MASTER

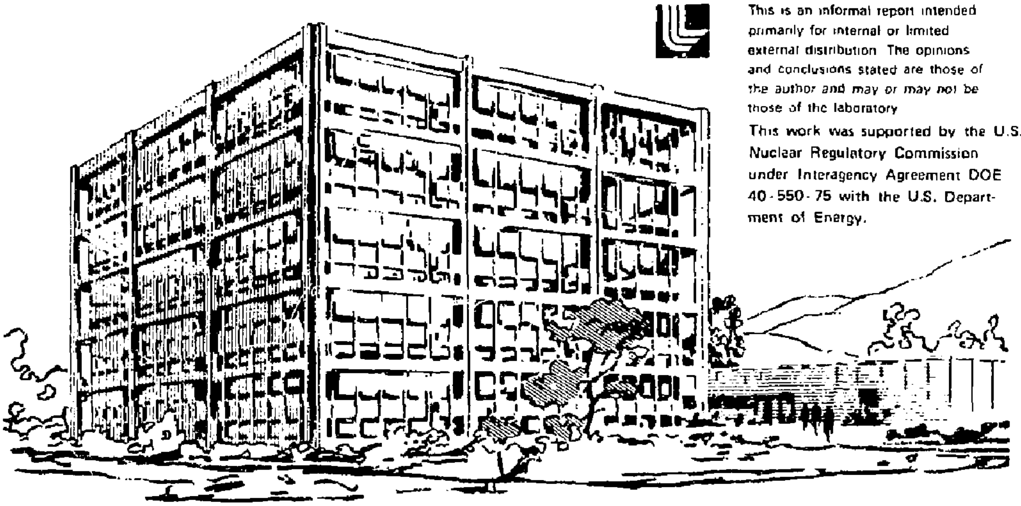
UCID-18125

Lawrence Livermore Laboratory

SEISMIC SAFETY IN NUCLEAR-WASTE DISPOSAL

David W. Carpenter
Donald Towse

April 26, 1979



This is an informal report intended primarily for internal or limited external distribution. The opinions and conclusions stated are those of the author and may or may not be those of the laboratory.

This work was supported by the U.S. Nuclear Regulatory Commission under Interagency Agreement DOE 40-550-75 with the U.S. Department of Energy.

FOREWORD

This report on seismic safety in nuclear-waste disposal was prepared as part of the Nuclear Regulatory Commission Waste Management Project at Lawrence Livermore Laboratory.

CONTENTS

Foreword iii
Abstract vii
Introduction 1
Other Studies 3
Seismic Effects 6
Primary Effects 6
Surface Faulting 6
Tectonic Creep 9
Permanent Ground-Level Changes 11
Ground Shaking 12
Secondary Effects 15
The Effects of Earthquakes on Underground Structures 17
Seismic Effects on Waste Repositories 23
Appendix A: Earthquake Mechanics 27
Appendix B: Earthquake Prediction 47
References 51

LIST OF ILLUSTRATIONS

A-1. Seismic source areas 39

A-2. Preliminary map of horizontal acceleration in rock with 90% probability of not being exceeded in 50 years 40

LIST OF TABLES

1. Surface displacements associated with certain major earthquakes in the western United States 8

2. Observed rates of tectonic creep on active faults, San Francisco Bay area, California 10

3. Peak ground-motion amplitudes for selected U.S. earthquakes 13

A-1. Modified-Mercalli Intensity Scale of 1931 (abridged and rewritten) 34

A-2. Seismic parameters for source zones 42

B-1. Potential earthquake precursors 49

ABSTRACT

Seismic safety is one of the factors that must be considered in the disposal of nuclear waste in deep geologic media. This report reviews the data on damage to underground equipment and structures from earthquakes, the record of associated motions, and the conventional methods of seismic safety-analysis and engineering. Safety considerations may be divided into two classes: those during the operational life of a disposal facility, and those pertinent to the post-decommissioning life of the facility. Operational hazards may be mitigated by conventional construction practices and site selection criteria. Events that would materially affect the long-term integrity of a decommissioned facility appear to be highly unlikely and can be substantially avoided by conservative site selection and facility design. These events include substantial fault movement within the disposal facility and severe ground shaking in an earthquake epicentral region. Techniques need to be developed to address the question of long-term earthquake probability in relatively aseismic regions, and for discriminating between active and extinct faults in regions where earthquake activity does not result in surface ruptures.

INTRODUCTION

Ground movements, whether the result of earthquakes or other causes, could conceivably damage equipment in a waste disposal facility, injure personnel, hamper operations, damage underground openings, propogate flaws that might compromise the integrity of natural or engineered seals in the system, or create other pathways for waste migration.

After a brief review of previous work we describe seismic hazards in general. Then we describe effects of recorded motions on underground facilities. The report includes a description of possible effects on waste repositories and regulatory procedures that might be used to lessen risk.

Appendices describe earthquake mechanisms, methods used to measure magnitudes and intensities, earthquake prediction, and more fully discuss regional seismic risk.

Our purpose is to supply technical information for the Nuclear Regulatory Commission to use in formulating guides and regulations for disposal of nuclear waste.

Seismicity is only one of the progressive or episodic geologic processes that might affect the operation of a disposal facility. Others include erosion, sedimentation, epeirogenic uplift or downwarp, sea-level changes, and changes in the hydrologic system due to local or regional climate variation. These all need consideration in the analysis of important geologic processes. This report concentrates on seismicity, which we define as earth movements due to displacement on faults. An important aspect of seismicity is displacement along a fault, which is the cause rather than an effect of seismicity, but which can cause considerable damage along the rupture surface. Other important seismic hazards include tectonic creep, permanent changes in ground levels, and ground shaking.

Additional effects of earthquakes include flooding, tsunamis, landsliding, and soil liquefaction and collapse. These are not treated in depth here, because many of these effects can have other causes, and because other criteria addressing soil and slope stability, elevation, coastal position, and flood-plain location will be used in waste-facility analyses and will mitigate these effects, whether caused by seismic events or not. We concentrate on those effects that are uniquely seismic.

Our concerns here are primarily with those effects of earthquakes that may cause a radiological hazard to the public. Second priority is given to hazards to facility personnel, and third is given to effects on facility operations that do not constitute an immediate hazard (but may be important operationally or logistically). Nonradiological occupational or public hazards are the subject of many existing regulations and legal codes that control facility siting, design, and operation in their areas of concern. These include rules of the Occupational Safety and Health Administration (OSHA), the Mine Safety and Health Administration (MSHA), and state and local mining-, building-, and industrial-safety regulations.

Our purpose is to produce a concise, complete document within these stated limits. We lay no claim to originality of most of the information presented. This report is basically a review of a considerable record, both published and unpublished, of man's historical concern with earthquakes and their effects on him and his works.

OTHER STUDIES

Seismic hazards have always been an expressed concern in waste disposal studies, as they are in connection with any major civil or industrial works. The distinctions between nuclear-waste facilities and others in this connection cannot be repeated too often: (1) For many types of construction there is little choice of location (for example, bridges, dams, tunnels, and some harbor works). (2) Waste-disposal facilities are expected to be located at sites specially selected for seismic safety. (3) Subsurface waste-disposal facilities will have a significantly longer design life than other projects, exceeding the time covered by good historical records and state-of-the-art seismic prediction.

Because many regions were settled before seismic safety became a matter of concern, there have been disasters in populated regions that have received considerable attention and have provided most of the historical and scientific record. Much of this published record is for seismically active regions, e.g., California and Japan, which would not be considered for waste-disposal sites using modern seismic-safety criteria. Therefore, the historic and scientific record must be extrapolated to consider the effects of infrequent events of significant intensity and the cumulative effects of a number of low-intensity events, which may be experienced during the long isolation phase of a nuclear-waste repository to produce estimates relevant to the practical problems of waste-disposal siting, design, and operation.

It should be noted that earthquakes are not totally random in time and space but are the result of global-scale orogenic processes. Lomnitz (1974) has documented the relationship of seismic activity to major faults and tectonic features. However, in smaller areas, and particularly in more seismically active regions, a random or statistical approach is the only possible approach to earthquake-risk assessment presently available.

An advisory group of the International Atomic Energy Agency (IAEA, 1976), observed that "areas of low seismicity and tectonic stability are favored for waste-disposal facilities," and listed some of the hazards from both ground rupture and shaking. They appeared to be optimistic on the chances of avoiding most risks by proper siting. The U.S. Geological Survey (1976) called ground shaking "a significant problem in the management of high-level radioactive waste." They propose studies of risk assessment and design criteria to develop risk-assessment methods for very low-risk levels, to develop models, to identify favorable regions, and to suggest ground motion criteria for waste-disposal facilities.

Claiborne and Gera (1974) calculated a probability of 4×10^{-11} per year for a ground rupture (faulting) event at the Waste Isolation Pilot Plant (WIPP) repository site in New Mexico. They used the historic record of regional faulting and assumed random (uniform) distribution in time and space. In a generic study for technical support of Nuclear Regulatory Commission development criteria (Heckman, et al., 1978), consideration of historical earthquake behavior in the western U.S. and assumptions regarding damage levels resulted in a probability of damaging earthquakes very close to the cited probability of faulting.

As noted by the Interagency Review Group on Nuclear Waste Management (1978), most siting guidelines recommend that sites "be located outside regions of high seismicity, volcanism, or other expressions of tectonism." This has been explicitly noted in several reports for agencies that are or may be responsible for some aspects of waste-repository supervision.

The Panel on Geological Site Criteria, Committee on Radioactive Waste Management, National Academy of Sciences (1978) specifically recommended that a waste-repository site avoid any fault that shows evidence of movement within the last million years of the Quaternary Period.

A report for the Environmental Protection Agency (A.D. Little, Inc., 1978), discusses earthquakes and faults. It notes the difficulty of precise earthquake prediction and the impossibility of proving zero-earthquake probability anywhere, but goes on to state that "once a repository has been sealed and its surface facilities abandoned, the effects of even large earthquakes are likely to be negligible." A committee of the California Energy Resources Conservation and Development Commission (1978), states that "Next to hydrology, seismic stability is regarded as the most important repository characteristic ...," and discusses the difficulties and the research needed for seismic-safety studies for the long term. The suggested Nuclear Regulatory Commission guide on format and content for environmental reports for waste repositories (NRC, 1978) suggests in-depth studies of site and area seismicity and estimates of anticipated ground motion in underground areas.

In summary, seismic design has been recognized as a problem, but neither the magnitude of the risk nor the specific methods for measuring it has been developed, although some studies have been undertaken and are described in later sections of this report.

SEISMIC EFFECTS

In this section, we document the principal physical effects of earthquakes. These data on motions, velocities, and accelerations are the primary ones needed for the analysis of hazards and for structural design. In this chapter, we shall review the record of effects of damaging earthquakes in the United States; in the next chapter, we shall describe qualitative earthquake effects on underground structures.

We can conclude that the hazard potential is a function of the energy released by an earthquake (indicated by its magnitude), of the location of the structure concerned relative to the epicenter or hypocenter of the earthquake, and of the propagation characteristics of the material between the center and the structure being analyzed. The maximum recorded and theoretical earthquake motion parameters are within civil- and mechanical-design experience, so the potential exists to design "earthquake-proof" waste facilities, given adequate advances in the art and science of earthquake prediction.

For the purpose of geologic and engineering analysis, the effects of an earthquake can be discussed in terms of phenomena grouped as either primary or secondary. We here emphasize the primary phenomena.

PRIMARY EFFECTS

Primary seismic phenomena include surface faulting, tectonic creep, permanent changes in ground levels, and ground shaking.

Surface Faulting

Surfacing of fault movement or ground rupture has been observed during a number of major earthquakes in the western United States and in some other portions of the world. Such surface displacements have not been observed during significant earthquakes in the eastern and midcontinent areas of the United States (Algermissen and Perkins, 1976).

Examples of surface faulting observed during several major earthquakes in the western United States are given in Table 1. The examples given are illustrative; additional data are available and has been summarized by several investigators (Bonilla and Buchanan, 1970), (Bonilla, 1970).

As shown in Table 1, while there is considerable scatter in the data, lengths of surface ruptures and amounts of displacement generally increase with increasing earthquake magnitude. Several empirical relations between earthquake magnitude and the length of associated surface ruptures along faults have been derived (Albee and Smith, 1966). These magnitude-fault-length relations may be used for crude estimates of the maximum-magnitude earthquake that might be expected from a particular fault if the length of the fault is well known (Wesson et al., 1975). Housner (1969) has demonstrated that the rupture length during a major earthquake approximates one-half the fault length.

The widths of zones disturbed by surface faulting vary with the magnitude of the causative earthquake and the type of faulting that occurs. Strike-slip faults, such as the San Andreas Fault system, commonly produce a main zone of varying (but generally narrow) width along which the principal offsets occur, and lesser branch or secondary faults that extend to, or occur at, considerable distance from the main zone. Reverse (thrust) faults commonly produce more complex rupture zones, and the zones typically are broader and less regular in plan. In the case of the San Fernando earthquake in 1971, surface displacements were noted on the thrust plate for a distance of nearly a mile north of the main zone of surface rupture (Wesson et al., 1975). The main zone itself was several hundred feet in width, and within this zone, almost every structure was damaged or destroyed (Slosson, 1975).

There is evidence indicating that major earthquakes may trigger movements on other faults within the epicentral region (Saul, 1975). Studies of several surface faulting events indicate that historic ground ruptures closely follow mappable geomorphic or subsurface features that delineate preexisting fault traces. Numerous studies of surface faulting have been performed in California in recent years, partly in response to legislation passed following

TABLE 1. Surface displacements associated with certain major earthquakes in the western United States.

Earthquake	Magnitude	Maximum displacement	Length of displacement zone
Hayward, CA[a] October 22, 1868	7 ± 0.5 (est.)	0.9 m horiz. 0.3 m vert.	30 km (Warm Springs to San Leandro, CA, possibly Berkeley, CA)
San Francisco, CA[a] April 18, 1906	8.25	5 m horiz.	430 km (San Juan Bautista to Shelter Cove or Pt. Delgada, CA)
Ft. Tejon, CA[b] 1857	8.25+ (est.)	9.5 m horiz.	275 km (near San Bernardino to Parkfield, CA)
San Fernando, CA[c] February 9, 1971	6.5	2 m reverse[e] slip 2 m left slip	15 km along strike 8 km down dip
Hebgen Lake, MT[d] 1959	7.1	20 ft. (6 m) vert.	Not reported.
Arvin-Tehachapi area,[d] CA 1952	7.7	2 ft. (0.6 m) reverse 2 ft. (0.6 m) left	Not reported.
Herlong, CA[d] 1950	5.75	"a few inches vertical"	Not reported.

[a]See Wesson, et al. (1975).
[b]See Sieh (1978).
[c]See Savage, et al. (1975).
[d]See Oakeshott (1969).
[e]Calculated from seismic data, maximum observed surface displacement totalled about 1.9 m.

the San Fernando earthquake in 1971. Over 200 such studies are on open file with the California Division of Mines and Geology in San Francisco, California.

Sparse data on zone widths for North American earthquakes in the magnitude range from 5.5 to about 8.5 were analyzed by Bonilla (1970). This analysis indicates that the maximum half-width of the zone (centerline of the main fault zone to the outer edge of the deformation zone), for strike-slip faults is about 92 m. For dip-slip faults, the zone is as much as 900 m.

These values are probably conservative estimates except for very large earthquakes. Private investigators working in California have specified a variety of avoidance zones from identified faults. Such zones have ranged from the outer limits of the visibly disturbed area to about 30 m.

Tectonic Creep

Tectonic-fault creep or aseismic slip consists of gradual relative movement along a fault without perceptible earthquakes. Such movements may be as large as a few centimeters per year, although as shown in Table 2, rates are generally less. With time, creep will break or offset streets, curbs, sidewalks, etc., and severely damage buildings located on fault traces.

The widths of actively creeping portions of faults are generally less than the total widths of areas affected by Holocene faulting. M. Lewis, Chief of Surveys for the City of Hayward, states that repeated surveys made over a 50-year period in the city of Hayward, California, have indicated that a foot (30 cm) of tectonic creep has occurred during that period within the length of one city block (about 100 m) oriented nearly at right angles to the Hayward Fault trace. Several strands of the Hayward Fault system occur in the same area and are spread out over a width of at least 600 ft (Slosson, 1974).

As noted previously, creep may occur along some segments of a major fault, while other segments are locked or inactive. Tectonic creep may relieve stress along an active fault, but it is unclear whether stress relief is sufficient to inhibit the occurrence of a large earthquake, whether creep is a precursor to such an event, or whether the actual situation is some combination

TABLE 2. Observed rates of tectonic creep on active faults, San Francisco Bay area, California.[a]

Fault	Site	Rate (cm/y)	Time period[b] (years)
Calaveras	Offset curb in Hollister	0.5	60
	Offset bridge at Anderson Reservoir	1.2	17
	Deformed survey array near Sunol	0.25	4.7
Concord	Offset curb in Concord	0.65	25
Hayward	Offset building in Irvington Dist., Fremont	0.6	44
	Offset curb in Hayward	0.6	54
	Offset tunnel in Berkeley	0.25	42
	Offset curb in San Pablo	0.5	27
San Andreas[c]	Offset fence north of San Juan Bautista	0.5	34

[a]See Wesson, et al. (1975).

[b]Time since affected object was placed. If creep began some time after installation of object, creep rate would be higher.

[c]San Andreas Fault is not actively creeping throughout much of San Francisco Bay area.

of these (Wesson et al., 1975). Greensfelder (1974) has estimated that the maximum credible earthquake for the actively-creeping central segment of the San Andreas Fault system is 7.5, while magnitudes of 8.5 are credible for the locked northerly and southerly segments.

There is evidence that creep may be an episodic process. As noted in Table 2, a long-term creep rate of about 0.6 cm/y is indicated for the portion of the Hayward Fault system from central Hayward south through Fremont, California. Such evidence can be observed throughout this area.

Trenching studies by private consulting firms have located active strands of the Hayward Fault near the Fremont Bay Area Rapid Transit (BART) station and on property proposed for a housing development south of the BART station (Burkland and Assoc., 1978). At both locations, Holocene and probably historic activity is indicated. The deformed warehouse in the Irvington District referred to in Table 2 is about 2 miles south-southeast along the fault. However, curbs installed in about 1972 on Walnut Avenue between the trenched sites show no evidence of deformation across the fault, although approximately 3.6 cm of creep should have occurred at this location based on historic creep rates.

Permanent Ground-Level Changes

In addition to ground rupture along fault traces, large areas of the ground surface can be permanently affected by vertical and horizontal distortions including uplift and subsidence. The 1964 Alaska earthquake (M - 8.5) caused crustal deformation over an area of about 285,000 km^2, producing a maximum uplift of 12 m and a maximum downwarp of 2.5 m (Plafker, 1969).

Re-leveling following the February 9, 1971, San Fernando earthquake demonstrated up to 2.5 m of uplift in portions of the San Fernando Valley immediately north of the surface-rupture zone; up to 0.5 m of uplift was detected within distances of 2.5 to 4.5 km north of the surface trace. Less than 0.1 m of subsidence affected a small area, which extended less than a kilometer south of the fault trace (Savage et al., 1975).

Considerable changes in ground levels, including both uplift and subsidence, were documented by Nuttli (1973) as having occurred during the New Madrid, MO series of earthquakes in 1811-1812.

Ground Shaking

Adequate records of ground motion have only been available recently, since the development and deployment of instruments capable of recording accurate numerical values. These instruments record, in either two or three directions, the time history of the velocity, acceleration, and displacement of earth motion. Some instruments located in special locations, such as buildings or other structures, record not the basic ground motion, but the induced and generally exaggerated motion of the structure to which it is attached. Seismic station arrays are, in general, deployed for special purposes or in particularly seismic areas, so the record is more complete for larger motions. While these may not provide the information for analysis of long-term fatigue failure, they do provide an indication of the maxima required for civil and mechanical design.

Table 3 (Hudson, 1974) lists peak surface-ground motions for a number of major earthquakes. The Feb. 9, 1971, earthquake was the destructive San Fernando earthquake in California. Note that the only velocities that exceed 60 cm/s or accelerations recorded near or above 0.5 g are at Pacoima Dam. These motions may have been amplified by their location on the structure and were recorded within 9.1 km of the earthquake epicenter. Peak values give some indication of hazard, particularly if taken together, but for adequate analysis, the whole spectrum and time history of the motion needs to be reviewed. A general correspondence is shown in Table 3 between peak motion and epicentral distance, but this is complicated by other factors, such as transmission characteristics of the rock and soil, and the location of the seismic stations.

Peak values depend on the frequencies of the motion, with maximum acceleration at higher frequencies, maximum velocity at lower frequencies, and maximum displacement at the lowest frequencies. Hudson's paper discusses the various aspects of ground motion in some detail.

TABLE 3. Peak ground-motion amplitudes for selected U.S. earthquakes.

CIT[a] Code	Location	Date	Ep dist[b] (km)	Mag[c]	Max ground accel (G's) H1[d]	H2[d]	V[e]	Max ground vel (cm/s) H1	H2	V	Max ground disp (cm) H1	H2	V
A001	El Cerrito	05-18-40	9.3	6.7	0.35	0.21	0.21	33.4	36.9	10.8	10.8	19.7	5.6
A002	NW California	10-07-51	56.3	5.8	0.10	0.11	0.03	4.8	7.4	2.2	2.4	2.7	1.6
A003	Kern County	07-21-52	43.0	7.7	0.15	0.18	0.10	15.7	17.7	6.7	6.7	9.2	5.0
A005	Kern County	07-21-52	89.5	7.7	0.09	0.13	0.04	11.7	19.2	5.0	4.6	5.8	2.2
A003	Kern County	07-21-52	125.0	7.7	0.05	0.05	0.03	6.2	9.1	4.5	2.7	2.9	3.0
A008	Eureka	12-21-54	24.0	6.5	0.17	0.26	0.08	31.5	29.3	8.2	12.4	14.0	4.7
A009	Ferndale	12-21-54	40.4	6.5	0.16	0.20	0.04	35.6	26.0	7.6	14.1	9.6	3.9
A010	San Jose	09-04-55	9.8	5.8	0.10	0.11	0.05	10.8	4.4	1.2	2.8	1.7	1.2
A015	San Francisco	03-22-57	11.8	5.3	0.03	0.10	0.04	4.9	4.6	1.2	2.3	0.8	0.7
A016	San Francisco	03-22-57	14.6	5.3	0.09	0.06	0.04	5.1	4.0	2.3	1.1	0.9	0.6
A017	Hollister	04-08-61	40.0	5.7	0.06	0.18	0.05	7.8	17.1	4.7	2.8	3.8	2.2
A019	El Centro	04-08-68	69.8	6.4	0.13	0.06	0.03	25.8	14.6	3.4	12.2	10.9	3.9
B021	Vernon	03-10-33	47.8	6.3	0.13	0.15	0.15	29.0	17.3	12.0	15.4	17.5	7.4
B024	El Centro	12-30-34	60.8	6.5	0.16	0.18	0.07	20.8	11.5	8.8	4.2	3.7	5.6
B025	Helena, MT	10-31-35	6.6	6.0	0.15	0.14	0.09	7.3	13.3	9.7	1.4	3.7	2.8
B026	Ferndale	09-11-38	55.3	5.5	0.14	0.09	0.03	6.6	6.8	1.4	3.9	1.7	0.6
B029	Olympia, WA	04-13-49	16.8	7.1	0.16	0.28	0.09	21.3	17.0	7.0	8.6	10.3	4.0
B028	Seattle, WA	04-13-49	57.8	7.1	0.07	0.07	0.02	9.2	7.9	2.4	2.4	2.7	2.3
B032	Olympia, WA	04-29-65	61.1	6.5	0.14	0.20	0.06	8.1	13.0	3.0	2.7	3.8	1.7
B037	Parkfield	06-27-66	31.0	5.6	0.27	0.35	0.13	14.5	22.5	4.4	4.7	5.5	1.4
B033	Parkfield	06-27-66	31.9	5.6	0.49	--	0.21	78.0	0.0	14.1	26.4	0.0	4.3
B034	Parkfield	06-27-66	32.4	5.6	0.35	0.43	0.12	23.1	25.4	7.3	5.3	7.1	3.4
B035	Parkfield	06-27-66	34.1	5.6	0.24	0.27	0.09	10.8	11.7	4.5	4.4	3.9	2.1
C041	Pacoima Dam	02-09-71	9.1	6.4	1.16	1.07	0.71	113.0	57.7	58.3	37.6	10.8	19.3
C048	San Fernando	02-09-71	22.4	6.4	0.25	0.13	0.17	29.9	23.9	31.9	14.8	13.8	14.6
J144	Lake Hughes	02-09-71	23.3	6.4	0.35	0.28	0.11	14.7	12.7	4.1	1.8	8.9	3.3
J143	Lake Hughes	02-09-71	26.6	6.4	0.12	0.11	0.07	4.8	4.5	3.0	2.0	2.4	2.2
J142	Lake Hughes	02-09-71	26.8	6.4	0.17	0.15	0.15	5.7	8.6	7.1	1.2	1.7	1.6
D056	Castaic	02-09-71	28.6	6.4	0.31	0.27	0.16	17.1	27.6	6.4	4.2	9.5	3.5
I137	Los Angeles	02-09-71	29.0	6.4	0.14	0.13	0.10	16.0	22.2	8.6	7.1	8.5	2.7
H115	Los Angeles	02-09-71	29.3	6.4	0.22	0.15	0.10	28.2	23.4	9.4	13.4	10.3	4.3
O233	Los Angeles	02-09-71	29.3	6.4	0.25	0.20	0.10	31.5	17.8	9.7	15.3	9.5	3.8
J141	Lake Hughes	02-09-71	29.6	6.4	0.15	0.11	0.09	17.9	14.4	1.6	3.4	3.0	2.9
L166	Los Angeles	02-09-71	30.8	6.5	0.17	0.15	0.07	12.4	14.9	5.0	4.9	5.4	2.4
G110	Pasadena	02-09-71	31.5	6.4	0.21	0.14	0.13	13.9	9.2	3.9	5.0	2.9	2.6
G114	Palmdale	02-09-71	32.3	6.4	0.11	0.14	0.09	14.1	9.1	7.8	3.8	2.8	2.4
E081	Santa Felicia Dam	02-09-71	32.9	6.4	0.22	0.20	0.06	9.9	6.2	4.6	7.0	4.6	2.8
D198	Griffith Park	02-09-71	34.0	6.4	0.18	0.17	0.12	20.5	14.5	7.4	7.3	5.5	3.4
F088	Glendale	02-09-71	34.1	6.4	0.27	0.21	0.13	30.8	23.4	15.6	11.0	5.3	5.6
J145	Los Angeles	02-09-71	34.9	6.4	0.12	0.10	0.11	31.6	28.7	18.1	17.5	15.2	7.0
Q236	Hollywood	02-09-71	34.9	6.4	0.17	0.12	0.07	13.4	10.3	7.5	6.1	5.9	1.9
R246	Los Angeles	02-09-71	35.7	6.4	0.12	0.11	0.08	16.7	18.3	7.1	8.3	10.4	2.0
R248	Los Angeles	02-09-71	35.7	6.4	0.19	0.18	0.09	19.7	8.2	6.3	7.7	10.2	2.8
G106	Pasadena	02-09-71	36.1	6.4	0.09	0.19	0.09	6.0	11.6	5.9	1.7	5.0	2.3
P214	Los Angeles	02-09-71	36.2	6.4	0.16	0.16	0.12	23.2	16.2	9.8	8.0	7.9	5.2
D058	Hollywood	02-09-71	37.1	6.4	0.17	0.21	0.09	16.5	21.1	5.1	8.1	14.7	3.0
P095	Los Angeles	02-09-71	37.4	6.4	0.10	0.09	0.03	16.8	17.8	6.2	10.6	12.1	3.9
I131	Beverly Hills	02-09-71	38.2	6.4	0.19	0.16	0.4	17.2	14.0	4.5	9.3	6.1	2.3
G239	Beverly Hills	02-09-71	38.4	6.4	0.12	0.16	0.04	17.7	19.1	7.2	9.8	11.6	2.9

TABLE 3. Cont'd.

CIT[a] Code	Location	Date	Ep dist[b] (km)	Mag[c]	Max ground accel (G's) H1[d]	H2[d]	V[e]	Max ground vel (cm/s) H1	H2	V	Max ground disp (cm) H1	H2	V
N189	Los Angeles	02-09-71	38.9	6.4	0.12	0.13	0.06	17.0	12.1	5.1	10.8	5.4	2.4
I134	Los Angeles	02-09-71	38.9	6.4	0.10	0.08	0.06	16.6	10.7	5.8	11.3	6.2	2.5
S255	Los Angeles	02-09-71	38.9	6.4	0.13	0.13	0.05	22.5	21.9	5.2	15.8	10.9	2.7
E072	Los Angeles	02-09-71	39.5	6.4	0.08	0.12	0.07	20.8	21.5	6.9	14.7	11.7	3.2
D059	Los Angeles	02-09-71	39.8	6.4	0.14	0.15	0.07	9.6	16.7	4.8	7.5	12.2	2.5
G107	Pasadena	02-09-71	39.8	6.4	0.10	0.11	0.0[illegible]	6.0	14.2	6.6	3.0	7.4	2.7
G108	Pasadena	02-09-71	39.8	6.4	0.20	0.18	0.09	9.8	16.4	9.0	2.7	6.9	2.4
I148	Los Angeles	02-09-71	39.9	6.4	0.11	0.11	0.05	16.1	17.4	6.7	7.3	11.1	3.4
S265	Los Angeles	02-09-71	39.9	6.4	0.11	0.13	0.05	17.8	18.2	6.8	8.7	12.6	3.6
D065	Los Angeles	02-09-71	40.0	6.4	0.15	0.16	0.07	18.0	22.0	9.1	10.3	12.8	4.9
D083	San Fernando	02-09-71	40.0	6.4	0.16	0.16	0.06	18.3	16.5	8.8	9.0	10.3	4.5
S266	Los Angeles	02-09-71	40.0	6.4	0.16	0.13	0.06	17.5	21.4	7.1	8.1	11.6	3.2
E075	Los Angeles	02-09-71	40.1	6.4	0.14	0.11	0.05	22.3	[illegible]	7.3	11.4	11.6	4.0
N192	Los Angeles	02-09-71	40.7	6.4	0.10	0.10	0.04	14.8	19.5	7.7	7.7	7.9	3.3
Q241	Los Angeles	02-09-71	41.8	6.4	0.09	0.14	0.06	17.9	19.6	8.7	9.2	10.0	5.1
R251	Los Angeles	02-09-71	41.8	6.4	0.20	0.19	0.07	16.7	18.7	7.8	8.9	9.5	4.8
R244	Los Angeles	02-09-71	41.9	6.4	0.15	0.13	[illegible]	18.3	18.7	8.5	9.8	9.9	4.4
C054	Los Angeles	02-09-71	41.9	6.4	0.15	0.12	0.05	17.3	17.3	10.6	11.8	11.7	5.1
R253	Los Angeles	02-09-71	42.0	6.4	0.25	0.22	0.08	19.2	18.0	9.9	11.4	12.4	5.4
O199	Los Angeles	02-09-71	42.0	6.4	0.14	0.24	0.15	17.6	21.3	10.4	9.8	10.3	5.7
K157	Los Angeles	02-09-71	42.5	6.4	0.17	0.12	0.06	17.4	16.7	9.6	10.3	8.7	5.3
G112	Los Angeles	02-09-71	42.5	6.4	0.10	0.08	0.05	16.9	15.6	10.0	10.9	9.2	5.2
E078	Los Angeles	02-09-71	42.5	6.4	0.13	0.17	0.07	23.3	36.1	10.2	13.7	8.9	6.5
F098	Los Angeles	02-09-71	42.7	6.4	0.24	0.20	0.07	21.7	18.4	9.6	13.1	13.4	5.3
C051	Los Angeles	02-09-71	42.8	6.4	0.10	0.12	0.05	17.1	21.9	7.8	9.2	11.6	5.8
D062	Los Angeles	02-09-71	42.8	6.4	0.12	0.13	0.08	16.1	17.6	9.0	11.9	6.9	4.1
M176	Los Angeles	02-09-71	42.9	6.4	0.09	0.12	0.04	20.9	17.8	8.9	13.7	13.7	4.3
H121	Alhambra	02-09-71	43.1	6.4	0.12	0.11	0.08	17.2	10.6	5.2	8.7	4.4	3.4
P221	Arcadia	02-09-71	43.3	6.4	0.14	0.17	0.05	5.3	6.7	4.5	3.2	5.9	2.5
F089	Los Angeles	02-09-71	44.0	6.4	0.13	0.14	0.08	20.8	20.7	10.0	14.5	11.6	6.0
F103	Pear Blossom	02-09-71	45.4	6.4	0.09	0.12	0.05	4.4	5.4	2.3	2.5	2.4	1.7
F086	Vernon	02-09-71	49.4	6.4	0.11	0.08	0.04	17.5	15.0	6.7	14.7	10.7	4.0
F104	Gorman	02-09-71	52.2	6.4	0.09	0.10	0.04	8.5	6.1	3.8	2.1	2.4	1.2
N186	Whittier Narrows	02-09-71	54.1	6.4	0.10	0.10	0.06	8.8	9.7	3.6	4.9	5.0	2.1
U299	Santa Barbara	06-30-41	35.9	5.9	0.24	0.18	0.07	21.7	21.6	3.6	3.7	3.9	2.6
U301	Hollister	03-09-49	29.3	5.3	0.20	0.12	0.07	11.7	8.3	3.6	1.4	1.7	1.0
U300	Ferndale	10-03-41	29.8	0.0	0.12	0.12	0.04	6.9	5.7	2.6	3.0	2.5	1.1
U309	Hollister	04-08-61	40.0	5.7	0.17	0.08	0.06	10.8	6.3	4.2	3.0	1.8	2.0
U310	Seattle, WA	04-29-65	22.3	6.5	0.05	0.08	0.03	5.6	9.4	2.4	2.6	5.4	1.6
U312	Ferndale	12-10-67	30.6	5.8	0.10	0.24	0.03	11.8	11.9	2.7	1.7	1.7	1.0
V315	Long Beach	03-10-33	27.2	6.3	0.20	0.16	0.28	29.4	16.5	30.1	22.7	11.8	26.3
V314	Los Angeles	03-10-33	54.9	6.3	0.06	0.10	0.06	17.3	23.6	9.1	8.2	16.3	5.7
V329	Port Hueneme	03-18-57	5.4	4.7	0.17	0.09	0.03	17.9	8.9	1.9	4.0	2.6	0.5
W334	Lytle Creek	09-12-70	13.4	5.4	0.14	0.20	0.05	8.9	9.6	3.2	2.2	1.0	1.4
W338	Lytle Creek	09-12-70	29.9	5.4	0.12	0.06	0.05	4.8	3.1	1.8	1.8	1.7	1.5

[a]California Institute of Technology.

[b]Epicentral distance.

[c]Richter magnitude.

[d]In a horizontal plane along mutually perpendicular lines.

[e]Vertical.

If the absolute possible maximum of ground motion could be described, a design could conceivably be made for absolute seismic safety. Some theoretical attempts have been made, e.g., Brune (1970), who suggested a theoretical maximum 2 g acceleration. If accepted, the design should be theoretically possible, cost considerations aside. Such theoretical computations depend on assumptions on type of rupture surface and strain history. Maximum estimates are controversial, but further expert analysis might produce an adequate criterion.

SECONDARY EFFECTS

The passage of seismic waves, in addition to causing ground shaking and rupture, can cause other damage in certain locations and in certain earth materials. These are called secondary effects and are generally limited to surface and near-surface materials. Many of them, flooding and landslides for example, can be caused by other phenomena. Because of this and because other criteria (e.g., relative to soil strength, flooding avoidance, landslide potential) guard against these hazards, we do not consider them in detail in our discussion of earthquake hazards and here only briefly describe them for completeness. Landslides occur on unstable rock and soil slopes and may be increased after periods of high rainfall (Oakeshott, 1969; Youd and Hoose, 1978).

Vibrational compaction, resulting in the settlement of poorly consolidated sands and silts, has been documented during some earthquakes. The effect is similar to regional subsidence and bearing-capacity failure and often occurs in areas that are affected by these events.

Liquefaction, resulting in lurch cracking, sand boil formation, and lateral spreading is a type of soil failure related to the presence of loose, water-saturated sands. Essentially, the passage of a seismic wave creates a "quick" condition in the sand strata. Structures on or in such sands may sink or float, depending upon their relative buoyancy. Fissuring occurs in overlying soils (lurch cracks), and water/sand mixtures may be expelled (sand boils). If a free face such as a river bank is present, the soil mass may slide toward the free face (lateral spreading). These effects occur chiefly in areas underlain by geologically young, saturated alluvial deposits. Areas underlain by shallow bedrock or dense, older alluvial deposits are generally not affected. Studies have shown that the duration of shaking is important, as well as the relative density of the material. Long duration shaking during a great earthquake may cause liquefaction of materials that would be unaffected by a short, sharp earthquake even if peak accelerations are similar.

More detailed descriptions of the effects of liquefaction and vibrational compaction are provided by Seed (1969), Smith and Fallgren (1975), and Youd and Hoose (1978).

These ground failures are relatively rare during earthquakes, but are spectacular and often cause severe structural damage. They are doubtless the cause of many of the horror stories associated with great earthquakes. Soil engineering techniques have been developed to identify materials subject to these hazards and some mitigational methods exist.

Tsunamis and seiches are, respectively, marine "tidal waves" and smaller oscillations in closed lakes or bays. Both types of wave action can cause damage to near-shore structures (Oakeshott, 1969), (Ritter and Dupre, 1972). These hazards can be prevented by attention to foundation conditions, topographic location, and position near large bodies of water.

THE EFFECTS OF EARTHQUAKES ON UNDERGROUND STRUCTURES

A survey of reports on damages to underground structures such as tunnels and mines leads to several important conclusions:

- Damage underground is less severe than that on the surface, and motion and damage decrease with depth.
- Tunnels in epicentral regions when subjected to accelerations over 0.4 g or velocities over 60 cm/s may suffer severe damage or collapse. Outside of those areas or with less motion, damage is seldom severe.
- Most major damage occurs where movement is along faults cutting the tunnel, or in unstable areas around surface openings.

These conclusions, together with state-of-the-art expertise in earthquake-resistant design, give promise of mitigating seismic hazards by conservative siting and good engineering.

Most accounts of earthquakes are based on the effects on surface structures; data on underground facilities are limited. Accounts compiled by Youd and Hoose (1978) record numerous failures of buried objects such as water pipes, but these were chiefly buried under soft soil or fill. They cite reports by contemporary investigators of the 1906 San Francisco earthquake, who were impressed by the failures in alluvium or in fills, and the infrequency of such failures in rock areas. Damages to tunnels during the 1906 earthquake were mostly at portals or in approach areas.

Damage to water-supply systems during the San Fernando earthquake in 1971 is instructive. The California Aqueduct passes near the earthquake epicenter and suffered no structural damage as a result of the earthquake. Major structures in this system were designed to resist a static lateral force based on 50% of gravity and a vertical force factor of 33% of gravity. In addition, articulation was provided to allow for vertical and horizontal movements. Two older aqueducts of the Los Angeles Department of Water and Power have a terminus in the heavily shaken area. These suffered considerable damage to surface sections such as penstocks, which were shattered by downslope movements of support piers, but damage to underground sections was limited to extensive cracking of unreinforced concrete lining. No collapses or other severe damages to tunnel segments were reported (Moran and Duke, 1975).

Dowding and Rozen (1978), and Stevens (1977), summarized case histories detailing the performance of tunnels and mines during earthquakes. Both of these studies indicate that underground openings are less affected than surface facilities during major earthquakes.

Dowding and Rozen (1978) analyzed 71 water and transportation tunnels that were subjected to earthquakes. The tunnels studies were built between the late 1800's and the present, and represented a wide variety of construction methods and lining types. They found that tunnels subjected to accelerations up to 0.19 g suffered no damage and that up to accelerations of about 0.5 g minor damage such as lining cracks and local rock falls were experienced.

Reported damages were separated into three main groups: shaking, active faulting, and ground or portal damage. Fault displacement, where experienced, always resulted in significant damage. They noted that the hazard of active fault displacement could be largely eliminated from future tunnels by careful site studies.

Approximately 57% of the cases of significant damage to tunnels studied by Dowding and Rozen involved failures near portals or under shallow cover. Some of the tunnel failures also involved surface effects such as landslide damage at portals. Damage at depth consisted primarily of minor rockfalls and formation of new cracks. Their investigations yielded the following conclusions:

- Collapse of tunnels from shaking occurs only under extreme conditions. It was found that there was no damage in both lined and unlined tunnels at surface accelerations up to 0.19 g. In addition, very few cases of minor damage due to shaking were observed at surface accelerations up to 0.25 g. There were a few cases of minor damage, such as falling of loose stones, and cracking of brick or concrete linings for surface accelerations above 0.25 g and below 0.4 g. Most of the cases of similar damage appeared above 0.4 g. Up to surface acceleration levels of 0.5 g, no collapse (damage) was observed due to shaking alone.

- Tunnels are much safer than above-ground structures for a given intensity of shaking. While only minor damage to tunnels was observed in MM-VIII to IX levels,* the damage to above-ground structures at the same intensities is considerable. It should be noted that the effect of the damage is a function of the use of the tunnel relative to that of the buildings.
- More severe but localized damage may be expected when the tunnel is crossed by a fault that displaces during an earthquake. The degree of damage is dependent on the fault displacement and on the conditions of both the lining and the rock.
- Tunnels in poor soil or rock, which suffer from stability problems during excavation, are more susceptible to damage during earthquakes, especially where wooden lagging is not grouted after construction of the final liner.
- Lined and fully grouted tunnels will only crack when subjected to peak-ground motions that result in rock drops in unlined tunnels.
- Tunnels deep in rock are safer than shallow tunnels.
- Total collapse of a tunnel was found associated only with movement of an intersecting fault.

Stevens (1977) investigated effects of earthquakes on underground mines. His study included some instances of tunnel damage, which were also reported by Dowding and Rozen.

Investigations revealed a number of instances in which earthquakes that were strongly felt on the surface were little noticed by persons in caverns or mines. Available reports ranged from instances of earthquakes not being felt in mines, to reports of flooding--possibly indicating fault displacement--to collapses. Stevens concluded that:

---

*For a discussion of MM (Modified Mercalli) scale values see Appendix A, page 33.

- Severe damage is inevitable when a mine or tunnel intersects a fault along which movement occurs during an earthquake. Possible damage includes offset of the workings on either side of the fault, destruction of timbering, collapse of roof and walls of workings, and flooding of the mine--all of which could have disastrous consequences.
- Mines in the epicentral region of strong earthquakes, but not transected by fault movement, may suffer severe damage by shaking. Timbering may fail, and collapse of roof or walls and mine shafts or their linings may occur. Flooding of mine workings by enlargement and interconnection of joints or old fractures is possible.
- Mines outside of the epicentral region are likely to suffer little or no damage from a strong earthquake. Some spalling of rock, falling of loose or weakened roof pendants, or some shaking, are the only effects to be expected, and in many cases the earthquake is not even noticed in mines so located.
- Other factors being equal, it appears reasonable that the severity of damage due to shaking would probably be least when the mine is located in highly competent, unweathered rock. Somewhat greater damage would probably be expected in a mine in weathered or less competent rock; greatest damage would be expected in a mine located in loose, unconsolidated or incompetent rock. However, comparative data on this are inadequate.
- The intensity of shaking below ground is commonly less severe than on the surface due seemingly to rock type. In general, the progression of rock type upward from depth is from highly competent unweathered rock, through weathered rock, to loose unconsolidated rock near the ground surface.

In addition, Stevens summarized the following instrumental data:

> Carder (1950) reporting on the operation of seismographs at the surface and at the 5,000-ft (1,524-m) level in the Homestake Mine, South Dakota, found that the records at 5,000 ft (1,524 m) showed no significant difference from those at the surface, except for the lack of minor local and superficial disturbances at the 5,000-ft level. In a later study, P-waves of one-second period were recorded at a depth of 300 ft (91.4 m) with twice the amplitude recorded at 5,000-ft (1,524-m) depth.

Kanai and Tanaka (1951) compared in detail the seismograms from instruments operated simultaneously at the surface and at depths of 150, 300, and 400 m (492, 984, and 1,312 ft) in the Hatachi Mine; the differences were not large. Subsequently seismographs operated at the surface and at depths of 150, 300, 450, and 600 m (492, 984, 1,476, and 1,969 ft) in a copper mine in Hatachi, recorded a very large number of small earthquakes. The ratio of maximum surface displacement to displacement at 300 m (984 ft) deep was about 6 at the mine and 10 at a school resting on alluvium 6 km (3.7 mi) away. Citing the data on seismograms from mines, Duke and Leeds (1959) state:

> Qualitatively, these researches demonstrate experimentally the following effects at depth:
>
> 1. At short periods, surface displacements are larger than underground displacements.
> 2. The ratio of surface to underground displacement depends on the type of ground. It is greater for alluvium than for weathered rock. It may reach a value of at least 10.
> 3. For wave periods over one second, the ratio becomes comparatively small, approaching unity as the period increases.
> 4. There is a particular average period of incoming waves for which a given type of ground will provide a maximum ratio of surface to underground displacement. If the average period of incoming waves is not approximately equal to this particular period, the ratio will be materially smaller. (pp. 308-309.)

Dowding and Rozen (1978) noted that certain site-specific studies point to deamplification of peak amplitude with depth, greater for soil and less for rock. Ground motion may be amplified upon intersection with a tunnel if wavelengths are the same as the tunnel's diameter or, at most, up to four times the diameter. They reported that measured peak accelerations are recorded at wavelengths much longer than normal tunnel diameters (their study involved tunnels 2 to 6 m in diameter) and therefore, amplification was not judged to be an important factor in damage analysis.

Dowding and Rozen expressed the opinion that in future work, high-frequency motions (not normally measured by strong motion equipment) should receive more attention, as they may contribute to the possibility of relative displacement between blocks along planes of weakness. This high-frequency effect was judged to be a possible explanation of the local spalling of rock or concrete, which was reported in several cases after earthquakes. Higher-frequency waves attenuate more rapidly than lower-frequency waves, and therefore destructive effects of such motions may be expected to extend outward only short distances from the source.

Duration of strong-motion shaking during an earthquake is of great importance since it may cause fatigue failure and lead to large deformations. This mode of failure is dependent on the total number of cycles induced by the ground shaking. Haimson and Kim (1972) found that long duration cyclic loading may cause fatigue failure in intact rock and Brown and Hudson (1974) proved it experimentally for jointed media.

The number of cycles required to cause fatigue failure is usually too large to be reached during a single earthquake. The cumulative cyclic effect, if any, has not been evaluated owing to a lack of available field data.

Dowding and Rozen also reported the results of large blasts on test tunnels. These blasts generated high-frequency waves that resulted in higher-particle velocities than normal earthquake waves. The threshold of damage for explosions was found to be lower than that associated with earthquakes.

Considerable unpublished data exist concerning ground motion and the damage to tunnels and large drill holes at the Nevada Test Site as a result of underground nuclear explosions. A correlation between peak velocity and damage was found.

Observed damage included rock falls in tunnels, sloughing of large-diameter uncased-drill holes and cased-drill holes going out of round. The velocity at the threshold of damage was 2 ft/s. At this velocity, minor rock falls occurred in fracture zones in tunnels and sloughing occurred in large-diameter, uncased-drill holes in desert alluvium.

According to D. L. Bernreuter (LLL) in 1978, damage data obtained from analysis of underground-nuclear explosions were judged to be conservative, because wave fronts from underground nuclear explosions are typically steeper than for earthquakes, and have a much smaller radius of curvature (therefore greater relative displacement) than for earthquakes.

SEISMIC EFFECTS ON WASTE REPOSITORIES

Building on the data on earthquake phenomena, we can relate this to the safety-sensitive components of a nuclear waste repository. Surface facilities will be subjected to the same conditions as other structures on the surface, for which there is a good background in engineering experience. Subsurface facilities will be similar to other deep underground workings. However, certain of the shafts and contained machinery will respond partly as surface and partly as subsurface facilities, and will therefore require engineering that is a blend of the two. Severe shaking could affect surface and shallow facilities, but damage to deeper openings should be effectively minimized by proper siting outside of epicentral regions. The potential for creep or slip along faults should also be minimized by siting outside of active-fault regions. Such motions could seriously affect any of the components of the repository.

Potential earthquake effects during the operating period will be largely dependent upon the geotechnical characteristics of the site selected. Many potential hazards can be eliminated by careful site selection.

Engineering procedures and regulations that exist for surface facilities should be adequate to assure safety during the operational period. However, development is required for analysis and design procedures for deep underground structures if these are to be left open and accessible for much longer time periods.

The Code of Federal Regulations (1978) lists seismic and geologic siting criteria for nuclear-power plants. These might be adapted to waste repositories. The requirements for geologic and seismic investigations are detailed, and there is a requirement to evaluate the maximum or "safe-shutdown earthquake" so the facility can be designed to mitigate or prevent potential off-site exposures that exceed guidelines. The "operating-basis earthquake" must be specified as that which could reasonably be expected to affect the plant during its operating life. The plant is designed to continue operation without undue risk to the public during such an earthquake.

Using a similar system, and classifying the repository components into a hierarchy depending on their critical roles in protecting the public from off-site exposure, analysis- and seismic-design criteria could be developed. The engineering methods to design equipment are available, given the ground motions to be expected. Inasmuch as severe damage to the rock structures themselves can be expected only during major earthquakes and in epicentral regions, long-term post-operational integrity can be enhanced by siting that avoids present- and potential-active faulting. Additional detail on site investigations is given in NUREG-75/094 (1975). Further requirements relative to tsunami flooding, stability of subsurface materials and foundations, and stability of slopes, embankments, and dams, should serve to mitigate hazards associated with the secondary or indirect effects of earthquakes.

As noted previously, damage to surface structures and to underground works, as a result of fault rupture (during major earthquakes) and tectonic creep, are frequently observed. Displacements of up to 9 m appear to have occurred during the 1857 Ft. Tejon earthquake in southern California, and displacements of up to 5 m were observed following the 1906 San Francisco earthquake.

Also, as discussed earlier, historic fault displacements have occurred along Holocene faults that are (or can usually be) recognized during thorough geologic investigations. Tectonic creep is also associated with such faults. Once recognized, active faults can be avoided during site selection. For the short term, such as the operating life of a repository, the historic record provides considerable confidence that avoidance of active faults will provide credible protection against the hazards of surface-fault rupture and tectonic creep.

Ground shaking will be an important design consideration. Even though our data indicate little effect on underground workings, special attention will have to be given to workings and equipment handling waste or that are essential to the protection of personnel and/or the public.

Shafts present a special problem in repository design and operations, since shafts extend from areas of surface influences to depths where different vibration characteristics are likely to exist. Shaft damage was documented during one earthquake in Utah in 1900, and may have occurred during several others (Stevens, 1977).

The waste-handling shafts should receive the same design considerations as other waste-handling structures. One or more of the personnel shafts must be designed as a critical facility to permit evacuation of any injured, or immediate descent of hazards-control teams, etc.

The potential for seismic hazard in the postoperational phase becomes increasingly less susceptible to evaluation as the time of concern lengthens. Historical data provide guidance for events in the range of 100 to 300 years. Detailed geologic studies of glacial and alluvial deposits might provide some worthwhile evidence for past great earthquakes up to about 30,000 years through the recognition of fossil-ground failures (see Sieh, 1978).

Many questions may defy any studies beyond very general probabilistic analyses. However, basic geologic considerations provide assistance in evaluating potential credible hazards.

There are certain possible geologic events to be considered. All faults were once new and have grown to their present dimensions as a result of repeated movement. However, geologic history provides some useful guidelines in such matters. Since the Jurassic Era (150,000,000 years B.C.) tectonic activity in the coterminous United States has been largely confined to the western states, with particular concentration along the Pacific margin. Active tectonism in the eastern United States appears to have ceased during the Triassic Era (about 200,000,000 years B.P.).

Certain aspects of regional and historical geology may be quite ambiguous, but could be very important in the longer term. Thus, several investigators have concluded that certain seismic "trends" can be recognized in the eastern and central United States. For instance, links between the seismicity of the upper Mississippi Valley and the St. Lawrence Lowlands have been drawn.

Different future seismic histories may be deduced if these are judged to represent the onset of rifting of the North American Continent or if they are believed to only reflect isostatic and/or postglacial rebound of the continental block.

There is a need for further geological and geophysical studies to permit identification of active basement faults in areas where seismic activity is not accompanied by surface rupture.

Repeated ground shaking leading to fatigue failure appears to be a seismic process that might affect repository long-term performance. Findings on the possible effects on underground openings have been summarized earlier.

The possibility of movement on an old or a new fault through the repository needs to be addressed. This might be approached through analysis of the historical record. Brooke (1977), for instance, determined the frequency of faults in a number of areas, and found from 0.147 to 10.05 per square mile. Combined with a dating of the faults, this might be combined as in the work of Claiborne and Gera (1974), at the Waste Isolation Pilot Project (WIPP) site, to estimate the probabilities of further faulting. Or the mechanical approach of Apps et al. (1978) might be used to determine the absolute possibility or impossibility of faulting based on present stress regimes and on predicted futures.

Consideration should be given to monitoring of seismic events and of stress-strain relationships as long as possible or as necessary to determine the processes and potential events at a repository site. Studies in active areas indicate that the frequency of microseismic or low-magnitude earthquakes greatly exceeds that of felt earthquakes. Microseismic monitoring of potential repository sites may provide important data on the seismic potential of regions with low frequency of larger events. For an example of the use of microseismic monitoring to deduce the seismicity of a region in which earthquake risk had been historically regarded as low, see Cramer et al. (1978).

APPENDIX A: EARTHQUAKE MECHANICS

In this appendix we briefly review the mechanics of earthquakes and the definitions of magnitude and intensity. We also present an expanded discussion of seismic risk within the coterminous United States. This is intended as supplementary background for the material in the main text. The interested reader may find further details in the cited references.

Stevens (1977) has provided an excellent description of earthquake mechanics. The following section is partly taken from his work.

EARTHQUAKE MECHANISMS

Earthquakes result from stresses that accumulate in rocks composing the outer 700 km of the earth's shell, the origins of these stresses are imperfectly understood. According to the elastic-rebound theory, an earthquake is initiated at a point where the gradually accumulating stress becomes equal to the strength of the rock and rupture occurs. The rupture surface is commonly called a fault. Earthquakes produce longitudinal- and transverse-seismic waves, which travel at speeds depending upon the physical properties of the rock. The "seismic waves" are a representation of the vibratory motion of rock particles as a function of time and space. Longitudinal waves (P, compression waves) always travel faster than transverse waves (S, shear waves). The energy is not propagated uniformly in all directions and the directional pattern of longitudinal waves is not the same as that of transverse waves. The direction of maximum radiation of transverse waves lies parallel and perpendicular to the fault, whereas the minimum longitudinal-radiation pattern is in the direction of the fault plane and at right angles to it. In earthquakes the amplitudes and periods of the transverse waves are usually greater than the amplitudes and periods of the longitudinal waves. P and S waves travel below the surface of the earth. Love waves and Rayleigh waves travel along the surface only. In most cases, the destruction produced by shear waves is greater than that produced by the other types of waves.

Theoretical mechanical considerations may indicate the conditions necessary for rock movement along a fracture. Apps et al. (1978) present such an analysis, considering the principal stresses and effective stresses and the coefficient of sliding friction and conclude that "the difference between the values of the maximum and minimum components of the principal stresses should be small" and ..."it seems reasonably safe to assume that the value of the maximum principal stress could not exceed the value of the minimum principal stress by more than 25 MPa." If these considerations are confirmed, and acceptable measurement techniques are developed, it would be possible to determine the possibility or impossibility of fracture or faulting and earthquake initiation.

The point at depth where faulting is initiated is called the focus or hypocenter. The surface point vertically above the focus or hypocenter is the epicenter. From the focus or hypocenter faulting proceeds along the fault surface in two directions. The direction of movements on the fault may be horizontal, vertical, or a combination. The intersection of the fault surface with the surface of the earth is the fault trace. The epicenter of an earthquake is on the fault trace only when the fault surface is vertical.

Earthquake waves are described by their fundamental physical properties: *transverse- and longitudinal-particle velocity*, acceleration or rate of change of particle velocity, frequency, and amplitude (Richter, 1958). Velocities are measured in centimeters per second. Accelerations are measured in percentage of the gravitational constant, e.g., 0.1 g means one tenth of the force of gravity. Frequencies are measured in cycles per second (Hertz), and amplitudes are in centimeters.

During a major earthquake, a series of accelerations and decelerations will be experienced at any affected point. As the earth absorbs the energy released by the earthquake, the accelerations decrease with distance from the hypocenter, resulting in reduced ground shaking, which in turn results in less damage and perceived-earthquake intensity. The actual ground response at any location is a function of the soils and rocks underlying the particular site as well as the distance and the earthquake hypocenter and the characteristics of the earth and rock material between the site and the earthquake source.

As the waves generated by an earthquake reach a given site, one wave will cause the peak acceleration experienced at that site. This maximum acceleration is generally reported to indicate the earthquake's effect at the particular location. In the Pacoima Dam record during the magnitude 6.5, San Fernando, California earthquake in 1971, a acceleration of 1.25 g was measured by a strong-motion instrument (Cloud and Hudson, 1975).

This acceleration was higher than any that had been previously recorded and provides an illustration of how site conditions can affect a seismic record. The instrument that recorded the 1.25 g acceleration was located on top of a spire-like rock mass, which was a natural analog to a high-rise building. H. B. Seed, in a lecture on September 9, 1978, in Pacific Grove, CA, remarked that the acceleration at the base of the rock spire was amplified by the shape of the spire, which resulted in exaggerated shaking of the top of the spire just as the upper floors of high-rise buildings often experience increased shaking during major earthquakes. He said that evidence for this amplification is provided by Pacoima Dam itself and by the nearby dam-tender's house, neither of which were seriously damaged, whereas both should have been destroyed by the powerful forces that were recorded.

While the peak acceleration is generally reported, the principal measure used in assessing structural response during a major earthquake is the average level of acceleration that is sustained for a period during the earthquake. This continued shaking can induce resonant or harmonic vibrations in the building and can lead to severe damage.

The motion during an earthquake is highly irregular and represents the sum of the harmonic oscillations of the individual waves. Waves with maximum displacement are, in general, not the same as those with maximum acceleration. Highest accelerations are usually associated with small-amplitude waves, and the large amplitudes are usually associated with low frequencies and low accelerations (Richter, 1958).

Perceptible motion includes a greater proportion of slow oscillation with long periods as distance or the magnitude of the shock increases. The increase in long-period waves with distance is in part a filtering effect; the shorter-period waves are attenuated (die out) more rapidly.

As earthquake waves pass from one geologic medium to another, they may be reflected, refracted, or attenuated, and they may change velocity and period, making the ground motion complex. In general, earthquake waves, in passing from more dense rock to less dense alluvial deposits or to water-saturated materials, tend to reduce velocity and increase in amplitude and acceleration. Ground motion lasts longer on loose, water-saturated, incompetent materials than on rock, and structures located on such materials suffer greater damage than those located on rock (Oakeshott, 1969).

The effects of ground motion on structures depend not only on the characteristics of the ground motion but also on the vibration characteristics of the structures themselves. According to Dr. Seed's lecture remarks, the vibration characteristics of a building are conveniently expressed in terms of its fundamental frequency of vibration--that is the predominant frequency with which the building would vibrate if it were pulled sideways at the top and then suddenly released.

If the base of a building is subjected to a series of vibrations with the same frequency as the natural frequency of the building, large-amplitude motions and large forces develop in the building. However, if the same building is subjected to vibrations having frequencies very different from the natural frequency of the building, comparatively small effects will be induced in the structure. Therefore, Seed maintains, in order to minimize the effects of ground shaking on buildings, it is desirable to develop as much difference as possible between the fundamental frequency of the building and the predominant frequency of the ground motions.

This requires a complex engineering analysis in which the motion characteristics of a typical earthquake that may affect a building are compared to building frequencies based on alternative design concepts. The wave spectrum generated by an earthquake will usually contain some waves that are similar to the fundamental frequency of the building, and it is often necessary to additionally brace the structure to resist lateral forces imposed or to build in a way such that the worst hazards are mitigated, accepting the risk of some damage should a major earthquake strike.

The latter process is usually adopted for buildings of ordinary importance, e.g., a warehouse or private residence, while a combination of response analysis and resistive design is adopted for major facilities such as hospitals or fire stations.

Large earthquakes are often preceded at intervals of hours or days by small foreshocks. A foreshock increases the stress on the fault in its neighborhood and thereby may hasten the advent of the main shock, although the final increment of gradually accumulating stress may also be a result of some external force (such as tidal stress) or some weakening mechanism in the rock (such as increased pore-fluid pressure). A large shallow earthquake is typically followed by thousands of aftershocks of smaller magnitude. The frequency of occurrence of aftershocks is greatest immediately following the principal shock and decreases rapidly with time so that the sequence usually ends within one or two years. A large earthquake sometimes is followed within a few hours, days, or months by another of similar or greater magnitude in the same area. Occasionally swarms of small earthquakes occur without any principal large shock.

The majority of earthquakes and those with the greatest energy occur in the upper 40 km of the earth's crust. Deeper earthquakes occur with decreasing frequency down to 250 km, below which the frequency of occurrence per unit depth interval becomes about constant to a depth of 700 km (Richter, 1958).

EARTHQUAKE MAGNITUDE

The energy released in the greatest earthquakes is very roughly equivalent to 10,000 of the original atomic bombs, such as the one dropped on Hiroshima; the energy released in the smallest-felt earthquakes is approximately equivalent to the energy released in the explosion of 1 lb (453.6 grams) of TNT. Because it is not simple to calculate the energy of earthquakes from generally available data, Richter (1958) devised a magnitude scale for classifying earthquakes by "size" or "strength" at the earthquake source on the basis of instrumental data. For shallow earthquakes the scale is based on the maximum recorded amplitude at a standard torsion seismograph 100 km from the source. The scale is logarithmic; a magnitude-8 earthquake represents recorded amplitudes 10 times larger than those of a magnitude-7 earthquake, 100 times larger than a shock of magnitude-6, etc. Empirical tables were constructed for calculation of the magnitude at all epicentral distances, for various focal depths, and for several types of waves. Each whole-unit increase in magnitude represents approximately a 30-fold increase in energy release.

Subsequent to the development of the Richter-magnitude (M_L) scale, other measures of magnitude have been developed using seismic-body waves (M_b) or seismic-surface waves (M_s). Also, the concept of seismic moment (M_o) was developed, where M_o relates event size to the size of surface faulting.

It is often unclear which modern measure-of-event magnitude should be used. For large events, controversy has developed concerning the possible saturation of M_s relative to M_o as a measure of event size. Various attempts at international standardization have been made, and as a result M_s has become the standard by which event size is judged when it is available in the record.

Available records and historic experience indicate that there is an upper bound to the maximum size of earthquakes. Richter (1958) noted this and attributed it to the limits in the ability of the earth's crust to accumulate strain. The maximum earthquake recorded had a magnitude of about 8.9 and this was judged by Richter to be about the expectable limit.

Except near the upper end of the range (above about $M = 8$), earthquakes appear to follow exponential distribution. That is, approximately 10 times the number of earthquakes of $M = 4$ than $M = 5$ may be expected, etc.

EARTHQUAKE INTENSITY

Whereas magnitude is an instrumental measure of the size or strength of an earthquake, seismic intensity is a somewhat subjective measure of the violence of shaking at a given point. An earthquake has one magnitude, but a range of intensities.

Prior to the development of instrumental methods, investigators sought to analyze earthquakes based upon observed intensities. As summarized by Richter, scales of intensity were developed to regularize this process. These efforts gradually evolved and led to the development of the Modified-Mercalli Scale, which is generally used today for geologic analyses of earthquakes and construction of isoseismals (lines of equal intensities). The Modified-Mercalli Scale is presented in Table A-1.

Higher intensities are reached only during major earthquakes and then are experienced in limited areas near the earthquake epicenter or adjacent to ruptured segments of the causative fault. Small-to-moderate magnitude earthquakes (for example, M 3 to 4) generally do not generate intensities above the range IV to V even in epicentral areas.

Studies of earthquakes show that intensity is a function of both proximity to the earthquake epicenter and of ground conditions. Thus, a site on unconsolidated alluvium located miles from the epicenter of a major earthquake may be severely shaken because of amplification of the seismic wave, while a closer site on hard, crystalline rock may not experience severe shaking because of the high frequency, low-amplitude character of the earthquake waves as they pass though the bedrock.

Richter (1958) notes that on a regional basis, "Isoseismals drawn from adequate data are rarely circular and often show elliptical elongation in the direction of the major structural trends. There is often a longer continuous extent of competent rocks along a structural trend than in the transverse direction; when the waves emerge from such rocks into alluvium or unconsolidated sediments there is considerable absorption, accompanied by increase in local intensity."

This phenomenon was well illustrated during the San Fernando earthquake of February 9, 1971, when unusually severe damage was experienced in the Sylmar area located on an alluvial plain at the toe of the crystalline San Gabriel Mountains (Oakeshott, 1975). This damage included the collapse of two hospital buildings.

Energy released during an earthquake is gradually absorbed by the rocks and soils of the earth's crust and the earthquake waves eventually are attenuated

TABLE A-1. Modified-Mercalli Intensity Scale of 1931 (abridged and rewritten).[a]

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.
V.	Felt outdoors; direction estimated. Sleepers wakened. Liquids disturbed, some spilled. Small unstable objects displaced or upset. Doors swing, close, open. Shutters, pictures move. Pendulum clocks stop, start, change rate.
VI.	Felt by all. Many frightened and run outdoors. Persons walk unsteadily. Windows, dishes, glassware broken. Knicknacks, books, etc., fell off shelves. Pictures off walls. Furniture moved or overturned. Weak plaster and masonry D cracked.[b] Small bells ring (church, school). Trees, bushes shaken (visibly, or heard to rustle--CFR).
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 (also unbraced parapets and architectural ornaments--CFR). 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 collapses. 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. (General damage to foundations--CFR.) 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.

TABLE A-1. (cont'd.)

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.

[a]See Richter, 1958.

[b]The quality of masonry, brick or otherwise, is specified by the following lettering:

Masonry A. Good workmanship, mortar, and design; reinforced, especially laterally, and bound together by using steel, concrete, etc.; designed to resist lateral forces.

Masonry B. Good workmanship and mortar; reinforced, but not designed in detail to resist lateral forces.

Masonry C. Ordinary workmanship and mortar; no extreme weaknesses like failing to tie in at corners, but neither reinforced nor designed against horizontal forces.

Masonry D. Weak materials, such as adobe; poor mortar; low standards of workmanship; weak horizontally.

smaller. Except for the local variations noted above, lesser intensities are experienced at progressively greater distances from the earthquake epicenter until the earthquake waves fall below the level of human perception.

In general, the area affected by a large earthquake will considerably exceed that affected by a small-to-moderate earthquake, a fact that is of considerable importance in the assessment of historic earthquakes for which no instrumental data are available. Thus, if the historic record indicates that a particular earthquake was widely felt, its magnitude was probably greater than that of an earthquake that was felt dramatically but within only a limited area.

A note of caution regarding the above generalization is in order. Algermissen and Perkins (1976) summarize data indicating that attenuation is less in the eastern and midwestern states beyond about 50 km from the epicenter than is attenuation in the western states. As a result, for acceleration of 0.01 g with earthquakes greater than magnitude 6.6 the area affected in the east is 10 times that in the west. However, for higher accelerations, e.g., 0.1 g, which may be reached closer to the epicenter, the ratio is 1.4 or less.

EARTHQUAKE FREQUENCY

Since earthquakes are the result of the rapid release of stresses that have slowly accumulated in the earth's crust, they are not truly random events. The historic record indicates that earthquakes occur most frequently in tectonically active areas characterized by geologically youthful mountain building, and are infrequent in other areas (Richter, 1958). Some earthquakes are experienced in regions that are generally regarded as seismically stable (Algermissen and Perkins, 1976). Earthquake distribution within the coterminous United States will be discussed in more detail later.

The frequency with which earthquakes occur may be expressed as the recurrence interval. Estimates of recurrence intervals for major earthquakes on the San Andreas Fault and Coyote Creek Fault have been made (Wallace, 1970), (Clark et al., 1972), and (Sieh, 1978). These estimates are based upon geologic evidence and in the case of Clark et al., and Sieh, include ^{14}C dates of displaced horizons.

In areas where evidence for Quaternary faulting is absent, estimates of recurrence intervals must be based on often very limited historic data (Algermissen and Perkins, 1976). In such circumstances, it is often difficult to relate earthquakes to other geologic features, although Algermissen and Perkins (1976) established correlations between certain structual trends and tectonic elements, and increased earthquake frequency in the eastern and midwestern United States.

Evidence from areas such as China and Turkey where long historic records are available suggests that recurrence intervals for major earthquakes fluctuate with time. Similar fluctuations for the southern segment of the San Andreas Fault system are also indicated by the work of Sieh (1978). In the case of the San Andreas Fault, recurrence intervals between major earthquakes average 160 years but vary from 50 to about 300 years.

During recorded history, the San Andreas Fault has exhibited contrasting styles of behavior between its individual reaches. In general the northern and southern segments of the fault have been seismically quiet except for infrequent large earthquakes. The intervening central segment, approximately 100 km in length, has been creeping relatively continuously throughout the 20th century and is characterized by frequent small to moderate earthquakes.

EARTHQUAKE DISTRIBUTION

Within human experience, earthquakes are not uniformly distributed in time or space. Rather, earthquakes are more frequent in certain portions of the earth than in other areas and there is evidence for worldwide and local variations in the frequency of earthquakes (Richter, 1958)(U.S.G.S., 1976).

To some extent, perceptions concerning relative seismicity are subjective and are based upon the amount of attention given to geologic evidence and historic records for a given area. For instance, the San Francisco Bay Region is generally regarded as an area of high seismic activity partly because of the widespread effects of the great San Francisco earthquake of 1906. However, records compiled by Youd and Hoose (1978) showed only four significant earthquakes with epicenters in the Bay Region during the period 1907-1977, and two of these caused negligible damage.*

---

*Note added in press.

On August 6, 1979, a strong earthquake (M 5.9) struck the southern San Francisco Bay Region. This was the strongest earthquake in the region in 68 years. It was felt widely in Central California and was perceptible as far east as Reno, NV. Despite its size the earthquake caused few casualties and relatively minor structural damage. The epicentral region, north of Hollister, California, had been extensively studied and heavily instrumented by the U.S. Geological Survey and therefore this earthquake is expected to yield important data concerning earthquake mechanisms and effects.

Evidence for variations in earthquake activity with time have been noted previously. Sieh (1978) documented variations in the recurrence interval for major earthquakes along the southern segment of the San Andreas Fault during a period of nearly 1500 years based on ^{14}C dates. In the San Francisco Bay Region, historic records indicate that seven major earthquakes occurred during the 70 years that culminated in the great earthquake of 1906 (Youd and Hoose, 1978). During the 73 years since 1906, only five earthquakes of any significance have occurred in the same area and none of these caused widespread damage.

To some extent such historic variations may reflect exaggerated reports of the effects of past construction practices (for example, collapses of 19th century adobes are poor indicators of high intensities). However, considerations of areas affected indicated that several 19th century events would be rated as major earthquakes were they to occur today.

Algermissen and Perkins (1976) have analyzed historic seismic data and developed probabilistic estimates of maximum-bedrock accelerations (90% probability of not being exceeded during a 50-year period) for different portions of the coterminous United States. As part of their research, they identified 71 areas where historic seismic activity appeared to exceed "background" levels. The findings of Algermissen and Perkins are reproduced as Figs. A-1 and A-2. Areas of major seismic activity are largely concentrated in the western United States, but several areas of increased earthquake probability appear in the eastern and midcontinent areas.

The concept developed by Algermissen and Perkins provides probabilities of the occurrence of maximum accelerations of interest to facilities with ordinary lifetimes. However, a consequence of the method of analysis chosen is that given enough time the level of acceleration shown in Fig. A-1 will be attained. This time period is given by the equation

$$\ln(0.90) = -\frac{50}{Ry(a)} , \qquad \text{(A-1)}$$

where Ry(a) is the return period in years for the acceleration mapped.

$$Ry(a) = \frac{50}{0.1054} \simeq 475 \text{ years} . \qquad \text{(A-2)}$$

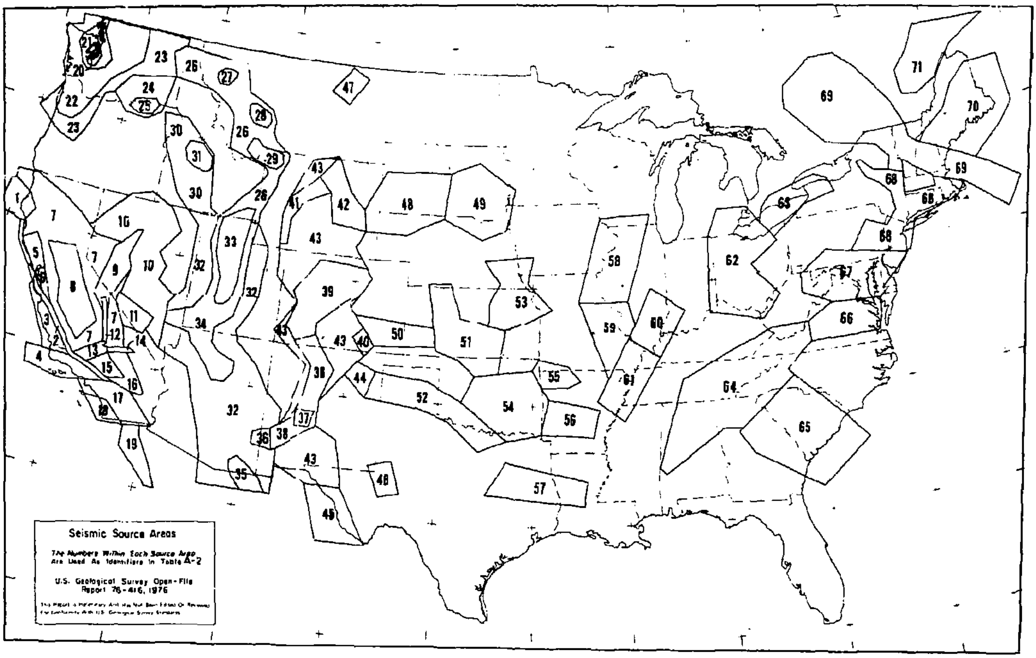


FIG. A-1. Seismic source areas.

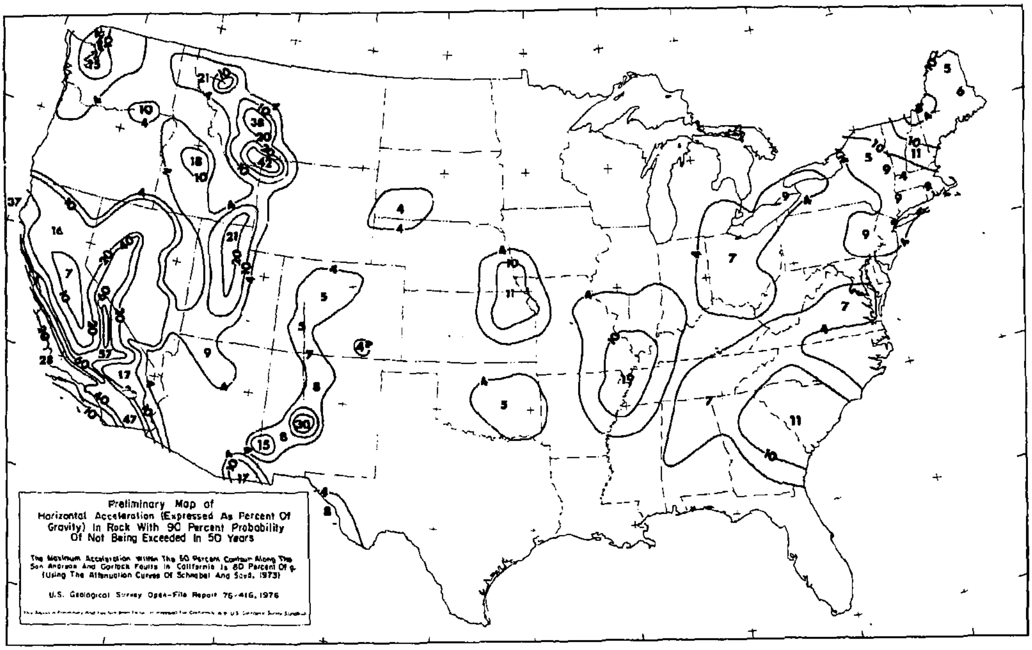


FIG. A-2. Preliminary map of horizontal acceleration in rock with 90% probability of not being exceeded in 50 years.

Presumably return periods for higher accelerations could be computed using the methods developed by Algermissen and Perkins but the uncertainty about the significance of the data developed would increase rapidly since the calculations would increasingly strain the available data base.

Seismic-source areas shown in Fig. A-2 are based largely on historic earthquake epicenters except for California and portions of Nevada and Utah, where evidence of Holocene faulting was used to define and shape source areas. In California the effects of fault-rupture length were also considered in determining accelerations. The result is that California earthquakes must be treated as linear rather than as point sources. In the remainder of the United States, source zones were defined based on epicenter distributions. In the Great Plains and southern Rocky Mountains, the zones thus defined were extended to include mapped faults where epicentral clusters could be seen to relate to such faults (Algermissen and Perkins, 1976).

Oliver et al. (1970) found a number of small, post-glacial, high-angle faults in a zone that extends north from east of New Hyde Park, New York, east of Lake Champlain and into Quebec. It could not be determined if these faults were of tectonic origin; no relationships between Holocene faulting and "seismic trends" described by several previous investigators have been established in the northeastern United States. Therefore, historic earthquake data were used during the analysis of the northeastern United States. In other portions of the United States, source areas established by Algermissen and Perkins were based on historical seismicity and tectonic trends.

Seismic parameters used by Algermissen and Perkins are reproduced in Table A-2. The values of b_I given in Table A-2 are constants used in the analysis equation:

$$\log N = a + b_I I_O \quad , \qquad \text{(A-3)}$$

where N is the number of yearly occurrences with maximum intensity I_O.

The number of Modified-Mercalli Maximum-Intensity V events per 100 years listed in Table A-2 is not a direct estimate of earthquake density in a given source zone since the areas of the zones vary considerably.

TABLE A-2. Seismic parameters for source zones.

Zone No.[a]	No. of Modified-Mercalli Maximum-Intensity V's /100 years	b_I	Maximum I_o	Maximum M_c[b]
1	245.2	-0.50	X	7.3
2	110.0	-0.40 up to XI then flat	XII	8.5
3	27.2	-0.45	XI	7.9
4	75.1	-0.45	XI	7.9
5	14.9	-0.50	X	7.3
6	44.4	-0.45	XI	7.9
7	299.6	-0.53	VIII	6.1
8	7.3	-0.49	VI	4.9
9	208.0	-0.40	XI	7.9
10	125.0	-0.51	VIII	6.1
11	80.1	-0.53	VIII	6.1
12	43.0	-0.43 up to XI then flat	XII	8.5
13	99.4	-0.45	XI	7.9
14	34.9	-0.45	XI	7.9
15	0.0	-0.53	VIII	6.1
16	33.9	-0.50	X	7.3
17	223.0	-0.45	XI	7.9
18	2.8	-0.50	X	7.3
19	613.6	-0.52	X	7.3
20	14.8	-0.29	VIII	7.1
21	79.8	-0.59	VII	5.5
22	80.1	-0.76	VI	4.9
23	12.7	Not applicable	V	4.3
24	6.0	Not applicable	V	4.3
25	8.5	-0.59	VII	5.5
26	137.1	-0.72	VI	4.9
27	99.9	-0.67	VII	5.5

TABLE A-2. cont'd.

Zone No.[a]	No. of Modified-Mercalli Maximum-Intensity V's /100 years	b_I	Maximum I_0	Maximum M_c [b]
28	35.3	-0.32	IX	6.7
29	90.4	-0.36	X	7.3
30	10.5	-0.26	VII	5.5
31	84.6	-0.63	VII	5.5
32	17.0	-0.56	VI	4.9
33	126.8	-0.56	IX	6.7
34	71.0	-0.56	VII	5.5
35	23.0	-0.56	VIII	6.1
36	15.3	-0.54	VII	5.5
37	15.6	-0.31	VIII	6.1
38	31.1	-0.54	VII	5.5
39	21.5	-0.54	VII	5.5
40	2.7	-0.40	VI	4.9
41	27.6	Not applicable	V	4.9
42	11.1	-0.40	VI	4.9
43	23.0	Not applicable	V	4.3
44	13.8	Not applicable	V	4.3
45	6.7	-0.31	VIII	6.1
46	2.7	-0.40	VI	4.9
47	2.7	-0.40	VI	4.9
48	14.7	-0.54	VII	5.5
49	10.3	Not applicable	V	4.3
50	4.6	Not applicable	V	4.3
51	7.4	-0.53	VI	4.9
52	13.0	-0.40	VI	4.9
53	9.3	-0.24	VIII	6.1
54	21.2	-0.55	VII	5.5
55	1.7	Not applicable	V	4.3

TABLE A-2. cont'd.

Zone No.[a]	No. of Modified-Mercalli Maximum-Intensity V's /100 years	b_I	Maximum I_o	Maximum M_c [b]
56	5.7	-0.53	VI	4.9
57	7.8	-0.55	VII	5.5
58	0.6	-0.50	VII	5.5
59	16.0	-0.50	VIII	6.1
60	16.0	-0.50	VIII	6.1
61	84.5	-0.50	X	7.3
62	22.0	-0.50	VIII	6.1
63	22.1	-0.64	VIII	6.1
64	54.4	-0.59	VIII	6.1
65	19.9	-0.33	X	7.3
66	13.0	-0.59	VIII	6.1
67	7.8	-0.59	VII	5.5
68	69.1	-0.67	VIII	6.1
69	117.6	-0.59	IX	6.7
70	33.5	-0.65	VIII	6.1
71	21.7	-0.49	X	7.3

[a]The zones are shown in Fig. A-1.

[b]$M_c = 1.3 + 0.6\ I_o$. If the observed M lies between $M_c - 0.3$ and $M_c + 0.3$, intensity I_o is assigned.

As previously noted, earthquake movement attenuates more slowly in the eastern and midcontinent areas than in the western states. The general effect is an extension of the shaken area several tens of kilometers further beyond the source boundary in the east than in the western United States (Algermissen and Perkins, 1976).

The minimum acceleration contour mapped by Algermissen and Perkins was 0.04 g. Their research indicated that below the 0.04-g contour level, ground shaking effects are largely controlled by earthquakes of M = 4.0 or less, and that wind loadings on structures are expected to be the controlling factors in design so that earthquake shaking, at the level of hazard assumed, is not likely to be important (Algermissen and Perkins, 1976).

In the eastern and central United States, regions that have experienced reasonably large damaging earthquakes in the past are outlined by the 0.10-g contour. While higher accelerations doubtless occurred during these major earthquakes, recurrence rates are much lower in the eastern states than for comparable events in the west and therefore the statistical acceleration levels are reduced (Algermissen and Perkins, 1976).

Regions in the United States where intensities of VII or less have been experienced as isolated events generally lie in the hazard-map areas that indicate below 0.04-g acceleration. This does not mean that damaging events cannot occur in these areas, but that for any given point in those regions there is no more than a 10% likelihood that accelerations larger than 0.04 g will be experienced in 50 years (Algermissen and Perkins, 1976).

Algermissen and Perkins tested the effects of changes in various assumptions relevant to their hazard map. They found that it would take a relatively large change in return period (e.g., greatly increased earthquake frequency) in order to double the mapped-peak accelerations. They also found relatively little influence on zone boundaries as a result of changes in seismic activity rates.

They did find a considerable effect upon their hazard data as a result of increasing the assumed maximum magnitude earthquake expectable within a given source area. The resulting effect was found to be dependent upon the number of occurrences assumed for the new maximum magnitude earthquake and was of little significance for an increase in magnitude less than or equal to one Richter magnitude or an assumed return period of greater than 500 years. The effect of increasing assumed-maximum magnitude and return period was found to be least in those portions of the map where high-motion levels already exist, but strongly affects areas where present motion levels are low.

Algermissen and Perkins found that variations in the attenuation functions would produce somewhat larger accelerations. For a standard deviation of 0.75 (roughly a factor of 2 in the acceleration curves), the acceleration at a given return period is increased over the zero-variability case by about 25%.

APPENDIX B: EARTHQUAKE PREDICTION

Earthquake prediction is a subject that has captured considerable public and professional attention during the past decade. In view of the potential to avert widespread death and reduce destruction, successful earthquake prediction is regarded by many as a desirable scientific goal and a contribution to public safety (Press, 1975).

A reliable means of earthquake prediction would be particularly valuable during the operating period of a nuclear-waste repository because it would permit an orderly suspension of waste-emplacement operations and provide time to secure facilities in order to minimize damage and radiation releases. However, it is instructive to compare the earlier optimistic views of Kisslinger and Wyss (1975) and Press (1975), regarding earthquake prediction, with the more cautious expressions of more recent investigators (Allen et al., 1978, Ward, 1979). In part, the more recent caution reflects findings concerning potential socioeconomic and legal aspects of an earthquake prediction, whether correct or incorrect (Haas and Mileti, 1977), and in part, it reflects the recognition that it will be necessary to acquire considerable geophysical data and a better understanding of earthquake mechanisms before reliable earthquake precursors can be identified (Allen et al., 1978, Ward, 1979).

In recent years, field instrument arrays have been deployed in seismically active areas and in at least two recent cases, instruments have closely monitored geophysical events preceding earthquakes (Iwatsubo and Mortensen, 1979, McNally et al., 1979). Also, reanalyses of older data have led to the recognition of possibe precusory phenomena for a number of historic earthquakes (Press, 1975). However, Allen et al., (1978) and Ward (1979) have emphasized that apparent precursors to certain earthquakes have not been seen prior to other events and that precursory phenomena monitored in one region may not appear in others because of differences in geological structures and the mechanics of specific earthquakes.

There are also the problems posed by anomalous geophysical events, which may or may not be earthquake precursors. For example, the so-called "Palmdale Bulge," an area in Southern California where geodetic measurements have identified as much as 45 cm of uplift since the early 1960s, began to rise prior to the destructive 1971 San Fernando earthquake (Bennet, 1977). Similar uplift preceded the destructive 1964 Niigata earthquake (Castle, 1977). However, an examination of old survey records has established that a similar uplift occurred in the Palmdale area sometime between 1897 and 1914. Castle (1977) stated that this uplift was not accompanied by a major earthquake although later studies reported by Ward (1979) indicate that the southern boundary of this uplift extended to the vicinity of Lompoc and Long Beach, California, where large earthquakes were experienced in 1927 and 1933, respectively, shortly after this uplift partly subsided.

Another important problem associated with earthquake prediction is the time frame in which prediction may be possible. A moderate earthquake with a magnitude of about 5 on the Richter scale may have precursory effects that last for about four months while precursors to a large earthquake ($M = 7$) may persist for about 14 years (Press, 1975), and provide information that is too imprecise to permit a sufficiently accurate forecast to meet societal needs (Allen et al., 1978). This problem is significant since it is the larger earthquakes ($M > 6$) that have the potential to cause widespread damage and casualties and are therefore desirable to predict. It will be necessary to recognize short-term vs long-term precursors before practical earthquake predictions will be possible.

A number of precursory phenomena have been described. These are listed in Table B-1 along with a brief description of the physical effects involved, methods of detection, and some results of studies concerning these phenomena.

It should be emphasized that this summary is based upon preliminary data and that *none* of the potential precursors listed have been subjected to the rigorous scientific study and review that will be necessary before their value as earthquake predictors can be determined.

TABLE B-1. Potential earthquake precursors.

Phenomenon	Physical process	Method of observation	Remarks
1) Seismicity: a) Changes in seismic patterns.	Partial releases of strain energy accumulating in seismically active regions, through small earthquakes and tectonic creep.	Seismographic data, creepmeters, repeated surveys, strain meters, geologic observations of past earthquake activity with dating techniques to establish frequency and age of events.	Changes in frequency and focal mechanisms may be precursors (Press, 1975), (Kisslinger and Wyss, 1975). Microseismic foreshock activity prior to Oaxaca, Mexico, earthquake, Nov. 29, 1978, showed pattern that closely delineated main earthquake epicenter (McNally, 1979). Geologic techniques described by Sieh (1978), survey techniques by Ward (1979).
b) Seismic gaps.	Reduction in release of accumulating strain energy causes strains to build to high levels providing sufficient energy for large earthquake (locking of fault segments).	Seismographic data, creepmeters, analyses of historic seismicity, strain meters.	Main use to identify regions where major earthquake may be expected (Perez and Jacob, 1979), (Kisslinger and Wyss, 1975), (Ward, 1979), potential long-term and generalized precursor. Quiet period noted in microseismic activity immediately preceding Oaxaca, Mexico, earthquake, Nov. 29, 1978 (McNally, 1979). If general, could provide final warning system.
2) Changes in physical properties of rocks.	Dilatancy theory, formation of microcrack network begins in rock when shear stresses approach about one-half breaking strength of rock, leads to nonelastic volumetric expansion and to changes in geophysical properties of effected rocks. Movements of water into fractures may be important triggering mechanism.	Seismic velocities, electrical resistivity, magnetic properties, gravity surveys.	Refs.: Press (1975), Kisslinger and Wyss (1975), Allen et al. (1978), Ward (1979). Anticipated physical changes not always observed or uncertain, problems with instrument sensitivity and "noise." Seismic velocity changes observed in Soviet Union, not confirmed for San Andreas Fault system in California.

TABLE B-1. cont'd.

Phenomenon	Physical process	Method of observation	Remarks
3) Surface effects.	Ground movements in response to dilatancy or rapid increase in tectonic forces, changes in slope, elevation, horizontal position.	a) Instrumental: Tiltmeters, repeated precise surveys, creepmeters, tide gauges.	Refs.: Press (1975), Kisslinger and Wyss (1975), Allen et al. (1978), Ward (1979), Iwatsubo and Mortensen (1979). On several occasions, changes in tilt meters found to precede small to moderate earthquakes along Calaveras Fault in central California. Problems with need for extensive instrument arrays, "noise," nonseismic effects, e.g., earthtides, soil properties.
		b) Human: Observations of gross changes.	Ref.: Allen et al. (1978). Historic record includes accounts of islands rising from sea prior to earthquakes, primarily receiving attention in Japan and China.
4) Hydrologic effects.	Ground water movements influenced by fracture formation and aperture changes, possible pressure effects in confined aquifers.	Water level observations, temperature measurements, turbidity measurements.	Refs.: Press (1975), Anderson et al. (1978). Receiving attention in China and Soviet Union, U.S. research recommended.
5) Geochemical effects.	Microfracturing releases radon (Rn) gas, which forms in rocks by radioactive decay.	Radiation detectors, microchemical methods.	Refs.: Press (1975), Anderson et al. (1978). Regarded as good precursor in Soviet Union and China.
6) Unusual animal behavior.	Unknown, relates to heightened animal senses relative to human level.	Observation of animal behavior by general public.	Refs.: Anderson et al. (1978), Ward (1979). Receiving serious attention in China, many accounts in historic record, difficult to assess validity, also reported to precede other geologic disasters such as large landslides.

REFERENCES

Albee, A. L., and J. L. Smith (1966), "Earthquake Characteristics and Fault Activity in Southern California," in Engineering Geology in Southern California (L. A. Section, Association of Engineering Geologists, Los Angeles, California), pp. 9-34.

Algermissen, S. T., and D. M. Perkins (1976), A Probabilistic Estimate of Maximum Acceleration in Rock in the Contiguous United States, U.S. Geological Survey Open File Report 76-416.

Allen, C., D. Anderson, and H. Kanamori (1978), "Predicting Earthquakes," California Geology 31, No. 10, pp. 237-241.

Apps J. A., N. G. W. Cook, and Paul Witherspoon (1978), An Appraisal of Underground Radioactive Waste Disposal in Argillaceous and Crystalline Rocks: Some Geochemical, Geomechanical, and Hydrogeological Questions, Lawrence Berkeley Laboratory, Berkeley, California, LBL-7047.

Bennett, J. (1977), "Palmdale 'Bulge' Update," California Geology 30, No. 8, pp. 187-189.

Bonilla, M. G. (1970), "Surface Faulting and Related Effects," in Earthquake Engineering, R. L. Wiegel, Ed. (Prentice-Hall, Englewood Cliffs, New Jersey), pp. 47-74.

Bonilla, M. G., and J. M. Buchanan (1970), Interim Report on World-wide Historic Surface Faulting, U.S. Geological Survey Open File Report, unnumbered.

Brooke, J. P. (1977), An Estimation of the Statistical Distribution of Faulting in Selected Areas and the Design of an Exploration Model to Detect these Faults, Lawrence Livermore Laboratory, Livermore, California, UCRL-13815.

Brown, E. T., and J. A. Hudson (1974), "Fatigue Failure Characteristics of Some Models of Jointed Rock," Earthquake Engineering and Structural Dynamics 2, 379-386.

Brune, J. N. (1970), "Tectonic Stress and the Spectra of Seismic Shear Waves from Earthquakes," J. Geophys. Res. 75 (26), 4997-5009.

Burkland and Associates (1978), Geologic and Seismic Hazards Investigation, Community Center Building Addition, Report to City of Fremont by Burkland and Associates, Palo Alto, California.

California Energy Resources Conservation and Development Commission (1978), Status of Nuclear Fuel Reprocessing Spent Fuel Storage and High-Level Waste Disposal, Draft Report.

Carder, D. S. (1950), "Seismic Investigations on the 5000-Foot Level, Homestake Mine, Lead, S. D.," Earthquake Notes 21, 13-14.

Castle, R. O. (1977), "Palmdale 'Bulge' - A Geological Puzzle," California Geology 30, No. 8, p. 189.

Claiborne, H. C., and F. Gera (1974), Potential Containment Failure Mechanisms and their Consequences at a Radioactive Waste Repository in Bedded Salt in New Mexico, Oak Ridge National Laboratory, Oak Ridge, TN, ORNL-Tm-4636.

Clark, M. M., A. Grantz, and M. Rubin (1972), "Holocene Activity of the Coyote Creek Fault as Recorded in the Sediments of Lake Cahuilla," in The Borrego Mountain Earthquake of April 9, 1968, U.S. Geological Survey Prof. Paper 787, pp. 112-113.

Cloud, W. K., and D. E. Hudson (1975), "Strong Motion Data from the San Fernando, California Earthquake of February 9, 1971, "in San Fernando, California Earthquake of 9 February, 1971, California Division of Mines and Geology, Bulletin 196.

Code of Federal Regulations (1978), Title 10, Energy (U.S. Government Printing Office, Washington, D.C.).

Cramer, C. H., T. R. Toppozada, D. L. Parke (1978), "Seismicity of the Foothills Fault System between Folsom and Oroville, California," Seismol. Soc. Amer. Bull. 63, 245-249.

Dowding, C. H., and A. Rozen (1978), "Damage to Rock Tunnels from Earthquake Shaking," J. Geotech. Eng. Div. 104, 175-191.

Duke, C. M., and D. J. Leeds (1959), "Effects of Earthquakes on Tunnels," in Protective Construction in a Nuclear Age, Proceedings of the Second Protective Construction Symposium (Santa Monica, California, J. J. O'Sullivan, Ed. (Macmillan, New York) Vol. 1, pp. 303-328.

Greensfelder, R. W. (1974), Maximum Credible Rock Accelerations from Earthquakes in California, California Division of Mines and Geology, Map Sheet 23.

Haas, J. E., and D. S. Mileti (1977), "Socioeconomic Impact of Earthquake Prediction on Government, Business, and Community," California Geology 30, No. 7, pp. 147-160.

Haimson, B. C., and C. M. Kim (1972), "Mechanical Behavior of Rock under Cyclic Loading," in Stability of Rock Slopes, Proc. of the 13th Symposium of Rock Mechanics, E. J. Cording, Ed. (Amer. Soc. Civ. Eng., New York), pp. 845-863.

Heckman, R. A., D. F. Towse, Dana Isherwood, Ted Harvey, Thomas Holdsworth (1978), High Level Waste Repository Site Suitability Study--Status Report, Lawrence Livermore Laboratory, Livermore, California, UCRL-52633.

Housner, G. W. (1969), "Engineering Estimates of Ground Shaking and Maximum Earthquake Magnitude," in Proc. World Conf. Earthquake Engineering, 4th (Editorial Universitaria, Santiago, Chile).

Hudson, D. E. (1974), "Destructive Earthquake Ground Motions," in Publication AMD, Vol. 8 Applied Mechanics in Earthquake Engineering, W. D. Iwan, Ed. (American Society of Mechanical Engineers, New York), pp. 1-34.

Interagency Review Group on Nuclear Waste Management (1978), Subgroup Report on Alternative Technology Strategies for the Isolation of Nuclear Waste (draft), Appendix A, "Isolation of Radioactive Wastes in Geologic Repositories: Status of Scientific and Technological Knowledge," Department of Energy, Washington, D.C.

IAEA (1976), Selection Factors for Repositories of Solid High-Level and Alpha-Bearing Wastes in Geological Formations, Vienna, Austria.

Iwatsubo, E. Y., and C. E. Mortensen (1979), "Short-term Tilt Anomalies Preceding Three Local Earthquakes near San Jose, California," Abs., EOS 60, p. 319.

Kanai, K., and T. Tanaka (1951), Observations of the Earthquake Motion at Different Depths of the Earth, Earthquake Research Institute Publication No. 29, pp. 107-113.

Kisslinger, C., and M. Wyss (1975), "Earthquake Prediction," Rev. Geophys. Space Phys. 13, No. 3, pp. 298-300.

Little, A. D., Inc. (1978), Assessment of Geologic Site Selection Factors, Draft report to U.S. Environmental Protection Agency by A. D. Little, Inc., Boston, Massachusetts.

Lomnitz, C. (1974), Global Tectonics and Earthquake Risk (Elsevier, New York).

McNally, K. C., E. Chael, and L. Ponce (1979), "The Oaxaca, Mexico, Earthquake (M_S=7.8) of 29 November 1978: New 'Pre-failure' Observations," Abs., EOS 60, p. 322.

Moran, D. F., and C. M. Duke (1975), "An Engineering Study of the Behavior of Public Utilities Systems in the San Fernando Earthquake of February 9, 1971," in San Fernando, California Earthquake of 9 February, 1971, California Division of Mines and Geology, Bulletin 196.

Nuclear Regulatory Commission (1978), Format and Content for Environmental Reports for Conventional Geologic High-Level Waste Repositories, Draft Waste Management Staff Guide, Nuclear Regulatory Commission, Washington, D.C.

NUREG-75/094 (1975), Standard Format and Content of Safety Analysis Reports for Nuclear Power Plants, U.S. Nuclear Regulatory Commission, Regulatory Guide 1.70, Revision 2.

Nuttli, O. W. (1973), "The Mississippi Valley Earthquakes of 1811 and 1812: Intensities, Ground Motion and Magnitudes," Bull. Sci. Soc. Amer. 63, 227-248.

Oakeshott, G. B. (1969, "Geologic Features of Earthquakes in the Bay Area," in Geologic and Engineering Aspects of San Francisco Bay Fill, California Division of Mines and Geology, Special Report 97.

Oakeshott, G. B. (1975), "Geology of the Epicentral Area," in San Fernando, California Earthquake of 9 February, 1971, California Division of Mines and Geology, Bulletin 196.

Oliver, J., T. Johnson, and J. Dorman (1970), "Post-glacial Faulting and Seismicity in New York and Quebec," Canadian J. Earth Sci. 7, 579-590.

Panel on Geological Site Criteria, Committee on Radioactive Waste Management (1978), Geological Criteria for Repositories for High-Level Radioactive Wastes, National Academy of Sciences, Washington, D.C.

Perez, O., and K. H. Jacob (1979), "The Tectonic Setting of the Large Gulf of Alaska Earthquake of February 28, 1979," Abs. EOS 60, p. 322.

Plafker, G. (1969), Tectonics of the March 27, 1964 Alaska Earthquake, U.S. Geological Survey Prof. Paper 543-I.

Press, F. (1975), "Earthquake Prediction," Scientific American 232, No. 5, pp. 14-23.

Richter, C. F. (1958), Elementary Seismology (W. H. Freeman and Co., San Francisco, California).

Ritter, J. R., and W. R. Dupre (1972), Map Showing Areas of Potential Inundation by Tsunamis in the San Francisco Bay Region, California, U.S. Geological Survey Misc. Field Inv. Map MF-480.

Saul, R. B. (1975), "Geology of the Southeast Slope of the Santa Susana Mountains and Geologic Effects of San Fernando Earthquake," in San Fernando, California Earthquake of 9 February, 1971, California Division of Mines and Geology, Bulletin 196.

Savage, J. C., R. O. Burford, and W. T. Kinoshita (1975), "Earth Movements from Geodetic Measurements," in San Fernando, California Earthquake of 9 February, 1971, California Division of Mines and Geology, Bulletin 196.

Seed, H. B. (1969), "Seismic Problems in the Use of Fills in San Francisco Bay," Geologic and Engineering Aspects of San Francisco Bay Fill, California Division of Mines and Geology, Special Report 97.

Sieh, K. E. (1978), "Prehistoric Large Earthquakes Produced by Slip on the San Andreas Fault at Pallett Creek, California," J Geophys. Res. 83, 3907-3939.

Slosson, J. E. (1974), Special Studies Zones, Map, Hayward Quadrangle, California Division of Mines and Geology.

Slosson, J. E. (1975), "Effects of the Earthquake on Residential Areas," in San Fernando, California Earthquake of 9 February, 1971, California Division of Mines and Geology, Bulletin 196.

Smith, J. L., and R. B. Fallgren (1975), "Ground Displacement at San Fernando Valley Juvenile Hall and the Sylmar Converter Station," in San Fernando, California Earthquake of 9 February, 1971, California Division of Mines and Geology, Bulletin 196.

Stevens, P. R. (1977), A Review of the Effects of Earthquakes on Underground Mines, U.S. Geological Survey Open File Report 77-313.

U.S. Geological Survey (1976), Program in Support of the National Waste Terminal Storage Program, submitted to the U.S. E.R.D.A.

Wallace, R. E. (1970), "Earthquake Recurrence Intervals on the San Andreas Fault," Geol. Soc. Amer. Bull. 81, 2875-2890.

Ward, P. L. (1979), "Earthquake Prediction," Rev. Geophys. Space Phys. 17, No. 2, pp. 343-353.

Wesson, R. L., E. J. Helley, K. R. Lajoie, and C. M. Wentworth (1975), "Faults and Future Earthquakes," in Studies for Seismic Zonation of the San Francisco Bay Region, U.S. Geological Survey Prof. Paper 941-A.

Youd, T. L., and S. N. Hoose (1978), Historic Ground Failures in Northern California Triggered by Earthquakes, U.S. Geological Survey Prof. Paper 993.

JK/jvb