

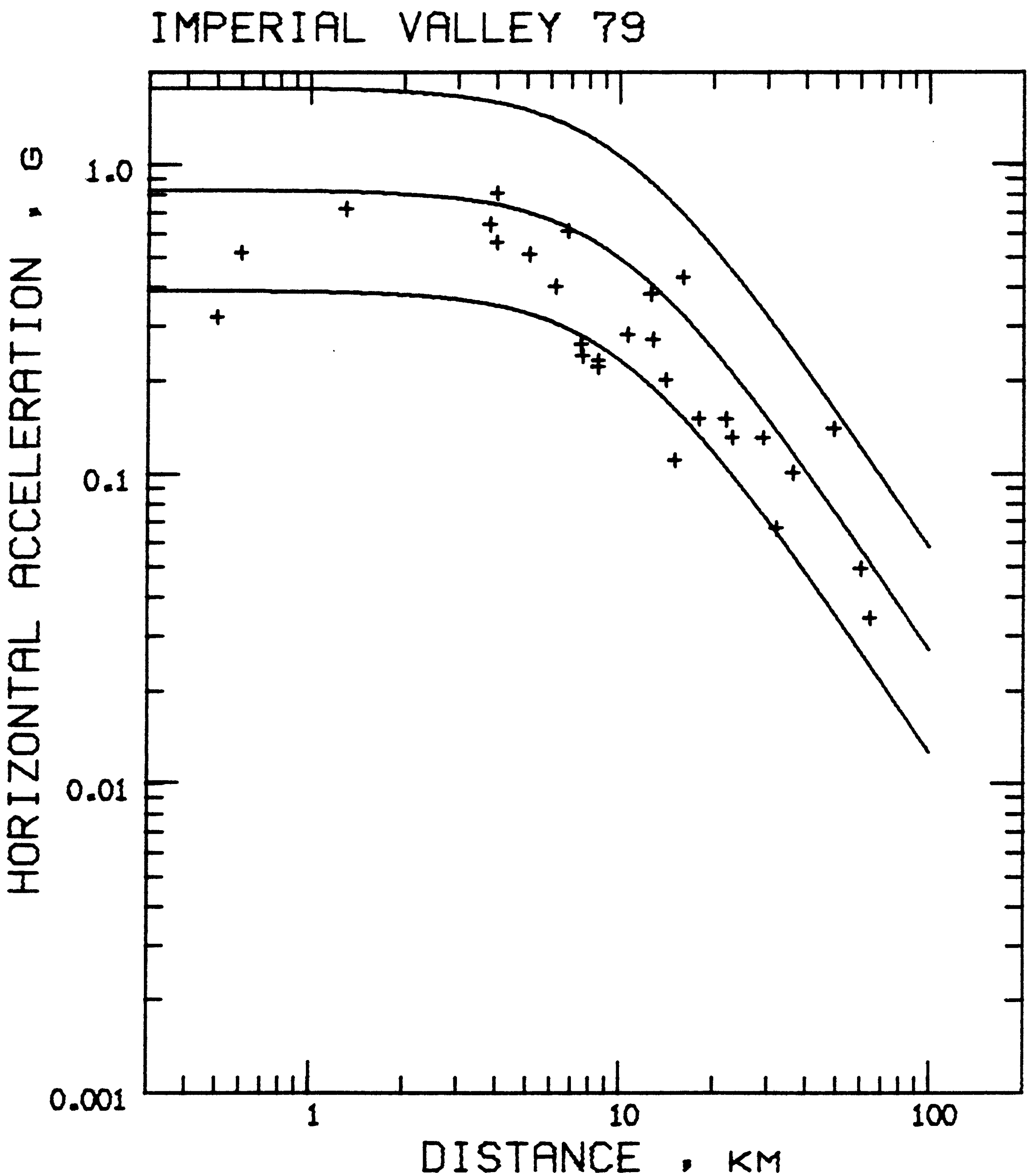



Figure 17: Mean estimated peak horizontal acceleration (center curve) and 68 percent prediction interval (outer curves) for $M_L = 6.6$ compared with data from the 1979 Imperial Valley earthquake.

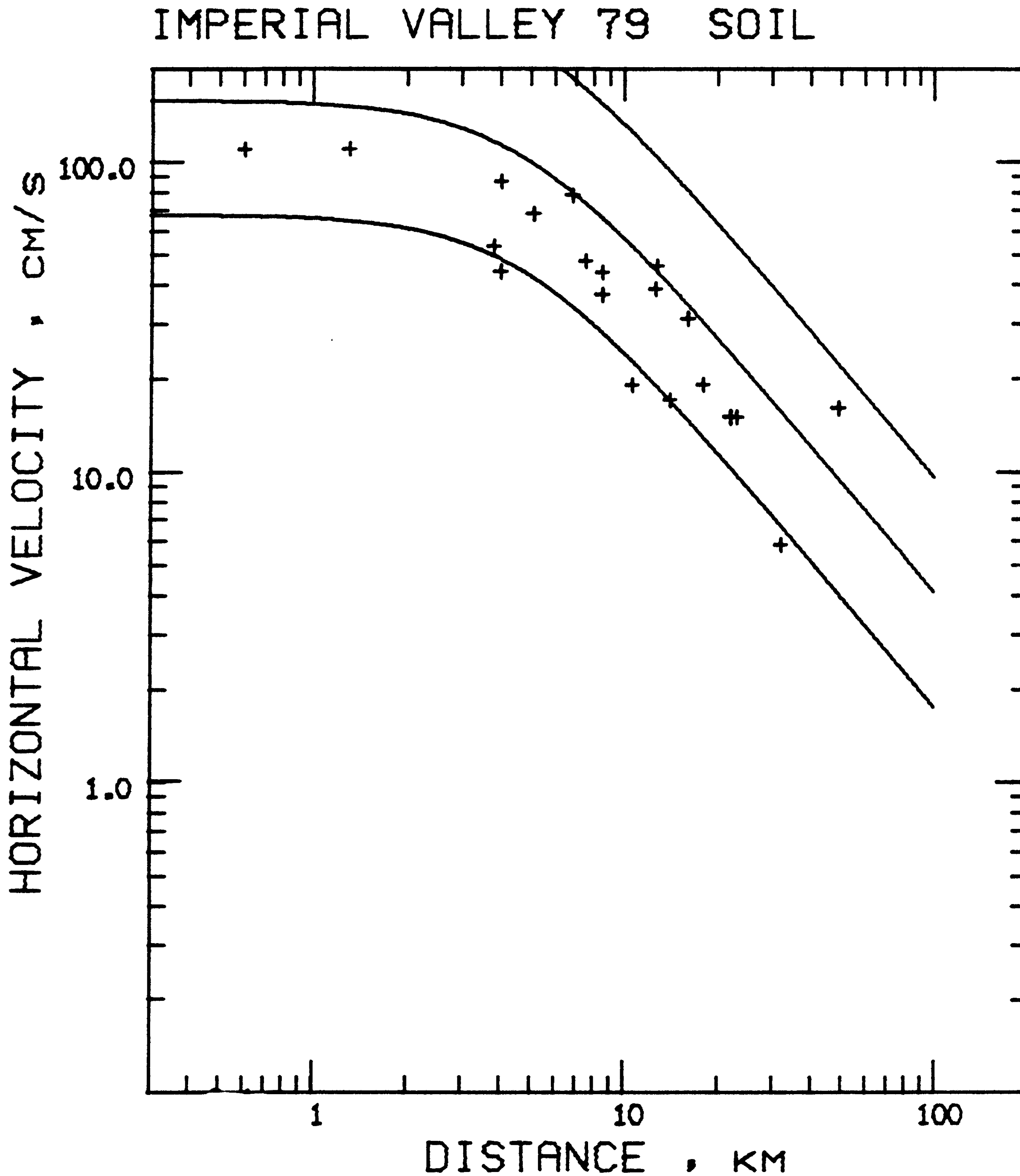



Figure 18: Mean estimated peak horizontal velocity (center curve) and 68 percent prediction interval (outer curves) at soil sites for $M_L$ = 6.6 compared with data from the 1979 Imperial Valley earthquake.

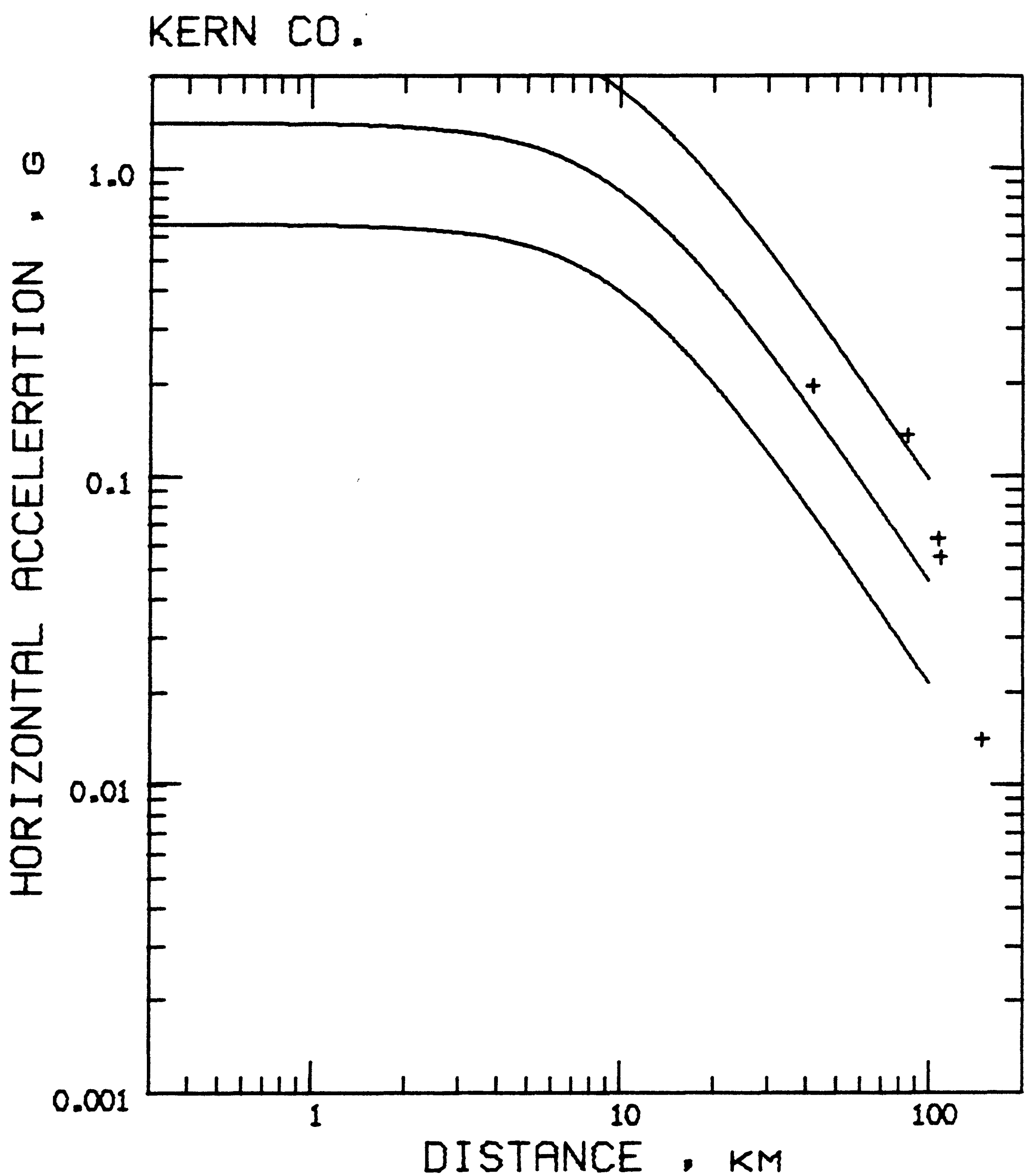



Figure 19: Mean estimated peak horizontal acceleration (center curve) and 68 percent prediction interval (outer curves) for $M_L = 7.2$ compared with data from the 1952 Kern County earthquake.

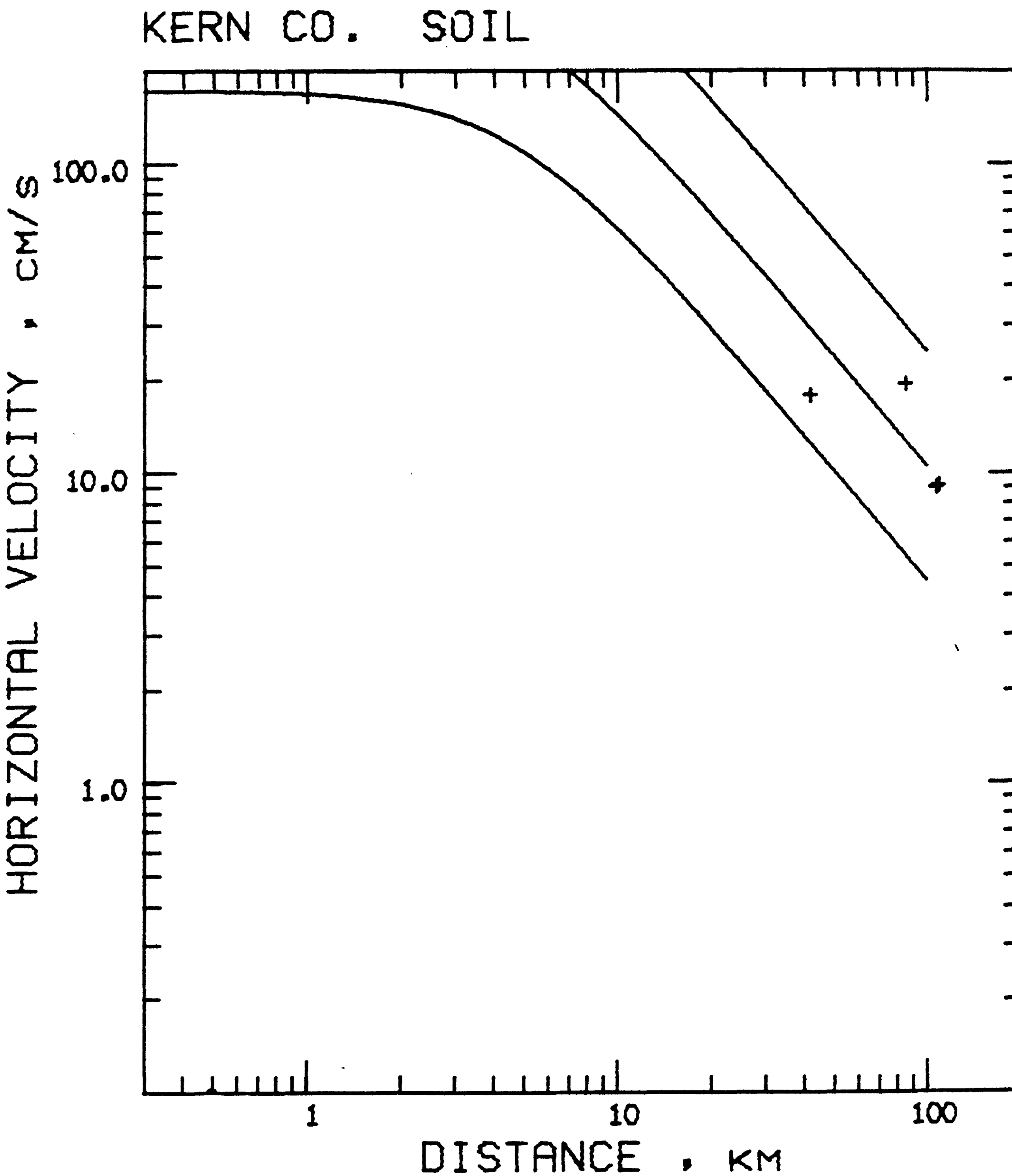



Figure 20: Mean estimated peak horizontal velocity (center curve) and 68 prediction interval (outer curves) at soil sites for $M_L = 7.2$ compared with data from the 1952 Kern County earthquake.

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