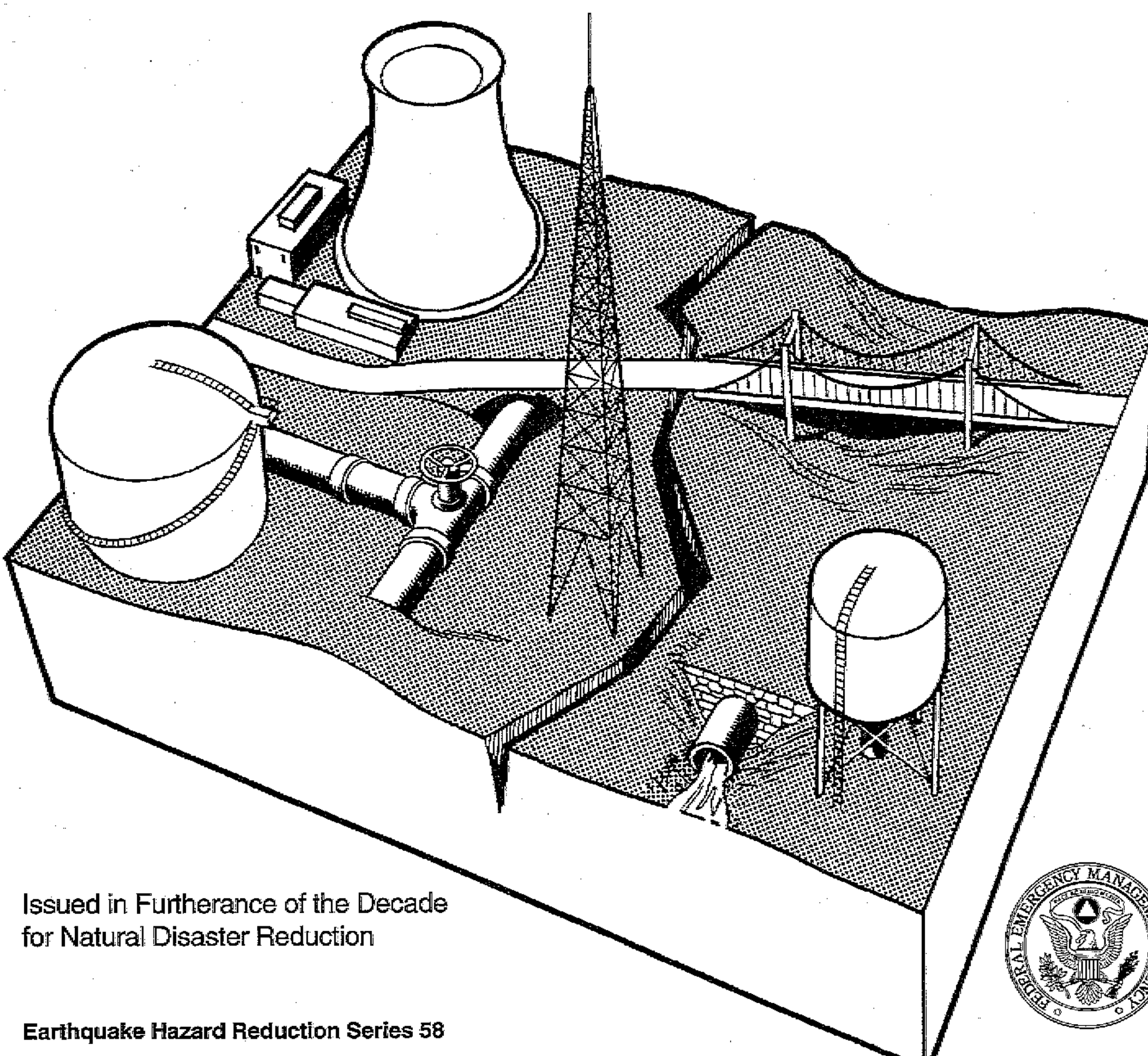
Seismic Vulnerability and Impact of Disruption of Lifelines in the Conterminous United States



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ATC-25
Seismic Vulnerability and Impact of Disruption of Lifelines in the Conterminous United States

by
APPLIED TECHNOLOGY COUNCIL
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Preface

In September 1988 Applied Technology Council (ATC) was awarded a contract by the Federal Emergency Management Agency to assess the seismic vulnerability and impact of disruption of lifeline systems nationwide. The purpose of the project is to develop a better understanding of the impact of disruption of lifelines from earthquakes and to assist in the identification and prioritization of hazard mitigation measures and policies. In addition, FEMA plans to utilize results from the project to promote national awareness of the importance of protecting lifeline systems from earthquakes, and assuring reliability and continued serviceability of lifelines.

The project is being conducted in several phases. Phase I, reported on herein, provides a national overview of lifeline seismic vulnerability and impact of disruption. Lifelines considered include electric systems, water systems, transportation systems, gas and liquid fuel supply systems, and emergency service facilities. The vulnerability estimates and impacts developed are presented in terms of estimated direct damage losses and indirect economic losses. These losses are considered to *represent a first approximation* because of the assumptions and methodology utilized, because several lifelines are not included, and because, in some case, the available lifeline inventory data lack critical capacity information.

Phase II, reported on in the ATC-25-1 Report, provides a practical model methodology for the detailed assessment of seismic vulnerability and impact of disruption of water transmission and distribution systems. Subsequent phases to develop model methodologies for the seismic assessment of other lifeline systems are also planned.

EQE Inc., a structural and earthquake engineering firm with experience in the seismic evaluation of lifeline systems, served as the project subcontractor and prepared this report. The research and engineering work was performed by Charles Scawthorn, Principal-in-Charge, Mahmoud Khater, Principal Research Engineer, and other EQE staff. Marvin Feldman of Resource Decisions served as consultant on the indirect economic loss methodology and data.

The ATC-25 Expert Technical Advisory Group (ETAG), comprised primarily of individuals drawn from the technical committees of the American Society of Civil Engineers (ASCE) Technical Council for Lifeline Earthquake Engineering (TCLEE), provided overall review and guidance for the project. Members were: Lloyd Cluff, James D. Cooper, Holly Cornell, John W. Foss, James H. Gates, Neal Hardman, Jeremy Isenberg, Anne S. Kiremidjian, Le Val Lund, Peter McDonough, Dennis K. Ostrom, Gerard Pardoen (ATC Board Representative), Michael Reichle, Anshel J. Schiff, J. Carl Stepp, and Domenic Zigant. The affiliations and addresses of these individuals are provided in Appendix A.

Applied Technology Council gratefully acknowledges the valuable assistance, support and cooperation provided by Kenneth Sullivan, FEMA Project Officer, and Arthur J. Zeizel and Kupussammy Thirumalai, prior Project Officers.

Christopher Rojahn
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Executive Summary

1. Introduction

Lifeline is an earthquake engineering term denoting those systems necessary for human life and urban function, without which large urban regions cannot exist. Lifelines basically convey food, water, fuel, energy, information, and other materials necessary for human existence from the production areas to the consuming urban areas. Prolonged disruption of lifelines such as the water supply or electric power for a city or urbanized region would inevitably lead to major economic losses, deteriorated public health, and eventually population migration. Earthquakes are probably the most likely natural disaster that would lead to major lifeline disruption. With the advent of more and more advanced technology, the United States has increasingly become dependent on the reliable provision of lifeline-related commodities, such as electric power, fuel, and water. A natural question is: What is the potential for major disruption to these lifelines, especially at the regional level?

The initiation of this study by the Federal Emergency Management Agency (FEMA) is based in part on a need to better understand the impact of disruption of lifelines from earthquakes and to assist in the identification and prioritization of hazard mitigation measures and policies. In addition, the report is intended to improve national awareness of the importance of protecting lifeline systems from earthquakes, and of assuring lifeline reliability and continued serviceability.

The specific contractual requirements of this project and report are:

- To assess the extent and distribution of existing U.S. lifelines, and their associated seismic risk; and
- To identify the most critical lifelines, and develop a prioritized series of steps for reduction of lifeline seismic vulnerability, based on overall benefit.

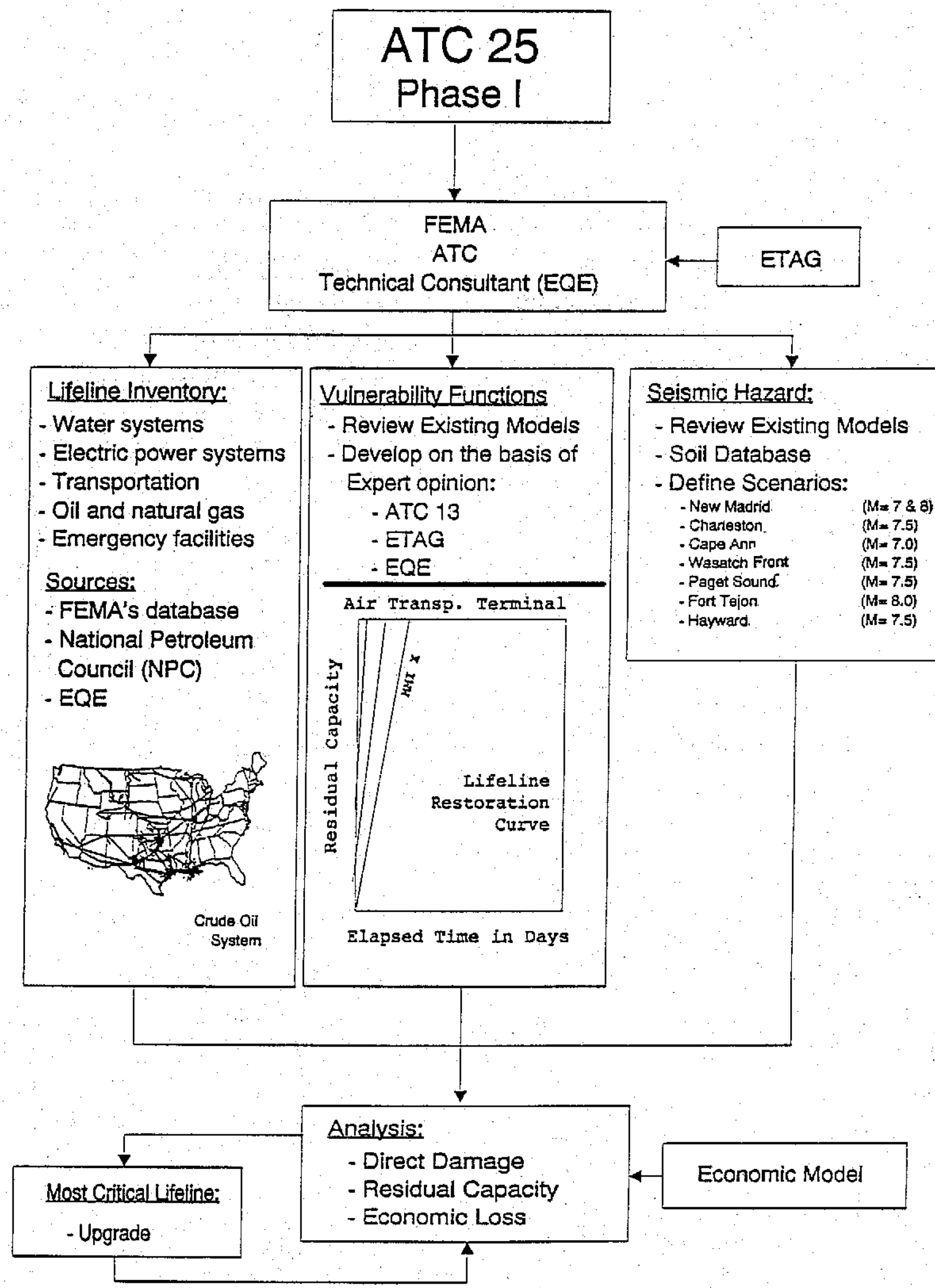
FEMA is also sponsoring a companion study to develop and demonstrate a model methodology for assessing the seismic vulnerability and impact of disruption of water transmission and distribution systems (ATC, in preparation).

In this initial study, lifelines of critical importance at the U.S. national level have been analyzed to estimate overall seismic vulnerability and to identify those lifelines having the greatest economic impact, given large, credible U. S. earthquakes. The lifelines examined include electric systems; water, gas, and oil pipelines; highways and bridges; airports; railroads; ports; and emergency service facilities. The vulnerability estimates and impacts developed are presented in terms of estimated direct damage losses and indirect economic losses. These losses are considered to *represent a first approximation* because of the assumptions and methodology utilized, because several lifelines are not included, and because, in some cases, the available lifeline inventory data lack critical capacity information.

Project Approach. As summarized in the project technical-approach flow chart (Figure 1), four basic steps were followed to estimate lifeline damage and subsequent economic disruption for given earthquake scenarios.

1. Development of a national lifeline inventory database.
2. Development of seismic vulnerability functions for each lifeline component/system,
3. Characterization and quantification of the seismic hazard nationwide, and
4. Development of direct damage estimates and indirect economic loss estimates for each scenario earthquake.

Limitations and Constraints. During development of this report and its supporting data, several problems were encountered that could not be resolved because of technical difficulties and lack of available data. For example, telecommunication systems, nuclear and fossil-fuel power plants, dams, and certain water, electric, and transportation facility types at the regional transmission level were excluded from consideration in this project because of the



Notation: ATC-13: ATC-13 Report, *Earthquake Damage Evaluation Data for California* (ATC, 1985)
ETAG: Expert Technical Advisory Group (project advisory panel)
EQE: EQE Engineering (project subcontractor)

Figure 1 *Flow chart showing main steps in project approach.*

unavailability of inventory data or the need for more in-depth studies.

Interaction effects between lifelines, secondary economic effects (the impact of a reduced capacity of one economic sector on a dependent sector), and damage resulting from landslide (due to lack of inventory data nationwide) were also not considered in developing this report. These limitations and others described in Chapters 2, 4, and 5 tend to underestimate the losses presented herein; and other factors, as described elsewhere in this report, tend to overestimate the losses. Lack of capacity information for most lifelines was also a definite limitation. In the aggregate, due primarily to the exclusion of certain systems (e.g., dams and telecommunication systems), we believe the estimates of losses presented in this report are, in fact, quite conservative.

We also emphasize that this report is a macroscopic investigation at the national level and the results should not be used for microscopic interpretations. The results, for example, are not intended to be used to evaluate any particular regional utility or lifeline, and no specific information on such specific facilities has been included.

2. National Lifeline Inventory

Development of the ATC-25 inventory, for all major lifelines in the United States, was a major task. The project scope required that lifelines be inventoried in sufficient detail for conducting lifeline seismic vulnerability assessments and impact of disruption at the national level. This in turn required that the inventory be compiled electronically in digital form and dictated that inclusion of lifelines at the transmission level, as defined below, was of primary importance.

Initially, a number of government, utility, trade and professional organizations, and individuals were contacted in an effort to identify nationwide databases, especially electronic databases. In most cases, these organizations or individuals referred the project back to FEMA, since they had either previously furnished the information to FEMA, or knew that the data had been furnished to FEMA by others. As a result, FEMA's database (FEMA, 1987) became a major source of data for several of the lifelines. A significant portion of these data consist of digitized U.S. Geological Survey (USGS) topographical maps and/or the National Atlas (Gerlach, no date), performed by the U.S. Geological Survey in support of national census requirements. With the exception of oil and gas pipeline data provided by the National Petroleum Council, the inventory data generally date from about 1966, unless later updated by FEMA. A number of other sources were employed in various ways, which are further discussed below.

The network inventory contained in the database is generally at the higher transmission levels, as opposed to lower distribution levels. That is, inventories were generally only compiled for networks at the bulk and/or regional level, as opposed to lifelines at the user-level (i.e., distribution level) *within* an area. To use an analogy, the inventory contains only the national *arterial* level, and neglects the distribution or *capillary* system. For example, all federal and state highways are inventoried (Figure 2), but county and local roads are not. The major reason for focusing on the transmission level is that at lower levels the systems only support local facilities. Thus, a disruption of a local activity could not be used to identify the overall regional importance of the lifeline. However, disruptions at the transmission level impact large regions and are therefore important for understanding the seismic vulnerability and importance of lifelines to the United States.

Inventory Overview. The inventory data (Chapter 2) have been compiled into an electronic database, which generally consists of (i) digitized location and type of facility for single-site lifeline facilities, and (ii) digitized right-of-way, and very limited information on facility attributes for network lifelines. The inventory is only a partial inventory, in that important information on a number of facility attributes (e.g., number or length of spans for highway bridges) was unavailable from FEMA.

The inventory data include information for the conterminous United States only. Lifeline data for Alaska, Hawaii, and U. S. territories, such as Puerto Rico, have been excluded because lifelines in these regions would not be affected by the scenario earthquakes (see Chapter 4) considered in this study.

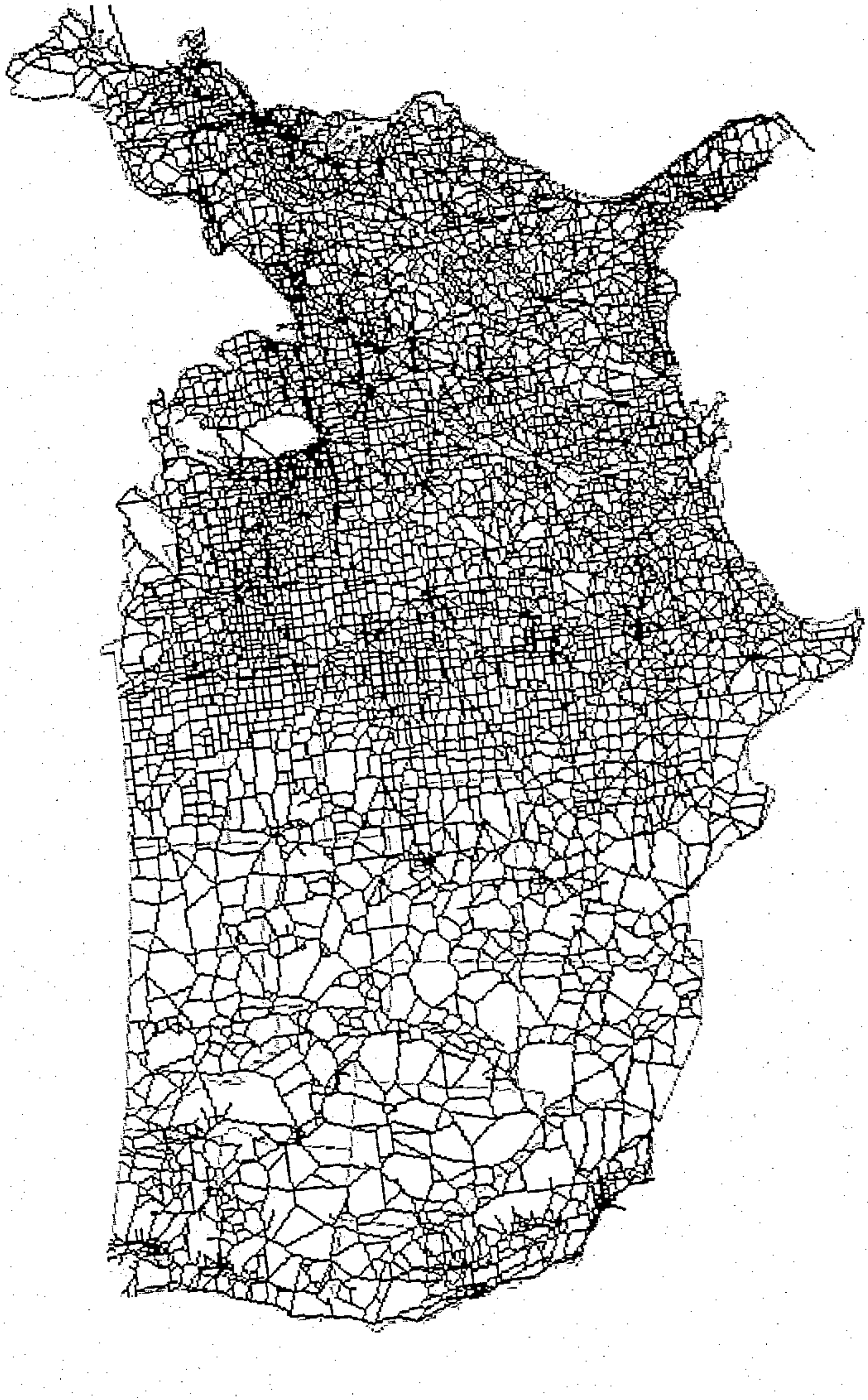


Figure 2 State and federal highways.

The specific lifelines that have been inventoried for the conterminous United States are:

Transportation

- Highways (489,892 km of highway (Figure 2); 144,785 bridges)
- Railroads (270,611 km of right-of-way)
- Airports (17,161 civil and general aviation airports)
- Ports (2,177 ports)

Energy

- Electric Power Transmission (4,551 substations; 441,981 km of transmission lines)
- Gas and Liquid Fuel Transmission (77,109 km of crude oil pipelines; 85,461 km of refined oil pipelines; 67,898 km of natural gas pipelines.)

Emergency Service Facilities

- Emergency Broadcast Facilities (29,586 stations)
- Hospitals (6,973 medical care centers)

Water Aqueducts and Supply (3,575 km of aqueduct; excludes aqueducts in Utah, which were unavailable)

An important lifeline, telecommunication systems, which would be severely impact by earthquake-induced ground shaking, was excluded because of the unavailability of data, as are certain regional transmission network facility types (e.g., railway terminals, bridges, and tunnels; certain aqueducts; major freeway/highway bridges; fossil-fuel power plants; and aqueduct pumping stations). In addition, data on nuclear reactors and dams are excluded because it was believed that such facilities should be the subject of special studies, particularly because of the existing regulations relating to seismic safety in many regions and the expected complexity of the performance and impact of these facility types. As a result, the losses provided by this study will be underestimated to the extent that these facility types are not included.

Also excluded from the inventory, but included in the analysis, are distribution systems at the local level (water, highway, and electrical systems) and police and fire stations. For these facility types, the number of facilities in each 25-km by 25-km grid cell, which is the grid size for the seismic hazard analysis, is estimated on the basis of proxy by population (see Chapter 2).

PC-Compatible Electronic Database. Because the data could also serve as a valuable framework (or starting point) for researchers who wish to investigate lifelines at the regional or local level, including applications unrelated to seismic risk, the data have been formatted for use on IBM-PC compatible microcomputers. The data are unrestricted and will be made available by ATC on 18, 1.2-megabyte, floppy diskettes, together with a simple executable computer program for reading and displaying the maps on a computer screen.

3. Lifeline Vulnerability Functions

The second step in the project was the development of lifeline vulnerability functions, which describe the expected or assumed earthquake performance characteristics of each lifeline as well as the time required to restore damaged facilities to their pre-earthquake capacity, or usability. Vulnerability functions were developed for each lifeline inventoried, for lifelines estimated by proxy, and for other important lifelines not available for inclusion in the inventory. The components of each vulnerability function and how they were developed are described in Chapter 3; the functions themselves, too lengthy to include in the main body of the report text, are provided in Appendix B.

The vulnerability functions developed for each lifeline consist of the following components:

- *General* information, which consists of (1) a *description* of the structure and its main components, (2) *typical seismic damage* in qualitative terms, and (3) *seismically resistant design* characteristics for the facility and its components in particular. This information has been included to define the assumed characteristics and expected performance of each facility and to make the functions more widely applicable (i.e., applicable for other investigations by other researchers).

- Direct damage information, which consists of (1) a description of its basis in terms of structure type and quality of construction (degree of seismic resistance), (2) default estimates of the quality of construction for present conditions and corresponding *motion-damage curves*, (3) default estimates of the quality of construction for upgraded conditions, and (4) *restoration curves*.

These functions reflect the general consensus among practicing structural engineers that, with few exceptions, only California and portions of Alaska and the Puget Sound region have had seismic requirements incorporated into the design of local facilities for any significant period of time. For all other areas of the United States, present facilities are assumed to have seismic resistance less than or equal to (depending on the specific facility) that of equivalent facilities in California NEHRP Map Area 7 (Figure 3). Three regions, representing these differences in seismic design practices, are defined for the United States:

a. California NEHRP Map Area 7, which we take to be the only region of the United States with a significant history of lifeline seismic design for great earthquakes,

b. California NEHRP Map Areas 3-6, Non-California Map Area 7 (parts of Alaska, Nevada, Idaho, Montana, and Wyoming), and Puget Sound NEHRP Map Area 5, which we take to be the only regions of the United States with a significant history of lifeline seismic design for major (as opposed to great) earthquakes, and

c. All other parts of the United States, which we assume have not had a significant history of lifeline seismic design for major earthquakes.

The two key quantitative vulnerability-function relationships developed under this project--*motion-damage curves* and *restoration curves*--define expected lifeline performance for each of these regions and form the heart of the quantitative vulnerability analysis. The curves are based on the data and methodology developed on the basis of expert opinion in the ATC-13 project (*Earthquake Damage Evaluation Data for California*, ATC 1985). Because the ATC-13 data and methodology are applicable for California structures only, however, the data were revised and reformatted to reflect differences in seismic design and construction practices nationwide and to meet the technical needs of the project. All assumptions operative in ATC-13, such as unlimited resources for repair and restoration, also apply to these results.

The *motion-damage curves* developed under this project define estimated lifeline direct damage as a function of seismic intensity (in this case, Modified Mercalli Intensity); direct damage is estimated in terms of repair costs expressed as a fraction or percentage of value. Curves are provided for each region defined above. An example set of motion-damage curves for ports/cargo handling equipment is provided in Figure 4.

The *restoration curves* developed for this project define the fraction of initial capacity of the lifeline (restored or remaining) as a function of elapsed time since the earthquake. Again curves are defined for each region. A sample set is provided in Figures 5 and 6.

4. Seismic Hazard

Seismic hazard, as used in this study, is the expectation of earthquake effects. It is usually defined in terms of ground shaking parameters (e.g., peak ground acceleration, Modified Mercalli Intensity, peak ground velocity) but, broadly speaking, can include or be defined in terms of fault rupture, ground failure (landslides, liquefaction), or other phenomena (earthquake-induced fire) resulting from an earthquake. Seismic hazard is a function of the size, or magnitude of an earthquake, distance from the earthquake, local soils, and other factors, and is independent of the buildings or other items of value that could be damaged.

The technical approach for evaluating the seismic hazard of lifeline structures in this project (see Chapter 4) involved identifying (1) the most appropriate means (parameter(s)) for describing the seismic hazard, (2) regions of high seismic activity, (3) representative potentially damaging, or catastrophic,

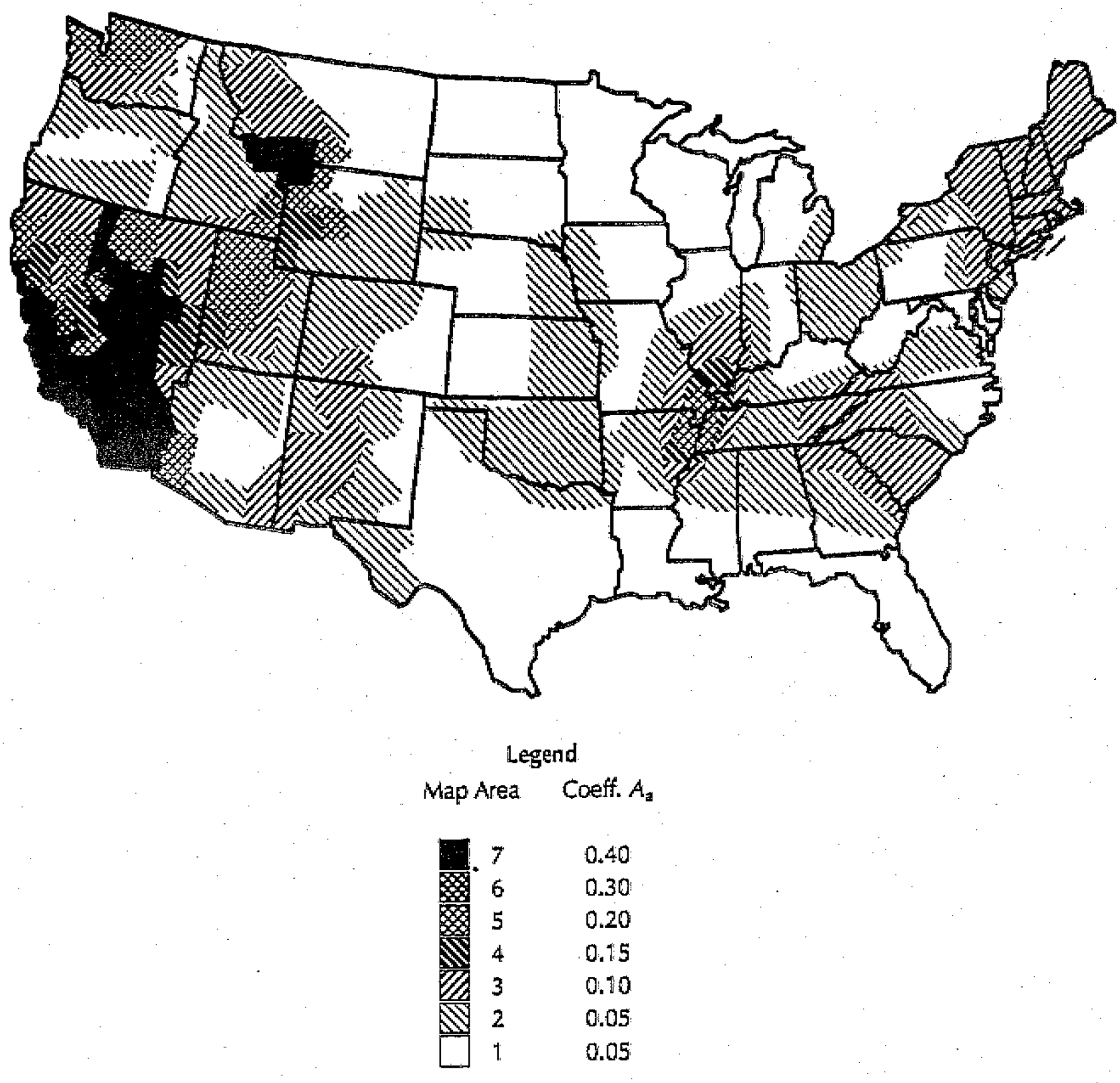


Figure 3 NEHRP Seismic Map Areas (ATC, 1978; BSSC, 1988).

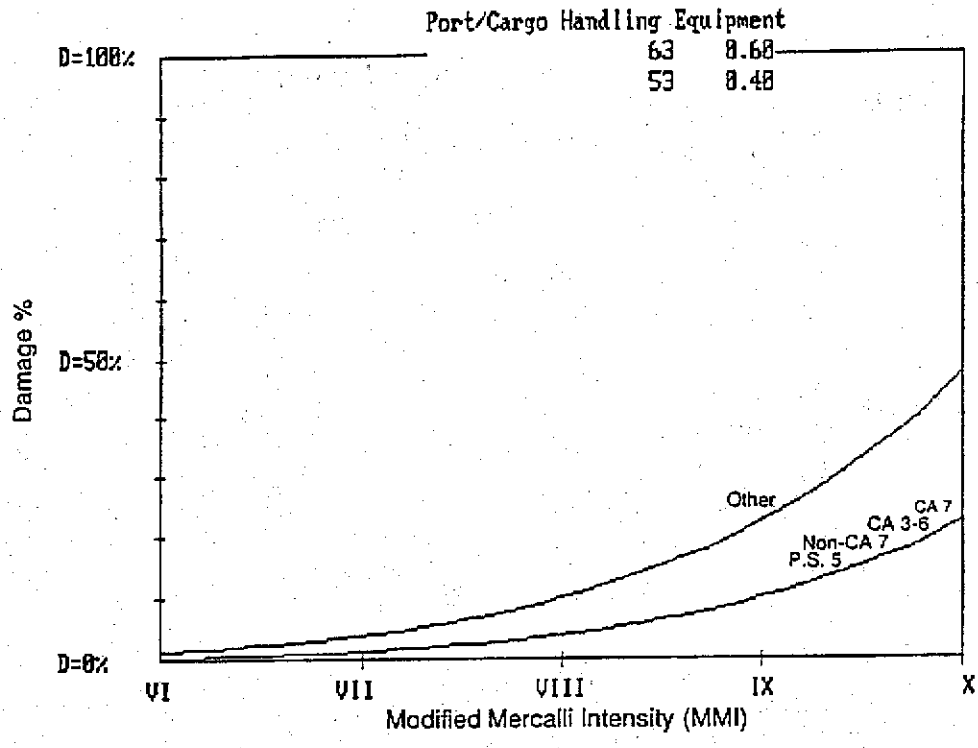


Figure 4 *Damage percent by intensity for ports/cargo handling equipment.*

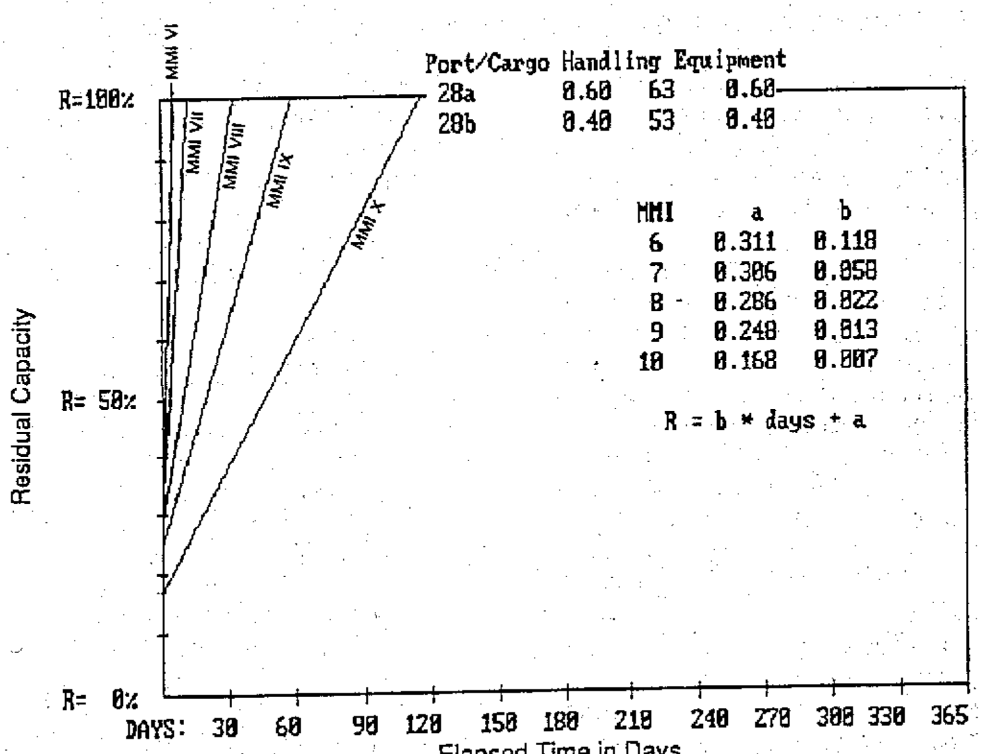


Figure 5 *Residual capacity for ports/cargo handling equipment (NEHRP Map Area: California 3-5, California 7, Non-California 7, and Puget Sound 5).*

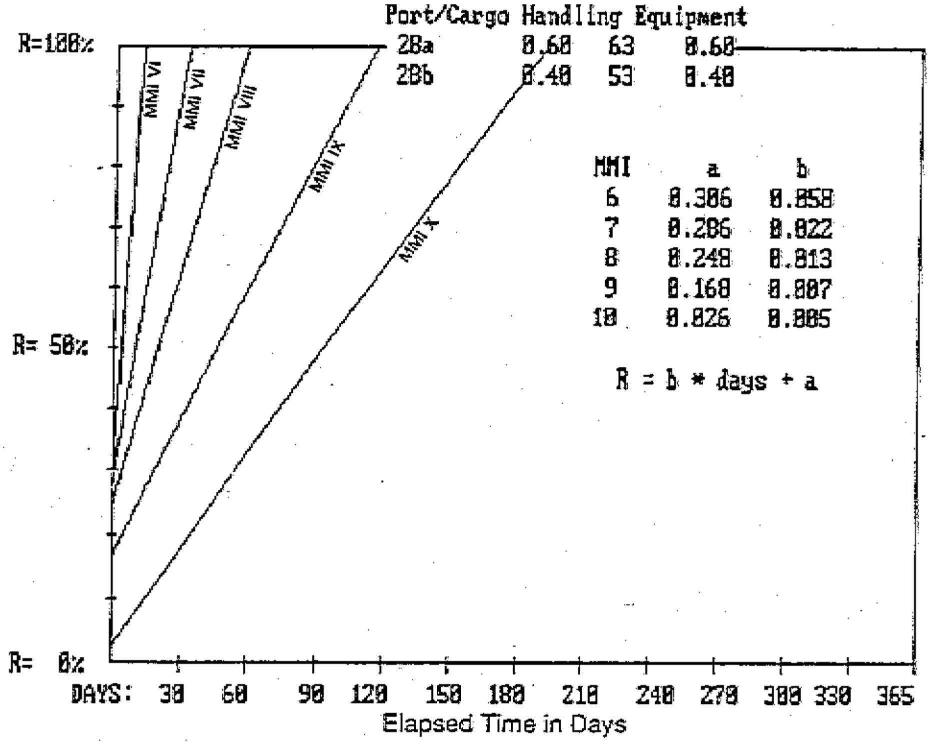


Figure 6 Residual capacity for ports/cargo handling equipment (all other areas).

earthquakes within each of these regions that could be used as scenario events for the investigation of lifeline loss estimation and disruption, and (4) a model for estimating the seismic hazard for each of these scenario events.

Descriptor of Seismic Hazard for this Study. Following a review of available parameters for characterizing seismic hazard, we elected to use the Modified Mercalli Intensity (MMI) Scale (Wood and Neumann, 1931), a commonly used measure of seismic intensity (effects at a particular location or site). The scale consists of 12 categories of ground motion intensity, from I (not felt, except by a few people) to XII (total damage). Structural damage generally is initiated at about MMI VI for poor structures, and about MMI VIII for good structures. MMI XI and XII are extremely rare. The MMI scale is subjective; it is dependent on personal interpretations and is affected, to some extent, by the quality of construction in the affected area. Even though it has these limitations, it is still useful as a general description of damage, especially at the regional level, and for this reason was used in this study as the descriptor of seismic hazard.

Seismicity Overview of the United States. For the purpose of characterizing seismicity in the conterminous United States, several regions may be identified (Algermissen, 1983):

1. Northeastern Region, which includes New England, New York, and part of eastern Canada;

2. Southeastern Region, including the central Appalachian seismic region activity and the area near Charleston, South Carolina;

3. Central Region, which consists of the area between the regions just described and the Rocky Mountains;

4. Western Mountain Region, which includes all remaining states except those on the Pacific coast;

5. Northwestern Region, including Washington and Oregon; and

6. California and Western Nevada.

The historical record indicates that each region appears to have significant historic precedent for a damaging earthquake of potentially catastrophic dimensions. For purposes of examining this potential, the earthquakes indicated in Table 1 are representative events for the investigation of lifeline loss estimation and disruption.

Evernden et al. (1981) estimates that these events represent almost the maximum earthquake expected in each area. Review of Algermissen et al. (1982) indicates general agreement.

Choice of a Model for Estimating the Distribution and Intensity of Shaking for Scenario Earthquakes. In order to estimate the seismic hazard (i.e., deterministic intensity) of the scenario events over the affected area associated with each event, a model of earthquake magnitude, attenuation, and local site effects is required. For the conterminous United States, two general models were considered: Evernden and Thomson (1985), and Algermissen et al. (1990).

Selection of one model over the other was difficult, but the Evernden model offered the following advantages for this study: (i) verification via comparison with historical events, (ii) incorporation of local soil effects and ready availability of a nationwide geologic database, and (iii) ready availability of closed-form attenuation relations. An important additional attribute for this project was that the Everden model would estimate the distribution and intensity of seismic shaking in terms of MMI, the shaking characterization used in the ATC-13 study and the basic parameter for the ATC-25 lifeline vulnerability functions.

Scenario Earthquakes. Based on the representative earthquakes identified in Table 1, which are considered representative of all major regions of the conterminous United States, eight scenario events were selected for this investigation. The eight events are indicated in Table 2. With the exception of the Cape Ann, Charleston, and Hayward events, all magnitudes are reflective of the representative earthquake for the region (as specified in Table 1). The scenario events for Cape Ann, Charleston, and Hayward have magnitudes one-half unit higher than the representative event. These magnitudes are interpreted as maximum credible for these locations.

Table 1 Representative Earthquakes for Lifeline Loss Estimation

Region	Event
Northeastern	Cape Ann, 1755
Southeastern	Charleston, 1886
Central	New Madrid, 1811-1812
Western Mountain	Wasatch Front, no date
Northwestern	Puget Sound, 1949
Southern California	Fort Tejon, 1857
Northern California	Hayward, 1868

The choice of a scenario event on the Hayward fault for the San Francisco Bay Area, rather than the 1906 San Francisco event, is based on the perceived high likelihood of a magnitude 7.0 event (USGS, 1990) as well as the potential for major damage and lifeline disruption, should such an event occur (CDMG, 1987). Since most lifelines approach San Francisco Bay from the east, more of them cross the Hayward Fault than cross the San Andreas Fault. So the Hayward event would appear to represent as disruptive an event, and potentially more so, than the 1906 event, which is presently perceived to be of low likelihood in the near future.

The Evernden model was employed to generate expected seismic intensity distribution in the conterminous United States for the eight scenario events. Shown in Figure 8 is an example intensity distribution for the New Madrid magnitude-8.0 scenario event.

Table 2 Scenario Earthquakes

Region	Event	Magnitude
Northeastern	Cape Ann	7
Southeastern	Charleston	7.5
Central	New Madrid	7 and 8
Western Mountain	Wasatch Front	7.5
Northwestern	Puget Sound	7.5
Southern California	Fort Tejon	8
Northern California	Hayward	7.5

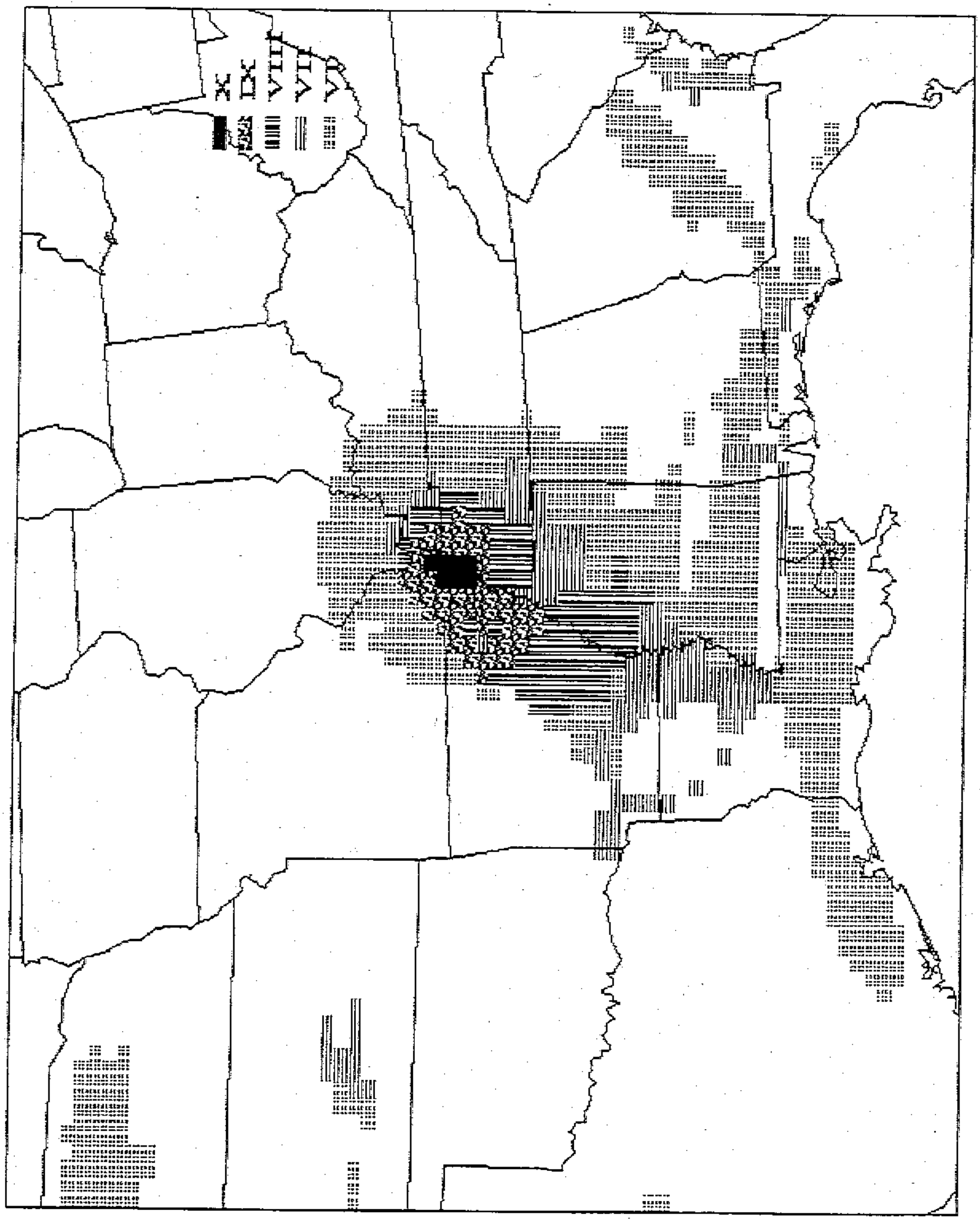


Figure 7 *Predicted intensity map for New Madrid (Magnitude 8).*

5. Estimates of Direct Damage

The analysis of seismic vulnerability of lifeline systems and the economic impact of disruption is based on an assessment of three factors:

- Seismic hazard,
- Lifeline inventory, and
- Vulnerability functions.

In this investigation these factors are used to quantify vulnerability and impact of disruption in terms of (1) direct damage and (2) economic losses resulting from direct damage and loss of function of damaged facilities. Estimates of direct damage to lifelines, expressed in terms of percent replacement value and dollar loss, are discussed in Chapter 5. Indirect economic losses are discussed in Chapter 6.

Direct damage is defined as damage resulting directly from ground shaking or other collateral loss causes such as liquefaction. For each facility, it is expressed in terms of cost of repair divided by replacement cost and varies from 0 to 1.0 (0% to 100%). In this project it is estimated using (1) estimates of ground shaking intensity provided by the seismic hazard model (from Chapter 4), (2) inventory data specifying the location and type of facilities affected (from Chapter 2), and (3) vulnerability functions that relate seismic intensity and site conditions to expected damage (from Chapter 3 and Appendix B).

The analysis approach to estimate direct damage considers both damage resulting from ground shaking as well as damage resulting from liquefaction. Damage due to other collateral loss causes, such as landslide and fire following earthquake, are not included because of the unavailability of inventory information and the lack of available models for estimating these losses nationwide.

The analysis approach for computing direct damage due to ground shaking proceeded as follows. For each earthquake scenario, MMI levels were assigned to each 25-km grid cell in the affected region, using the Everden MMI model, assigned magnitude, and assigned fault rupture location (from Chapter 4). Damage states were then estimated for each affected lifeline component in each grid cell, using the motion-damage curves provided in Appendix B. The procedure for utilizing the motion-damage curves varied slightly by facility type, depending on whether the lifeline was a site specific facility, or a regional transmission (extended) network.

Site-Specific Lifelines. Direct damage to site-specific lifelines, i.e., lifelines that consist of individual sited or point facilities (e.g., hospitals), were estimated using the methodology specified above. For airports, ports and harbors, medical care facilities (hospitals), and broadcast stations, the inventory data summarized in Chapter 2 were used to define the number and distribution of facilities. For fire and police stations, locations were assumed to be lumped at the center of the Standard Metropolitan Statistical Areas, and number of facilities affected were estimated by proxy, assuming certain established relationships between population and number of facilities.

For summary and comparative purposes, four damage states are considered in this study:

- Light damage (1-10% replacement value);
- Moderate damage (10-30% replacement value);
- Heavy damage (30-60% replacement value); and
- Major to destroyed (60-100% replacement value).

The total number of affected facilities and the percentage of facilities in each damage state are summarized for each lifeline and scenario earthquake (see Chapter 5, Tables 5-1 through 5-6). Following is a discussion of the direct damage impact on an example lifeline--ports and harbors.

<u>Ports and Harbors</u>. Since ports and harbors are located in the coastal regions, only those scenario earthquakes affecting these regions will negatively impact this facility type. As indicated in Table 3, the most severe damages to ports and harbors are expected for the Charleston and Puget Sound events. For example, one hundred percent, or 20 ports and harbors, in South Carolina can be expected to sustain heavy damage (30 to 60%), and 73%, or approximately

Table 3 **Damage Percent for Ports and Harbors for Selected Scenario Earthquakes (Percent of Ports and Harbors in State)**

CAPE ANN (M=7.0)

Massachusetts 34	*Connecticut 22*	*Delaware 10*	*Rhode Island 22*	*New Hampshire 9*
100%	0%	0%	86%	0%
0%	0%	0%	0%	0%
0%	0%	0%	0%	0%
0%	0%	0%	0%	0%

CHARLESTON (M=7.5)

Total Number	*South Carolina 20*	*North Carolina 16*	*Georgia 30*
Light Damage 1-10 %	0%	0%	10%
Moderate 10-30 %	0%	0%	0%
Heavy 30-60 %	100%	0%	73%
Major to Destructive 60-100 %	0%	0%	0%

	HAYWARD (M=7.5)	*FORT TEJON (M=8.0)*	*PUGET SOUND (M=7.5)*
Total Number	*California 125*	*California 125*	*Washington 77*
Light Damage 1-10 %	4%	0%	25%
Moderate 10-30 %	22%	34%	26%
Heavy 30-60 %	0%	0%	14%
Major to Destructive 60-100 %	0%	0%	0%

22 such facilities would be similarly affected in Georgia. In Washington, 14% of the ports (approximately 11) would be similarly affected. Numerous ports and harbors in these states would also sustain moderate damage (10 to 30%), as would approximately 22 such facilities in California for the Hayward magnitude-7.5 event. The primary cause of such damage, of course, is poor ground.

Extended Lifeline Networks. With the exception of pipeline systems, direct damage to extended network lifelines, such as highways, railroads and other networks at the bulk and/or regional level, was estimated using the methodology specified above. For pipelines direct damage was estimated using an analytical model that estimates the probability of breaks occurring within given lengths of pipe subjected to given earthquake shaking intensities (Khater et al., 1989).

Results are presented in terms of (1) the same four damage states used for site-specific lifelines, and (2) maps indicating the damaged portions of each extended network for the various scenario earthquakes (see Chapter 5). Example results for two extended lifeline networks follow.

Railroad System. The railroad system is a highly redundant system, and damage to the system due to the selected events was found to be relatively localized to the epicentral area. Direct damage estimates for the railroad system are based on damage curves for track/roadbed and exclude damage to related facility types not included in the project inventory--railway terminals, railway bridges and tunnels.

The direct damage data (Chapter 5, Table 5-7) suggest that the magnitude-8 New Madrid, Fort Tejon, and Hayward events would cause the most extensive damage, with 2,265 km, 872 km, and 585 km of roadbed, respectively, sustaining damage in the 30 to 100% range. Damage in the Charleston, Puget Sound, and magnitude-7.0 New Madrid events would also be severe, with 980, 650, and 640 km of roadbed, respectively, sustaining heavy damage (30-to-60 %). A map showing the distribution of damage to the railroad system for the magnitude-8 New Madrid earthquake scenario is shown in Figure 8.

Crude Oil. Direct damage to the crude oil system as a result of the magnitude-8 New Madrid event, estimated using damage curves for transmission pipelines and the special probabilistic model for pipelines, is plotted in Figure 9. This figure indicates that three pipeline sections would be damaged due to the magnitude-8.0 New Madrid event and suggests that crude oil flow to the north-central section of the United States would be disrupted. Pipelines would also be damaged as a result of the magnitude-7 New Madrid and magnitude-8 Fort Tejon earthquake scenarios.

Dollar Loss Estimates. Summaries of dollar loss estimates for direct damage to site-specific systems and extended regional lifeline networks during the eight scenario earthquakes are provided in Tables 5a and 5b. Estimated dollar losses due to direct damage to local electric, water, and highway distribution systems are provided in Table 6.

The estimates provided in Tables 5a,b and 6 are based on the available inventory data, cost per facility assumptions, and other models and assumptions described throughout the report. As a result, the accuracy of these estimates may vary from lifeline to lifeline. Estimates for electric systems, in particular, are believed to be more sensitive to the lack of capacity information than are the other lifelines.

By combining the data from Tables 5a,b and 6, we estimate the total direct damage dollar losses (in billions of U. S. dollars) for the eight scenario earthquakes as follows:

Earthquake	*Direct Dollar Loss (in Billions, 1991$)*
Cape Ann	$4.2
Charleston	$4.9
Fort Tejon	$4.9
Hayward	$4.6
New Madrid, M = 8.0	$11.8
New Madrid, M = 7.0	$3.4
Puget Sound	$4.4
Wasatch Front	$1.5

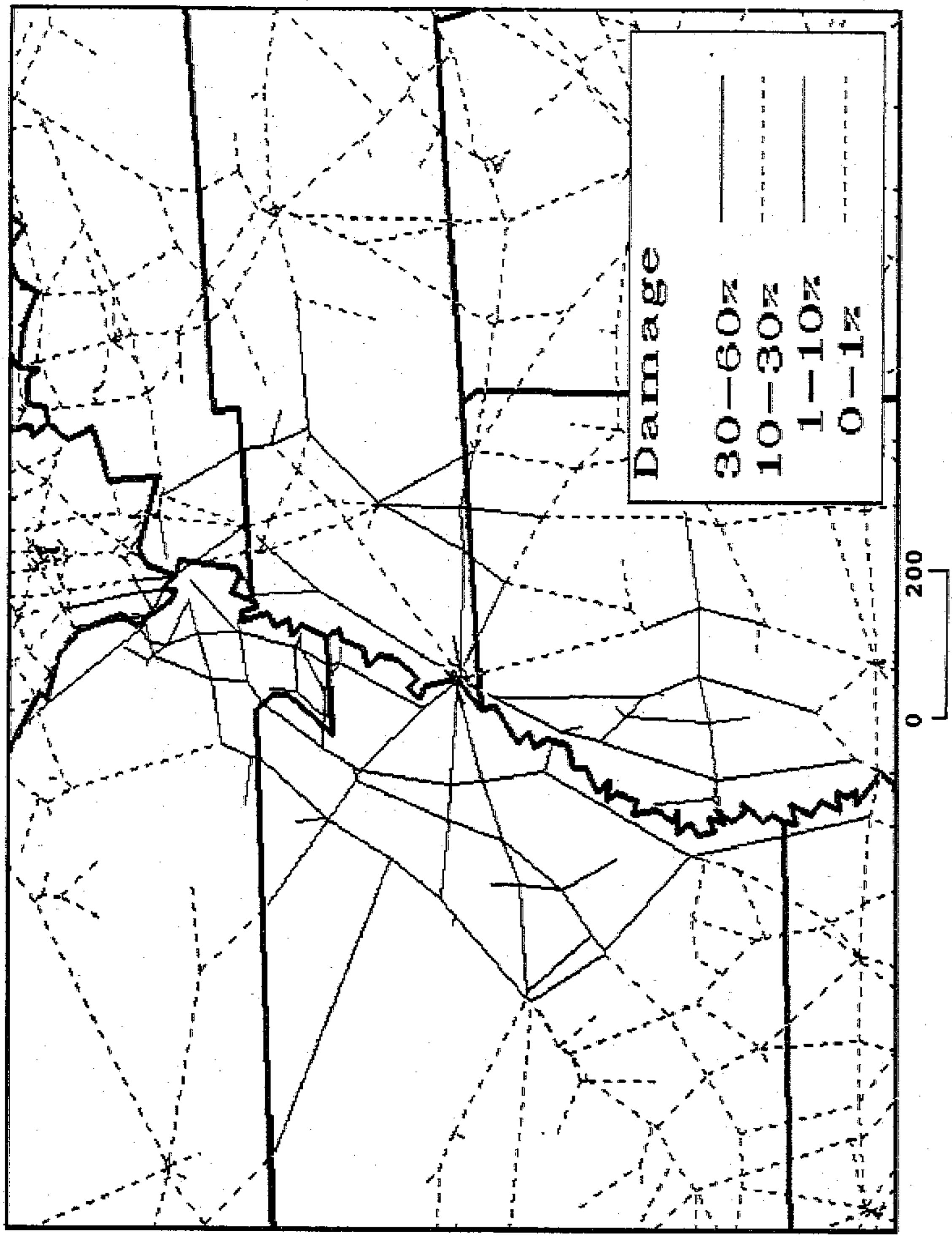


Figure 8 *Damage to railroad system following magnitude-8 New Madrid Event.*

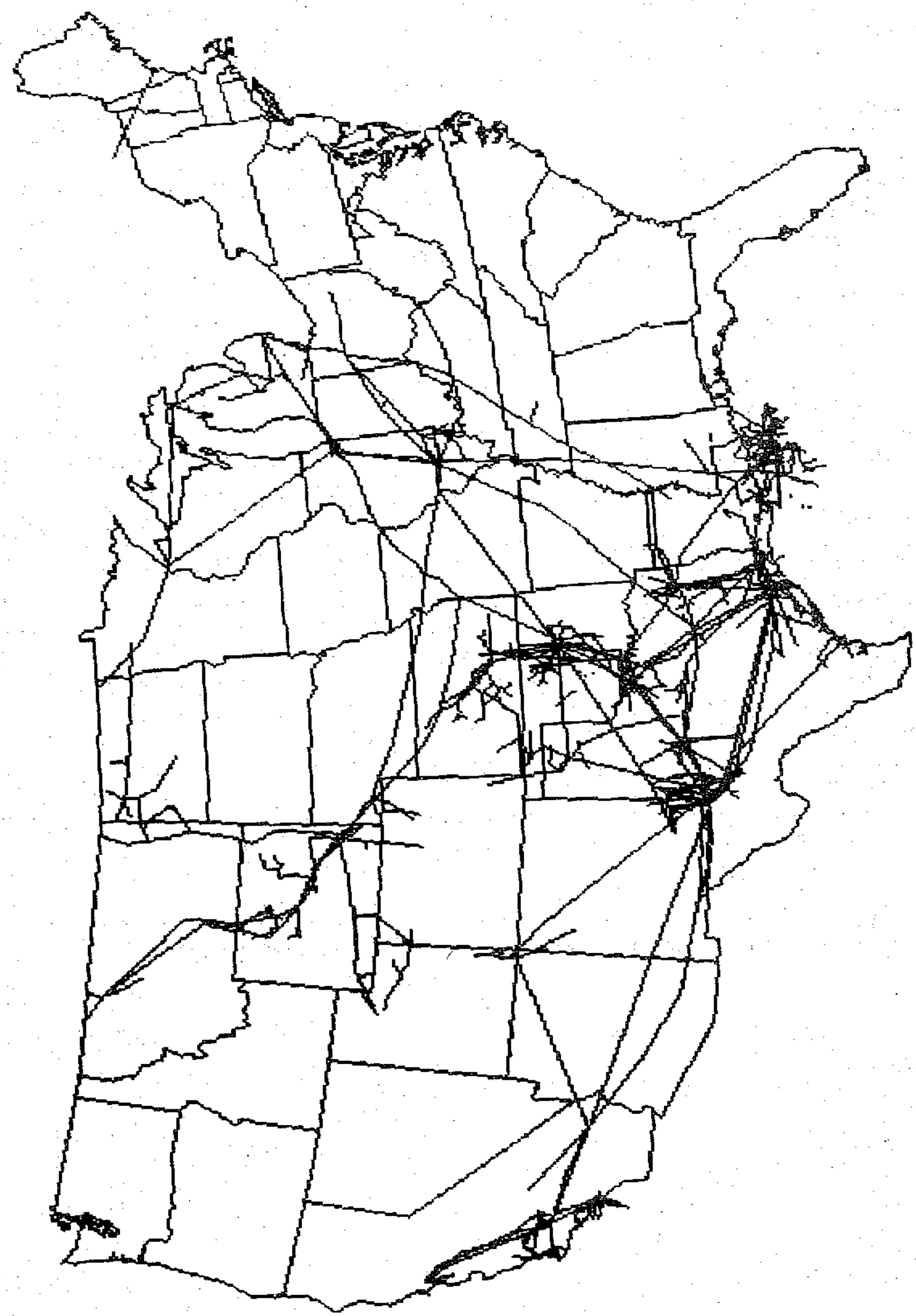


Figure 9 *Damage to crude oil system following magnitude-8 New Madrid Event. Broken pipelines are shown in red; unbroken pipelines are shown in black.*

Table 5a Direct Damage Losses to Site-Specific Lifelines ($ Millions)

Scenario Earthquake	*Airports*	*Ports*	*Hospitals*	*Broadcast Stations*	*Fire Stations*
Cape Ann	$91	$53	$490	$19	$6
Charleston	142	380	565	68	9
Fort Tejon	148	170	1,431	26	48
Hayward	37	115	1,297	17	7
New Madrid (M=8)	411	0	1,297	91	13
New Madrid (M=7)	145	0	396	34	3
Puget Sound	210	196	507	49	13
Wasatch Front	29	0	205	44	2

Table 5b Direct Damage Losses to Regional Network Lifelines ($ Millions)

Scenario Earthquake	*Highways*	*Electric*	*Railroads*	*Natural Gas*	*Refined Oil*	*Crude Oil*	*Water*
Cape Ann	$382	$1,312	$9	$0	$0	$0	$0
Charleston	773	1,264	156	0	0	0	0
Fort Tejon	470	886	158	11	0	28	140
Hayward	208	1,310	115	6	0	0	91
New Madrid (M=8)	2,216	2,786	458	56	28	47	0
New Madrid (M=7)	204	1,077	108	19	9	19	0
Puget Sound	496	1,834	96	6	0	0	18
Wasatch Front	323	90	31	6	0	0	0

Table 6 Direct Damage Losses to Local Distribution Systems

Event	*Electric $ Billion*	*Water $ Billion*	*Highways $ Billion*
Cape Ann	$0.89	$0.30	$0.60
Charleston	0.74	0.31	0.50
Fort Tejon	0.91	0.23	0.23
Hayward	0.90	0.20	0.25
New Madrid (M=8.0)	2.07	0.88	1.40
New Madrid (M=7.0)	0.65	0.28	0.44
Puget Sound	0.58	0.09	0.28
Wasatch Front	0.38	0.13	0.26

6. Estimation of Indirect Economic Effects

Earthquakes produce both direct and indirect economic effects. The direct effects, such as dollar loss due to fires and collapsed structures, are obvious and dramatic. However, the indirect effects that these disruptions have on the ability of otherwise undamaged enterprises to conduct business may be quite significant. Although the concept of seismic disturbances and their effect on lifelines has been investigated for at least two decades, there is very little literature on indirect economic losses.

This study provides a first approximation of the indirect economic effects of lifeline interruption due to earthquakes. To accomplish this the relevant literature was surveyed. Then a methodology was developed to relate lifeline interruption estimates to economic effects of lifeline interruption in each economic sector. This required a two-step process:

1. Development of estimates of interruption of lifelines as a result of direct damage

2. Development of estimates of economic loss as a result of lifeline interruption

Estimates of Lifeline Interruption. Lifeline interruption resulting from direct damage is quantified in this investigation in residual capacity plots that define percent of function restored as a function of time. The curves are estimated for each lifeline type and scenario earthquake using (1) the time-to-restoration curves discussed in Chapter 3 and provided in Appendix B, (2) estimates of ground shaking intensity provided by the seismic hazard model (from Chapter 4), and (3) inventory data specifying the location and type of facilities affected (from Chapter 2).

For site-specific systems (i.e., lifelines consisting of individual sited or point facilities, such as airports or hospitals) the time-to-restoration curves are used directly whereas for extended regional networks, special analysis procedures are used. These procedures consist of:

- connectivity analyses, and

- serviceability analyses.

Connectivity analyses measure post-earthquake completeness, "connectedness," or "cut-ness" of links and nodes in a network. Connectivity analyses ignore system capacities and seek only to determine whether, or with what probability, a path remains operational between given sources and given destinations.

Serviceability analyses seek an additional valuable item of information: If a path or paths connect selected nodes following an earthquake, what is the remaining, or residual, capacity between these nodes? The residual capacity is found mathematically by convolving lifeline element capacities with lifeline completeness.

A complete serviceability analysis of the nation's various lifeline systems, incorporating earthquake effects, was beyond the scope of this project. Additionally, capacity information was generally not available for a number of the lifelines (e.g, for the highway system, routes were available, but not number of lanes). Rather, for this project, a limited serviceability analysis has been performed, based on a set of simplifying assumptions.

The fundamental assumption has been that, on average, all links and nodes of a lifeline have equal capacities, *so that residual capacity has been determined as the ratio of the number of serviceable (i.e., surviving) links and nodes to the original number of serviceable links and nodes, for a given source/destination pair, or across some appropriate boundary*. For example, if the state of South Carolina has 100 airports, and 30 of these are determined to be unserviceable at some point in time following a major earthquake, then the air transport lifeline residual capacity is determined to be 70% of the initial capacity.

An example illustrating the residual capacity plots for one lifeline and their implication is discussed below. Included in Chapter 6 are example residual capacity plots for all lifelines considered. Appendix C contains all residual capacity plots developed under this project (for the various lifelines and scenario earthquakes).

Ports. An example residual capacity plot for South Carolina, the worst-case situation, is provided in Figure 10. In this example, the initial loss is nearly 100 percent of capacity, and full

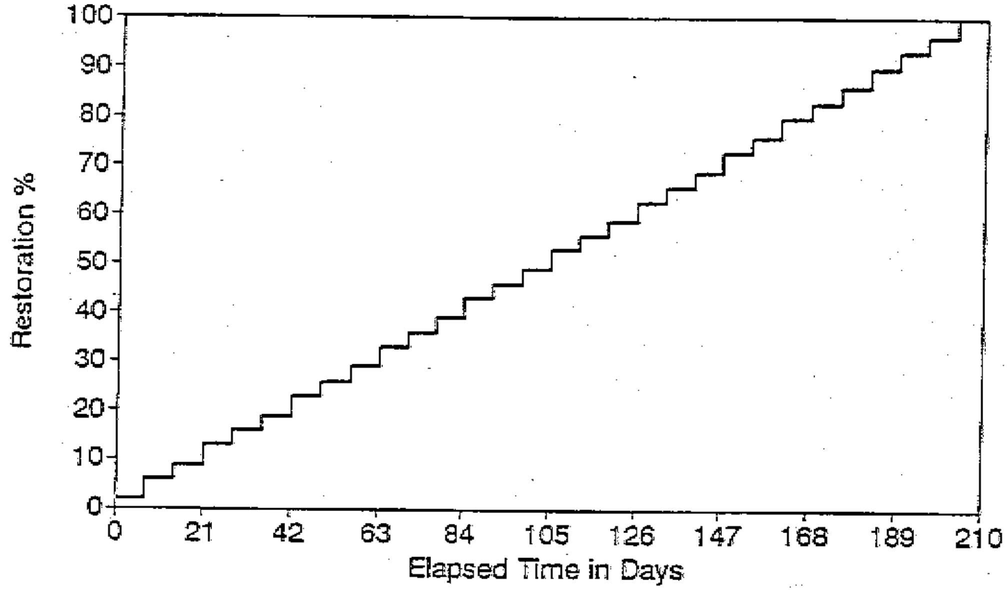


Figure 10 *Residual capacity of South Carolina ports following Charleston event (M=7.5).*

capacity is not restored until about day 200. Georgia would also experience similarly high losses due to the Charleston event. Massachusetts and Rhode Island would experience the largest losses due to the Cape Ann event.

Estimates of Indirect Economic Losses. Economic activity within each industrial sector was measured in terms of value added. Value added refers to the value of shipments (products) less the cost of materials, supplies, contract work and fuels used in the manufacture or cultivation of the product. The United States Bureau of Economic Analysis publishes annual data for value added for each industrial sector. For simplicity, data from the 99 sectors were collapsed into 36 sectors. Data for 1983 were the latest available (published by BEA, 1989), and were used in this study.

Reduction in Value Added Due to Lifeline Interruption. Table 7 presents the percent reduction in value added for each sector resulting from increasingly severe crude oil lifeline interruptions. (Similar tables are shown for all lifelines in Appendix D.) Values are shown for each decile of lifeline interruption and are assumed to pertain to *monthly* Gross National Product (GNP).

Indirect Economic Loss Results. Indirect economic losses were estimated for each lifeline system and scenario event using the residual capacity plots provided in Appendix C and the economic tables described above. The calculation procedure are described in Chapter 6.

Summaries of the total indirect economic losses resulting from damage to site-specific systems and extended regional networks, based on 1986 GNP data, are provided in Table 8. Total indirect economic losses resulting from damage to local distribution systems are presented in Table 9. We note that Table 8 contains total loss amounts expressed in terms of lower bound, upper bound, and best estimate. The lower bound represents economic loss caused by the singular lifeline system causing the greatest loss; the upper bound is the sum of losses caused by all systems; and the best estimate is the square root of the sum of the squares (SRSS) of losses

Table 7 Percent Value-Added Lost Due to Specified Percent Loss of Oil Supply Lifeline

L/L Capacity Loss-->	*U.S. Econ. Value Added (Percent)*	*10%*	*20%*	*30%*	*40%*	*50%*	*60%*	*70%*	*80%*	*90%*	*100%*
1 Livestock	0.45%	2.63%	7.89%	13.16%	18.42%	23.68%	28.95%	34.21%	39.47%	44.74%	50.00%
2 Agr. Prod.	1.06%	4.21%	12.63%	21.05%	29.47%	37.89%	46.32%	54.74%	63.16%	71.58%	80.00%
3 AgServ For. Fish	0.11%	4.21%	12.63%	21.05%	29.47%	37.89%	46.32%	54.74%	63.16%	71.58%	80.00%
4 Mining	3.89%	4.74%	14.21%	23.68%	33.16%	42.63%	52.11%	61.58%	71.05%	80.53%	90.00%
5 Construction	5.52%	4.74%	14.21%	23.68%	33.16%	42.63%	52.11%	61.58%	71.05%	80.53%	90.00%
6 Food Tobacco	2.41%	2.63%	7.89%	13.16%	18.42%	23.68%	28.95%	34.21%	39.47%	44.74%	50.00%
7 Textile Goods	0.37%	2.63%	7.89%	13.16%	18.42%	23.68%	28.95%	34.21%	39.47%	44.74%	50.00%
8 Misc Text. Prod.	0.73%	2.63%	7.89%	13.16%	18.42%	23.68%	28.95%	34.21%	39.47%	44.74%	50.00%
9 Lumber & Wood	0.52%	2.63%	7.89%	13.16%	18.42%	23.68%	28.95%	34.21%	39.47%	44.74%	50.00%
10 Furniture	0.34%	2.63%	7.89%	13.16%	18.42%	23.68%	28.95%	34.21%	39.47%	44.74%	50.00%
11 Pulp & Paper	0.87%	2.63%	7.89%	13.16%	18.42%	23.68%	28.95%	34.21%	39.47%	44.74%	50.00%
12 Print & Publish	1.31%	2.63%	7.89%	13.16%	18.42%	23.68%	28.95%	34.21%	39.47%	44.74%	50.00%
13 Chemical Drugs	1.40%	2.63%	7.89%	13.16%	18.42%	23.68%	28.95%	34.21%	39.47%	44.74%	50.00%
14 Petrol. Refining	0.96%	5.26%	15.79%	26.32%	36.84%	47.37%	57.89%	68.42%	78.95%	89.47%	100.00%
15 Rubber & Plastic	1.03%	2.63%	7.89%	13.16%	18.42%	23.68%	28.95%	34.21%	39.47%	44.74%	50.00%
16 Leather Prods.	0.12%	2.63%	7.89%	13.16%	18.42%	23.68%	28.95%	34.21%	39.47%	44.74%	50.00%
17 Glass Stone Clay	0.62%	2.63%	7.89%	13.16%	18.42%	23.68%	28.95%	34.21%	39.47%	44.74%	50.00%
18 Prim. Metal Prod.	1.04%	4.74%	14.21%	23.68%	33.16%	42.63%	52.11%	61.58%	71.05%	80.53%	90.00%
19 Fab. Metal Prod.	1.64%	2.63%	7.89%	13.16%	18.42%	23.68%	28.95%	34.21%	39.47%	44.74%	50.00%
20 Mach. Exc. Elec.	1.56%	2.63%	7.89%	13.16%	18.42%	23.68%	28.95%	34.21%	39.47%	44.74%	50.00%
21 Elec. & Electron	2.52%	2.63%	7.89%	13.16%	18.42%	23.68%	28.95%	34.21%	39.47%	44.74%	50.00%
22 Transport Eq.	2.62%	4.74%	14.21%	23.68%	33.16%	42.63%	52.11%	61.58%	71.05%	80.53%	90.00%
23 Instruments	0.68%	2.63%	7.89%	13.16%	18.42%	23.68%	28.95%	34.21%	39.47%	44.74%	50.00%
24 Misc. Manufact.	0.69%	2.63%	7.89%	13.16%	18.42%	23.68%	28.95%	34.21%	39.47%	44.74%	50.00%
25 Transp & Whse.	3.46%	4.74%	14.21%	23.68%	33.16%	42.63%	52.11%	61.58%	71.05%	80.53%	90.00%
26 Utilities	5.89%	2.63%	7.89%	13.16%	18.42%	23.68%	28.95%	34.21%	39.47%	44.74%	50.00%
27 Wholesale Trade	5.63%	2.63%	7.89%	13.16%	18.42%	23.68%	28.95%	34.21%	39.47%	44.74%	50.00%
28 Retail Trade	5.63%	4.74%	14.21%	23.68%	33.16%	42.63%	52.11%	61.58%	71.05%	80.53%	90.00%
29 F.I.R.E.	16.64%	3.16%	9.47%	15.79%	22.11%	28.42%	34.74%	41.05%	47.37%	53.68%	60.00%
30 Pers./Prof. Serv.	8.03%	3.16%	9.47%	15.79%	22.11%	28.42%	34.74%	41.05%	47.37%	53.68%	60.00%
31 Eating Drinking	2.12%	4.21%	12.63%	21.05%	29.47%	37.89%	46.32%	54.74%	63.16%	71.58%	80.00%
32 Auto Serv.	1.09%	4.74%	14.21%	23.68%	33.16%	42.63%	52.11%	61.58%	71.05%	80.53%	90.00%
33 Amuse & Rec.	0.70%	4.74%	14.21%	23.68%	33.16%	42.63%	52.11%	61.58%	71.05%	80.53%	90.00%
34 Health Ed. Soc.	6.30%	1.05%	3.16%	5.26%	7.37%	9.47%	11.58%	13.68%	15.79%	17.89%	20.00%
35 Govt & Govt Ind.	11.79%	1.05%	3.16%	5.26%	7.37%	9.47%	11.58%	13.68%	15.79%	17.89%	20.00%
36 Households	0.25%	2.63%	7.89%	13.16%	18.42%	23.68%	28.95%	34.21%	39.47%	44.74%	50.00%
TOTAL	100.00%	3.25% Avg.	9.74% Avg.	16.23% Avg.	22.72% Avg.	29.21% Avg.	35.70% Avg.	42.19% Avg.	48.68% Avg.	55.18% Avg.	61.67% Total V.A Pct. V.A.

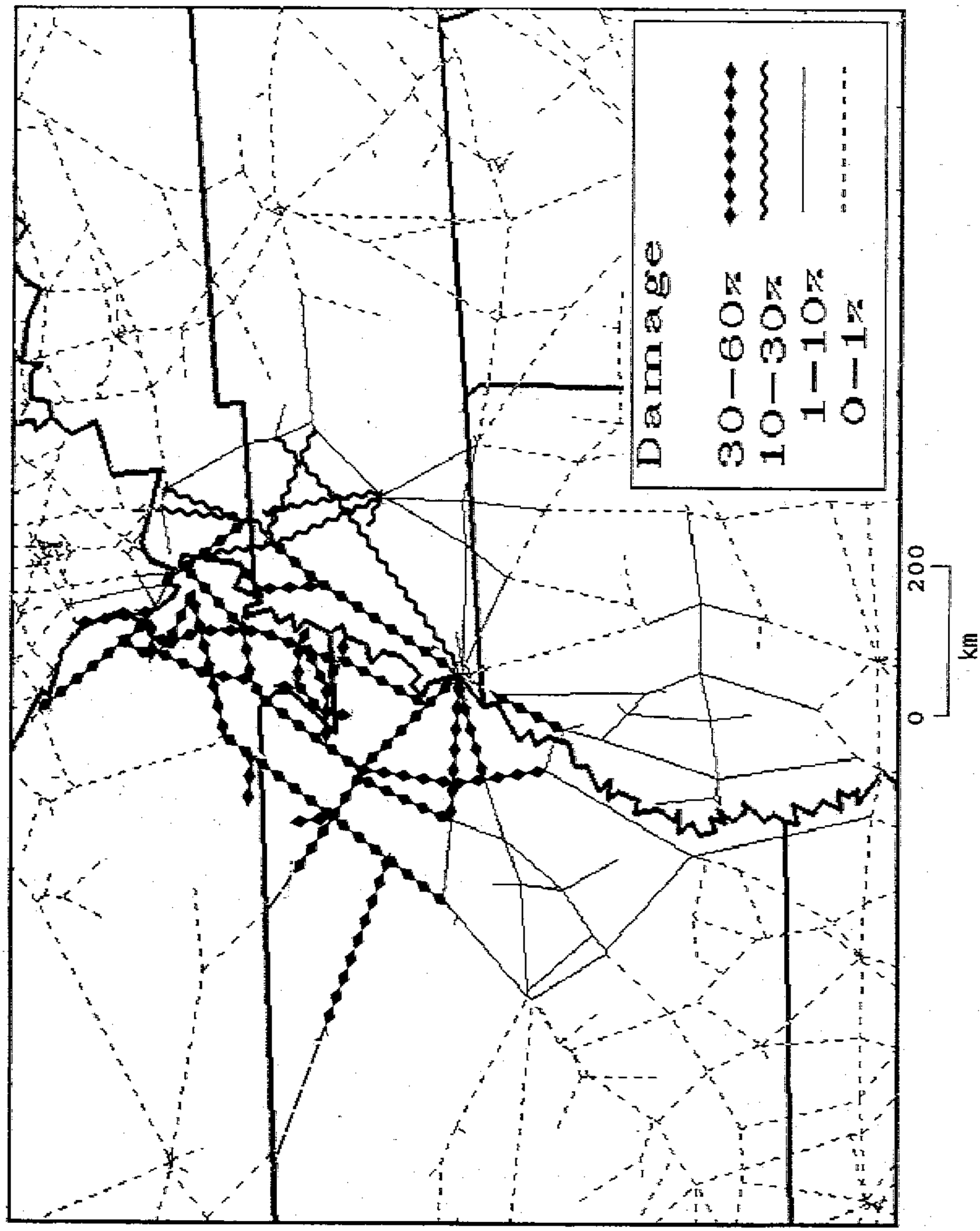


Figure 16 *Damage to railroad system following magnitude-8 New Madrid Event.*

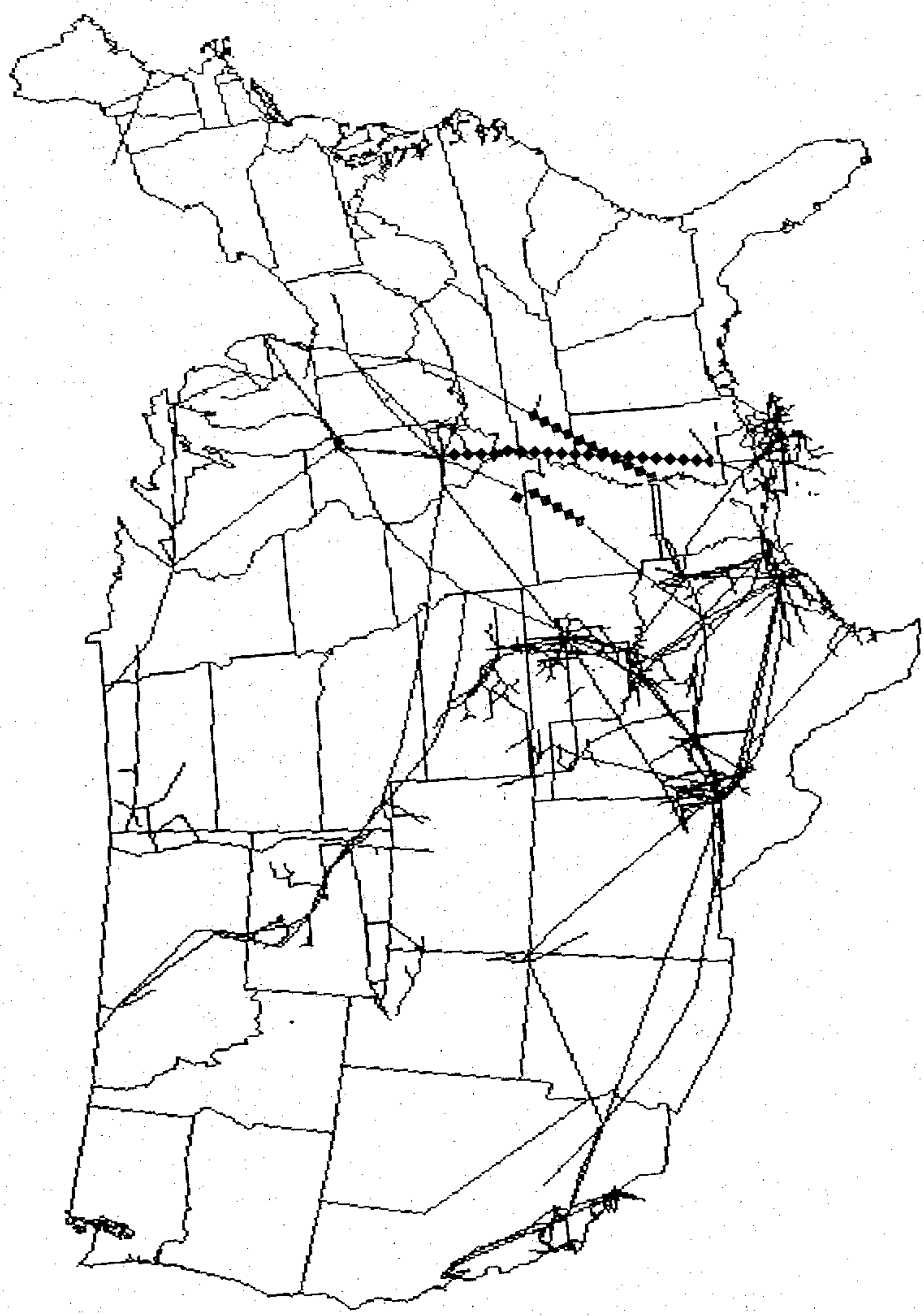


Figure 17 *Damage to crude oil system following magnitude-8 New Madrid Event. Broken pipelines are shown with solid diamonds.*

caused by each lifeline. We note also that the SRSS procedure was used to estimate total indirect economic losses resulting from damage to local distribution networks (Table 9).

By combining like system data from Tables 8 and 9 in a least squares (SRSS) fashion, we estimate the total indirect economic losses for the eight scenario earthquakes as follows:

Earthquake	*Indirect Loss (in Billions, 1991$)*
Cape Ann	$9.1
Charleston	$10.2
Fort Tejon	$11.7
Hayward	$11.1
New Madrid, M = 8.0	$14.6
New Madrid, M = 7.0	$4.9
Puget Sound	$6.1
Wasatch Front	$3.9

Bar charts showing the indirect losses caused by transmission lines (upper bound data) by state for each scenario earthquake were also developed. An example plot for the magnitude-8 New Madrid scenario event is provided in Figure 11. We note that estimates of indirect economic losses for each state are sensitive to the assumed location of the source zone for large-magnitude events (e.g., had the assumed source zone for the magnitude-8 New Madrid event been located further north, estimates of direct damage in Missouri would have been substantially larger).

The data provided in Figure 11 suggests Mississippi and Arkansas would experience the highest indirect losses due to the magnitude-8.0 New Madrid event. Similar plots for the other scenario earthquakes (Chapter 6) indicate that: Massachusetts would experience the highest indirect losses due to the Cape Ann event with the electric system contributing the highest portion; and South Carolina, Utah, Washington, Northern and Southern California would experience the highest indirect losses due to the Charleston, Utah, Seattle, Hayward, and Fort Tejon events, respectively. The electric system contributes the highest indirect losses, among all systems, for most of the events.

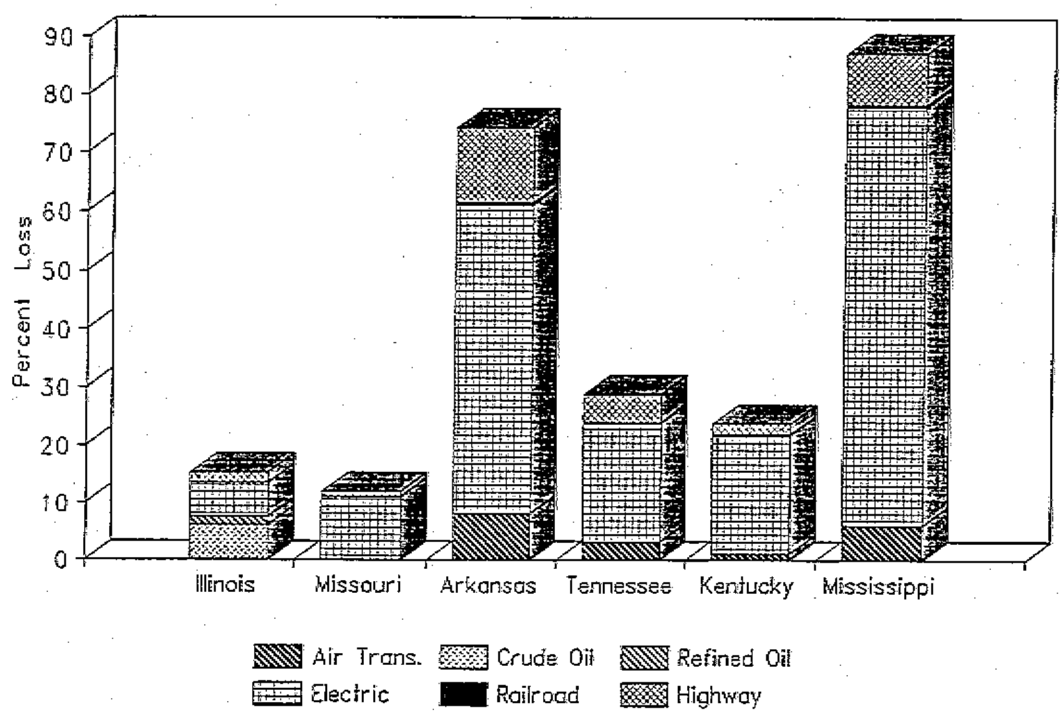


Figure 11 *Percent indirect economic loss by state (monthly GNP) resulting from damage to various lifelines, New Madrid event (M=8.0). Note that the relatively low losses for Missouri reflect the assumed location of the scenario earthquake source zone and the estimated distribution of intensity (see Figure 7).*

7. Combined Economic Losses, Deaths and Injuries

Human Death and Injury. It is generally felt that lifeline performance and continuity of operation is vital to human survival in the modern, urban, world. Most observers believe that damage to lifelines would result in human death and injury. Analogous to direct damage to property and indirect economic losses, human death and injury resulting from lifeline damage can be categorized as follows:

1. Human death and injury caused by lifeline functional curtailment, where persons suffer as a result of deprivation of vital services; and

2. Human death and injury resulting from direct damage to lifelines (e.g., occupant injuries resulting from the collapse of an air terminal building).

Casualties Due to Lifeline Functional Curtailment. Without the benefit of hard data it is difficult to estimate with high confidence the number of casualties that will result from curtailment of lifeline function. Our preliminary assessment is that human death and injury due to functional curtailment of lifelines can generally be expected to be very low. This is a fundamental assumption of this study, and will probably cause some debate. Each lifeline was considered, and this conclusion was found to hold, based on the following assumptions: (1) most vital installations that normally require a lifeline service have back-up emergency supplies, and (2) most lifelines have considerable elasticity in demand, and the level of service necessary for life maintenance is very low. Examples follow:

- Electricity. Persons can survive without power, even in the Northeast in the winter. Most hospitals and similar installations have emergency generators. Those that lack emergency generators can transfer patients to other sites.

- Water. Water for human survival is very minimal. Humans can survive without water for 48 or more hours, and water for human survival can be imported if necessary.

- Gas and Liquid Fuels. Gas and liquid fuel systems are probably the most critical of all lifelines, yet capacity is very elastic, and only short-term shortages are expected. Fuel for heating in the Northeast in the winter can be conserved if necessary by clustering people in school gymnasia, national guard armories, and so on.

- Rail, Air, and Highway Transportation. Transportation lifelines are highly redundant and thus very elastic; emergency food and medicines would be expected to be deliverable regardless of earthquake damage.

Casualties Resulting From Lifeline Direct Damage. Casualties can result from direct damage, especially catastrophic collapse, of lifeline components. Although few deaths occurred directly as a result of lifeline damage in U. S. earthquakes prior to 1989, life-loss due to lifeline failure was tragically demonstrated during the October 17, 1989, Loma Prieta, California, earthquake. Approximately two thirds of the 62 deaths from this earthquake resulted from the failure of a lifeline component--partial collapse of the Cypress structure, a double-decked highway viaduct in Oakland approximately 100 km from the earthquake source zone.

Although it can be argued that the deaths and injuries caused by lifeline failure in the Loma Prieta earthquake were the exception, not the rule, the vulnerability functions developed for this project suggest that substantial life-loss from lifeline component failure should be anticipated. Lifeline failures that could cause substantial life loss or injury include bridge failure, railroad derailment, and pipeline failure.

Unfortunately, data necessary for estimating life loss associated with these component failures are not readily available, precluding development of reliable casualty estimation methodology and data for lifeline structures.

Combined Direct and Indirect Economic Losses. Summaries of total dollar losses from direct damage and indirect economic losses are combined and summarized for each scenario earthquake and lifeline in Table 10. The total

Table 10 Total Direct Plus Indirect Dollar Losses for Each Scenario Earthquake and Lifeline (Billions of Dollars)

Scenario	*Electric*	*Highways*	*Water*	*Medical Care*	*Ports*	*Railroads*	*Airport*	*Natural Gas*	*Crude Oil*	*Refined Oil*	*Broadcasting Stations*	*Fire Stations*	*Total*
Cape Ann	$11.24	$2.06	$0.91	$0.49	$0.50	$0.03	$0.58	$0.00	$0.00	$0.00	$0.02	$0.01	$13.25
Charleston	$10.82	$2.05	$0.94	$0.57	$5.30	$0.18	$0.59	$0.00	$0.00	$0.00	$0.07	$0.01	$15.11
Fort Tejon	$9.66	$5.18	$5.27	$1.43	$2.65	$0.41	$1.57	$1.68	$4.38	$0.00	$0.03	$0.05	$16.58
Hayward	$12.21	$2.52	$4.38	$1.30	$1.46	$0.22	$0.44	$0.09	$0.00	$0.00	$0.02	$0.01	$15.66
New Madrid 8	$15.68	$13.19	$2.68	$1.30	$0.00	$0.71	$1.22	$0.34	$0.46	$0.23	$0.09	$0.01	$26.37
New Madrid 7	$5.17	$4.12	$0.85	$0.40	$0.00	$0.15	$0.31	$0.18	$0.13	$0.16	$0.03	$0.00	$8.29
Puget Sound	$8.29	$1.95	$0.90	$0.51	$0.73	$0.21	$0.62	$0.21	$0.00	$0.00	$0.05	$0.01	$10.48
Wasatch Front	$2.21	$3.85	$0.40	$0.20	$0.00	$0.05	$0.11	$0.04	$0.00	$0.00	$0.04	$0.00	$5.41

losses for each scenario earthquake are as follows:

Earthquake	*Direct Plus Indirect Losses (in Billions, 1991$)*
Cape Ann	$13.3
Charleston	$15.1
Fort Tejon	$16.6
Hayward	$15.7
New Madrid, M = 8.0	$26.4
New Madrid, M = 7.0	$8.3
Puget Sound	$10.5
Wasatch Front	$5.4

8. Hazard Mitigation of Critical Lifelines

Identification of Critical Lifelines. Based on the combined direct and indirect economic losses presented above and with due consideration of the assumptions and limitations expressed throughout this report, we offer the following relative ranking of the criticality of different lifelines in terms of the estimated impact of damage and disruption:

Rank	Lifeline	Event/Location
1.	Electric System	New Madrid (M=8.0)
		Hayward
		Cape Ann, Charleston, Fort Tejon
2.	Highways	New Madrid (M=8.0)
		Fort Tejon
		Hayward, New Madrid (M=7.0)
3.	Water System*	Fort Tejon
4.	Ports	Charleston
5.	Crude Oil	Fort Tejon

*The ranking for the water system may be underestimated because critical components such as pumping stations and dams were not included in the study.

Measures for Reducing Vulnerability of Lifeline Systems. The seismic vulnerability of lifeline systems, from the point of view of fulfilling function, can be reduced through three primary approaches:

1. Damage reduction measures. In this approach reliability of function is enhanced by reducing damage. This approach may take the form of :
   - Strengthening a building, bracing equipment, or performing other corrective retrofit measures to mitigate shaking effects;
   - Densifying the soil beneath a structure, or placing a structure on piles, or using other techniques to mitigate hazardous geotechnical conditions, e.g., liquefaction potential,
   - Other component improvements, depending on the component and potential earthquake impacts, e.g., replacement of vulnerable systems/components with new systems/components that will provide improved seismic resistance.
2. Provision for system redundancy. In this approach, reliability of function is enhanced by providing additional and alternative links (e.g., new highways, pipelines, other transmission or distribution links). Because earthquake damage is fundamentally a random phenomena, addition of system links will tend to increase system reliability.
3. Operational improvements. In this approach reliability of function is enhanced by providing emergency response planning and the capability to rapidly and effectively repair damage, redirect functions, or otherwise mitigate earthquake damage impacts on system operations and thereby re-establish system function.

Of these measures, the most common are component strengthening/retrofit measures, which are discussed at length in Appendix B of this report. The proposed measures (Appendix B) include generic solutions, such as designing structures to meet current seismic design or retrofit standards of the local community, or anchoring equipment. In addition, there are numerous specific measures that relate to unique systems or components within each lifeline. Special attention should be directed to those systems and conditions that are of greatest concern, such as porcelain components in electric substations.

Following are recommended steps when implementing a program to reduce seismic hazards of existing lifelines:

1. Review existing descriptions of seismic performance and rehabilitation measures for the lifeline(s) of concern, i.e., familiarize yourself and your organization with the overall problem. Sources include Appendix B and Chapter 10 (References) of this report.

2. Conduct an investigation of the seismic vulnerability and impact of disruption for the lifeline(s) and region(s) of concern. Lifeline seismic evaluation methodologies and other potential resources for this purpose have been developed by the ASCE Technical Council for Lifeline Earthquake Engineering (see references, Chapter 10), the Applied Technology Council (ATC, in preparation) and others.

3. Focus first on the most vulnerable lifelines, components, and conditions (e.g., liquefaction or landslide potential). Vulnerable components include:

   For electric systems:
   - Substations
   - Power stations

   For water systems:
   - Pumping stations
   - Tanks and reservoirs
   - Treatment plants
   - Transmissions aqueducts

   For highway systems
   - Bridges
   - Tunnels
   - Roadbeds

   For water transportation systems:
   - Port/cargo handling equipment
   - Inland waterways

   For gas and liquid fuels:
   - Distribution storage tanks
   - Transmission pipelines
   - Compressor, metering and pressure reduction stations

4. Conduct cost-benefit studies to determine the most cost effective measures. We note that, in some cases, retrofit measures may not be very cost effective. In regions where the return period for large earthquakes is quite long, for example, replacement over the life cycle of the facility or component may be a reasonable approach.

5. Implement the selected hazard reduction measures.

9. Recommendations for Further Work

The ATC-25 project has raised a number of questions and indicated areas in which knowledge is inadequate or nonexistent with respect to the impact of lifeline disruption due to earthquake. Following are recommendations for further research and other efforts. This list is not meant to be all inclusive but rather an overview of some of the more important issues that should be pursued.

Lifeline Inventory. Organizations such as the Federal Emergency Management Agency, Department of Transportation, and American Society of Civil Engineers Technical Council of Lifeline Earthquake Engineering are encouraged to build on the work performed in this project, develop standards for complete lifeline inventories, and coordinate the acquisition of the needed additional and updated data from various lifeline owners.

Lifeline Component Vulnerability. We recommend a major effort to acquire data on lifeline seismic performance and damage, and conduct analysis towards the development of improved component vulnerability functions. This effort should also investigate lifeline recovery data, and incorporate the extensive experience realized during the 17 October 1989 Loma Prieta, California, earthquake, as well as from other damaging earthquakes.

Seismic Hazard Data. We suggest that the U. S. Geological Survey develop, or coordinate through the various states' Office of Geologists, a series of digitized soils/geologic databases.

Economic Analysis and Impacts Data and Methodology. We recommend further research, especially in economic areas such as:

- Economic impacts associated with lifeline disruption,
- Second-order economic effects (e.g., interaction between lifelines),
- Elasticities of demand, or substitution of a lesser disrupted lifeline for a more disrupted lifeline ,
- Inter-regional impacts, and
- So-called "benefits," such as increased economic activity associated with repair, or replacement of older equipment with new technology.

Lastly, we note that this study did not address environmental consequences associated with lifeline disruption, especially the potential for oil spills from broken pipelines in the nation's waterways following a New Madrid event. Investigation of this issue is critically important.

1. Introduction

1.1 Background and Purpose

Lifeline is an earthquake engineering term denoting those systems necessary for human life and urban function, without which large urban regions cannot exist. Lifelines basically convey food, water, fuel, energy, information, and other materials necessary for human existence from the production areas to the consuming urban areas. Prolonged disruption of lifelines such as the water supply or electric power for a city or urbanized region would inevitably lead to major economic losses, deteriorated public health, and eventually population migration. Earthquakes are probably the most likely natural disaster that would lead to major lifeline disruption. With the advent of more and more advanced technology, the United States has increasingly become dependent on the reliable provision of lifeline-related commodities, such as electric power, fuel, and water. A natural question is: What is the potential for major disruption to these lifelines, especially at the regional level?

The initiation of this study by the Federal Emergency Management Agency (FEMA) is based in part on a need to better understand the impact of disruption of lifelines from earthquakes and to assist in the identification and prioritization of hazard mitigation measures and policies. In addition, the report is intended to improve national awareness of the importance of protecting lifeline systems from earthquakes, and of assuring lifeline reliability and continued serviceability.

The specific contractual requirements of this project and report are:

- To assess the extent and distribution of existing U.S. lifelines, and their associated seismic risk; and
- To identify the most critical lifelines, and develop a prioritized series of steps for reduction of lifeline seismic vulnerability, based on overall benefit.

FEMA is also sponsoring a companion study to develop and demonstrate a model methodology for assessing the seismic vulnerability and impact of disruption of water transmission and distribution systems (ATC, in preparation).

In this study, lifelines of critical importance at the U.S. national level have been analyzed to estimate overall seismic vulnerability and to identify those lifelines having the greatest economic impact, given large, credible U. S. earthquakes. The lifelines examined include electric systems; water, gas, and oil pipelines; highways and bridges; airports; railroads; ports; and emergency service facilities. The vulnerability estimates and impacts developed are presented in terms of estimated direct damage losses and indirect economic losses. These losses are considered to *represent a first approximation* because of the assumptions and methodology utilized, because several lifelines are not included, and because, in some cases, the available lifeline inventory data lack critical capacity information.

1.2 Importance of the Lifeline Earthquake Risk Problem

The critical importance and earthquake vulnerability of lifelines were probably first strongly emphasized in the earthquake and ensuing fires in San Francisco in 1906. The disaster in San Francisco, which was the worst urban fire in history to that time, and which continues today to be the worst earthquake disaster in U.S. history, was in large part attributable to the failure of several lifelines, including:

- Breakage of gas distribution and service lines, leading to numerous outbreaks of fire.
- Damage to fire stations, resulting in inoperable apparatus and injured fire fighters. The single worst example of this was the fatal injury of San Francisco Fire Chief Dennis Sullivan, effectively "decapitating" the fire department at the worst possible moment.
- Worst of all, literally hundreds of breaks to the water distribution system within San

Francisco, resulting in total loss of water for fire-fighting purposes.

After that disaster and in recognition of the absolute necessity of water following an earthquake, the San Francisco Fire Department built and today still operates the Auxiliary Water Supply System (AWSS), a unique high-pressure water system separate and redundant from the domestic drinking water supply.

Following 1906, major earthquakes in the U.S. and elsewhere continued to illustrate the prime importance of lifelines in earthquakes. In the 1933 Long Beach Earthquake, for example, numerous authorities at the time cited the prompt shutdown of the municipally operated gas system with the prevention of major fires (e.g., NBFU, 1933; Smethurst, 1933; Binder, 1952):

> Instructions had been issued and signs had been posted near the control valves of the gas and light public utility control stations to the effect that, in the event of an earthquake, these switches must be pulled or valves closed, and this was the reason that the gas lights were shut off in less than four minutes after the earthquake had occurred (Smethurst, 1933).
>
> Broken gas services and devices caused 7 of the 19 fires reported in Long Beach during the night of 10 March 1933. Prompt closing of valves, together with a major break in a high pressure main, undoubtedly prevented fires in numerous locations in the business district. Preparedness for disturbance is of very great importance in connection with gas service (NBFU, 1933).

The 1971 San Fernando Earthquake illustrated more than any other event the essential interaction of lifelines and earthquakes. Examples of lifeline effects in that relatively modest earthquake included:

- Major damage to electrical substations, including overturning of extra high voltage (EHV) transformers;
- Literally hundreds of breaks in the water distribution system;
- Major damage to a telephone central switching office, and loss of telephone service due to this damage as well as saturation;
- Near-collapse of a major dam;
- Numerous breaks in the gas distribution system, resulting in large burning gas flares at several intersections;
- Collapse of major freeway overcrossings, resulting in fatalities and major disruption of traffic; and
- Major damage to emergency facilities, including collapse and major loss of life at a hospital, and major damage or partial collapse at several other hospitals, including very modern structures at one hospital.

Since the 1971 San Fernando Earthquake, significant research into lifelines has been conducted, too extensive to summarize herein (see the following references for major compilations: Kubo and Jennings, 1976; ASCE-TCLEE, 1977; Kubo and Shinozuka, 1981; ASCE-TCLEE, 1981; Smith, 1981; Ariman, 1983; Cooper, 1984; Scawthorn, 1985; Eguchi, 1986; BSSC, 1987). Additionally, several design guidelines have resulted from this research (ASCE-TCLEE, 1983; GLFC, 1984; ATC-6, 1981; ATC-6-2, 1983), which should result in improved future lifeline design and performance.

Based on these efforts, it is fair to say that substantial lifeline earthquake engineering knowledge, data, and experience are presently available today, for the purpose of designing or retrofitting lifelines to withstand the effects of earthquakes. However, because much of the U.S. national infrastructure was constructed prior to the research and guideline development of the 1970s and 1980s, the United States is still faced with the problem of existing lifelines that are seismically vulnerable and that, if disrupted, would result in major economic displacements, and probable environmental damage and human injury.

This last point was tragically demonstrated on October 17, 1989, when the magnitude 7.1 Loma Prieta Earthquake struck the San Francisco Bay Area, resulting in 62 deaths, more than 3,700 injuries, and leaving more than 12,000 persons homeless. Approximately two-thirds of the fatalities in this event were due to the failure of a lifeline--the collapse of the Cypress double-decked highway structure in Oakland. Lifeline damage and disruption were one of the most significant features of this earthquake, the most damaging to strike the conterminous United States since 1906. One of the world's major bridges, the San Francisco-Oakland Bay Bridge, was closed for a month due to structural failure. Power was disrupted over a widespread area, water systems failed in several communities, and other lifeline problems contributed to major disruptions.

1.3 Project Approach

This study is concerned with the seismic risk to lifelines and provides a first approximation of the indirect economic effects of lifeline interruption due to earthquakes. The analysis is first order in that uncertainties in vulnerability functions, seismic hazard, and all other factors were not considered. The overall objective of the study is to quantify the extent and distribution of lifelines in the lower 48 States, to identify the most critical lifelines in terms of their vulnerability and impact on the national economy, and to develop a prioritized series of steps for reducing seismic risk to these lifelines.

Figure 1-1 summarizes the main steps of the approach used to develop this report. Four basic steps were followed to estimate lifeline damage and subsequent economic disruption for given earthquake scenarios.

1. Development of a national lifeline inventory database.

2. Development of seismic vulnerability functions for each lifeline system,

3. Characterization and quantification of the seismic hazard nationwide, and

4. Development of direct damage estimates and indirect economic loss estimates for the various scenario earthquakes.

1.4 Limitations and Constraints

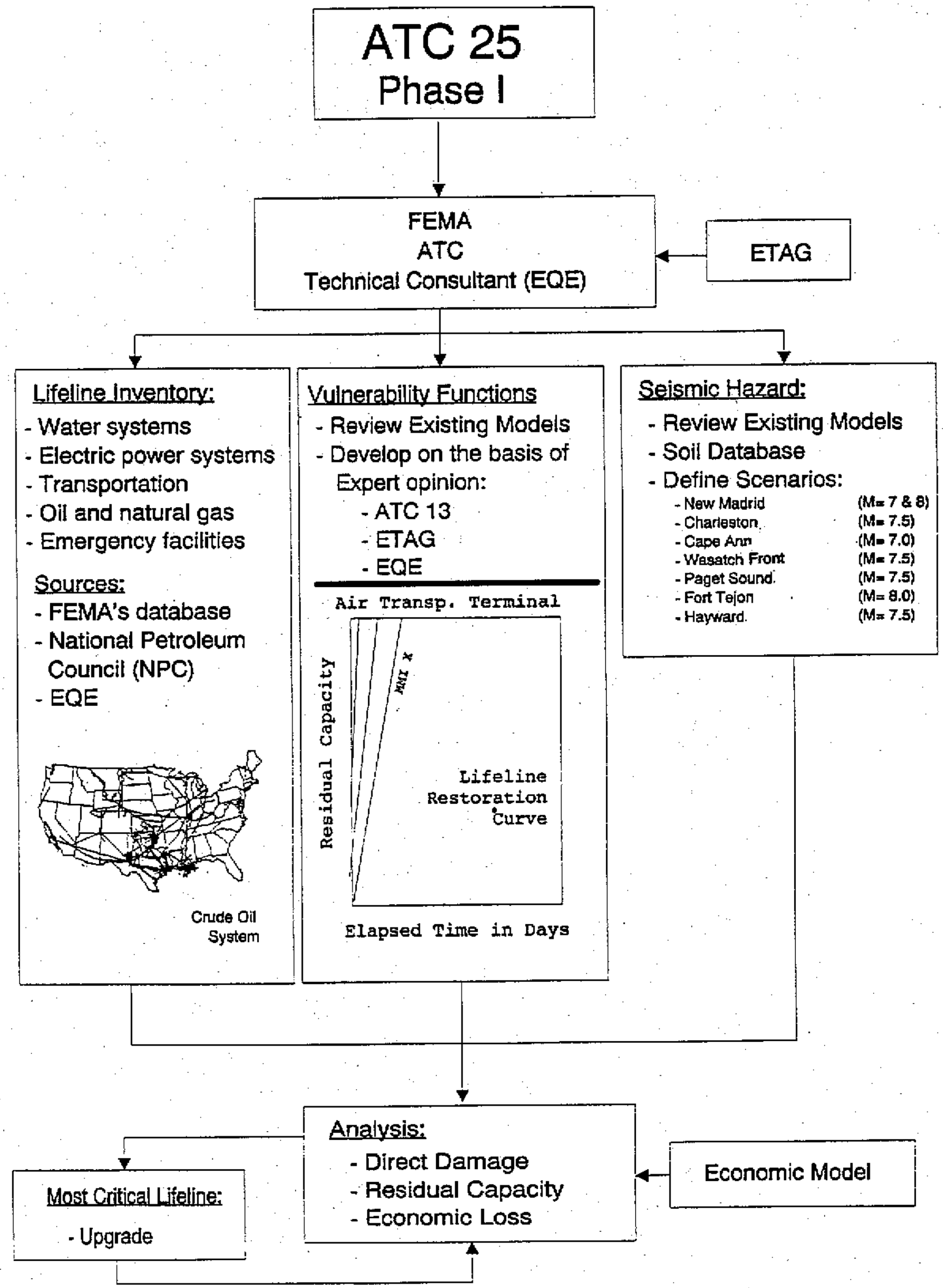
During development of this report and its supporting data, several problems were encountered that could not be resolved because of technical difficulties and lack of available data. For example, telecommunication systems, nuclear and fossil-fuel power plants, dams, and certain water, electric, and transportation facility types at the regional transmission level were excluded from consideration in this project because of the unavailability of inventory data or the need for more in-depth studies.

Interaction effects between lifelines, secondary economic effects (the impact of a reduced capacity of one economic sector on a dependent sector), and damage resulting from landslide (due to lack of inventory data nationwide) were also not considered in developing this report. These limitations and others described in Chapters 2, 4, and 5 tend to underestimate the losses presented herein; and other factors, as described elsewhere in this report, tend to overestimate the losses. Lack of capacity information for most lifelines was also a definite limitation. In the aggregate, due primarily to the exclusion of certain systems (e.g., dams and telecommunication systems), we believe the estimates of losses presented in this report are, in fact, quite conservative.

We also emphasize that this report is a macroscopic investigation at the national level and the results should not be used for microscopic interpretations. The results, for example, are not intended to be used to evaluate any particular regional utility or lifeline, and no specific information on such specific facilities has been included.

1.5 Organization of the Report

The organization and contents of this report have been dictated in large part by the project approach. Following this introduction is Chapter 2, which contains a description of the inventory data developed for and utilized in this project. Seismic vulnerability functions, in the form of damage curves and restoration curves for all lifelines considered, are developed and described in Chapter 3. In Chapter 4 we discuss the seismic hazard nationwide, identify available seismic hazard models that could have been used in the analysis stages of this project, indicate the model that was selected and describe its advantages and disadvantages, and define the eight earthquake scenarios that provide the basic framework for all damage and



Notation: ATC-13: ATC-13 Report, *Earthquake Damage Evaluation Data for California* (ATC, 1985)
ETAG: Expert Technical Advisory Group (project advisory panel)
EQE: EQE Engineering, Inc. (project subcontractor)

Figure 1-1 *Flow chart showing main steps in project approach.*

loss estimates presented in this report. Direct damage estimates and estimates of indirect economic loss are developed in Chapters 5 and 6. The direct damage and indirect economic loss estimates are combined, summarized, and discussed in Chapter 7. In Chapter 8 we identify the most critical lifelines, identify hazard mitigation strategies, and discuss the potential benefits of implementing such strategies.

Chapter 9 provides brief remarks about additionally needed research and other efforts. References are provided in Chapter 10. The report concludes with a series of appendices containing names and affiliations of project participants and substantial amounts of lifeline vulnerability assessment data too voluminous to include in the main body of the report.

2. National Lifeline Inventory

2.1 Introduction

Development of the ATC-25 inventory, for all major lifelines in the United States, was a major task. The project scope required that lifelines be inventoried in sufficient detail for conducting lifeline seismic vulnerability assessments and impact of disruption at the national level. This in turn required that the inventory be compiled electronically in digital form and dictated that inclusion of lifelines at the transmission level, as defined below, was of primary importance. At the same time, the level of effort that could be devoted to this task was constrained by the budget available.

Initially, a number of government, utility, trade and professional organizations, and individuals were contacted in an effort to identify nationwide databases, especially electronic databases. In most cases, these organizations or individuals referred the project back to FEMA, since they had either previously furnished the information to FEMA, or knew that the data had been furnished to FEMA by others. As a result, FEMA's database (FEMA, 1987) became a major source of data for several of the lifelines. A significant portion of these data consist of digitized U.S. Geological Survey (USGS) topographical maps and/or the National Atlas (Gerlach, no date), performed by the U.S. Geological Survey in support of national census requirements. With the exception of oil and gas pipeline data provided by the National Petroleum Council, the inventory data generally date from about 1966, unless later updated by FEMA. A number of other sources were employed in various ways, which are further discussed below.

The network inventory contained in the database is generally at the higher transmission levels, as opposed to lower distribution levels. That is, inventories were generally only compiled for networks at the bulk and/or regional level, as opposed to lifelines at the user-level (i.e., distribution level) *within* an area. To use an analogy, the inventory contains only the national *arterial* level, and neglects the distribution or *capillary* system. For example, all federal and state highways are inventoried, but county and local roads are not. The major reason for focusing on the transmission level is that at lower levels the systems only support local facilities. Thus, a disruption of a local activity could not be used to identify the overall regional importance of the lifeline. However, disruptions at the transmission level impact large regions and are therefore important for understanding the seismic vulnerability and importance of lifelines to the United States. For some lifelines, such as highways and railroads, an additional reason for focusing on the transmission level is the increasing redundancy that contributes to system reliability as one descends in the lifeline hierarchy. Lastly, even at the transmission level, the inventory effort alone is considerable.

The inventory data have been compiled into an electronic database, which generally consists of (i) digitized location and type of facility for single-site lifeline facilities, and (ii) digitized right-of-way, and very limited information on facility attributes for network lifelines. The inventory is only a partial inventory, in that important information on a number of facility attributes (e.g., number or length of spans for highway bridges) was unavailable from FEMA.

2.2 National Lifeline Inventory Data--Overview

The inventory data include information for the conterminous United States only. Lifeline data for Alaska, Hawaii, and U. S. territories, such as Puerto Rico, have been excluded because lifelines in these regions would not be affected by the scenario earthquakes (see Chapter 4) considered in this study.

The specific lifelines that have been inventoried for the conterminous United States are:

Transportation
- Highways
- Railroads
- Airports
- Ports and Harbors

Energy
- Electric Power Transmission
- Gas and Liquid Fuel Transmission Pipelines

Emergency Service Facilities
- Emergency Broadcast Facilities
- Hospitals

Water Aqueducts and Supply

An important lifeline, telecommunication systems, which would be severely impact by earthquake-induced ground shaking, was excluded because of the unavailability of data, as are certain regional distribution network facility types (e.g., railway terminals, bridges, and tunnels; certain aqueducts; major freeway/highway bridges; fossil-fuel power plants; and aqueduct pumping stations). In addition, data on nuclear reactors and dams are excluded because it was believed that such facilities should be the subject of special studies, particularly because of the existing regulations relating to seismic safety in many regions and the expected complexity of the performance and impact of these facility types. As a result, the losses provided by this study will be underestimated to the extent that these facility types are not included.

Also excluded from the inventory, but included in the analysis, are distribution systems at the local level (water, highway, and electrical systems) and police and fire stations. For these facility types, the number of facilities in each 25-km by 25-km grid cell, which is the grid size for the seismic hazard analysis (see Chapter 4), is estimated on the basis of proxy by population.

Each of the above-specified lifelines has been inventoried in terms of its nodes and/or links. Nodes are points on the lifeline, connected by links. Examples of nodes are highway intersections and electric substations. Links would be sections of highway, sections of pipeline, or electric transmission lines. Intermediate points between links have been introduced in some lifelines to provide better location information on the path of a lifeline (i.e., to capture path curvature between nodes).

The data were compiled and reduced on a graphical interactive lifelines seismic risk analysis/database management computer program named *LLEQE** (*L*ife*L*ine *E*arth*Q*uake *E*ngineering). Two operations were required: (1) reduction in the number of links by a factor of about ten to reduce the size of the database to a manageable size for analysis (i.e., minor curvatures at the local level have been eliminated), and (2) continuity corrections so that transmission lines between separately digitized sections (e.g., across state boundaries) would be continuous. The reduction effort was substantial and utilized a significant portion of the financial resources allocated to the inventory task.

The inventory was generally compiled in terms of nodes, links, and descriptive attributes, if available. These attributes are:

1. Measures of lifeline inventory, appropriate to the lifeline. These are, for example:
   - Miles of oil pipeline, by diameter;
   - Number of electric substations;
   - Miles of water pipeline; and
   - Number of emergency facilities, such as hospitals, fire stations.
2. Additionally, where available, measures of function and redundancy have been compiled on this database. For transmission line links, these include:
   - The capacity of the lifeline and/or the population served;
   - The end points of the nodes; and
   - Whether the nodes are served by other links.

Each of the inventoried lifelines, as well as those estimated by proxy, are discussed below.

2.3 Transportation Data

State and Federal Highway System. A comprehensive national digitized data set on the highway system was obtained from FEMA, as shown in Figure 2-1. The system includes state and federal highways, but excludes county and local roads. It consists of 27,761 links (about 489,892 km of highways). Right-of-way alignment is indicated, but capacity (i.e., number of lanes) is not.

Local Highway Distribution. Detailed highway networks at the local level were not readily available in an electronic format. Based on statistics provided by the California Department of Transportation, we have determined that there is approximately 1 mile of local roadway for every 300 persons. This would correspond to approximately 15 feet of local roadway per person.

Federal and State Highway Bridges. Figure 2-2 shows 144,785 bridges, which have been obtained from FEMA's database. Bridges included are those for state and federal highways. Number of spans and structure types were not available.

Railroad System. This system shown in Figure 2-3 consists of about 11,340 links (about 270,611 km). The railroad system was provided by FEMA in digitized form; only right-of-way was indicated.

Airports. Locations of 17,161 civil and general aviation airports were provided by FEMA, as shown in Figure 2-4.

Ports and Harbors. Location information only for about 2,177 ports was provided by FEMA, as shown in Figure 2-5.

2.4 Energy and Fuel Data

Electric Power Generation and Transmission. The electric system provided by FEMA included 230 kV and above and some 115 kV systems (Figure 2-6). The inventory contains 4,551 substations, and 27,372 links, including links used to define path curvature between nodes (about 441,981 km of transmission lines). The number of circuits, and their voltage or capacity, however, are not included in the database. While the lack of capacity information has not been a serious limitation for this study, as discussed elsewhere, we recommend that users of this inventory data seek to add capacity information before using the data to conduct regional or local studies.

Local Electrical System Distribution. Detailed electrical distribution networks at the local level were not readily available in an electronic format. It was assumed, therefore, that the person-to-unit-length ratio for electrical distribution systems was the same as that for highways. In other words, there is approximately 1 mile of electrical distribution line for every 300 persons. This would correspond to approximately 15 feet of electric line per person.

Gas and Liquid Fuel Transmission Pipelines. The National Petroleum Council (NPC, 1989) furnished relatively comprehensive national digitized data on oil and gas pipelines, including size and material of piping. Figures 2-7, 2-8, and 2-9 picture the crude oil, refined oil, and natural-gas pipelines, respectively. The crude oil system includes about 77,109 km of pipelines. The refined oil system consists of about 85,461 km of pipelines and natural gas system has about 67,898 km of pipelines. The database had been developed as part of a major study on the transportation and capacities for this important sector of the economy, and potential catastrophic disruptions (NPC 1989; it is interesting to note that earthquake was not considered as a possible source of disruption in this study).

Refineries. Figure 2-10 shows 19 refineries nationwide having capacities of 80,000 barrels or more per day (the size considered in this study). Locations of these refineries have been digitized from the National Atlas (Gerlach, no date).

2.5 Emergency Service Facility Data

Emergency Broadcast Facilities. The locations of 29,586 stations were obtained from FEMA and are shown in Figure 2-11.

Medical Care Centers. Locations of about 6,973 centers were obtained from FEMA's database and are shown in Figure 2-12. Structural types were not available.

Police and Fire Stations. Detailed information was not available for these facilities. They were estimated as follows:

> Fire Stations. Detailed nationwide fire station inventory data were not readily available in an electronic format. Data for the San Francisco and Los Angeles region fire stations were available (AIRAC, 1987) and were correlated with jurisdictional population to determine a relation, which

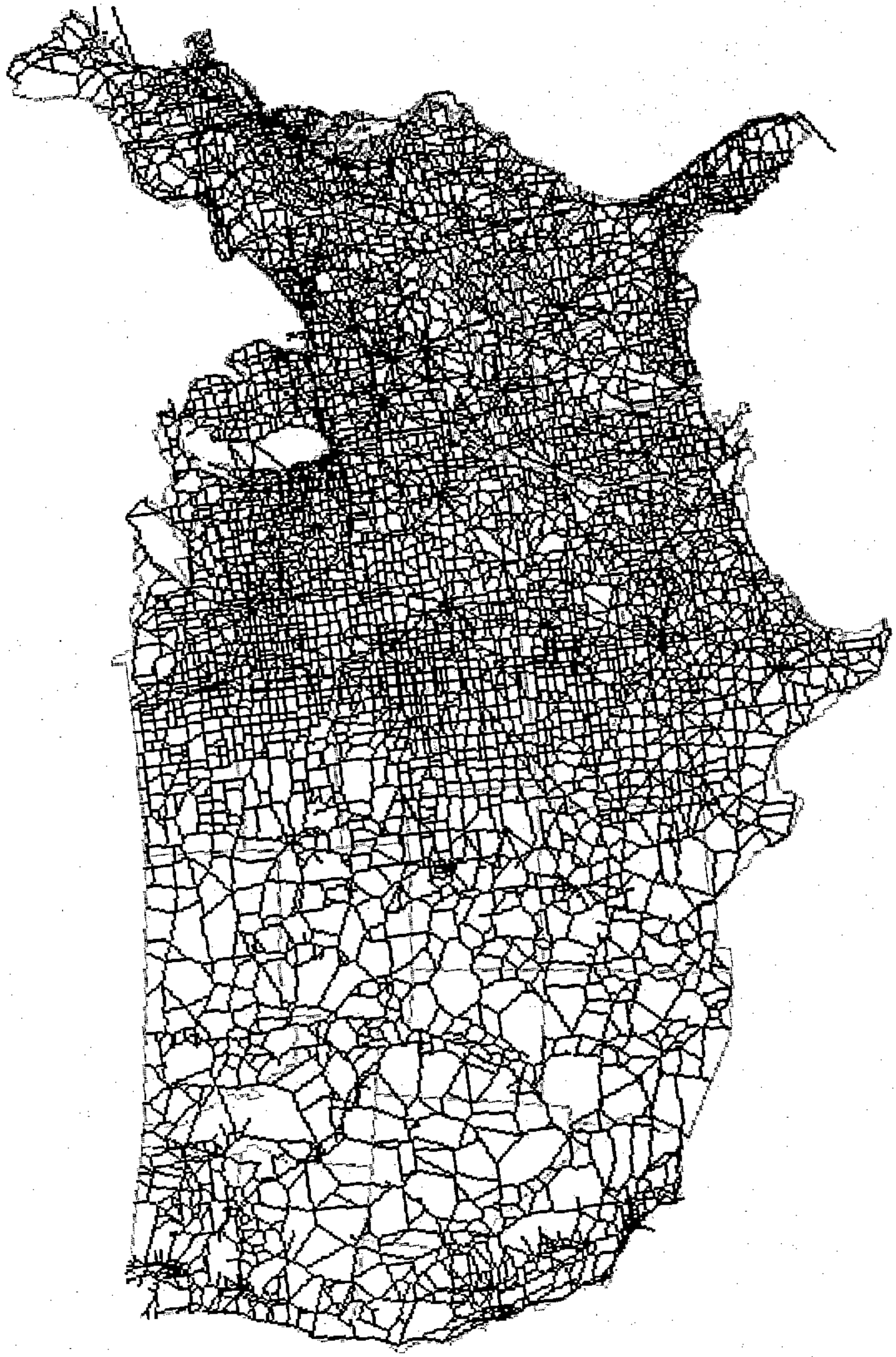


Figure 2-1 *State and federal highways.*

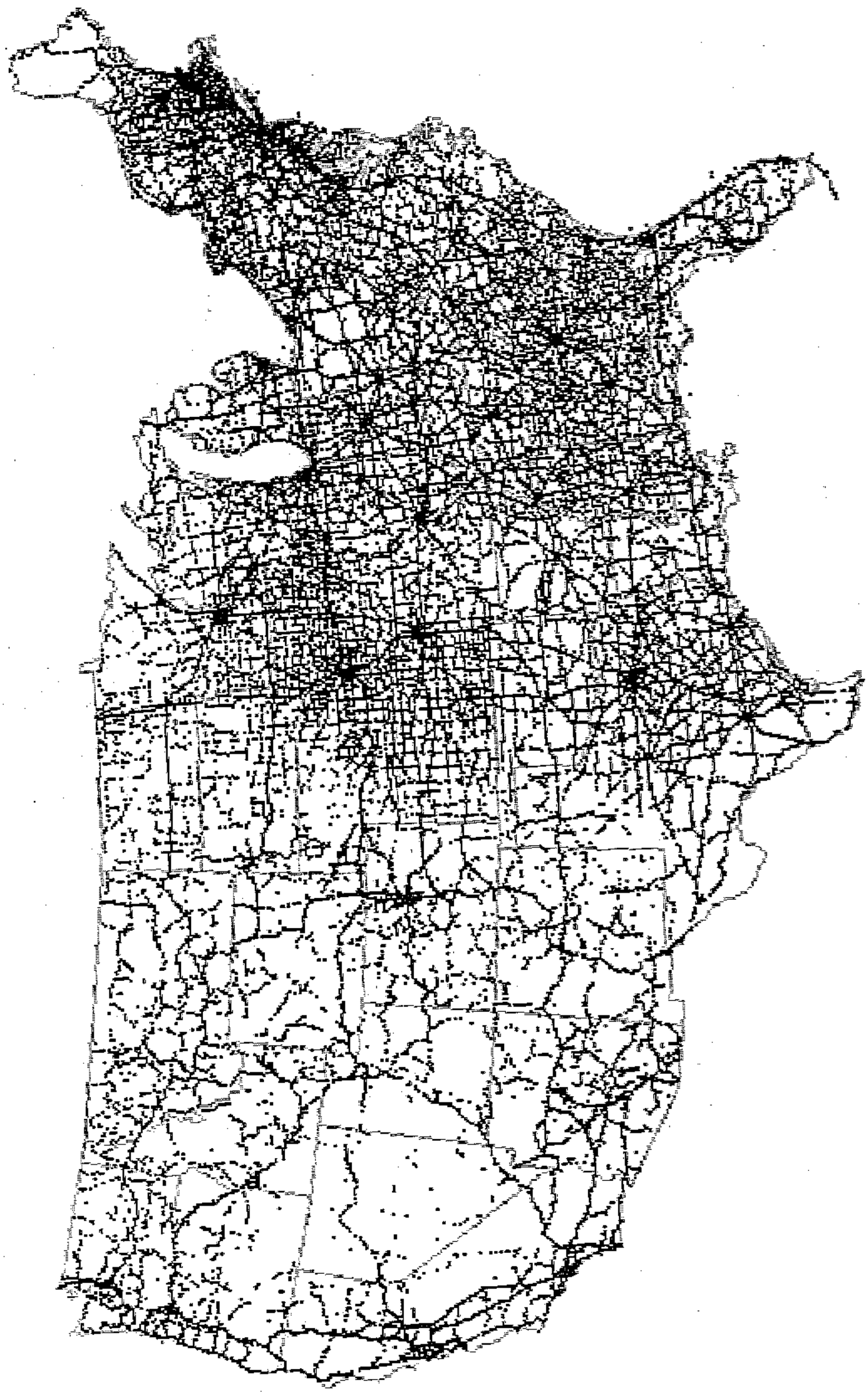


Figure 2-2 *State and federal highway bridges.*

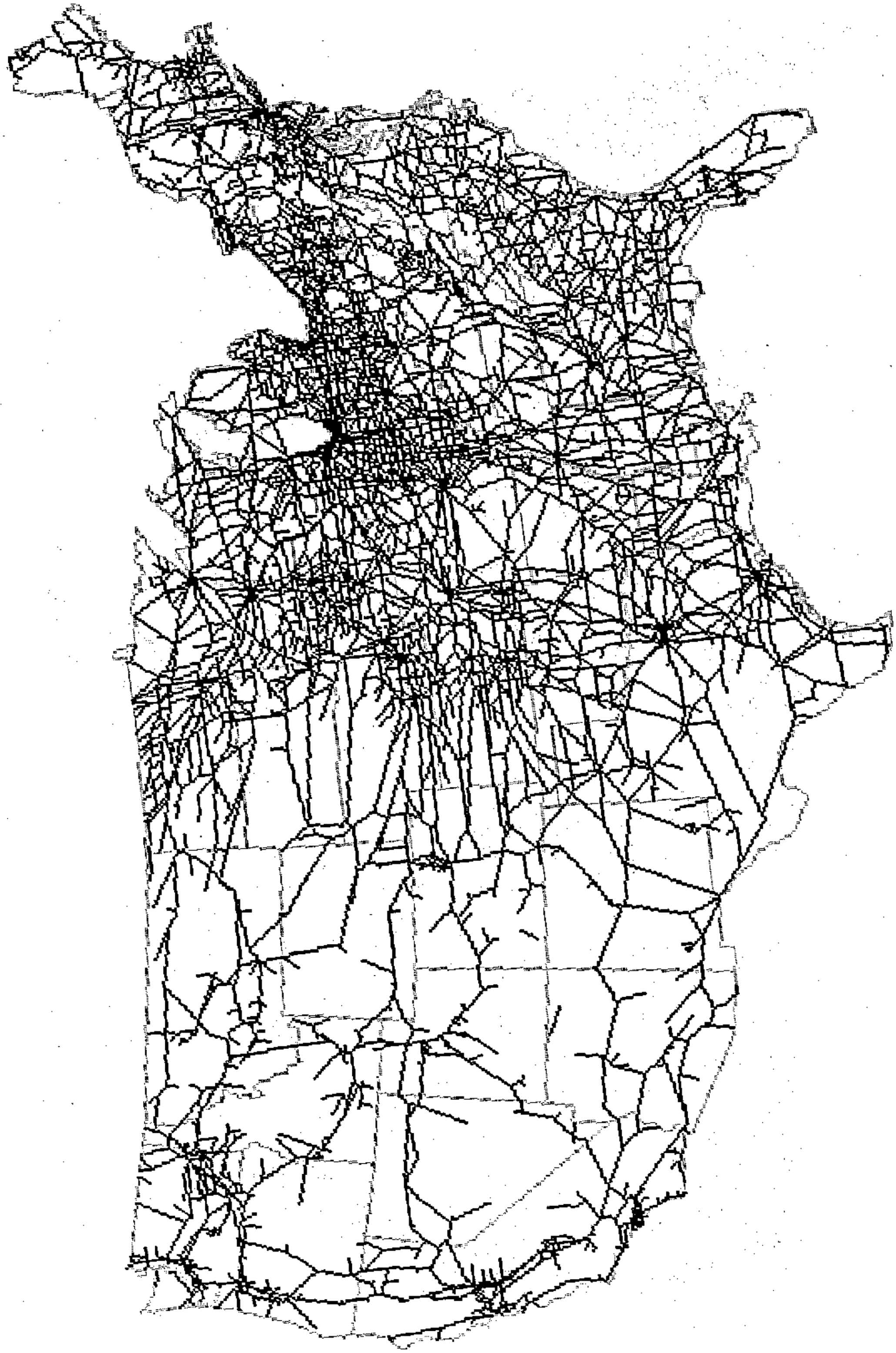


Figure 2-3 *Railroad system.*

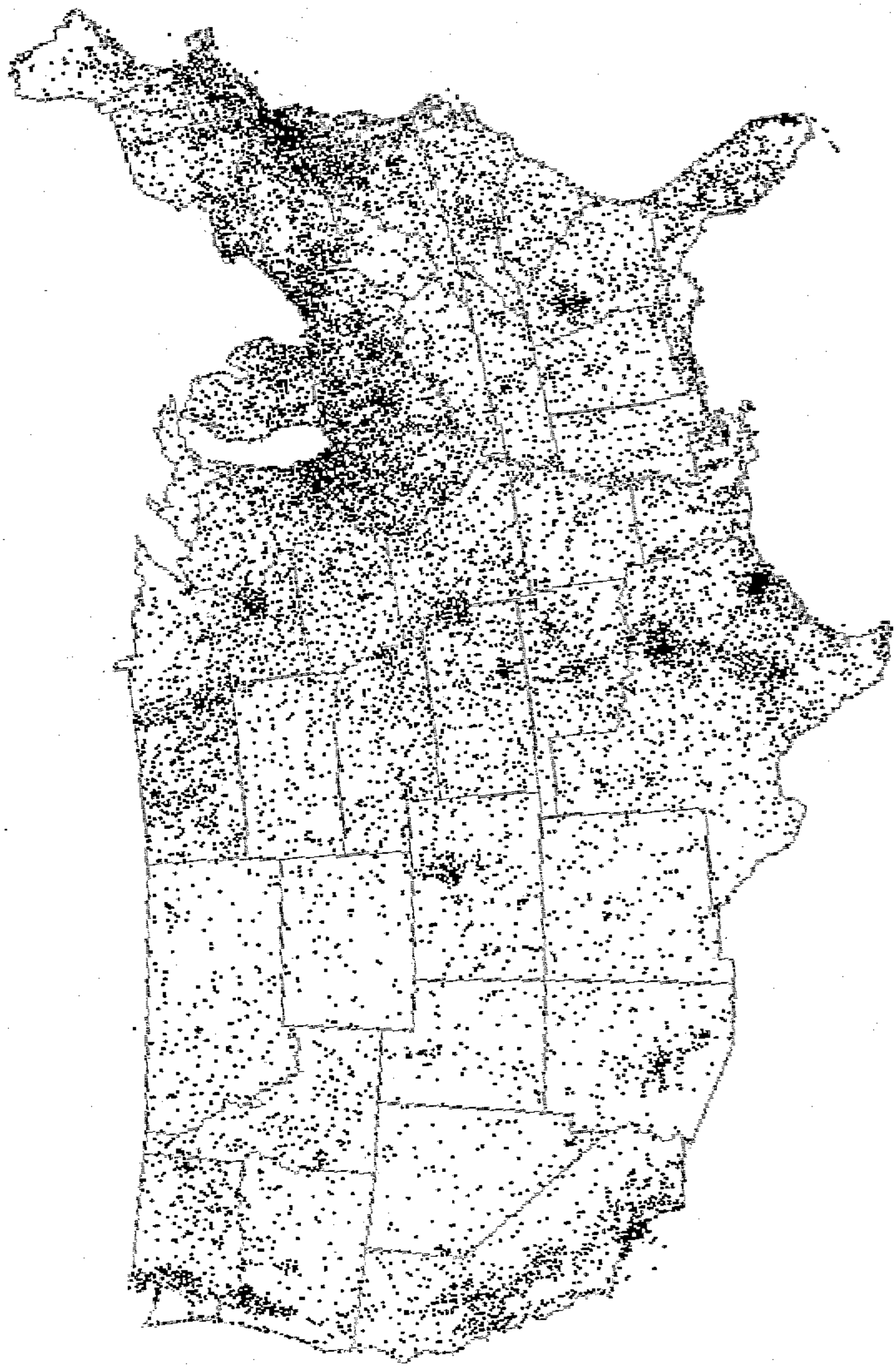


Figure 2-4 *Airports.*

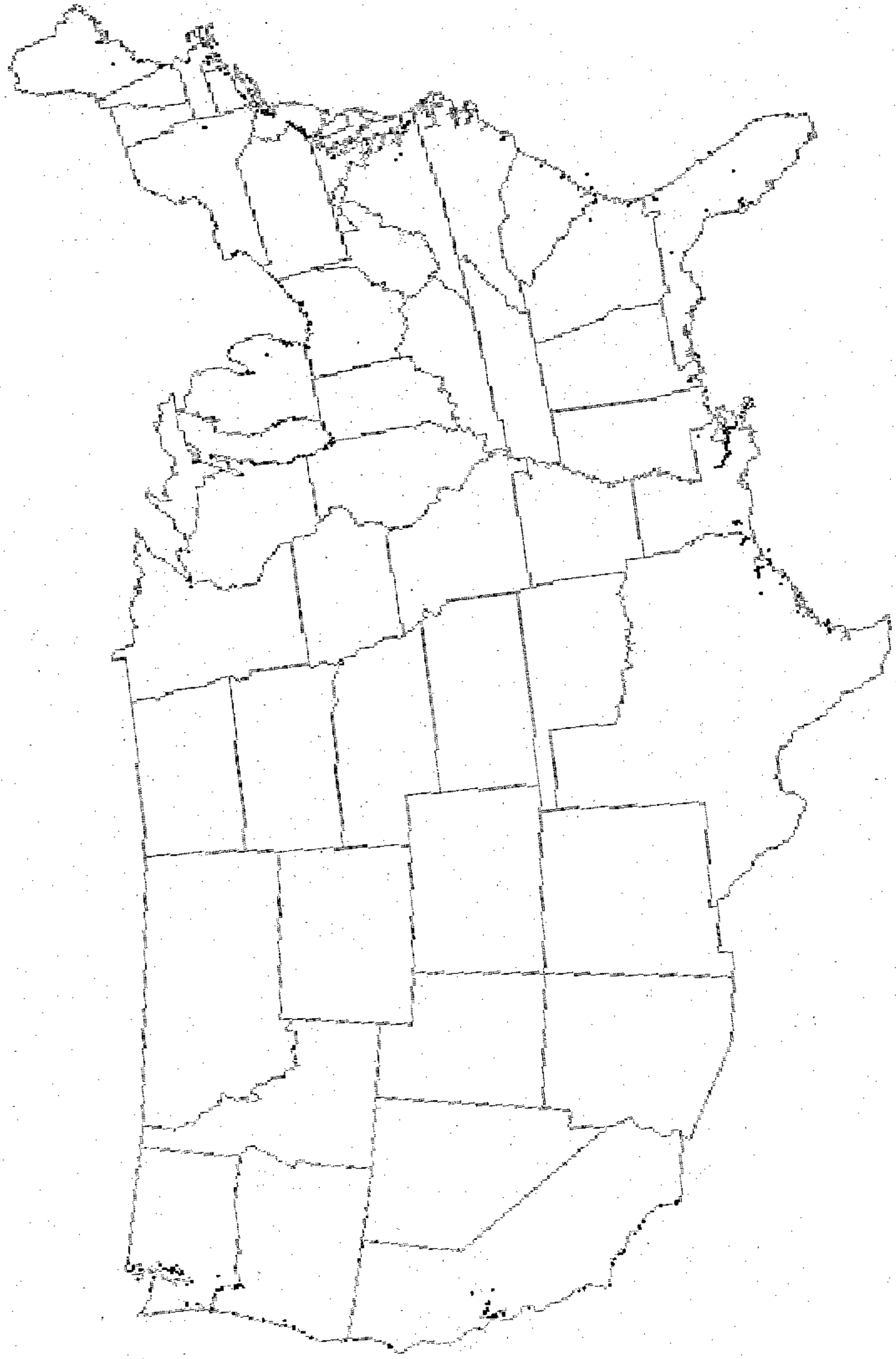


Figure 2-5 Ports and harbors.

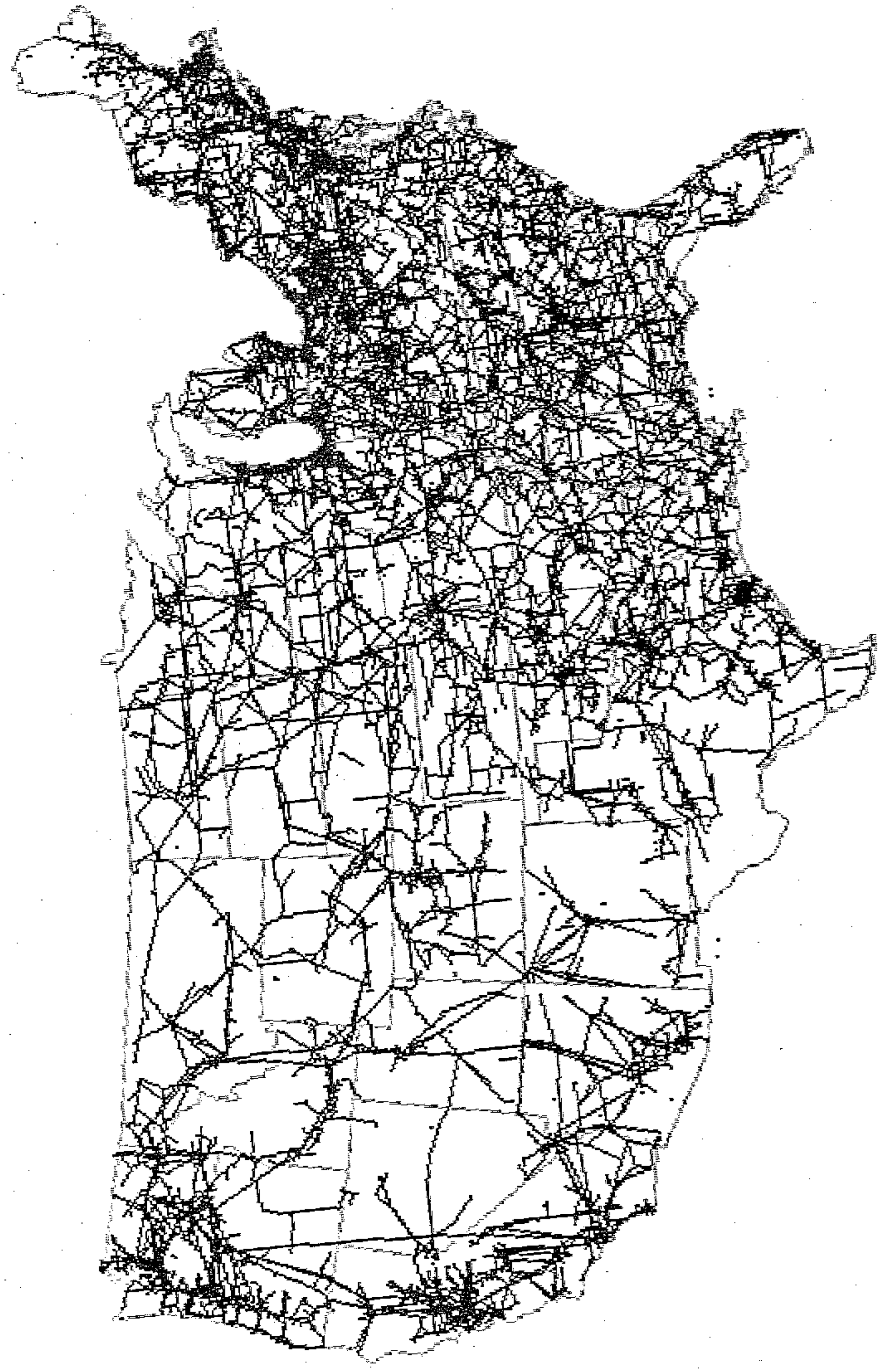


Figure 2-6 *Electric transmission system.*

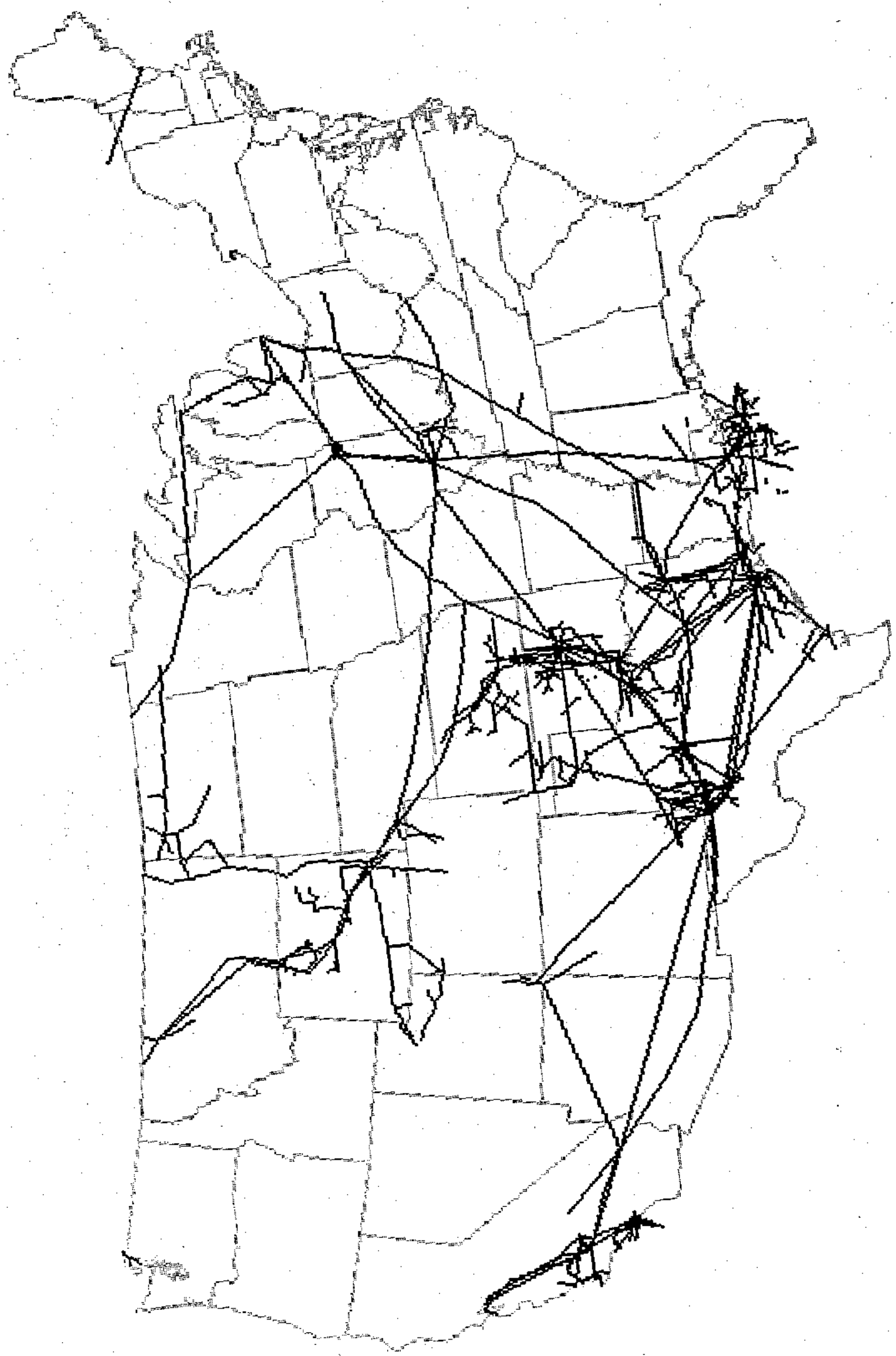


Figure 2-7 Crude oil pipelines.

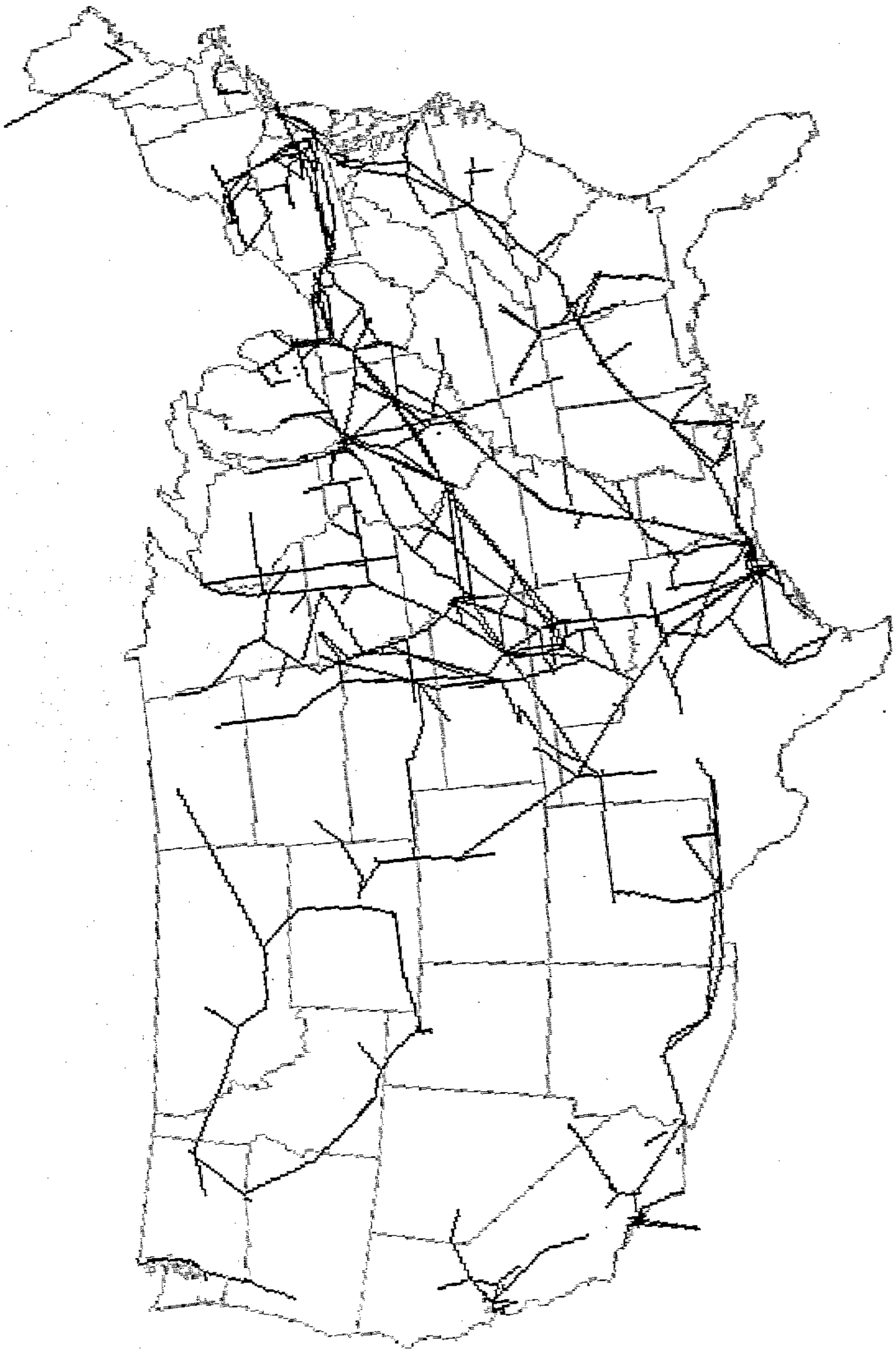


Figure 2-8 Refined oil pipelines.

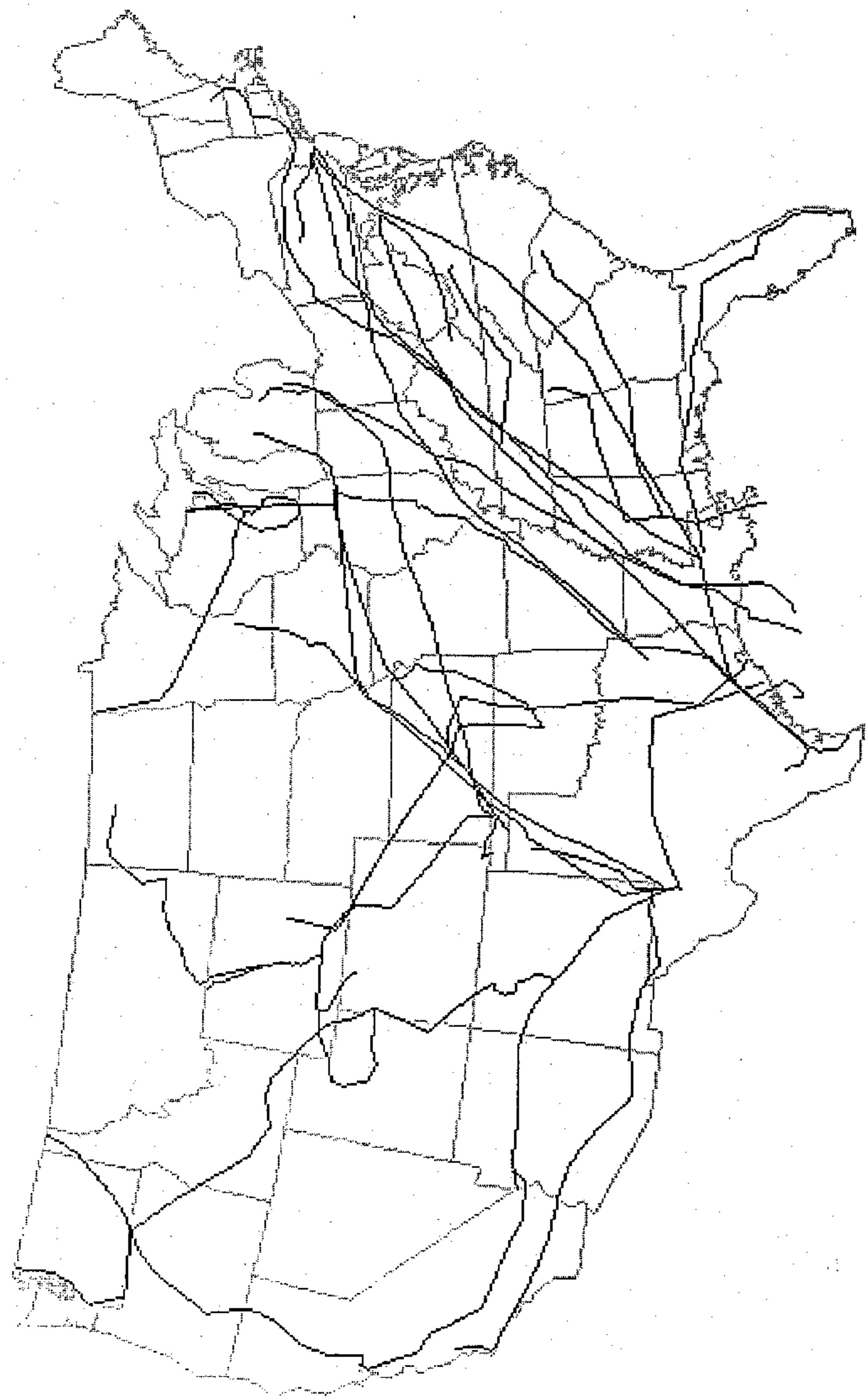
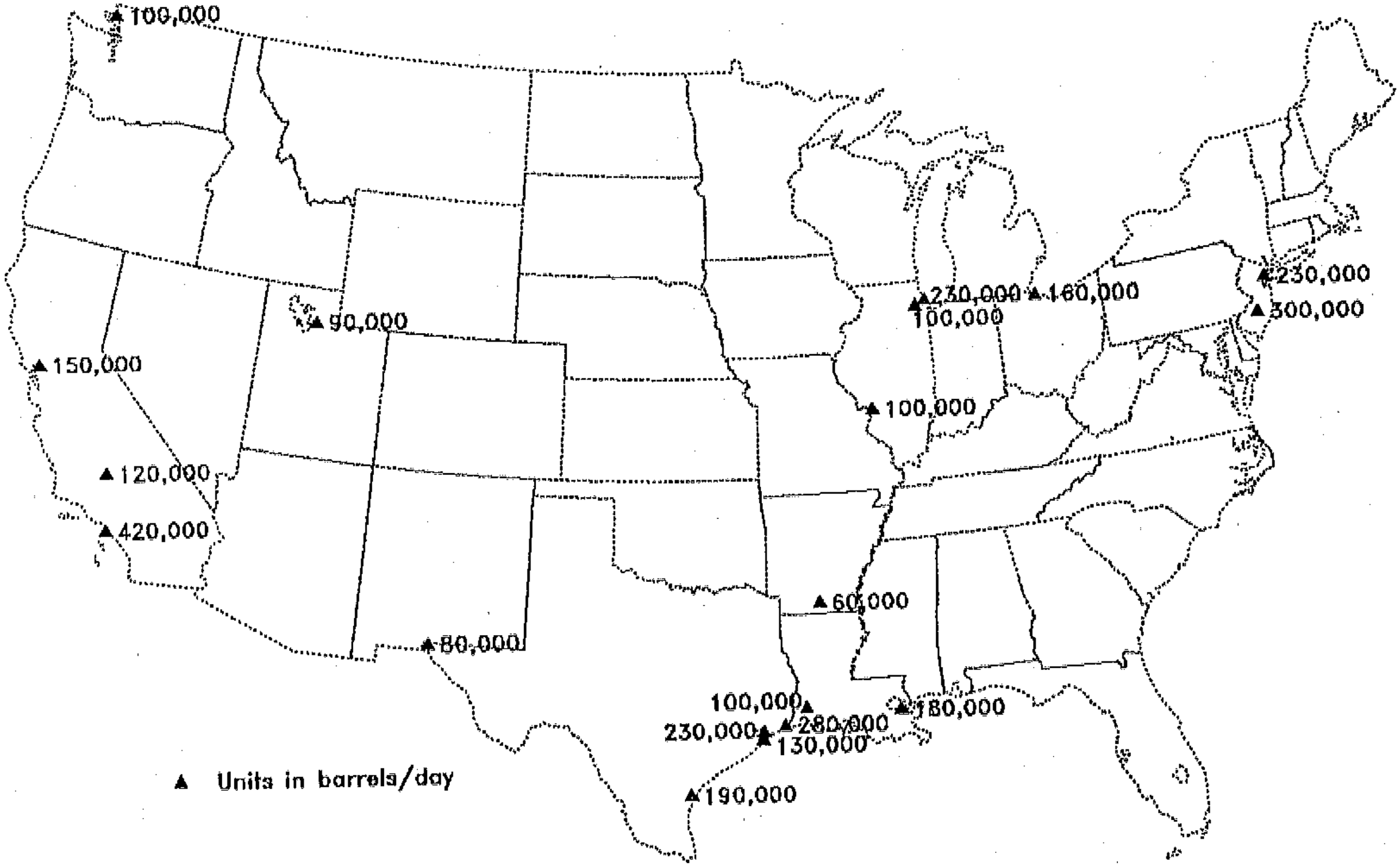


Figure 2-9 *Natural gas pipelines.*

Figure 2-10 Refineries.



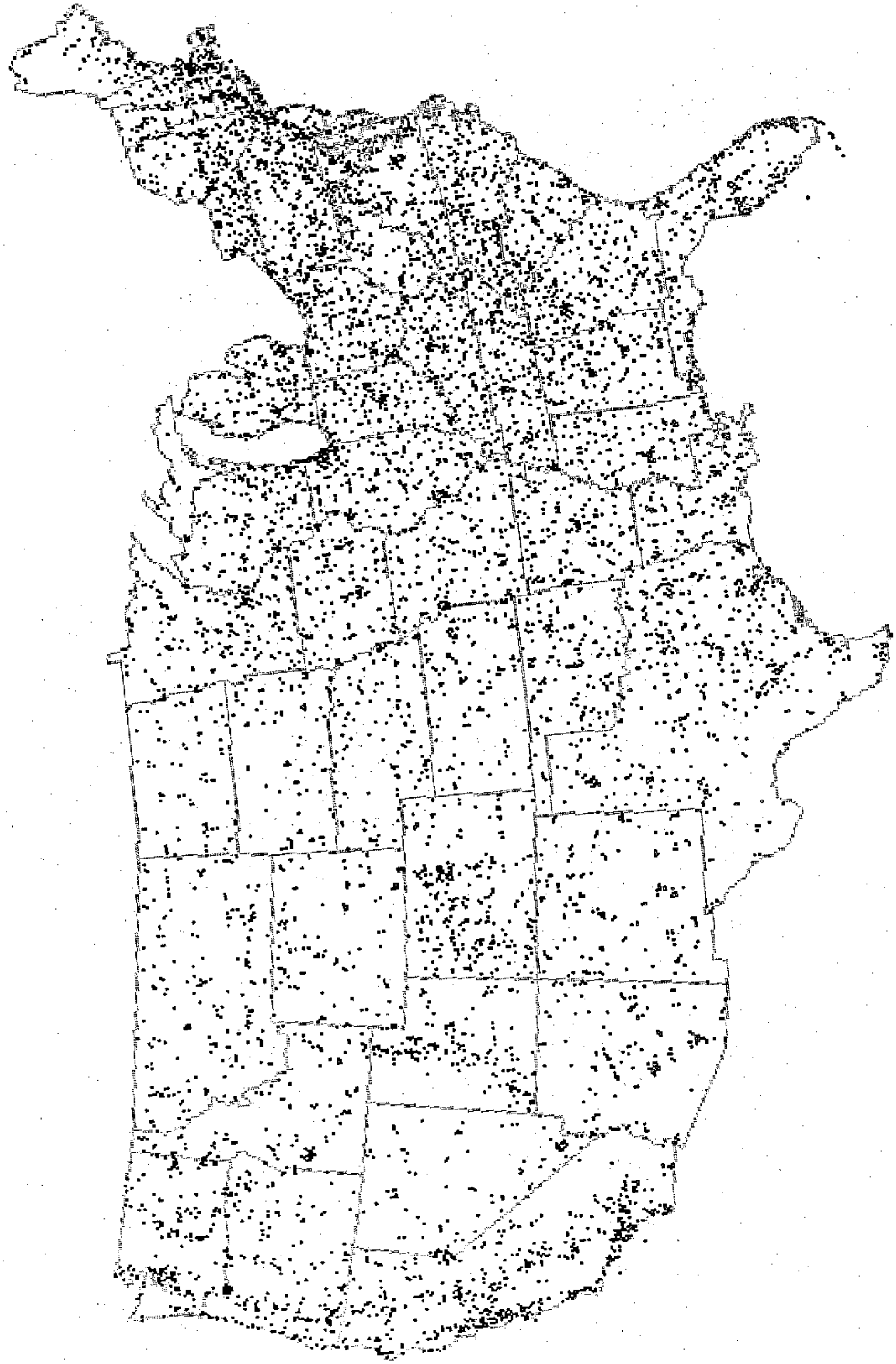


Figure 2-11 Emergency broadcast stations.

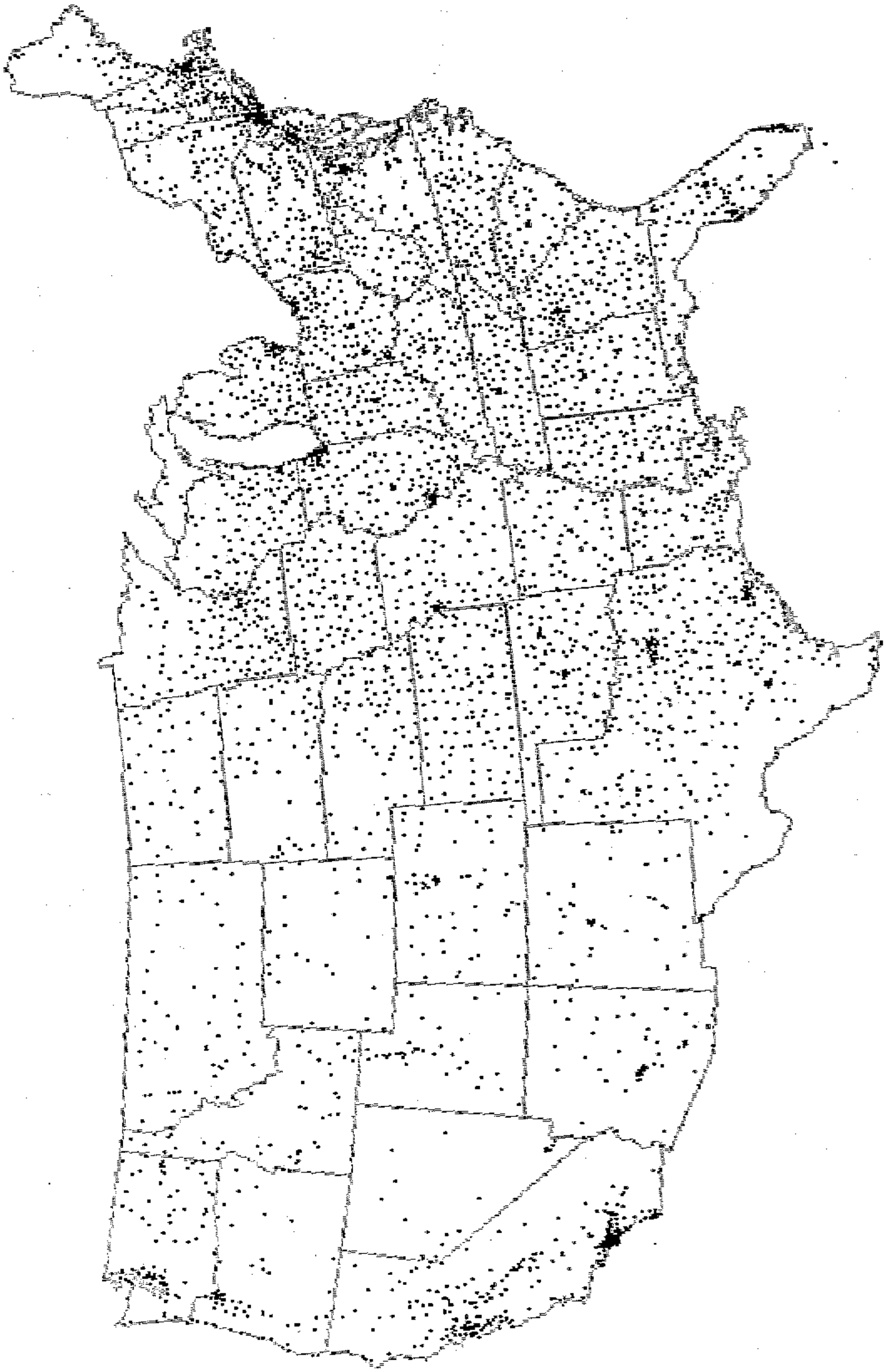


Figure 2-12 *Medical care centers.*

permits population to be used as the proxy measure of the number of fire stations. The data exhibit a trend that makes population appear to be a good basis for estimating the number of fire stations in an area. Intuition tells us that this would not be a linear function, since at the lower end of the population scale (a very small town), there would be at least one station (perhaps a volunteer unit) in most towns or areas. In rural forest areas, there may be few or no people residing in an area, but it might have several forest fire fighting crews available. A bilinear curve was deemed to be simple enough to be usable in a nationwide inventory, yet more capable of capturing the higher presence of fire stations in the less dense areas. The relationship developed is that there is one fire station per every 13,000 people in a municipality of less than 100,000 people. For municipalities of more than 100,000 people, there are 9 fire stations plus one more for every 36,000 additional people.

Police Stations. Detailed nationwide police station inventory data were not readily available in an electronic format. Data from a limited survey of municipalities with different attendant populations were obtained and correlated with the jurisdictional populations in an attempt to determine a relation, which permits population to be used as a proxy measure of the number of police stations. The data did not exhibit a strong correlation between the number of police stations and the jurisdictional population. There appears to be only one police or law enforcement station per municipality--cities with more than one police station are few, except for the largest cities. More than one police station in a municipality appears to be a relic of older days, with slower travel and communications. The data do make possible a stronger correlation to geography (such as the presence of a municipality) than directly to population, but intuition would say that the existence of law enforcement stations in rural areas, where the station size would be approximately uniform (one or two officers), would follow along population bounds. The relationship developed is that there is approximately one police station per every 60,000 people.

2.6 Water Supply Data

Water Transmission. Detailed information nationwide, on water storage, transmission, and treatment was not readily available. A variety of sources were employed to digitize reservoir locations and long-line transmission lines for large urban areas, of which only a few exceed tens of miles in length, that is, exceed our grid size (e.g., San Francisco, Los Angeles, New York). The inventory includes approximately 3,575 km of aqueduct, as shown in Figure 2-13. Excluded from the inventory are aqueducts in Utah, which were not available for inclusion in this study. It is also possible that other significant water transmission lines are inadvertently omitted from this study, as the project team had neither time nor funding to contact all potential sources of data.

Water Distribution. Detailed water distribution network inventory data were not readily available in an electronic format. Data from a survey of the largest water districts were available (AWWA report no. 20212 "1984 Water Utility Operating Data") and were used to correlate the quantity of piping with population. The data exhibit an apparent relationship between the population served by the water district and the total number of miles of piping in the distribution network. The values vary between different municipalities, apparently according to population density. New York City is one of the most densely populated municipalities in the United States, and the water distribution data reflect this. Overall, the average figure, which reflects the relationship between quantity of piping and populations for almost half the population of the United States, should be a reasonable figure to apply nationwide. The relationship we developed is that there is approximately 1 mile of distribution piping for every 330 persons. This would correspond to approximately 16 feet of distribution piping per person.

2.7 PC-Compatible Electronic Database

The data discussed above, developed as part of this project, form a very significant nationwide database on infrastructure at the regional level. Because the data could also serve as a valuable framework (or starting point) for researchers who wish to investigate lifelines at the regional

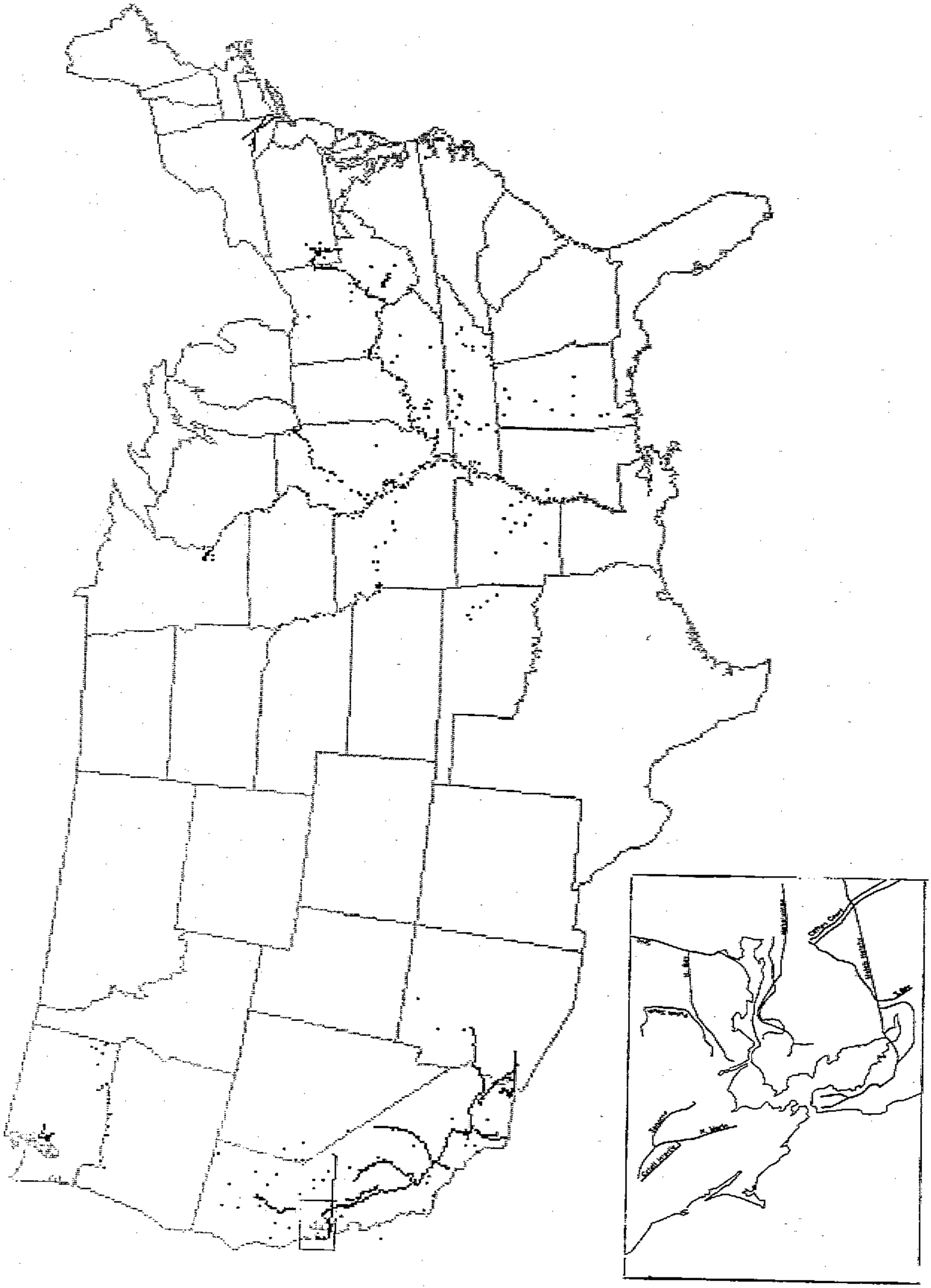


Figure 2-13 *Water aqueducts and supplies.*

or local level, including applications unrelated to seismic risk, the data have been formatted for use on IBM-PC compatible microcomputers. The data are unrestricted and will be made available by ATC on 18, 1.2-megabyte, floppy diskettes, together with a simple executable computer program for reading and displaying the maps on a computer screen. The disks contain 25 files, as shown in Table 2-1. For many of the networks, two files are presented, a .DAT file representing an ASCII file of latitude and longitude coordinates, and a .DEM file representing an x/y coordinate file for screen plotting purposes, in binary.

Table 2-1 National Lifeline Inventory Electronic Database

File No.	*File Name*	*Contents*
1.	DEMO.EXE	
2.	HW.DEM	(the highway network in x/y coordinates)
3.	HW.DAT	(the highway network in longitude/latitude coordinates)
4.	RAILR.DEM	(the railroad network in x/y coordinates)
5.	RAILR.DAT	(the railroad network in longitude/latitude coordinates)
6.	ELECTRIC.DEM	(the electric network in x/y coordinates)
7.	ELECTRIC.DAT	(the electric network in longitude/latitude coordinates)
8.	CRUDE.DEM	(the crude oil network in x/y coordinates)
9.	CRUDE.DAT	(the crude oil network in longitude/latitude coordinates)
10.	REFINED.DEM	(the refined oil network in x/y coordinates)
11.	REFINED.DAT	(the refined oil network in longitude/latitude coordinates)
12.	NGAS.DEM	(the natural gas network in x/y coordinates)
13.	NGAS.DAT	(the natural gas network in longitude/latitude coordinates)
14.	BRIDGES.DEM	(the bridges in x/y coordinates)
15.	BRIDGES.DAT	(the bridges in longitude/latitude coordinates)
16.	AIRPORTS.DEM	(the airports in x/y coordinates)
17.	AIRPORTS.DAT	(the airports in longitude/latitude coordinates)
18.	PORTS.DEM	(the ports in x/y coordinates)
19.	PORTS.DAT	(the ports in longitude/latitude coordinates)
20.	BRDSTNS.DEM	(the broadcast sta. in x/y coordinates)
21.	BRDSTNS.DAT	(the broadcast sta. in longitude/latitude coordinates)
22.	MEDCARE.DEM	(the hospitals in x/y coordinates)
23.	MEDCARE.DAT	(the hospitals in longitude/latitude coordinates)
24.	WATER.DEM	(the water system in x/y coordinates)
25.	WATER.DAT	(the water system in longitude/latitude coordinates)

3. Development of Lifeline Vulnerability Functions

3.1 Introduction

Vulnerability functions are used to describe the expected or assumed earthquake performance characteristics of each lifeline as well as the time required to restore damaged facilities to their pre-earthquake capacity, or usability. Functions have been developed for each lifeline inventoried for this project, or estimated by proxy (see Chapter 2). The components of each vulnerability function and how they were developed are described herein in Chapter 3. The functions themselves, too lengthy to include in this chapter, are provided in Appendix B.

The vulnerability function for each lifeline consists of the following components:

- *General* information, which consists of (1) a *description* of the structure and its main components, (2) *typical seismic damage* in qualitative terms, and (3) *seismically resistant design* characteristics for the facility and its components in particular. This information has been included to define the assumed characteristics and expected performance of each facility and to make the functions more widely applicable (i.e., applicable for other investigations by other researchers).

- *Direct damage* information, which consists of (1) a description of its basis in terms of structure type and quality of construction (degree of seismic resistance), (2) default estimates of the quality of construction for present conditions, and corresponding *motion-damage curves*, (3) default estimates of the quality of construction for upgraded conditions, and (4) *restoration curves*. As described below, these curves are based on data developed under the ATC-13 project (ATC, 1985).

In the following sections we describe the general approach and specific methodology utilized to develop the quantitative relationships for each vulnerability function (Direct Damage versus Modified Mercalli Intensity and Residual Capacity versus Modified Mercalli Intensity). Example computations are provided. In addition, a sample of a complete vulnerability function (*general information* plus *direct damage information*) is included as an illustrative example.

3.2 General Approach for Characterizing Earthquake Performance

The lifeline facility vulnerability functions used for this project are based on those developed on the basis of expert opinion in the ATC-13 project (*Earthquake Damage Evaluation Data for California*, ATC 1985). The ATC-13 direct damage data, presented in the form of Damage Probability Matrices (DPMs, Table 3-1), are applicable for Standard construction in California, as defined below, and may be modified per procedures outlined in ATC-13, which shifts the curves one-to-two intensity units down for Special construction, as defined below (i.e., -1 or -2), and one to two intensity units up for Nonstandard construction, as defined below (i.e., +1 or +2). Standard construction is defined (in ATC-13) to include all facilities except those designated as Special or Nonstandard. Special construction refers to facilities that have special earthquake damage control features. Nonstandard refers to facilities that are more susceptible to earthquake damage than those of Standard construction. Older facilities designed prior to modern design code seismic requirements or those facilities designed after the introduction of modern code seismic requirements but without their benefit can be assumed to be Nonstandard. In exceptional cases, older facilities may have had special attention paid to seismic forces and may qualify as Standard construction. While Special is defined in ATC-13 to refer to facilities that have special earthquake damage control features, in this study we take this to include, in some cases, facilities designed according to the most modern design code seismic requirements. Standard is assumed to represent existing California

Table 3-1 Typical ATC-13 Damage Probability Matrix (ATC, 1985) (Example for Liquid Storage Tanks, on ground)

Central Damage Factor	*Modified Mercalli Intensity*						
	VI	*VII*	*VIII*	*IX*	*X*	*XI*	*XII*
0.00	94.0	2.5	0.4	***	***	***	***
0.50	6.0	92.9	30.6	2.1	***	***	***
5.00	***	4.6	69.0	94.6	25.7	2.5	0.2
20.00	***	***	***	3.3	69.3	58.1	27.4
45.00	***	***	***	***	5.0	39.1	69.4
80.00	***	***	***	***	***	0.3	3.0
100.00	***	***	***	***	***	***	***

***Very small probability

facilities (i.e., a composite of older non-seismically designed facilities, more recent facilities designed to the seismic requirements of their day, and modern facilities designed to current seismic requirements).

With regard to regional U.S. seismic design practice, the general consensus appears to be that, with few exceptions, only California and portions of Alaska and the Puget Sound region have had seismic requirements incorporated into the design of local facilities for any significant period of time. For all other areas of the United States, present facilities are assumed to have seismic resistance less than or equal to (depending on the specific facility) that of equivalent facilities in California NEHRP Map Area 7 (Figure 3-1) (ATC, 1978; BSSC, 1988). In this regard, we have broken the United States into three regions:

a. California NEHRP Map Area 7 (the general focus of ATC-13), which we take to be the only region of the United States with a significant history of lifeline seismic design for great earthquakes,

b. California NEHRP Map Areas 3-6, Non-California Map Area 7 (parts of Alaska, Nevada, Idaho, Montana, and Wyoming), and Puget Sound NEHRP Map Area 5, which we take to be the only regions of the United States with a significant history of lifeline seismic design for major (as opposed to great) earthquakes, and

c. All other parts of the United States, which we assume have not had a significant history of lifeline seismic design for major earthquakes.

As an example, examine on-ground liquid storage tanks (ATC-13 Facility Class 43, Table 3-1), for which ATC-13 indicates mean damage from ground shaking of Modified Mercalli Intensity (MMI) IX to be 4.6% of replacement value for Standard construction. If the construction is modern and judged to be Special construction, then the mean damage is indicated to be 0.5% (corresponding to MMI VII) for the same intensity of ground shaking. Alternatively, if the construction is judged to be Nonstandard (e.g., predating seismic design), then the mean damage is indicated to be 27.9% (corresponding to MMI XI) for the same intensity of ground shaking.

3.3 Method for Obtaining Lifeline Direct Damage and Residual Capacity Functions

This section presents the calculational algorithms employed in obtaining the quantitative lifeline component vulnerability functions for use in the ATC-25 project. Two vulnerability functions are determined: (1) direct damage to a lifeline component, in terms of repair costs expressed as a fraction or percentage of value, and (2) fraction of initial capacity (restored or remaining) as a function of elapsed time since the earthquake, for a given

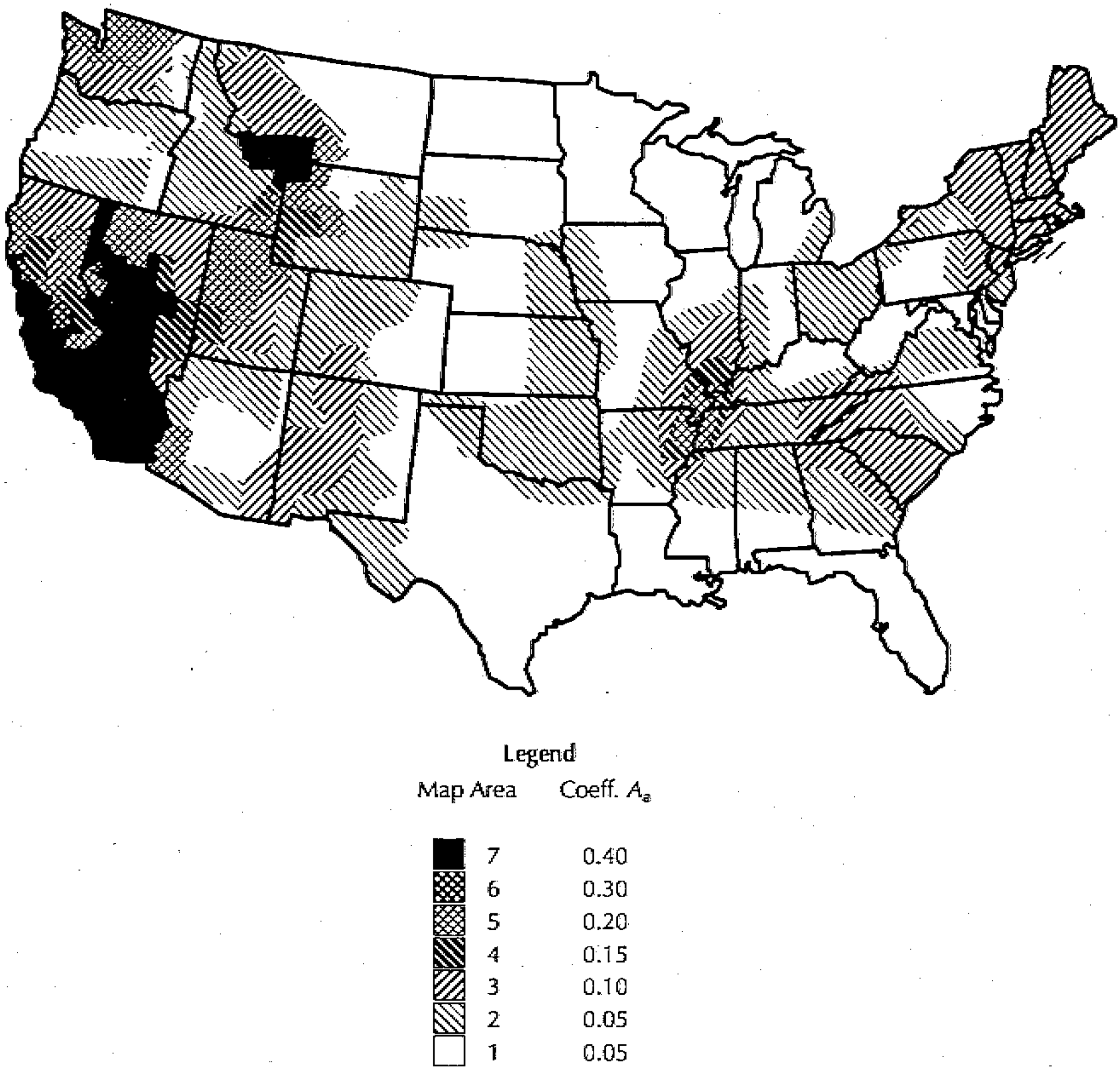


Figure 3-1 *NEHRP Seismic Map Areas (ATC, 1978; BSSC, 1988).*

MMI, herein termed restoration curves. All assumptions operative in ATC-13, such as unlimited resources for repair and restoration, apply to these results.

Three main steps are involved in obtaining the vulnerability functions for each component. Each of these steps is described below.

STEP 1

In order to obtain a continuous relation between seismic damage (DMG) and intensity (MMI), a regression of the form

$$DMG = \exp(a)\, MMI^{b} \quad (3.1)$$

is performed on the damage data points in Appendix G of ATC-13. The regression coefficients a and b are obtained for each Facility Class (FC) corresponding to a lifeline component. A damage curve of the form shown in Figure 3-2 is thus obtained for each Facility Class in ATC-13.

STEP 2

Data on time-to-restoration for different Social Function (SF) classes, which are facility types defined in terms of the four-digit Standard Industrial Classifications of the U. S. Department of Commerce, (provided in Table 9.11 of ATC-13), are used to perform the following regression, which gives a continuous relation between the damage state and the corresponding restoration time for each social function class:

$$T_R = \exp(c)\, DMG^{d} \quad (3.2)$$

where:

T_R = restoration time, in days
DMG = Central Damage Factor (CDF) for each damage state (DS)
c, d = regression coefficients

Regressions of the above form are performed for each of the social function classes using the data in ATC-13 on restoration times for 30%, 60%, and 100% restoration.

Thus,

$$T_{R=0.3} = \exp(c1)\, DMG^{d1}$$
$$T_{R=0.6} = \exp(c2)\, DMG^{d2}$$
$$T_{R=1.0} = \exp(c3)\, DMG^{d3}$$

Figure 3-3 shows the form of the regression curves we obtained.

STEP 3

The regressions obtained from the previous two steps are used to arrive at the restoration curves. The restoration curve for each lifeline component, for each intensity (MMI), is obtained by fitting a straight line through the three points corresponding to 30%, 60%, and 100% restoration time. The regression line has the following form:

$$R = f + (g)(T_R) \quad (3.3)$$

where:

R = % restored
T_R = restoration time, in days
f, g = regression coefficients

The three points used to fit a straight line by the above regression are obtained in the manner described below:

For a given lifeline component, the damage corresponding to a particular MMI is assumed to have a lognormal distribution. The time to restoration is then obtained numerically as the weighted average of the restoration time (given by Equation 3.2) taken over equal intervals of the lognormal distribution of the damage. The weight factors are the areas of the equal intervals of the lognormal distribution, i. e., the probabilities of the corresponding damage. For example,

$$T_R(30\%\ R, MMI) = \sum_{i=1}^{N} \left(p_i \times \exp(c1) \times DMG_i(MMI)^{d1}\right) \quad (3.4)$$

where T_R(30% R, MMI)) is the restoration time to 30% restoration for a given MMI, p_i is the probability that the damage = DMG_i, i.e., the area of the interval, i, on the lognormal distribution of the damage, and N is the number of intervals of the lognormal distribution.

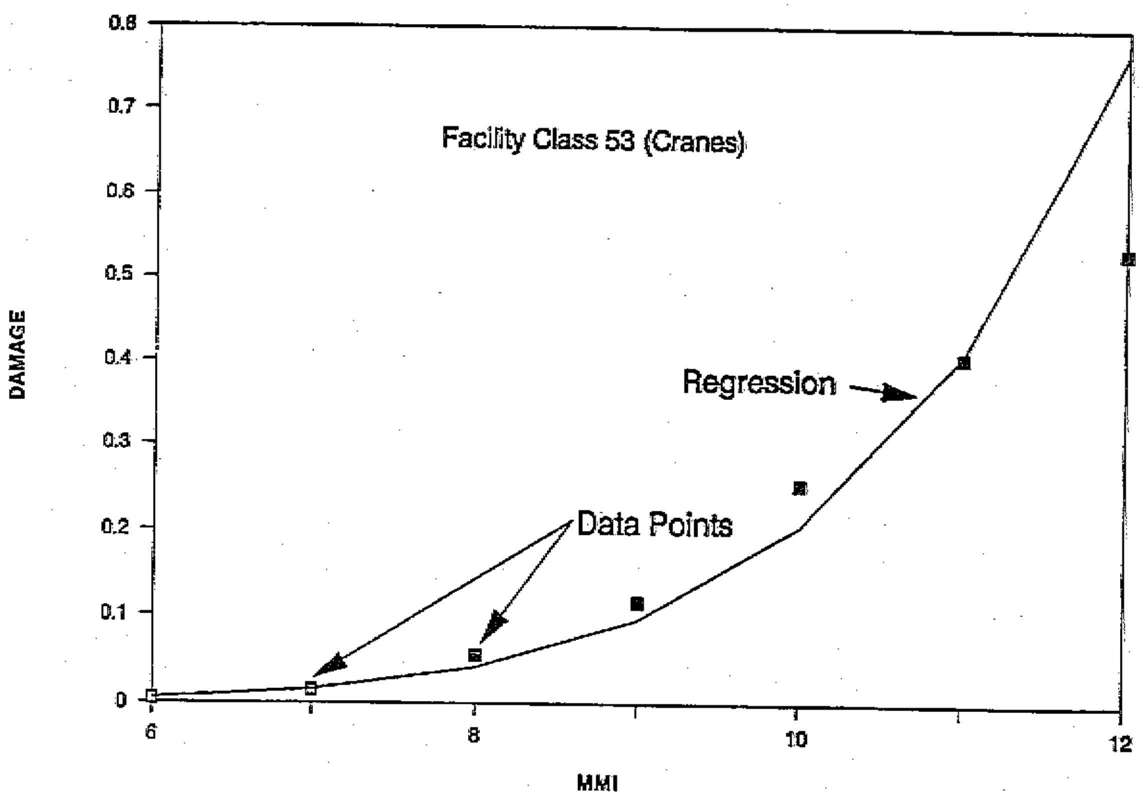


Figure 3-2 *Comparison of ATC-13 Appendix G data (Statistics of Expert Responses for Motion-Damage Relationships) versus regression curve.*

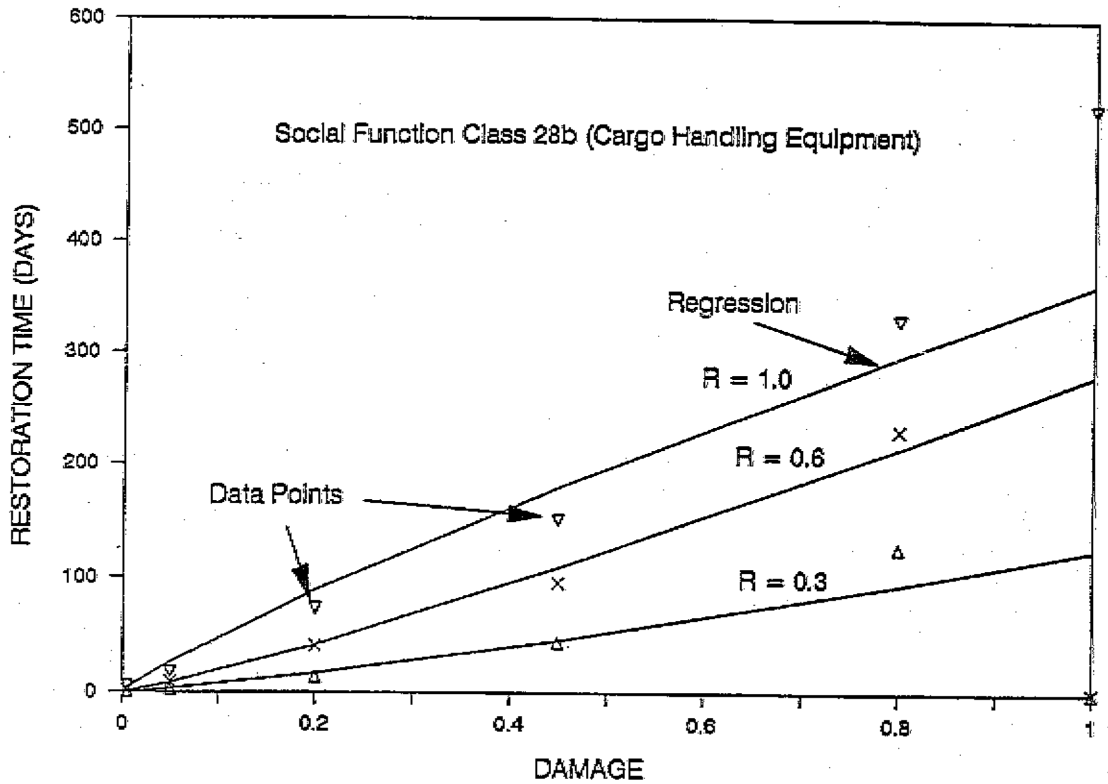


Figure 3-3 *Comparison of ATC-13 Table 9.1 data (Weighted Statistics for Loss of Function Restoration Time of Social Function Classifications) versus regression curve.*

Similar calculations are also carried out for 60% R and for 100% R.

Next, the weighted average of T_R(30%R, MMI) for the different social function classes corresponding to the lifeline component is obtained. This serves as one of the three points for fitting the restoration curve. The other two points are obtained by repeating the process for 60% and 100% restoration time. The regression line given by Equation 3.3, obtained using these three data points, is the restoration curve for the lifeline component. An example to illustrate the method of obtaining

(1) the direct damage curve and

(2) the restoration curves, for the Ports/Cargo Handling Equipment component of the Sea/Water Transportation lifeline

is provided below.

3.4 Example Direct Damage and Residual Capacity Computations

The following example illustrates the method of obtaining (1) the direct damage curve, and (2) the restoration curves, for the Ports/Cargo Handling Equipment component of the Sea/Water Transportation lifeline. Ports/Cargo Handling Equipment are typically container or general cargo cranes on piers. This component is taken to be composed of two ATC-13 Social Function Classes: 28a (Ports) and 28b (Cargo Handling Equipment), and of two Facility Classes: 63 (Waterfront Structures) and 53 (Cranes), weighted by the factors indicated in Table 3-2.

STEP 1

Regression coefficients for seismic damage are computed from Equation 3.1 for each Facility Class (FC) as follows:

Facility Class		Regression Coefficient	
Class	Factor	a	b
63	0.6	-20.0847	8.0976
53	0.4	-18.2783	7.2508

The damage regression curve obtained in this manner is illustrated in Figure 3-2 for Facility

Table 3-2 Weighting Factors Used to Determine Percent of Social Function and Facility Classes Contributing to Ports/Cargo Handling Equipment

Social Function		Facility	
Class	Factor	Class	Factor
28a	0.6	63	0.6
28b	0.4	53	0.4

Class 53 (Cranes). The values for the damage are listed below, together with the ATC-13 data (from ATC-13, Appendix G, weighted mean of best estimate of damage factor):

MMI	DMC (ATC-13)	Regr (DMC)
6	0.004	0.005
7	0.014	0.015
8	0.055	0.041
9	0.117	0.096
10	0.253	0.205
11	0.406	0.410
12	0.535	0.771

The damage curve for the component as a whole is obtained by calculating, for each MMI, the weighted average of the damage for each of the facility classes corresponding to the component.

$$\begin{aligned} DMG &= e^{a1} MMI^{b1} \, x \, factor(1) + e^{a2} MMI^{b2} \, x \, factor(2) \\ &= 0.101 \, x \, 0.6 + 0.096 \, x \, 0.4 \\ &= 0.099 \text{ for MMI} = IX \end{aligned}$$

STEP 2

Regression coefficients for restoration time are computed from Equation 3.2 as follows:

	Regression Coefficients			
	Social Function 28a		Social Function 28b	
Restoration %	c	d	c	d
30%	6.4575	2.7162	4.8240	1.2514
60%	5.4769	1.1671	5.6373	1.1880
100%	6.1996	1.0445	5.8890	0.8725

The values for the time to 30% restoration, for the Social Function Class 28b are listed below, together with the ATC-13 data from Table 9.11:

DMG	ATC-13	Regression Values
0.005	0.2	0.1643
0.05	2.3	2.93
0.2	13.3	16.61
0.45	44.4	45.82
0.8	127.0	94.14
1.0	*	125.46

*No statistics provided.

Figure 3-3 shows the curves obtained by the above regressions, as well as the ATC-13 mean data points.

STEP 3

Mean restoration times for each Facility Class (FC) are obtained from Equation 3.4 as follows:

Mean Restoration time =

$$\sum_{i=1}^{N} [p_i \exp(c) DMG_i^{d}]$$

where c and d are given above for 30%, 60%, and 100% restoration.

For MMI = XI, for example, mean restoration times are computed as follows:

	$T_R=0.3$	$T_R=0.6$	$T_R=1.0$
FC = 28a	79.73	93.20	211.23
FC = 28b	45.45	107.66	177.27
Mean T_R	66.02*	98.98	197.65

*e.g., Mean T_R = 79.73 x 0.6 + 45.45 x 0.4 = 66.02

(Note: P_i is 1/N where N is the number of intervals used to divide the lognormal distribution of the damage; N=100 in this example and DMG_i is the corresponding damage value for each interval, i.)

The final restoration curve for MMI = XI is the best-fit straight line using Equation 3.3 through the 3 points corresponding to restoration times 66.02, 98.98, and 197.65 days. In this case, the regression equation is as follows:

$$R = 0.026 + 0.005 (T_R)$$

Determination of these relations permits calculation of residual capacity of the lifeline as a function of time. From the above equation we see that Ports/Cargo Handling Equipment subjected to MMI XI will be restored to approximately 18% of pre-earthquake capacity after 30 days, and to 48% approximately 90 days after the earthquake.

3.5 Sample Lifeline Vulnerability Function

Following is a sample of a complete lifeline vulnerability function for ports/cargo handling equipment. Complete vulnerability functions for all lifelines are given in Appendix B.

3.5.1 Ports/Cargo Handling Equipment

1. General

Description: In general, ports/cargo handling equipment comprise buildings (predominantly warehouses), waterfront structures, cargo handling equipment, paved aprons, conveyors, scales, tanks, silos, pipelines, railroad terminals, and support services. Building type varies, with steel frame being a common construction type. Waterfront structures include quay walls, sheet-pile bulkheads, and pile-supported piers. Quay walls are essentially waterfront masonry or caisson walls with earth fills behind them. Piers are commonly wood or concrete construction and often include batter piles to resist lateral transverse loads. Cargo handling equipment for loading and unloading ships includes cranes for containers, bulk loaders for bulk goods, and pumps for fuels. Additional handling equipment is used for transporting goods throughout port areas.

Typical Seismic Damage: By far the most significant source of earthquake-induced damage to port and harbor facilities has been pore-water pressure buildup in the saturated cohesionless soils that prevail at these facilities. This pressure buildup can lead to application of excessive lateral pressures to quay walls by backfill materials, liquefaction, and massive submarine sliding. Buildings in port areas are subject to generic damage due to shaking, as well as damage caused by loss of bearing or lateral movement of foundation soils. Past earthquakes have caused substantial lateral sliding, deformation, and tilting of quay walls and sheet-pile bulkheads. Block-type quay walls are vulnerable to earthquake-induced sliding between layers of blocks. This damage has often been accompanied by extensive settlement and cracking of paved aprons. The principal failure mode of sheet-pile bulkheads has been insufficient anchor resistance, primarily because the anchors were installed at shallow depths, where backfill is most susceptible to a loss of strength due to pore-water pressure buildup and liquefaction. Insufficient distance between the anchor and the bulkhead wall can also lead to failure. Pile-supported docks typically perform well, unless soil failures such as major submarine landslides occur. In such cases, piers have undergone extensive sliding and buckling and yielding of pile supports. Batter piles have damaged pier pile caps and decking because of their large lateral stiffness. Cranes can be derailed or overturned by shaking or soil failures. Toppling cranes can damage adjacent structures or other facilities. Misaligned crane rails can damage wheel assemblies and immobilize cranes. Tanks containing fuel can rupture and spill their contents into the water, presenting fire hazards. Pipelines from storage tanks to docks can be ruptured where they cross areas of structurally poor ground in the vicinity of docks. Failure of access roads and railway tracks can severely limit port operations. Port facilities, especially on the West Coast, are also subject to tsunami hazard.

Seismically Resistant Design: At locations where earthquakes occur relatively frequently the current design practice is to use seismic factors included in local building codes for the design of port structures. However, past earthquakes have indicated that the seismic coefficients used for design are of secondary importance when compared to the potential for liquefaction of the site soil materials. Quay wall and sheet-pile bulkhead performance could be enhanced by replacing weak soils with dense soils, or designing these structures to withstand the combination of earthquake-induced dynamic water pressures and pressures due to liquefied fills. Pier behavior in earthquakes has been good primarily because they are designed for large horizontal berthing and live loads, and because they are not subject to the lateral soil pressures of the type applied to quay walls and bulkheads. However, effects on bearing capacity and lateral resistance of piles due to liquefaction and induced slope instability should also be considered.

2. Direct Damage

Basis: Damage curves for ports/cargo handling equipment in the sea/water transportation system are based on ATC-13 data for Facility Class 53, cranes, and Facility Class 63, waterfront structures. Ports/cargo handling equipment are assumed to be a combination of 60% waterfront structures and 40% cranes.

Standard construction is assumed to represent typical California ports/cargo handling equipment under present conditions (i.e., a composite of older and more modern ports/cargo handling equipment). Only minimal regional variation in construction quality is assumed, as seismic design is performed only for selected port structures, and soil performance is the most critical determinant in port performance.

Present Conditions: In the absence of data on the type of material, age, etc., the following factors were used to modify the mean curve for the two facility classes listed above, under present conditions:

	MMI Intensity Shift	
NEHRP Map Area	FC 53	FC 63
California 7	0	0
California 3-6	0	0
Non-California 7	0	0
Puget Sound 5	0	0
All other areas	+1	+1

The modified motion-damage curves for ports/cargo handling facilities are shown in Figure 3-4.

Upgraded Conditions: For areas where it appears cost-effective to improve facilities, assume on a preliminary basis that upgrades result in a beneficial intensity shift of one unit (i.e., -1), relative to the above present conditions.

Time-to-restoration: The time-to-restoration data assigned to Social Function (SF) 28a, ports, and SF 28b, cargo handling equipment, were assumed to apply to all ports/cargo handling equipment. Ports/cargo handling facilities were assumed to be a combination of 60% ports and 40% cargo handling facilities. By combining these data with the damage curves derived using the data for FC 53 and 63, the time-to-restoration curves shown in Figures 3-5 and 3-6 were derived.

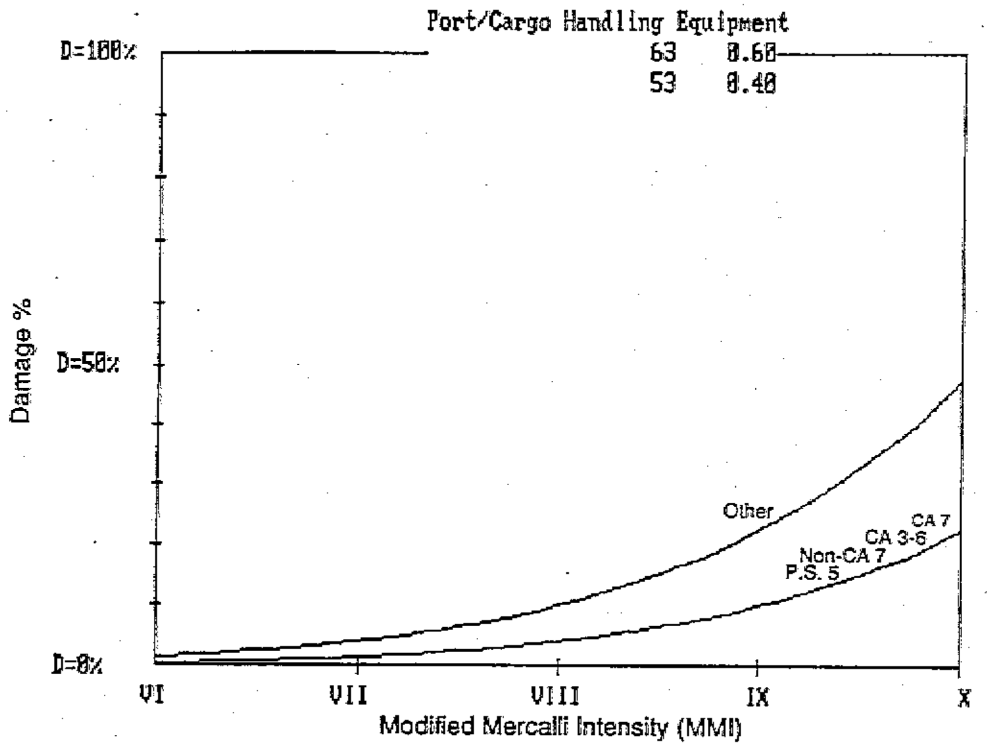


Figure 3-4 Damage percent by intensity for ports/cargo handling equipment.

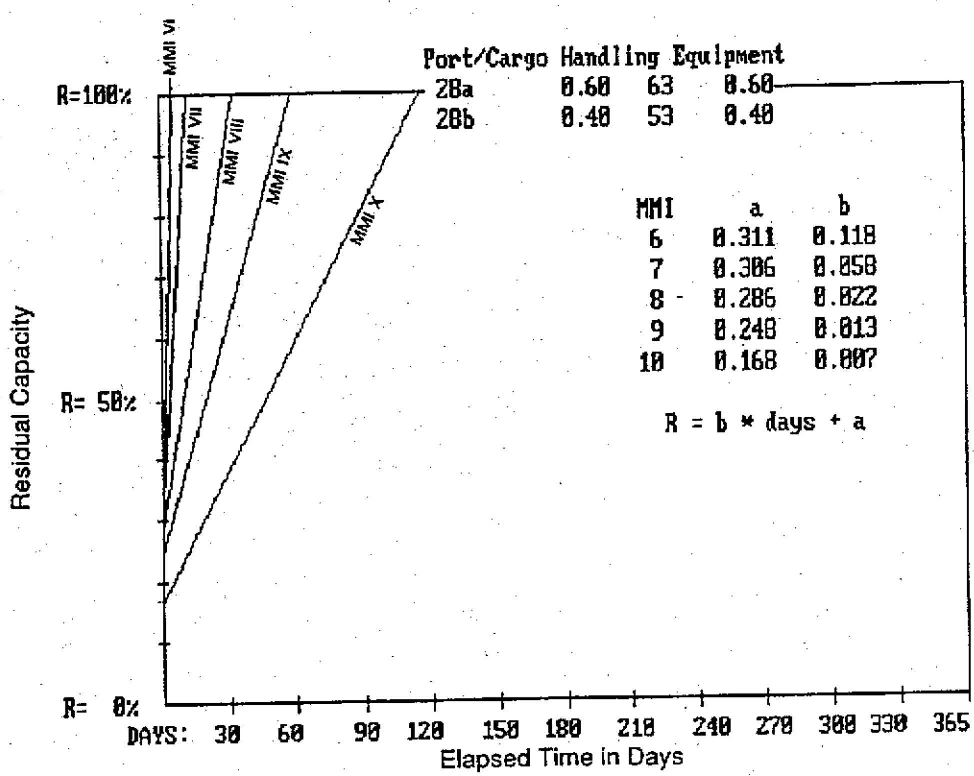


Figure 3-5 Residual capacity for ports/cargo handling equipment (NEHRP Map Area: California 3-5, California 7, Non-California 7, and Puget Sound 5).

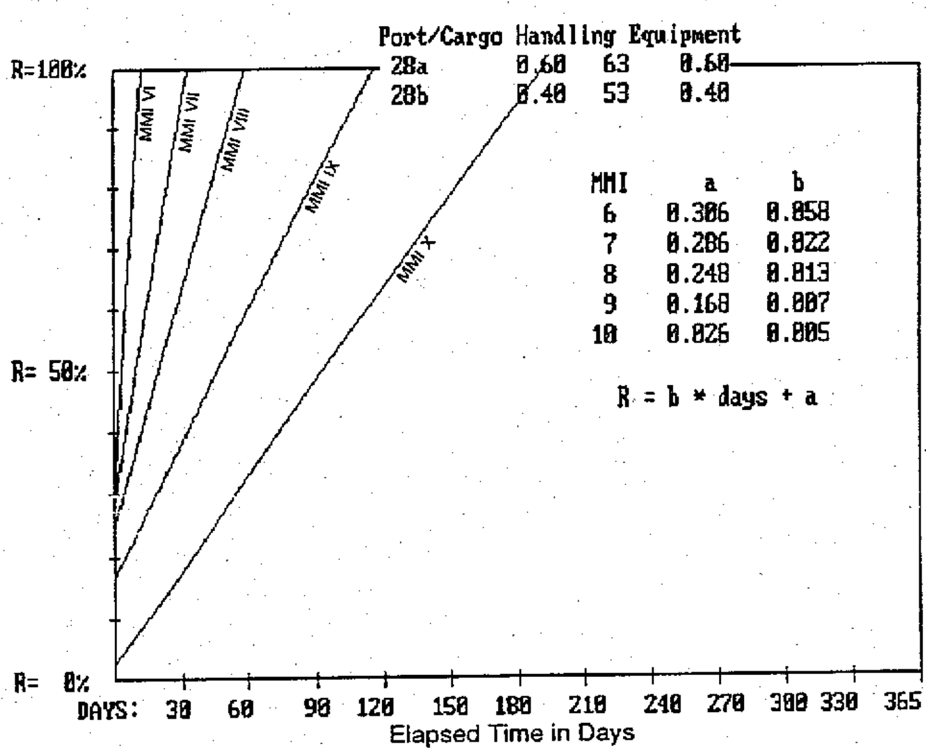


Figure 3-6 Residual capacity for ports/cargo handling equipment (all other areas).

4. Seismic Hazard

4.1 Introduction

Seismic hazard, as used in this study, is the expectation of earthquake effects. It is usually defined in terms of ground shaking parameters (e.g., peak ground acceleration, Modified Mercalli Intensity, peak ground velocity) but, broadly speaking, can include or be defined in terms of fault rupture, ground failure, or other phenomena resulting from an earthquake. Seismic hazard is a function of the size, or magnitude of an earthquake, distance from the earthquake, local soils, and other factors, and is independent of the buildings or other items of value that could be damaged. Estimation of seismic hazard can be performed on a deterministic (e.g., Evernden et al., 1981) or probabilistic (Cornell, 1968; McGuire, 1974; Scawthorn et al., 1978; Algermissen and Perkins, 1976; Algermissen, and Perkins, 1982) basis, depending on the needs of the users. In either case, the methodology follows a process beginning with the definition of seismic sources, based in part on historic seismicity.

The historical record of earthquakes in the United States is relatively short--the only data available for earthquakes prior to about 1900 are historical accounts of earthquake effects (Coffman et al., 1982), which have been used to estimate the distribution of intensities, and the locations and magnitudes of earthquakes. The record of large earthquakes in the 19th century is reasonably well documented for the eastern United States but not for other parts of the country. The large 1857 Ft. Tejon event, for example, is not well documented, when compared with the documentation for the 1886 Charleston, South Carolina event (Dutton, 1887). Instrumental data from stations in the United States were not available until after 1887 (Poppe, 1979) when the first seismograph stations in the country were established at Berkeley and Mt. Hamilton (Lick Observatory).

4.2 Magnitude and Intensity

The earthquake magnitude scale is a well-known but typically misunderstood means of describing the energy released during an earthquake. The best-known scale is that developed by C. F. Richter (Richter, 1958); and relationships between the Richter scale and other scales have been established. Magnitude scales are intended to be objective, instrumentally determined measures of the size of an earthquake, and a number of magnitude scales have been developed since Richter's (Aki and Richards, 1980). The most recent widely used scale is moment magnitude, M_W (Hanks and Kanimori, 1979). An increment in magnitude of one unit (i.e., from magnitude 5.0 to 6.0) represents an increase of approximately 32 times the amount of energy released. Unless otherwise noted, earthquake magnitude as used in this study refers to surface wave magnitude, M_S.

While *magnitude* describes the size of an earthquake, *intensity* describes its effects at a particular location or site. Intensity at a site is governed by the magnitude of an earthquake, the distance from the site to the earthquake epicenter or rupture surface, and local geologic conditions. A small or moderate earthquake may generate strong ground shaking, but the areal extent of this shaking will be substantially less than that generated by a major earthquake. The 1931 Modified Mercalli Intensity (MMI) Scale (Wood and Neumann, 1931, Table 4-1) is a commonly used measure of intensity. The scale consists of 12 categories of ground motion intensity, from I (not felt, except by a few people) to XII (total damage). Structural damage generally is initiated at about MMI VI for poor structures, and about MMI VIII for good structures. MMI XI and XII are extremely rare. The MMI scale is subjective; it is dependent on personal interpretations and is affected, to some extent, by the quality of construction in the affected area. Even though it has these limitations, it is still useful as a general description of damage, especially at the regional level, and for this reason will be used in this study, as the descriptor of seismic hazard.

4.3 Earthquake Hazards

Physical damage to structures and lifelines during and after an earthquake can be produced by ground shaking, fault rupture, landslides,

Table 4-1 Modified Mercalli Intensity Scale

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

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

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

IV. Hanging objects swing. Vibration like passing of heavy trucks; or sensation of a jolt like a 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 frames 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, knickknacks, books, etc., off shelves. Pictures off walls. Furniture moved or overturned. Weak plaster and masonry D cracked. Small bells ring (church, school). Trees, bushes shaken (visible, or heard to rustle).

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). Some cracks in masonry C. Waves on ponds; water turbid with mud. Small slides and caving in along sand or gravel banks. Large bells ring. Concrete irrigation ditches damaged.

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

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

X. Most masonry and frame structures destroyed with their foundations. Some well-built wooden structures and bridges destroyed. Serious damage to dams, dikes, embankments. Large landslides. Water thrown on banks to 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.

Source: Richter, C.F., 1957, *Elementary Seismology*, W. H. Freeman Co., San Francisco, Calif.

Note: To avoid ambiguity, the quality of masonry, brick, or other material is specified by the following lettering system. (This has no connection with the conventional classes A, B, and C construction.)

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 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 to resist horizontal forces.

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

liquefaction, and earthquake-induced fire. Ground shaking is the primary and best-known hazard associated with earthquakes. It produces scattered but widespread damage. Ground shaking includes both horizontal and vertical motions, can last up to several minutes during major earthquakes, and can be destructive at distances of even hundreds of kilometers, depending on soil conditions. It is estimated that such shaking causes over 90% of earthquake-related damage to buildings.

Ground or fault rupture produces local concentration of structural damage. A *fault* is a fracture in the crust of the earth along which blocks have moved or been displaced in relation to each other. This displacement can be in either a horizontal, a vertical, or an oblique direction. Near fault lines, fault displacements produce forces so great that the best method of limiting damage to structures is to avoid building in areas close to ground traces of active faults.

Secondary seismic hazards are those related to soil instabilities. *Liquefaction* is the sudden loss of shear strength that can occur when saturated, soils that lack cohesion (sands and silts) are strongly and repetitively vibrated. Liquefaction typically occurs in loose sand deposits where there is subsurface groundwater above a depth of about 20 feet. Shallow groundwater and loose soil are usually localized conditions, resulting either from natural or human-made causes. As a result, site-specific data generally are necessary to accurately determine if liquefaction may occur at a location. It usually severely damages civil engineering works and low-rise buildings. Mid- and high-rise buildings in these soils will tend to have pile foundations, which mitigate the structural effects of liquefaction, or reduce liquefaction potential, but may not completely eliminate the threat.

Settlement or compaction of loose soils and poorly consolidated alluvium can occur as a result of strong seismic shaking, causing uniform or differential settlement of building foundations. Buildings supported on deep (pile) foundations are more resistant to such settlements. Substantial compaction can occur in broad flat valley areas recently depleted of groundwater.

Landslide is the downslope movement of masses of earth under the force of gravity. Earthquakes can trigger landslides in areas that are already landslide prone. Slope gradient is often a clue to stability. Landslides are most common on slopes of more than 15^{0} and can generally be anticipated along the edges of mesas and on slopes adjacent to drainage courses.

4.4 Seismicity

Seismicity is the space-time occurrence of earthquakes. The historical seismicity of the United States is shown in Figure 4-1, which depicts the spatial distribution of earthquakes with maximum MMIs of V or greater, known to have occurred through 1976. For the purpose of characterizing seismicity in the conterminous United States, several regions may be identified (Algermissen, 1983), as shown in Figure 4-2:

1. Northeastern Region, which includes New England, New York, and part of eastern Canada;

2. Southeastern Region, including the central Appalachian seismic region activity and the area near Charleston, South Carolina;

3. Central Region, which consists of the area between the regions just described and the Rocky Mountains;

4. Western Mountain Region, which includes all remaining states except those on the Pacific coast;

5. Northwestern Region, including Washington and Oregon; and

6. California and Western Nevada.

We discuss each of these regions briefly largely using information from Algermissen (1983) and Coffman et al. (1982). These references can provide a more detailed discussion.

Northeastern Region. The Northeastern Region contains zones of relatively high seismic activity--earthquakes of at least magnitude 7.0 have occurred in New England and the St. Lawrence River Valley in Canada (Algermissen, 1983). The historic seismicity of this region is shown in Figure 4-3.

One of the largest earthquakes to have affected this area was the November 18, 1755,

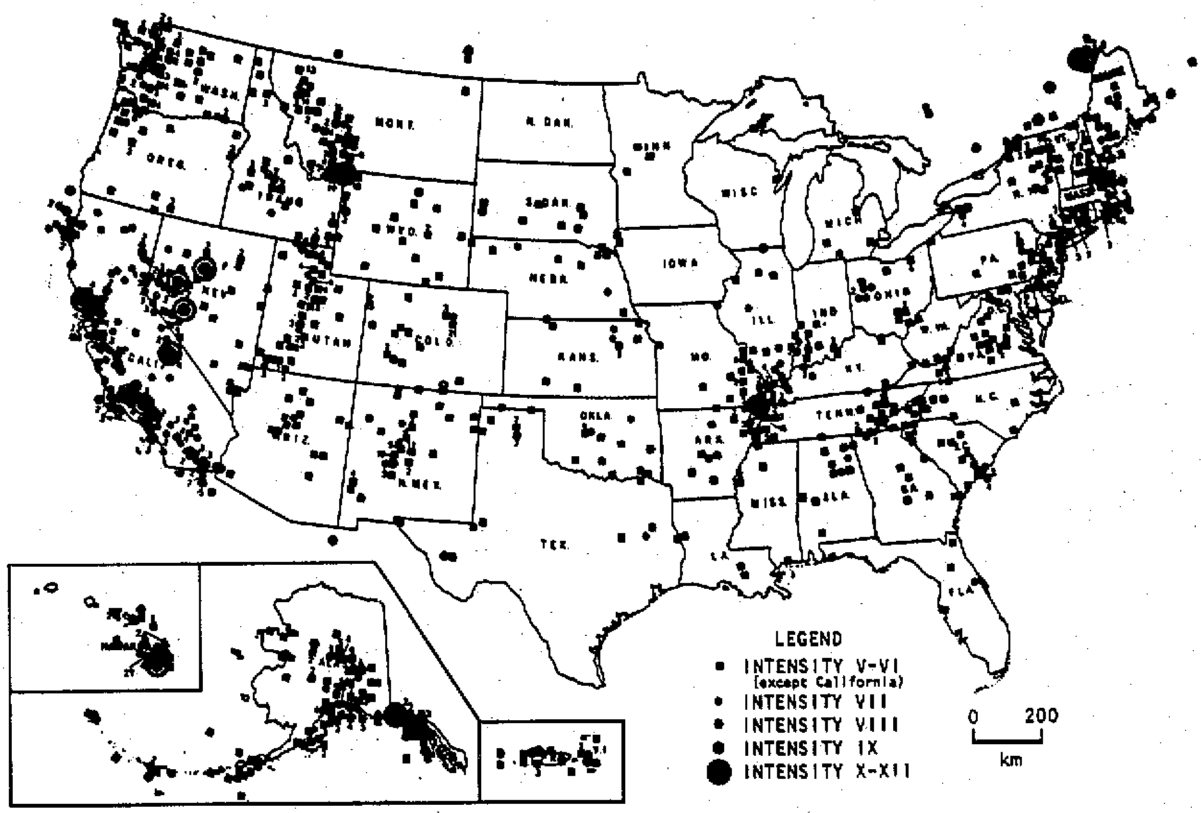


Figure 4-1 *Earthquakes with maximum Modified Mercalli Intensities of V or above in the United States and Puerto Rico through 1989 (Algermissen, 1983, with some modifications).*

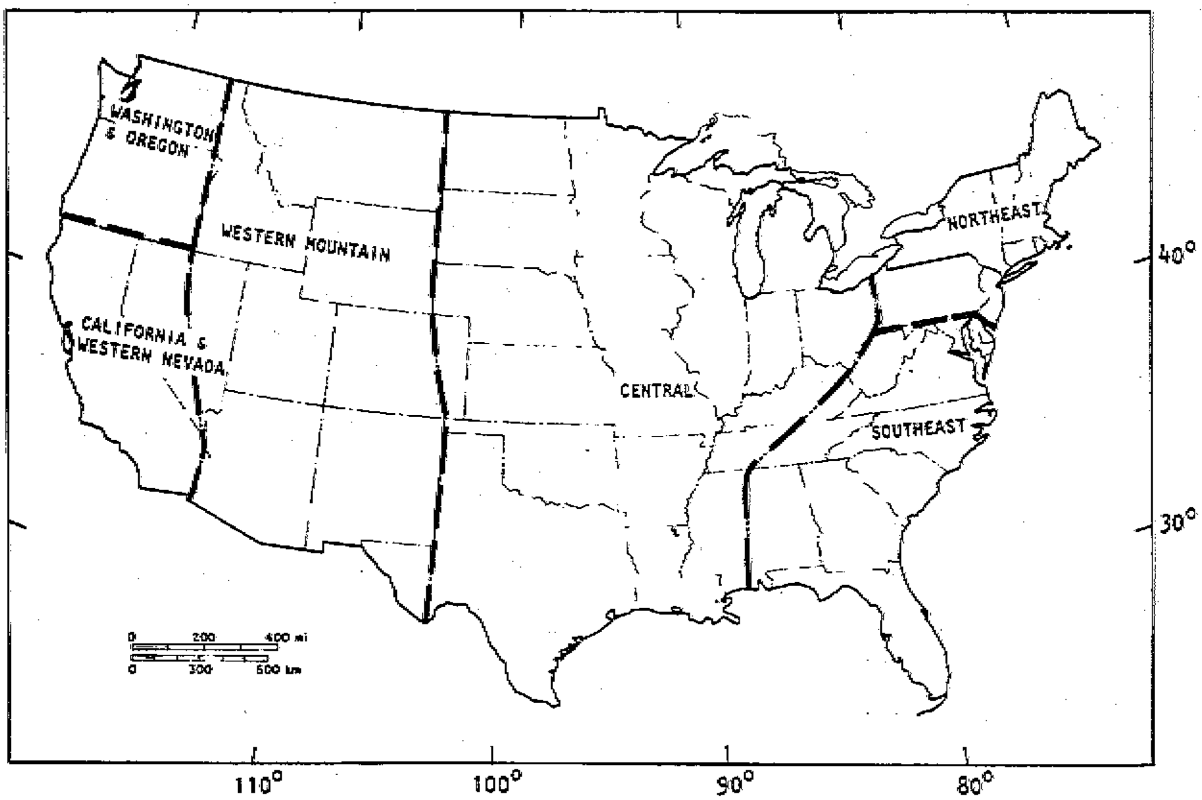


Figure 4-2 *Regional scheme used for the discussion of the seismicity of the conterminous United States.*

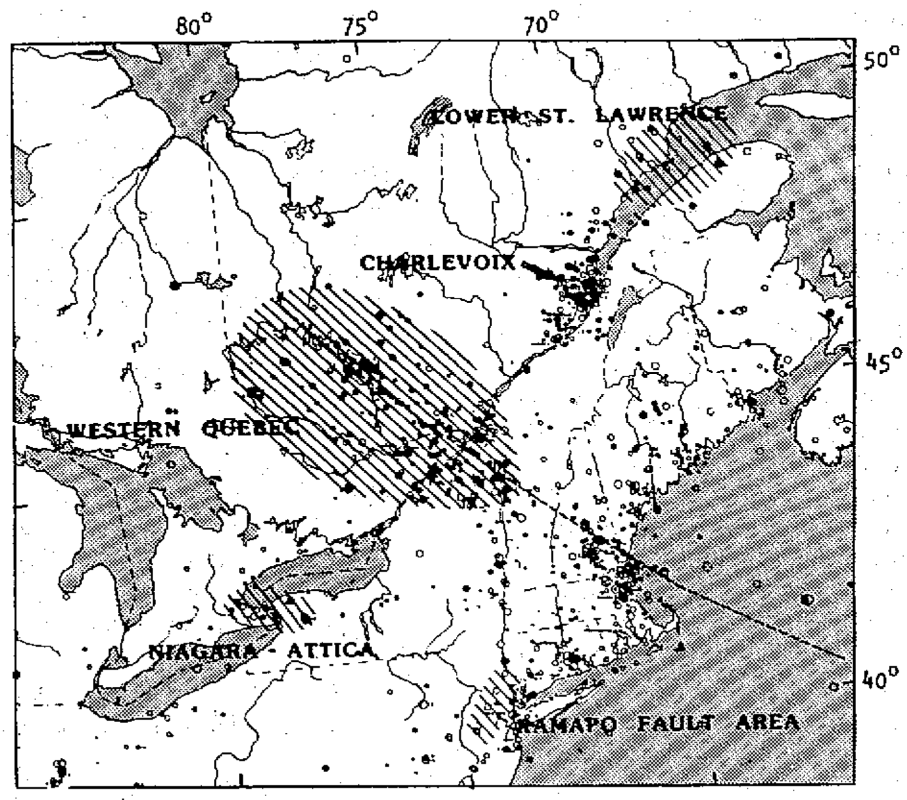


Figure 4-3 *The seismicity of the northeastern region of the United States and Eastern Canada for the period 1534-1959 (from Algermissen, 1983). The solid circles are principally instrumentally determined epicenters, while the open circles represent earthquakes located in using intensity data. The hachured and named areas represent concentrations of seismicity grouped together only for the purpose of discussion in the text. The dashed line represents the strike of the New England (Kelvin) sea mount chain offshore. Onshore, the line has been extended to show the northwest-southwest alignment of seismicity known as Boston-Ottawa trend.*

earthquake east of Cape Ann, with an epicenter located at about 42.5 N and 70.0 W, with magnitude 6.0 (magnitude and epicenter location estimated on the basis of seismic intensity data). The shock was felt from Chesapeake Bay to Annapolis River, Nova Scotia; and from Lake George, New York, to a point at sea 200 miles east of Cape Ann, an area of about 300,000 square miles.

Southeastern Region. The seismicity of this region is shown in Figure 4-4. With the exception of the Charleston, South Carolina, earthquake, this region has a moderate level of earthquake activity. The largest and by far the most destructive earthquakes in this region occurred on August 31, 1886, with their epicenter about 15 miles northwest of Charleston, South Carolina (32.9 N, 80.0 W). The first shock was at 21:51, the second about 8 minutes later. An area with a radius of 800 miles was affected; the strongly shaken portion extended to 100 miles.

The bending of rails and lateral displacement of tracks due to ground displacements were very evident in the epicentral region, though not at Charleston. There were severe bends of the track in places and sudden and sharp depressions of the roadbed. At one place, there was a sharp S-curve. At a number of locations, the effect on culverts and other structures demonstrated strong vertical force in action at the time of the earthquake. Figure 4-5 shows the effects in the epicentral area, and Figure 4-6 shows the isoseismal map for the event (Bollinger, 1977).

Central Region. Compared to the interior of other continents, the central region of North America, especially the Upper Mississippi embayment, is one of relatively frequent small-to-moderate size earthquakes and infrequent large events. In fact, three of the largest earthquakes in North American history occurred there (Hopper, 1985). These latter events occurred in 1811-1812, near the present town of New Madrid, Missouri. They were powerful enough to alter the course of the Mississippi River. Although masonry and stone structures were damaged to distances of 250 kilometers, and chimneys destroyed to distances of 400 kilometers, the sparse settlement of the area prevented grave damage. The extent and severity of ground failure and topographic effects from these shocks have not been equaled by any other earthquake in the conterminous United States.

The seismicity of this region is shown in Figure 4-7. Earthquakes of small magnitude (less than 5.0) are scattered throughout the region, and the major seismicity is associated with the rift structure identified in the New Madrid area. Since the 1811-1812 sequence, nine events of estimated magnitude greater than 5.0 have occurred through 1980, only one of which is estimated to have been greater than magnitude 6.0 (m_b 6.2, in 1895) (Algermissen, 1983).

The New Madrid Seismic Zone lies within a 40-mile-wide, 120-mile-long portion of the northern Mississippi embayment--a south-plunging trough of sedimentary rocks. The boundaries of this zone are at present somewhat uncertain. The zone may extend farther to the south than presently recognized. The epicenter pattern in the New Madrid area shows well-defined lineations: a northeast-striking zone that extends about 60 miles from near Marked Tree, Arkansas (approximately 40 miles northwest of Memphis), to near Caruthersville, Missouri; a north-northwest-striking zone from southeast of Ridgely, Tennessee, to west of New Madrid; and another northeast-striking zone extending from west of New Madrid to near Charleston, Missouri. The first zone is less active, but earthquakes along it have relatively higher magnitudes. The third zone includes frequent events of small magnitude. Note that no identifiable surface faults or offset landforms or drainage features have been identified.

Because seismic attenuation through frictional damping, or dissipation of earthquake energy with distance, is less in the eastern and central United States than in the west, earthquakes in this area have the potential or producing strong ground shaking over comparatively wide areas. The isoseismal map of the December 16, 1811, New Madrid earthquake (Nuttli, 1981) is shown in Figure 4-8. Algermissen and Hopper (1985) have developed maps of hypothetical intensities for the region, based on enveloping effects that would result from an earthquake occurring "anywhere from the northern to southern end of the seismic zone."

Western Mountain Region. Important earthquake activity in this region has occurred in

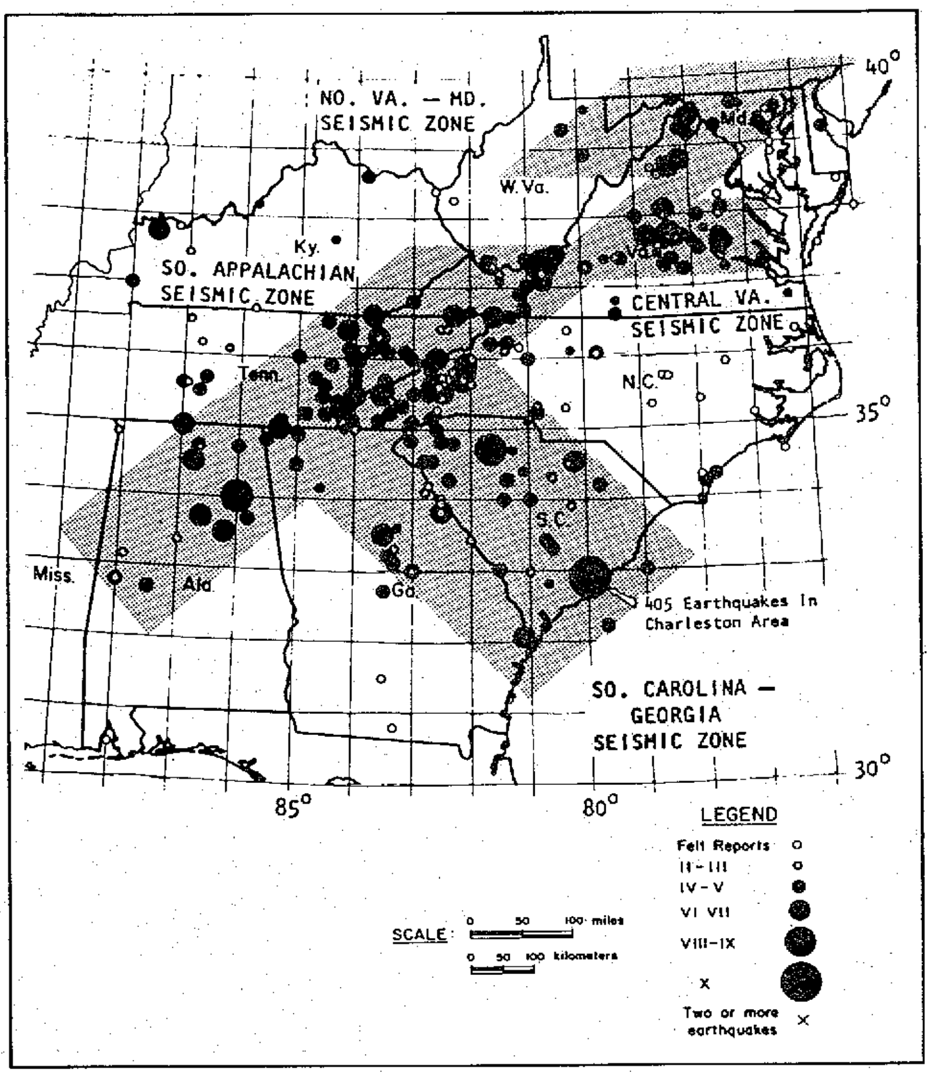


Figure 4-4 *Seismicity of the Southeastern region, 1754-1970 (from Bollinger, 1977).*

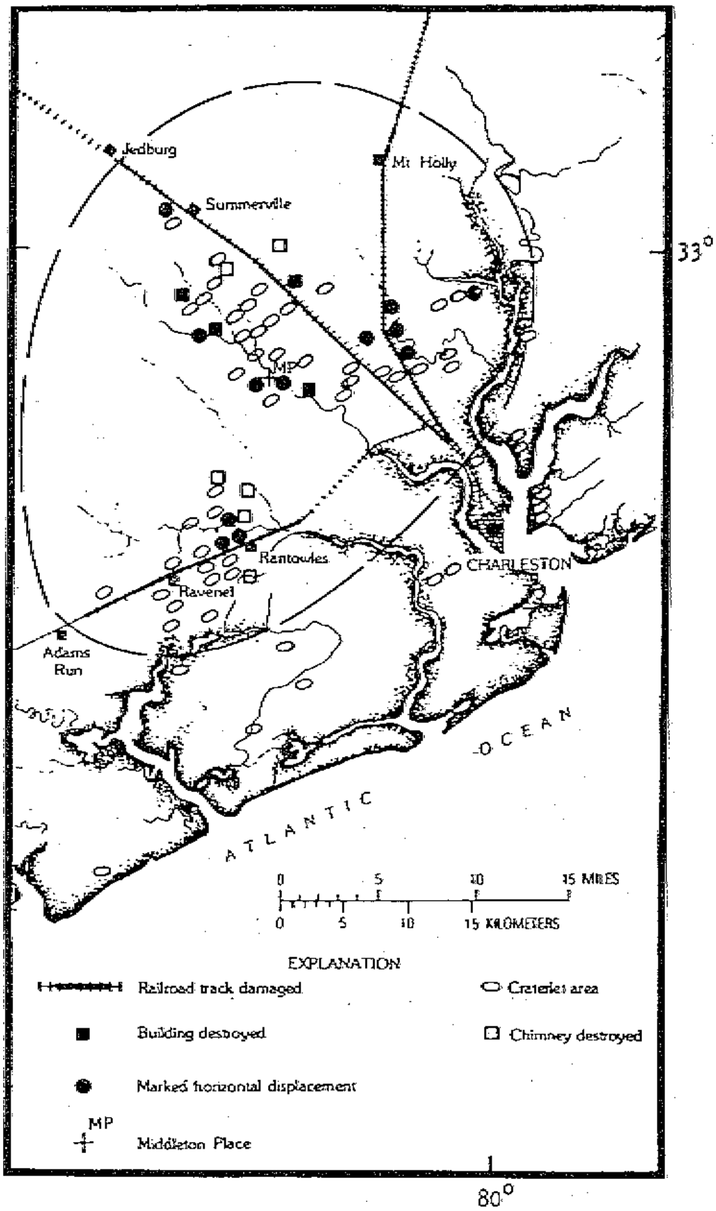
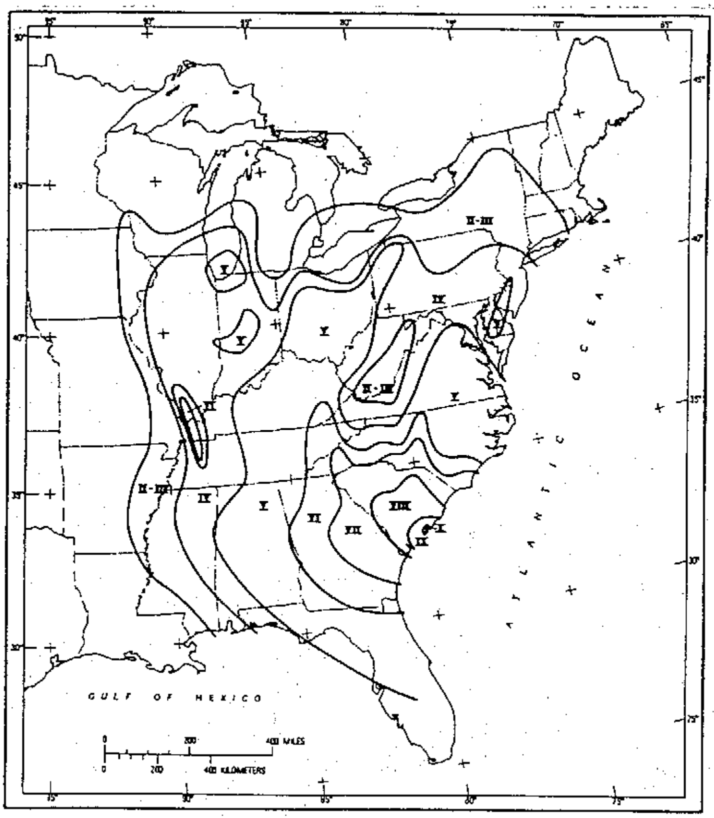
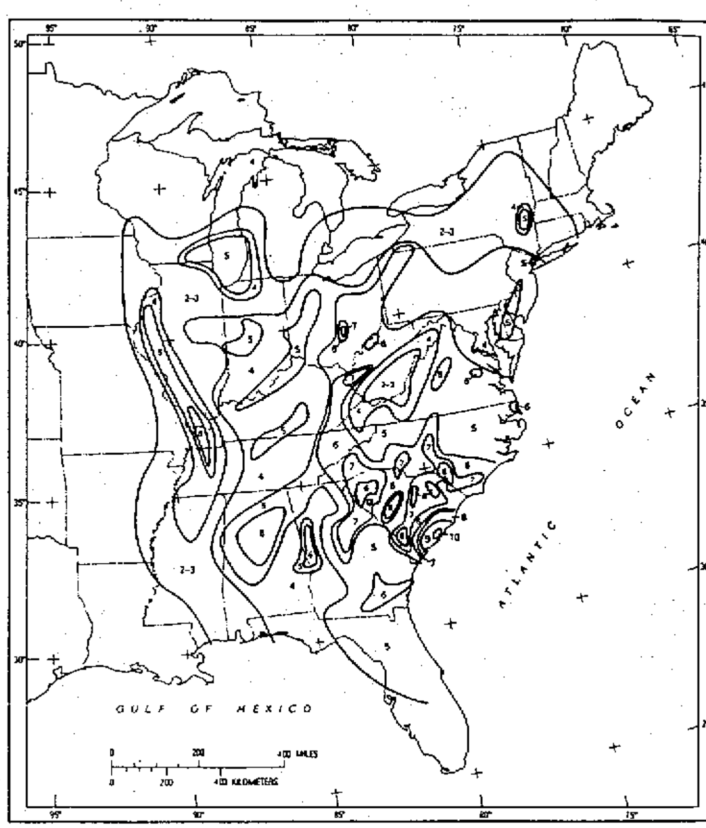


Figure 4-5 *Effects in the epicentral area of the 1886 Charleston, South Carolina, Earthquake (from Algermissen, 1983).*



a) *Broad map, based on detailed map (below)*



b) *Detailed map of seismic intensity.*

Figure 4-6 *Isoseismal map of the 1886 Charleston, South Carolina, Earthquake (from Bollinger, 1977).*

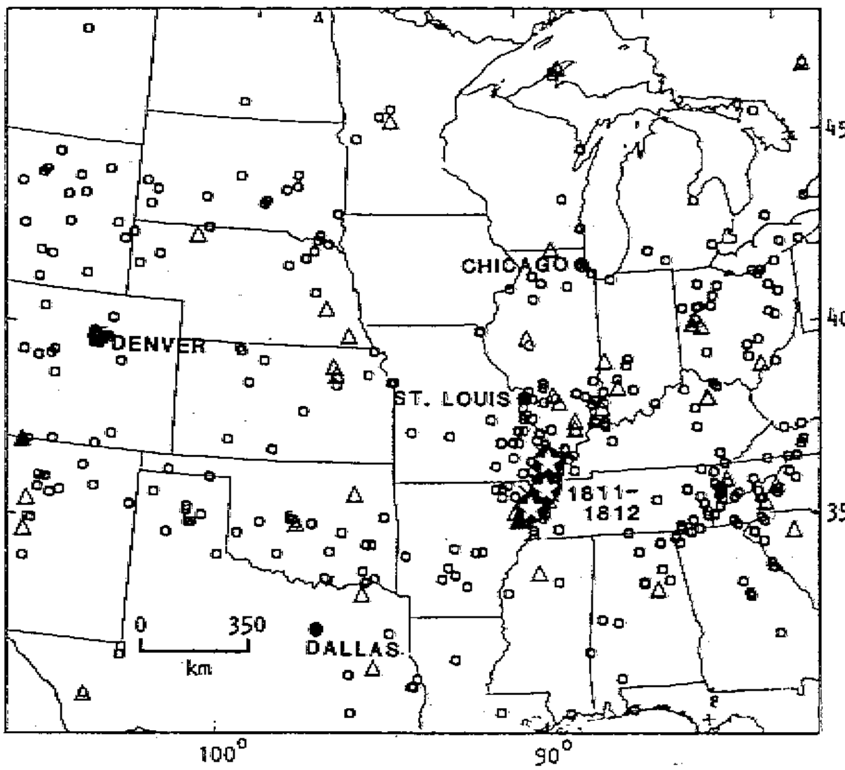


Figure 4-7 *Seismicity of the Central Region, 1811-1976. The data are taken principally from Algermissen (1983) with minor changes and additions. The stars represent earthquakes with maximum MMIs of IX or greater; triangles represent earthquakes with maximum intensities of VII-VIII; squares represent earthquakes with maximum intensities of V-VI.*

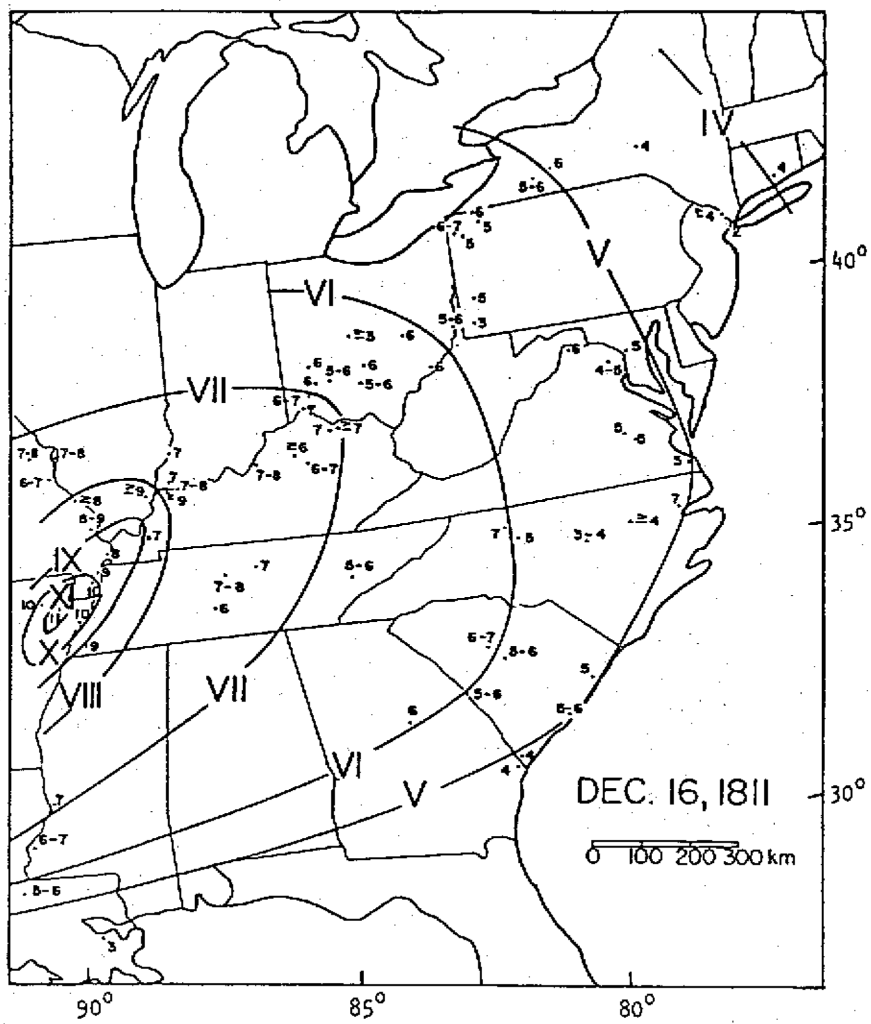


Figure 4-8 *Isoseismal map of the December 16, 1811, earthquake (from Nuttli, 1979). The Arabic numbers give the Modified Mercalli intensities at each data point.*

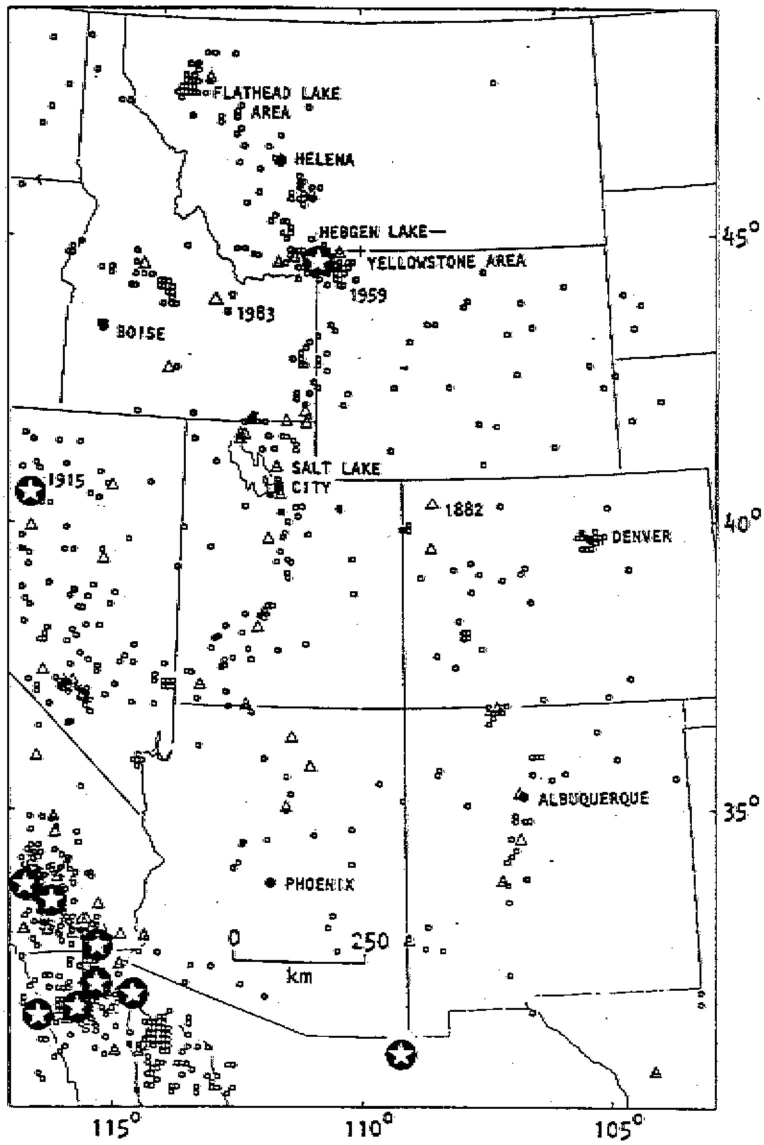


Figure 4-9 *Seismicity of the Western Mountain Region (Algermissen, 1983). Stars represent earthquakes with maximum intensities of IX or greater; triangles represent earthquakes with maximum intensities of VII-VIII; and squares represent earthquakes with maximum intensities of V-VI.*

the Yellowstone Park-Hebgen Lake area, in western Montana, in the vicinity of the Utah-Idaho border, and sporadically along the Wasatch Front, as shown in Figure 4-9. Major earthquakes occurred in Helena, Montana, in 1925 (M_S 6.7), at Hebgen Lake, Montana, in 1959 (M_S 7.1) and at Borah Peak, Idaho, in 1983 (M_S 7.3).

Probably the most serious risk in the Western Mountain Region, however, exists along the Wasatch Front region of north-central Utah. This area is dominated by the Wasatch Fault, a 220-mile-long, north-south-trending zone extending from Gunnison, Utah, in the south, to Malad City, Idaho, in the north, and directly threatening the Salt Lake City area. In this zone, young mountain blocks have been uplifted to form the prominent west-facing scarp (the Wasatch Front), which forms the eastern boundary of the Salt Lake and Utah valleys. Included in this zone is the active East Cache Fault System located on the eastern side of Cache Valley. Another related fault system of interest is the Hansel Valley Fault Zone, located north of the Great Salt Lake near the border with Idaho. It has been the most active fault in the state for larger-size events (Arabasz and Smith, 1979).

Historic records of earthquake activity in Utah date back to 1853, shortly after the region was settled permanently. Since that time, over 1,000 felt events have occurred on a regular basis. The earliest event recorded that has been estimated to have a magnitude of 6.0 or greater was the Bear Lake Valley Earthquake in 1884 (estimated magnitude 6.1). The 1909 event in Hansel Valley was assigned a maximum intensity of VIII and a magnitude of 6.0, and resulted in waves being sent over the railway causeway at the north end of the Great Salt Lake and windows being broken as far away as Salt Lake City. The largest earthquake to date in Utah, the 1934 Hansel Valley event (M_S 6.6) severely damaged brick buildings in Kosmo, produced 2-foot scarps in the ground surface, greatly altered groundwater flow patterns, and caused nonstructural damage to buildings in Salt Lake City. It occurred in a sparsely populated area, otherwise great damage could have resulted.

Historic earthquake damage to the Utah Valley area has thus far been due to local earthquakes with magnitudes of approximately 5.0 or less, with maximum intensities of about MMI VI or less. Damage has been mostly limited to cracked walls and chimneys, and broken windows. Since 1960, there has been very little notable earthquake activity in the Utah Valley. However, research has shown that many large seismic events (magnitudes 6.5 to 7.5) have taken place along the Wasatch Front during the past 10,000 years (Swan et al., 1980).

Northwestern Region. The seismicity of Washington and Oregon is shown in Figure 4-10. Most of the earthquake activity has occurred in the vicinity of Puget Sound. Although a few geologically recent faults thought to be potentially active have been located in western and central Washington, no historic seismic activity has been associated with them. Instead, most recorded seismic activity in Washington has been attributed to the subduction of the offshore Juan de Fuca crustal plate beneath the North American continental plate.

Subduction zones occur at locations where, under the influence of tectonic plate movement, one piece of the earth's crust is forced beneath another. Subduction zones have been associated with very large earthquakes including the 1985 Mexico City (M_S 8.1) and 1964 Alaska (M_S 8.3) events. Subduction zones are frequently associated with volcanic activity as well as earthquakes. The presence of the volcanically active Cascade range supports the evidence for an active Juan de Fuca subduction zone. Further supporting evidence includes the mountains on the Olympic peninsula, which appear to have been formed by debris scraped off the Juan de Fuca plate by the overriding North American plate.

Available geologic information indicates that great earthquakes, with magnitudes in excess of 8.0, have occurred on the Juan de Fuca subduction zone at least eight times in the last 5,000 years. The last such event is thought to have occurred about 300 years ago. Evidence for such an earthquake includes geologically recent submerged marsh lands and fossil forests along the Washington coastline. It is believed that portions of the Washington coast subsided by as much as 3 feet in that event.

In addition to the great earthquakes described above, extensive but more moderate seismicity

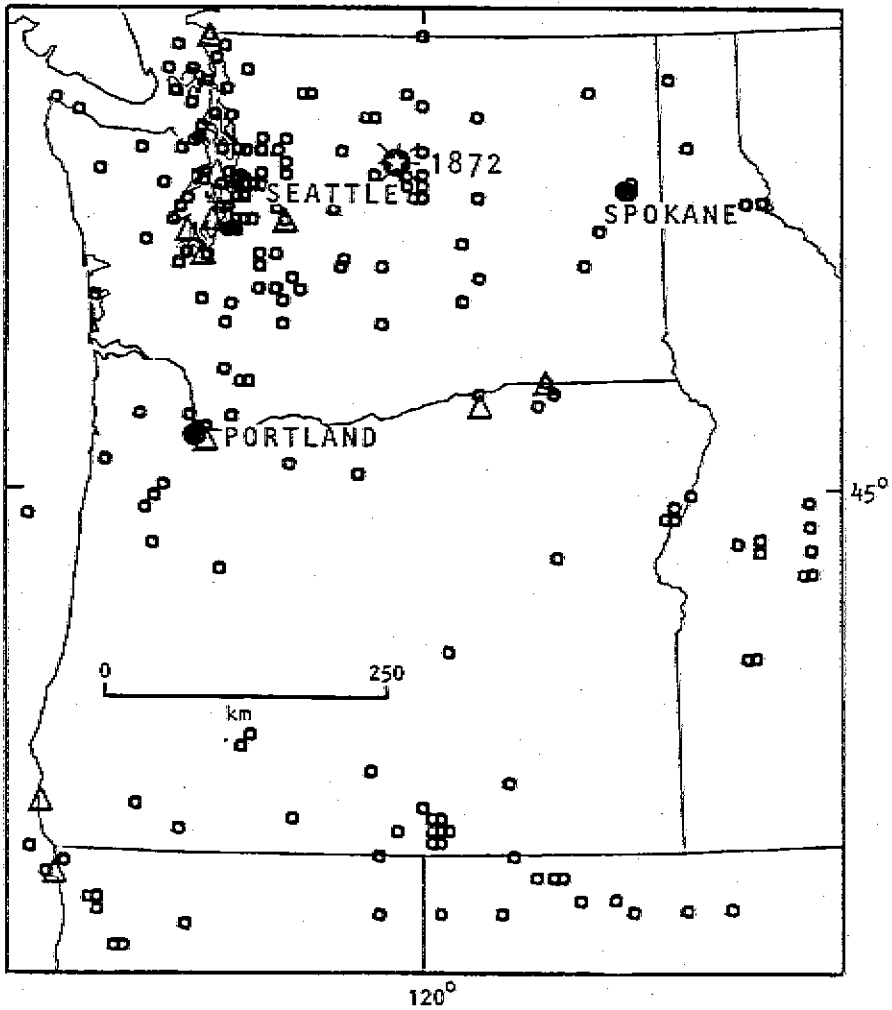


Figure 4-10 *Seismicity of Oregon and Washington, 1859-1975. The star represents an earthquake with maximum Modified Mercalli intensity of IX; triangles represent earthquakes with maximum intensities of VII-VIII; and small squares represent earthquakes with maximum intensities of V-VI (Algermissen, 1983).*

has been associated with the same subduction zone, deep beneath the Puget Sound trough between Seattle and Olympia. In this area, termed the Puget Trough Intercrustal Zone, the friction between the underlying Juan de Fuca plate and overriding North American plate has resulted in many mid-size events with occasional strong damaging shocks. Typically these events occur at depths from 20 to 30 miles below the surface and are therefore less damaging than events of similar size in California, which occur at shallower depths. Two of the largest recorded earthquakes in the Pacific Northwest have occurred in this zone. A M_S 7.1 event in 1949, located near Olympia, caused extensive damage in Seattle, Tacoma, and Olympia. A 1965 (M_S 6.5) event, centered near the Seattle-Tacoma airport, caused MMI VII and VIII damage in both Seattle and Tacoma. A mean return period of approximately 30 years has been calculated for events of this size. Great earthquakes of magnitude 7.5 or larger are believed credible.

An earthquake in the northern Cascades in 1872 had an estimated magnitude of 7.3 and a maximum intensity of MMI IX. Earthquake intensities of MMI VII were experienced on the Olympic peninsula in 1891 and again in 1904. Two moderate earthquakes in 1932 and 1945 shook the central Cascades with maximum MMI VII.

The Vancouver-Victoria area, located in the northern portion of Puget Sound, has had a relatively large number of smaller earthquakes. However, the maximum magnitudes experienced have been much lower than those in the southern portion of Puget Sound. Only three earthquakes as large as magnitude 5.5 have occurred in the Vancouver-Victoria area. The corresponding maximum intensities were on the order of MMI VII. The estimated maximum magnitude for the Vancouver-Victoria area is about 6.5.

Further north on Vancouver Island, over 200 miles from Seattle, two earthquakes of magnitudes 7.0 and 7.4 occurred in 1918 and 1946, respectively. These events produced maximum intensities of MMI VIII but did not cause significant damage in Washington.

California and Western Nevada. Earthquakes in California and Western Nevada represent a high percentage of the seismic activity of the conterminous United States. The majority of these shocks occur at relatively shallow focal depths of 10 to 15 miles and along known rupture zones or faults. Figure 4-11 shows the seismicity of this region, while Figure 4-12 shows faults with historic displacements in this region.

While this area is the most seismically active region of the conterminous United States, only three events with magnitudes greater than M_S 8.0 have occurred in historical times. Two of these events occurred on the principal fault in this area, the San Andreas, which extends over 600 miles through California, from near the Salton Sea in Southern California northwest to Cape Mendocino. The most famous of these San Andreas events was the April 18, 1906, San Francisco Earthquake (M_S 8.3), caused by a rupture of approximately 270 miles in length, from San Juan Bautista to off Cape Mendocino. Devastation was extremely widespread, with enormous losses in San Francisco caused by the ensuing conflagration (Lawson et al., 1908). The other of these events, the Ft. Tejon Earthquake, occurred on January 9, 1857, on a segment of the San Andreas Fault between Cholame and south of Cajon Pass. It may be regarded as a Southern California counterpart of the 1906 event. The isoseismal maps for these events are shown in Figure 4-13. In addition to these two great earthquakes, a number of large, potentially damaging earthquakes have occurred on the San Andreas Fault, including events in 1838, 1865, and, most recently, the October 17, 1989, Loma Prieta Earthquake (M_S 7.1). This last event resulted in very significant disruption to almost all lifelines, especially the highway and electric power networks (Khater et al., 1990).

The third of the great historic California earthquakes is the 1872 Owens Valley event, resulting from approximately 150 kilometers of faulting. The area was relatively sparsely populated but still resulted in about 10% fatalities in Lone Pine, because of the predominantly adobe construction.

Another very important fault in Northern California is the Hayward Fault, located on the eastern side of San Francisco Bay and extending approximately 55 miles from San Jose northwesterly to San Pablo (Figure 4-12). The Hayward Fault is one of the major active branches of the San Andreas Fault System, and is particularly significant because it passes

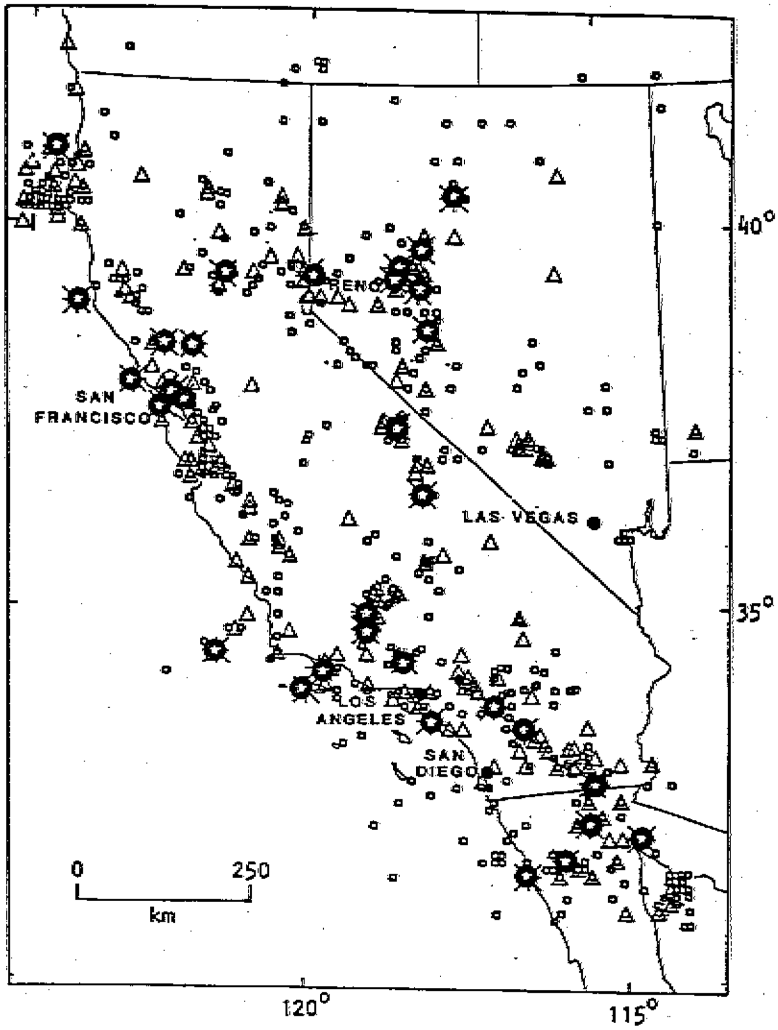


Figure 4-11 *Seismicity of Western Nevada and California, 1811-1976 (Algermissen, 1983). Stars represent earthquakes with Modified Mercalli intensities of IX or greater, triangles represent shocks with maximum intensities of VII-VIII; and small squares represent shocks with maximum intensities of VI.*

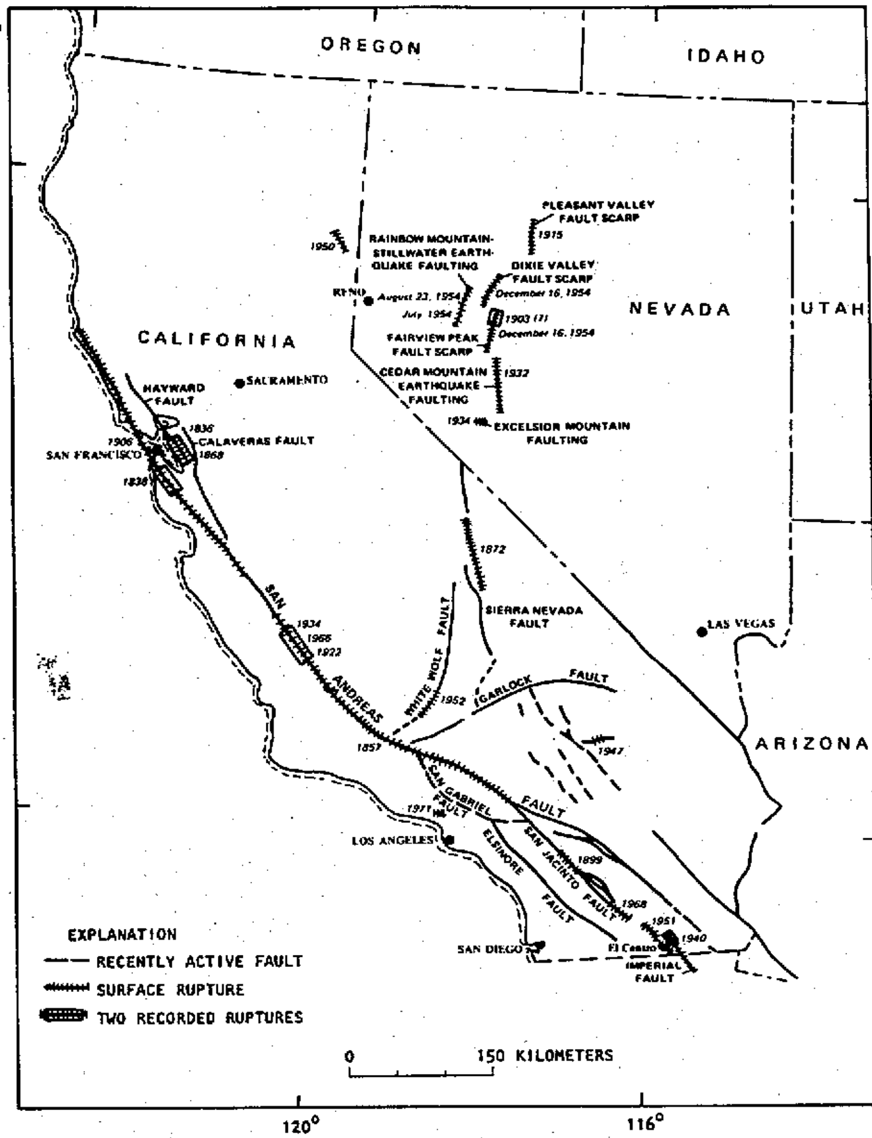


Figure 4-12 *Faults with historic displacements in California and Nevada. The year of occurrence for selected large earthquakes is shown (Algermissen, 1983).*

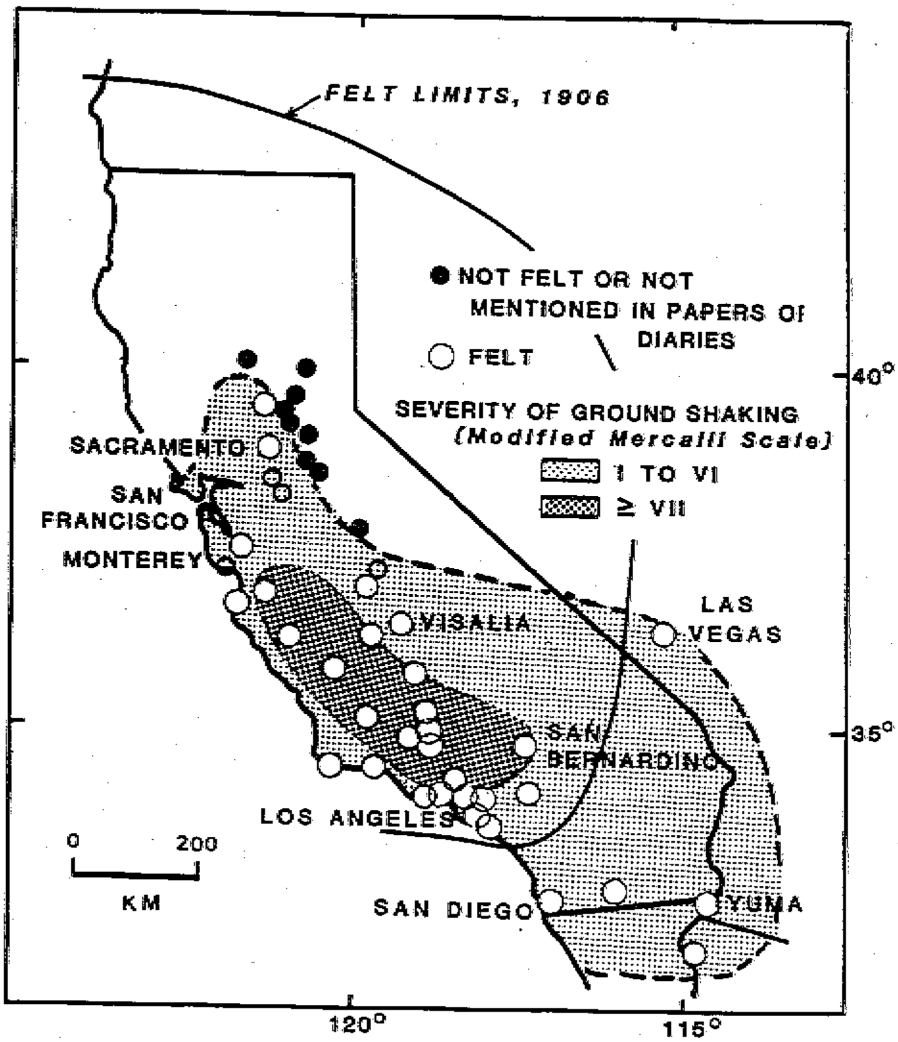


Figure 4-13 *Isoseismal map for the January 9, 1857, earthquake on the San Andreas Fault near Fort Tejon (Algermissen, 1983). Also shown, for comparison, are the felt limits for the 1906 San Francisco Earthquake.*

directly through the heavily populated cities such as Hayward, San Leandro, Oakland, and Berkeley. It was the source of the Hayward Earthquake of 1836 (estimated M_S 6.8), in which fissures opened along the fault from San Pablo to Mission San Jose, and ground shaking caused havoc in the settlements of San Jose and Monterey. In 1868 an earthquake (estimated M_S 6.8) ruptured the fault the fault for 20 miles and severely damaged every building in the village of Hayward. More recent damaging earthquakes occurred in 1915, 1933, and 1937. The Hayward Fault is believed capable of producing earthquakes as large as magnitude 7.5, and is presently judged highly likely to rupture with a magnitude of about 7.0 in the near future [United States Geological Survey (USGS), 1990]; this judgment is based, among other evidence, on the pairing of San Andreas/Hayward events in 1838/1836 and 1865/1868. A large earthquake on this fault is of potentially catastrophic proportions (Steinbrugge et al., 1987).

Similar to the Hayward Fault situation in the San Francisco Bay Area, the Los Angeles region is threatened by a number of additional faults, including the Newport-Inglewood, Santa-Monica Raymond, Elsinore, Norwalk, and other faults and fault zones. Significant events have included the 1933 Long Beach event (M_S 6.3) on the Newport-Inglewood Fault (NBFU, 1933; Binder, 1952), the 1971 San Fernando event (M_S 6.4, San Fernando Fault), and the 1987 Whittier (M_S 5.9) event.

Other significant events in California have included the 1940 El Centro (M_S 7.1), the 1952 Kern County (M_S 7.7), and the 1983 Coalinga (M_S 6.5) events.

4.5 Regional Representative Earthquakes

Based on the foregoing review of conterminous U.S. regional seismicity, each region appears to have significant historic precedent for a damaging earthquake of potentially catastrophic dimensions. For purposes of examining this potential, the earthquakes indicated in Table 4-2 are representative events for the investigation of lifeline loss estimation and disruption.

Evernden et al. (1981) estimates that these events represent almost the maximum earthquake expected in each area. Review of Algermissen et al. (1982) indicates general agreement.

Table 4-2 Representative Earthquakes for Lifeline Loss Estimation

Region	Event
Northeastern	Cape Ann, 1755
Southeastern	Charleston, 1886
Central	New Madrid, 1811-1812
Western Mountain	Wasatch Front, no date
Northwestern	Puget Sound, 1949
Southern California	Fort Tejon, 1857
Northern California	Hayward, 1868

4.6 Estimation of Seismic Intensities and Choice of Scenario Earthquakes for this Project

Choice of a Model. In order to estimate the seismic hazard (i.e., deterministic intensity) of the scenario events over the affected area associated with each event, a model of earthquake magnitude, attenuation, and local site effects is required. For the conterminous United States, two general models were considered: Evernden and Thomson (1985), and Algermissen et al. (1990).

Both models are applicable for the entire conterminous United States, and each offers many advantages but addresses two fundamentally different users. The Algermissen model is oriented toward probabilistic mapping of seismic hazard, while the Evernden model is oriented toward exploration of the effects of deterministic events. Both models were considered for use in this investigation. Selection of one over the other was difficult, but the Evernden model offered the following advantages for this study: (i) verification via comparison with historical events, (ii) incorporation of local soil effects and ready availability of a nationwide geologic database, and (iii) ready availability of closed-form attenuation relations. While determination of seismic intensities is fundamental to the results of this investigation, the choice of one of these models over the other was not felt to be crucial to this study, because (i) the primary purpose of this study is not the investigation of seismic hazards in the conterminous United States, or comparison of these two models, but rather the performance of selected lifelines; and (ii) both models probably provide similar results in the mean (it should be noted, however, that the two models have not been systematically compared, to the author's knowledge).

Use of the Evernden Model. Attenuation of ground motion away from the epicenter has been estimated by employing Evernden's model (Evernden et al., 1981). The model contains several parameters whose evaluations are based on empirical data. Only three factors in the model are regionally dependent: the local attenuation factor, the length of rupture, and a parameter related to depth of earthquake focus. The local attenuation factor changes significantly across different regions. Its value is about 1.75 in coastal California, 1.5 in eastern California and the Mountain States, 1.25 in the area of the Gulf and Atlantic Coastal plains including the Mississippi Embayment, and 1.0 in the rest of the eastern United States. Rupture length and energy released are related by an empirical relation, which leads to the observation that all major earthquakes of the Eastern United States have fault lengths of 10-to-40 kilometers maximum. With the local attenuation factor and rupture length established, peak intensity at the epicenter serves to establish the depth of focus.

The geological map of the United States published in the *National Atlas of the United States of America* (Gerlich, no date) was used for the complementary geologic base, digitized on a 25- by 25-kilometer grid.

As noted by Evernden et al. (1981), digitization at this resolution generally results in saturated poor ground not constituting the dominant ground condition in any particular grid element. Therefore, the resulting intensities should generally be interpreted as those on bedrock, per Evernden. This study generally concurs with this point, noting however that even the 25- by 25-kilometer digitization captures poor ground conditions in certain important locations, especially in the Mississippi Valley and along the eastern seaboard. As a generalization, intensities estimated by the Evernden model can be considered to provide lower bounds on site intensities.

Table 4-3 Geologic and Ground Condition Units, Conterminous United States (per Evernden et al., 1981)

Units of Geologic Map	*Ground Condition Unit*	*Relative Intensity*
Sedimentary rocks		
Quaternary	A	0.00
Upper Tertiary	B	-1.00
Lower Tertiary	C	-1.50
Cretaceous	D	-2.00
Jurassic and Triassic	E	-2.25
Upper Paleozoic	F	-2.50
Middle Paleozoic	G	-2.75
Lower Paleozoic	H	-2.75
Younger Precambrian	I	-2.75
Older Precambrian	J	-3.00
Volcanic rocks		
Quaternary and Tertiary volcanic rocks	K	-3.00
Intrusive rocks		
All ages	L	-3.00

Table 4-3 indicates the ground condition unit and relative intensity that correspond to the geologic units of the geologic map. Figure 4-14 shows the conterminous United States mapped in terms of these seismic units.

Scenario Earthquakes. Based on the earthquakes discussed above, representative of all major regions of the conterminous United States, eight scenario events were selected for this investigation. The eight events are indicated in Table 4-4. With the exception of the Cape Ann, Charleston, and Hayward events, all magnitudes are reflective of the representative earthquake for the region (as specified in Table 4-2). The scenario events for Cape Ann, Charleston, and Hayward have magnitudes one-half unit higher than the representative event. These magnitudes are interpreted as maximum credible for these locations.

The choice of a scenario event on the Hayward fault for the San Francisco Bay Area, rather than the 1906 San Francisco event, is based on the perceived high likelihood of a magnitude 7.0 event (USGS, 1990) as well as the potential for major damage and lifeline disruption, should such an event occur (CDMG, 1987). Since most lifelines approach San Francisco Bay from the east, more of them cross the Hayward Fault than cross the San Andreas Fault. So the

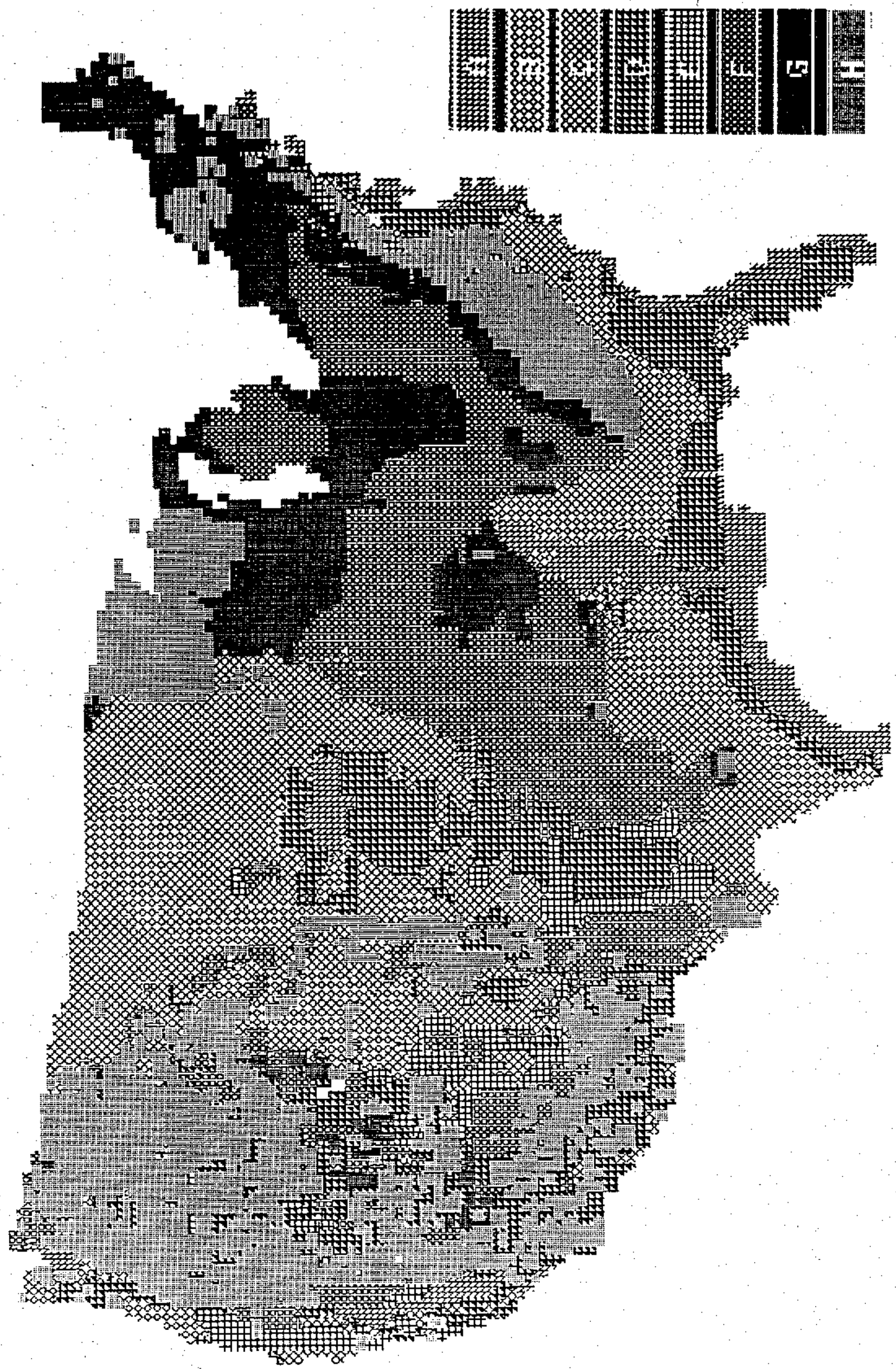


Figure 4-14 Map of conterminous United States showing ground condition units from Evernden et al. (1981). See Table 4-3 for explanation of units.

Table 4-4 **Scenario Earthquakes**

Region	*Event*	*Magnitude*
Northeastern	Cape Ann	7
Southeastern	Charleston	7.5
Central	New Madrid	7 and 8
Western Mountain	Wasatch Front	7.5
Northwestern	Puget Sound	7.5
Southern California	Fort Tejon	8
Northern California	Hayward	7.5

Hayward event would appear to represent as disruptive an event, and potentially more so, than the 1906 event, which is presently perceived to be of low likelihood in the near future.

Intensity Distributions. The Evernden model was employed to generate expected seismic intensity distribution in the conterminous United States for the eight scenario events. These intensity distributions are presented in Figures 4-15 through 4-22.

The intensity patterns for these events are seen to be basically circular, centered at the earthquake's epicenter. Deviations from the circular shape are due to local geologic conditions. Comparison of estimated intensities with historic event isoseismals indicates general agreement, though historical events are in some cases smaller than the scenario event.

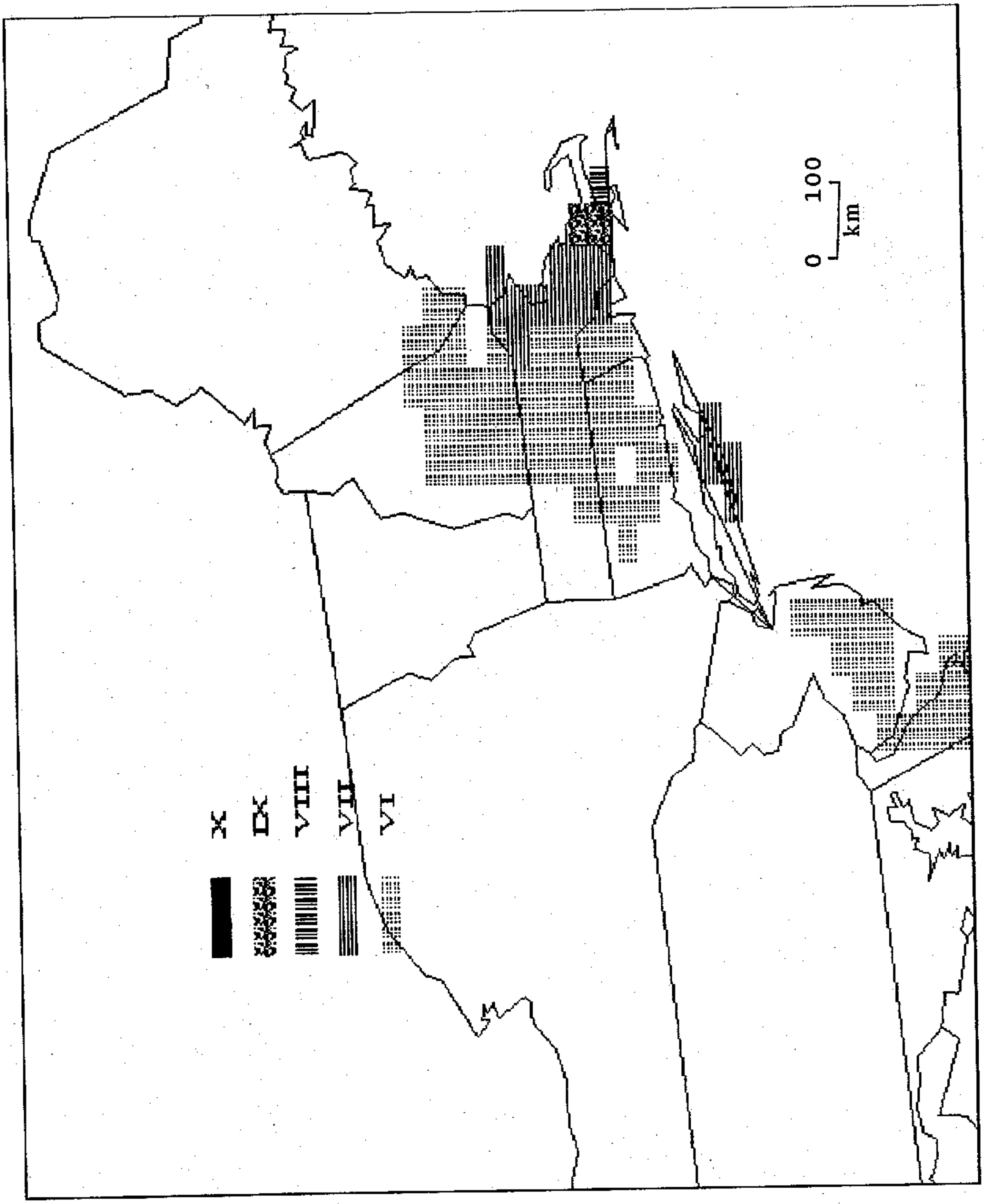


Figure 4-15 *Predicted intensity map for Cape Ann (Magnitude 7).*

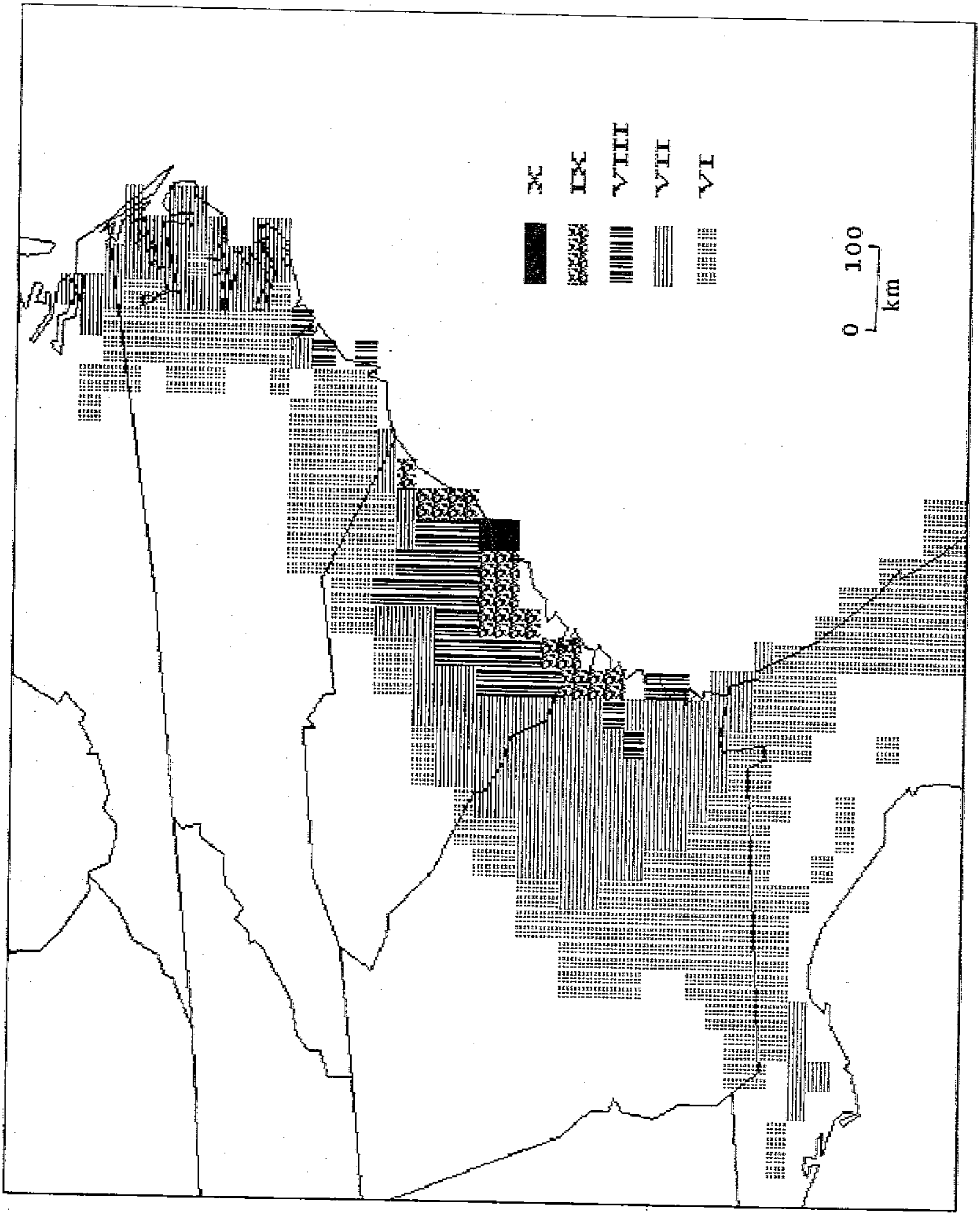


Figure 4-16 Predicted intensity map for Charleston (Magnitude 7.5).

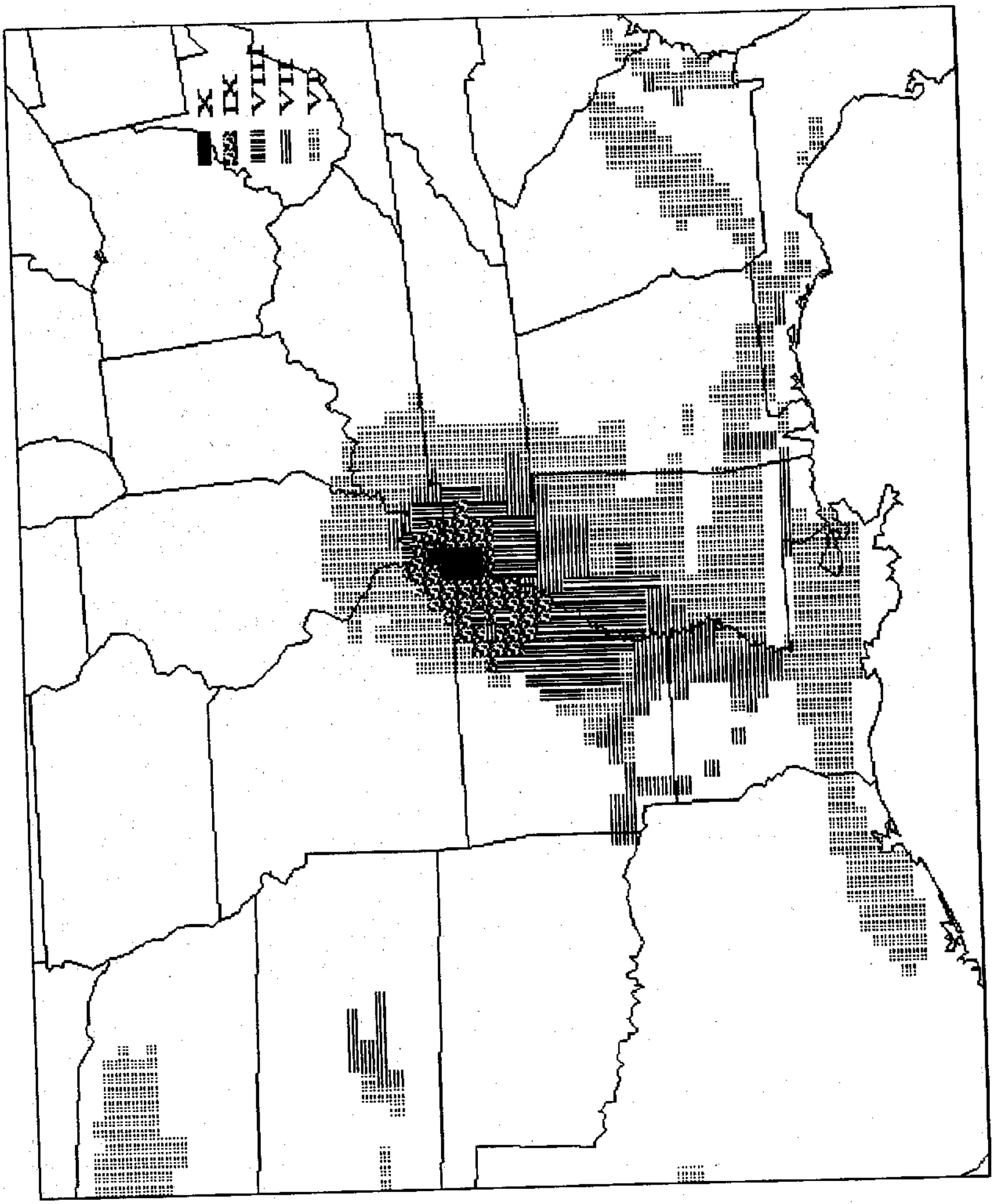


Figure 4-17 *Predicted intensity map for New Madrid (Magnitude 8).*

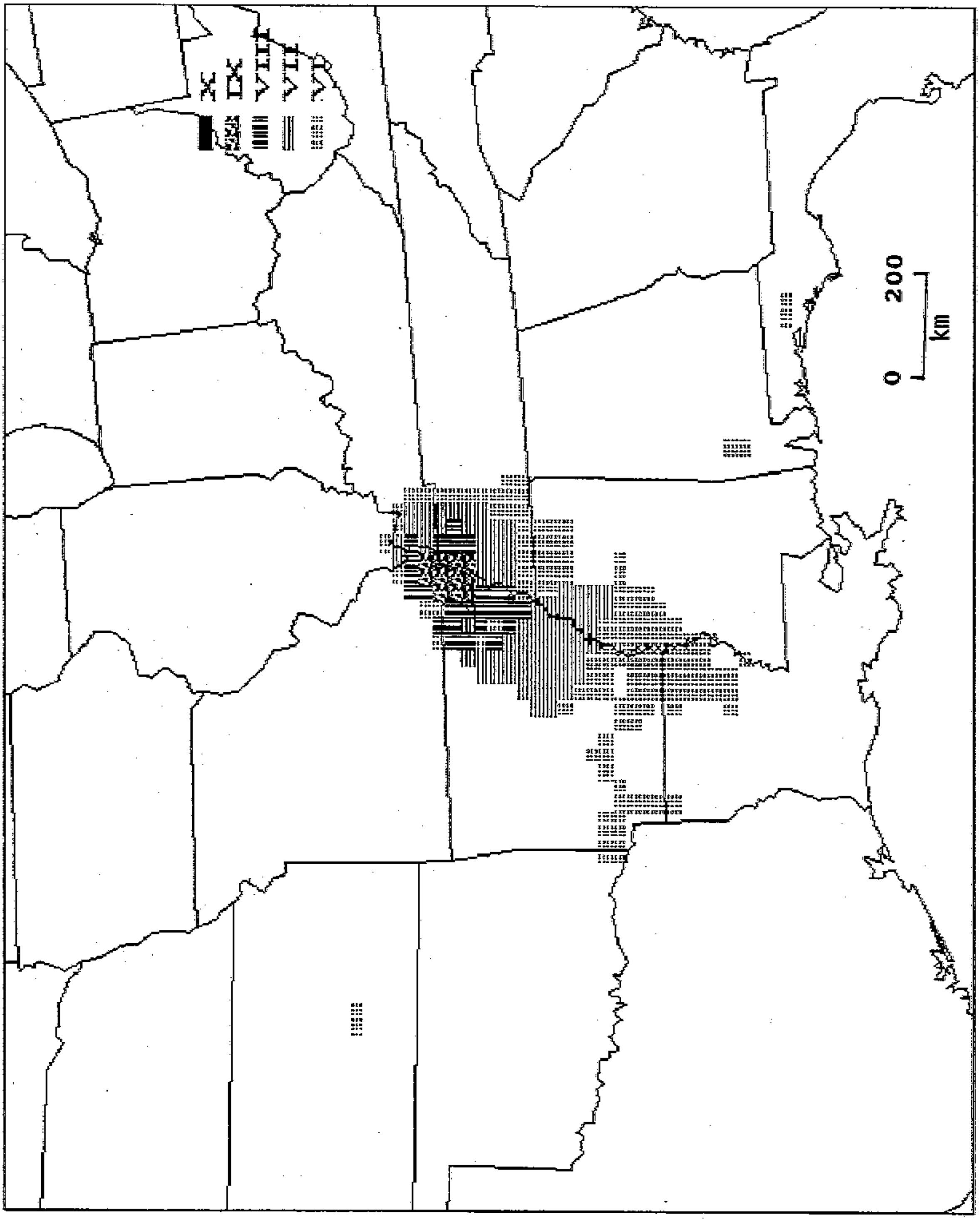


Figure 4-18 Predicted intensity map for New Madrid (Magnitude 7).

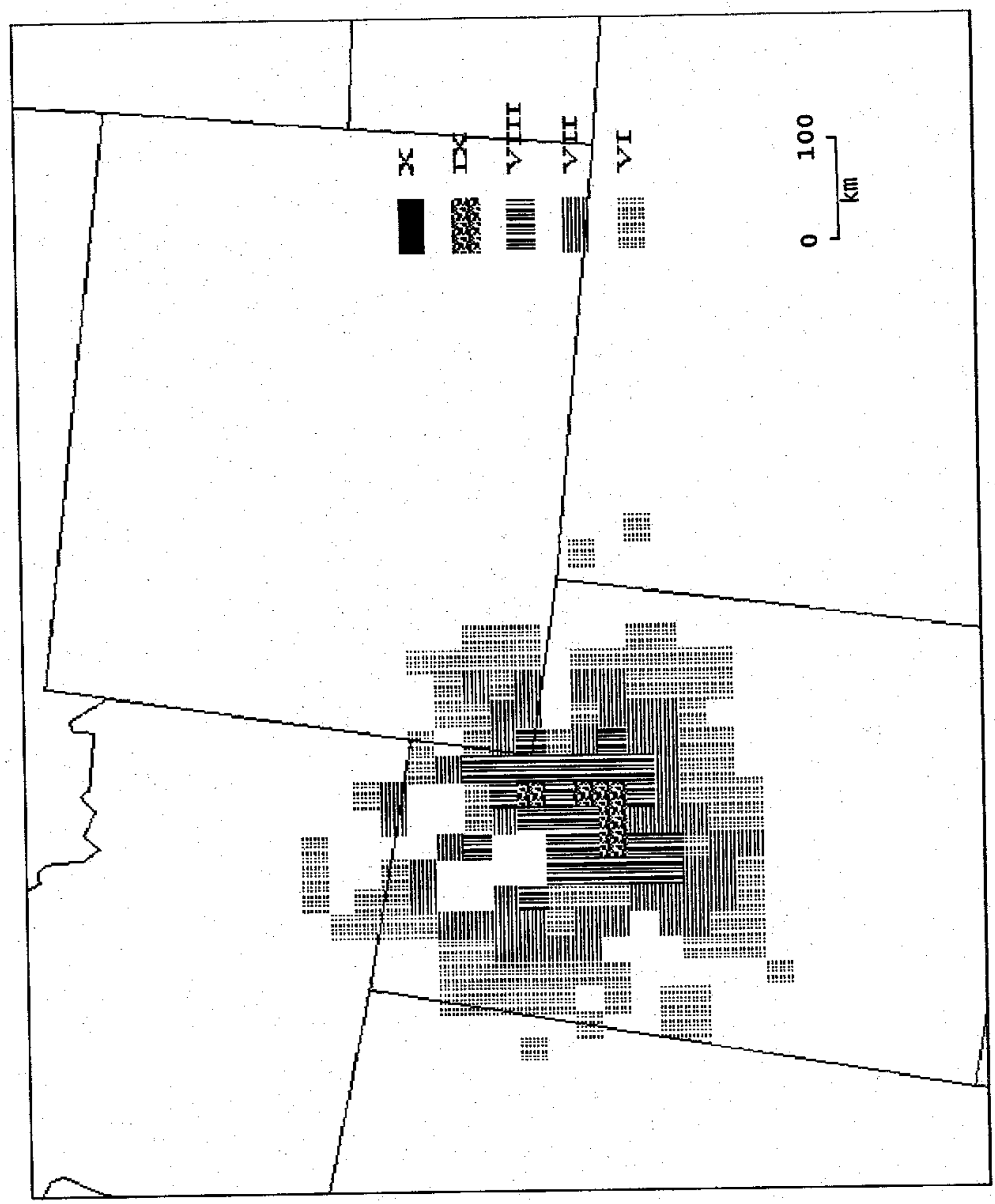


Figure 4-19 Predicted intensity map for Wasatch Front (Magnitude 7.5).

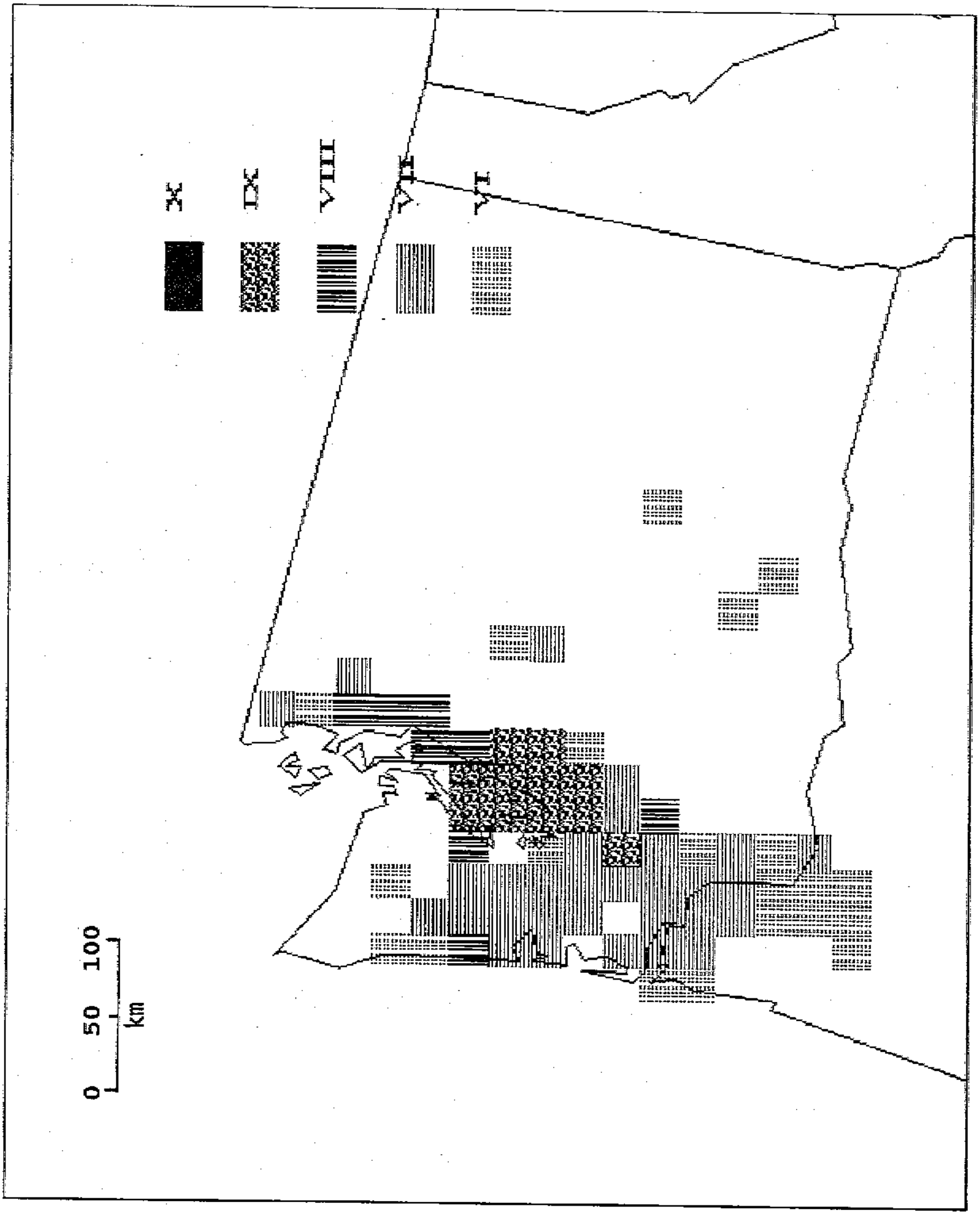


Figure 4-20 Predicted intensity map for Puget Sound (Magnitude 7.5).

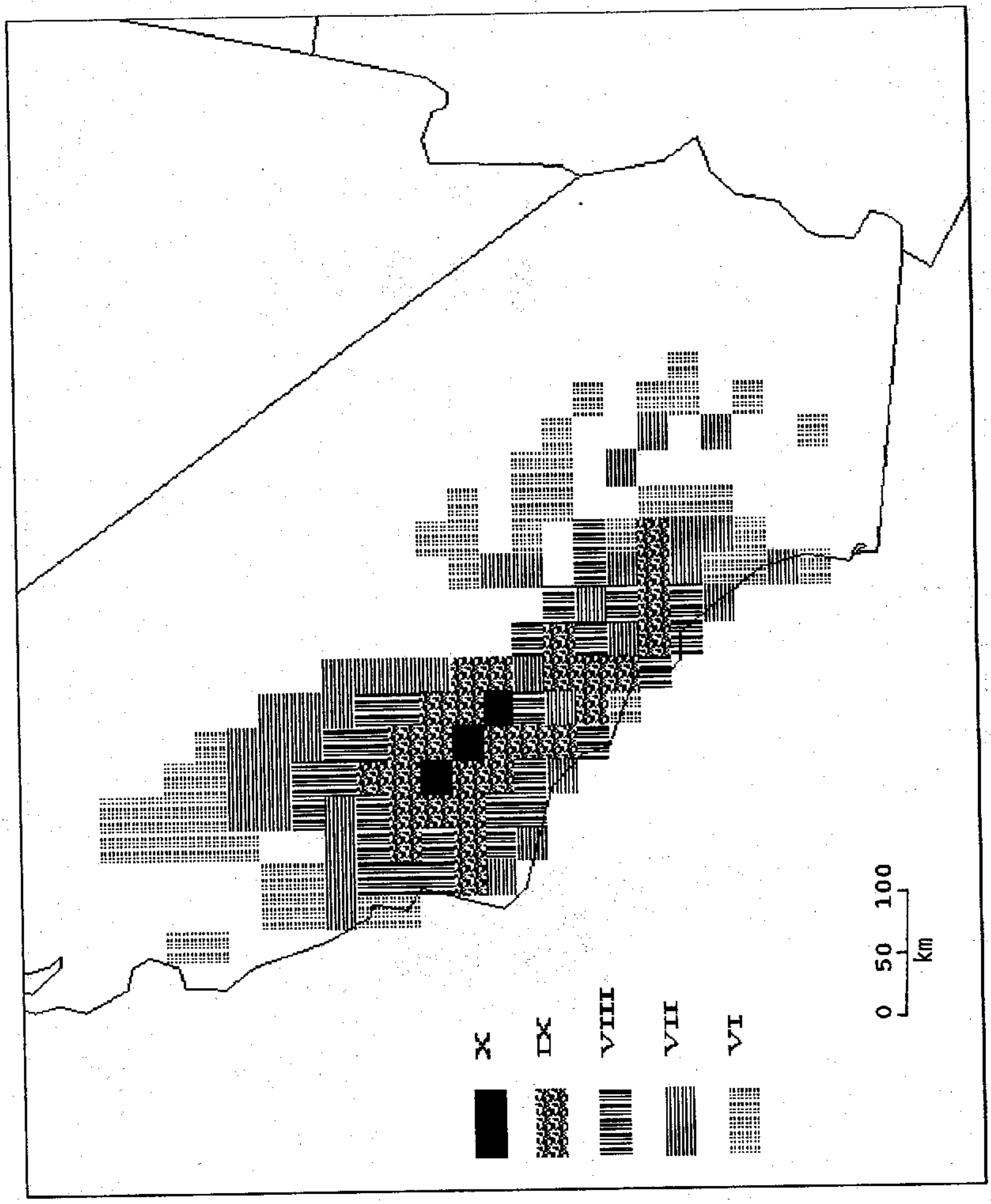


Figure 4-21 *Predicted intensity map for Fort Tejon (Magnitude 8).*

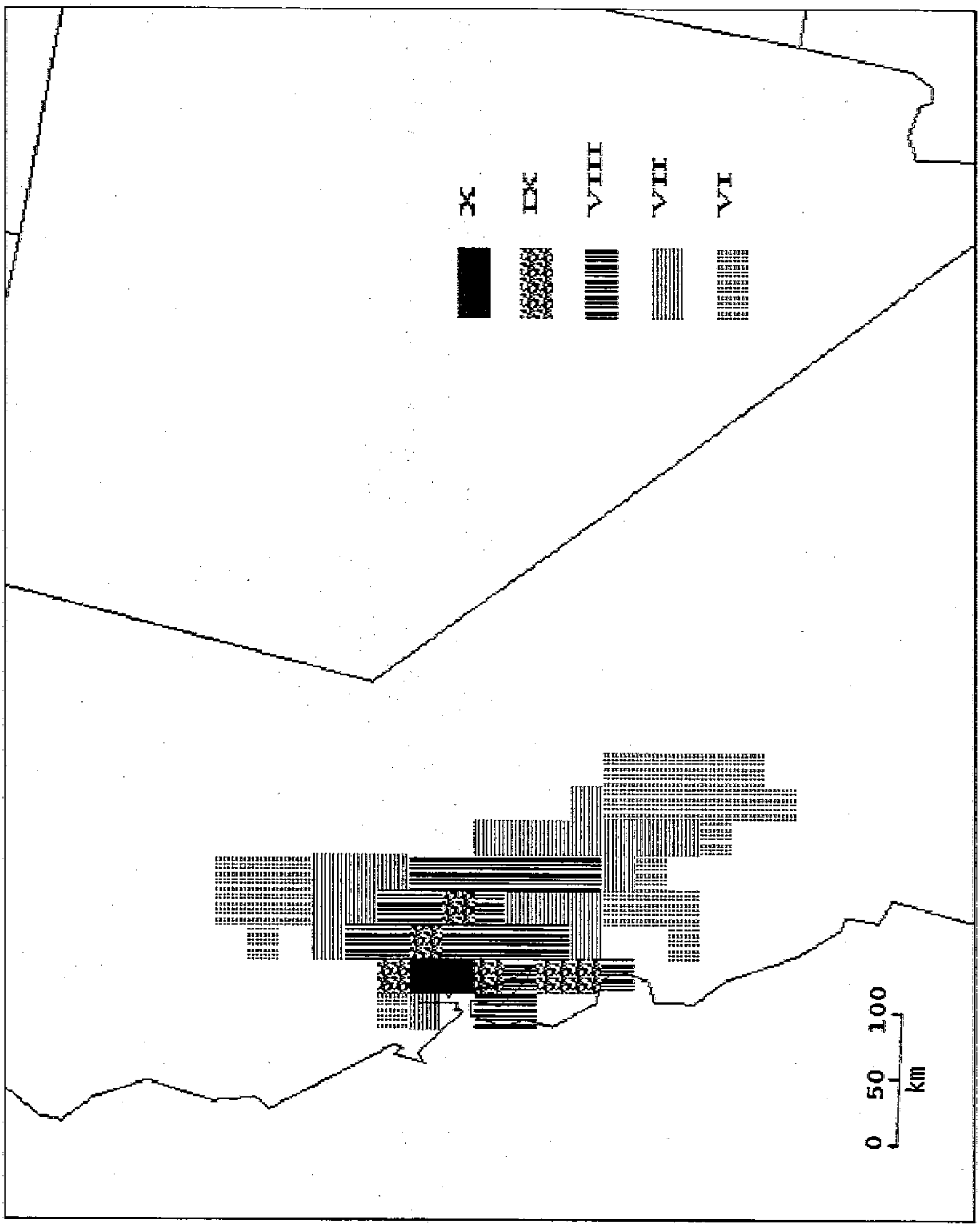


Figure 4-22 Predicted intensity map for Hayward Fault (Magnitude 7.5).