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A Methodology for Assessing the Risk of Hazardous Materials Release Following Earthquakes - A Demonstration Study for the Los Angeles Area

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ABSTRACT

A methodology for estimating the risk of earthquake-induced hazardous materials releases was developed for the National Science Foundation and the National Center for Earthquake Engineering Research. Seismic hazard analyses, fragility modeling for facilities handling hazardous materials and data on airborne materials releases were used in the development of the methodology. The risk was estimated in terms of population within the study area exposed to hazardous materials as a result of a postulated earthquake event. The procedure was developed to be used as a tool by communities interested in regional hazard management.

In order to demonstrate the methodology, Los Angeles County was selected as a study area. Population data was integrated into the methodology to predict the population exposure to hazardous materials releases for three earthquake scenarios: a Magnitude 8+ event on the San Andreas fault, a Magnitude 7 event on the Newport-Inglewood fault, and a Magnitude 5.9 simulation of the 1987 Whittier Narrows earthquake.

INTRODUCTION

Exposure to hazardous materials as a result of an earthquake-induced materials release is a threat to the population in the immediate vicinity of any storage, handling and processing facilities, as well as to the surrounding communities. Although there has never been a major incident involving hazardous materials in a U.S. earthquake, smaller releases have occurred in events that were moderate in size. In the 1989 Loma Prieta earthquake, numerous minor releases were reported, including a leak of at least 5000 pounds of anhydrous ammonia from a food processing plant in Watsonville (ABAG, 1990).

Responding to an earthquake-induced hazardous materials release presents challenges not faced in other hazardous materials emergencies. Following a major earthquake event, heavy demands are likely to be made on community emergency response capabilities and resources, making it difficult to effectively deal with secondary emergencies such as hazardous materials releases and fires. Problematic tasks associated with response to a hazardous materials release, including warning the public and evacuating hazardous areas, would be much more difficult following a major earthquake. Further, resource problems will be compounded by possible simultaneous hazardous materials release.

While awareness of the risk is growing, there has been little research to date on the seismic sources of hazardous materials releases, and seismic vulnerability models for chemical facilities are almost nonexistent. The research for this project combines seismic hazard analyses, findings from research on earthquake-related failures in industrial facilities, and data on airborne toxic releases to develop a general methodology that would enable local jurisdictions to determine the magnitude of the problem in their community and identify areas that are susceptible to exposure due to earthquake-generated releases. This paper demonstrates the application of this methodology to the Los Angeles County area.

METHODOLOGY

The methodology developed for this project is diagrammed in Figure 1 and discussed more fully in Tierney et al.,

1991. Its application in this demonstration study may be summarized as follows:

Hazardous Material Inventory

Hazardous materials number in the thousands, and new products are constantly being developed. Before a systematic analysis can be undertaken, it is necessary to determine which hazardous substances are likely to pose the biggest threat to the community in an earthquake. For this demonstration, we have chosen to focus on two hazardous materials; chlorine and ammonia. These substances were selected because: (1) they are responsible for the majority of fatalities and casualties in U.S. hazardous materials incidents; (2) they are present in large quantities in the study area, Greater Los Angeles; and (3) they form clouds that can spread to adjacent areas, thus presenting a hazard beyond the plant gates.

The facilities assumed to be possible sources of hazardous materials in this study are twenty-two of the largest users of chlorine and anhydrous ammonia in the greater Los Angeles area. These users include petroleum refineries, chemical manufacturers, and wastewater treatment plants. Although the methodology as developed calls for data obtained from inventories prepared under state and federal laws, data on the subject facilities were actually obtained from a survey conducted by the South Coast Air Quality Management District.

These facilities, dispersed throughout the study area, store and use varying amounts of chemicals. Facilities have been categorized into three facility types based on chemical usage patterns: chlorine storage facilities, ammonia storage facilities, and ammonia processing facilities. Chlorine storage amounts range from 4 to 1000 tons, while ammonia storage varies from 2 to 206 tons.

Earthquake Scenarios and Ground Shaking Estimates

Seismic hazard estimates have been developed for three different earthquake scenarios. In this demonstration, strong ground shaking was the only hazard considered, although additional hazard estimates could be developed for other earthquake effects, such as fault rupture, liquefaction and other ground failures.

Scenario 1 is a Magnitude 7.0 event on the Newport-Inglewood fault. This fault was the source of the 1933 Long Beach earthquake (M 6.3), which caused 120 deaths and $41 million (1933 dollars) in damage. A major earthquake on the Newport-Inglewood Fault would likely result in numerous fatalities and injuries, billions of dollars in damages, and severe disruption of economic activity at the local, regional, state and even national levels.

Scenario 2 is a Magnitude 8.3 earthquake on the San Andreas fault. This event involves 300 km of fault rupture along the Mojave, San Bernardino Mountains, and Coachella Valley segments of the fault. Such an event would be expected to cause high ground shaking levels throughout the Los Angeles Basin. As with the Newport-Inglewood event, losses and disruption would be significant.

Scenario 3 is a Magnitude 5.9 simulation of the 1987 Whittier Narrows Earthquake. This earthquake, with localized strong ground shaking, caused few deaths and injuries, but produced losses exceeding $350 million. In addition, the earthquake caused a significant hazardous materials incident. A tank in the City of Santa Fe Springs ruptured and leaked 240 gallons of chlorine into the air. The resulting plume, which drifted through the industrial section of the city toward Whittier, prompted evacuation of some areas (FEMA, 1987).

Ground shaking intensities at each facility were computed for each of the three earthquake scenarios, as follows. Peak ground accelerations (PGAs) were calculated at each location using a deterministic magnitude-distance attenuation relationship. Calculated PGAs were then converted to values of ground shaking intensity based on the Modified Mercalli Intensity (MMI) scale. These conversions yield MMI values equivalent to PGA values for sites located on "basement rock". These MMI values were then modified to account for variations in local ground conditions from "basement rock". Figure 2 shows the resulting seismic hazard map for Scenario 1 and indicates the locations of the 22 hazardous materials sources.

Chemical Facilities Modeling

Two "generic" facility models, a "generic" chemical processing facility and a "generic" storage and transfer facility, were developed for reasons of economy and efficiency. It was assumed that facilities that perform the same function have more or less the same components, allowing for analysis by generalized facility type, rather than on an individual facility basis. This assumption is particularly applicable to the Los Angeles area, where the range of chemical facilities types is somewhat limited. Facilities are generally comprised of the same components and follow similar process operations, using gaseous toxic chemicals as reactants in the manufacturing process.

Components of the chemical processing facility model that are subject to failure include the: (1) pressurized storage vessel; (2) exothermic reactor; (3) piping; and (4) separator/regenerator. The storage and transfer facility model is simply a subset of the processing model, consisting of a storage vessel and associated piping.

Facility Vulnerability Assessment

In analyzing complex systems, such as chemical facilities, it is not possible to identify just one or two failure modes that lead to overall system failure. Instead, all conceivable failure modes must be identified, and their individual contributions to overall facility failure must be systematically combined. Fault tree analysis is useful for this kind of assessment. In fault tree analysis, boolean techniques are used to model the interdependency of individual component failures. Cases where several failure modes must occur for some "fault" to occur are modeled using "AND gates." Cases where some "fault" can occur due to one or more failure modes are modeled using "OR gates". For this study, fault tree models were developed for earthquake-generated failures and toxic releases for chemical processing facilities, and storage and transfer facilities. The development of these fault tree models and the resultant failure curves for each facility type is discussed in detail in Tierney et al. (1991).

Plume Modeling

A chemical dispersion analysis was performed to estimate the size and shape of the area exposed to anhydrous ammonia (NH_3) or chlorine gas (Cl_2) following an earthquake-induced hazardous materials release. The dispersion of the resulting hazardous materials clouds was modelled using the SLAB dispersion model (Ermak, 1989), for various meteorological conditions typical of the Southern California Air Basin. The results of this analysis yield a conservative estimate of the zone of vulnerability, or area in which specific health criteria may be exceeded, for a given release and meteorological condition.

In order to determine potential zones of vulnerability, it was necessary to establish health criteria for both Cl_2 and NH_3. The chemical-specific health criteria used were based on the Emergency Response Planning Guidelines (ERPGs) developed by a committee of the American Industrial Hygiene Association (AIHA). The criteria selected for this study was ERPG 3, "the maximum airborne concentration below which it is believed that nearly all individuals could be exposed for up to one hour without experiencing or developing life-threatening health effects." This exposure level is 20 ppm for Chlorine and 1000 ppm for Ammonia.

For each meteorological condition and mode of chemical release, a zone of vulnerability or hazard footprint was determined. As a conservative estimate, the composite maximum width and length were taken to represent a generalized footprint for each release mode (i.e., the largest width and length from all meteorological conditions are used to define the exposure area for each release mode).

Because it would be virtually impossible to account for all of the variables that influence the position of the hazardous materials plume, such as wind speed and direction, a probabilistic approach was used to determine the likelihood that a given site will be within a hazardous material plume. Although hazard footprints are sometimes irregular, varying from tear-drop shape to circular, hazardous materials plumes were modelled as ellipses. This general model was deemed appropriate because it captured most of the characteristics of the irregular footprints.

A mathematical derivation yields the probability of a given site being located within a plume of given dimensions. Given an elliptical plume pattern, the plume must exist somewhere within a circle defined by sweeping the ellipse (fixed at the source) through a 360 degree arc. The plume's exact position within this circle is unknown. Only sites within this circle can be exposed to the chemical plume.

If one draws a circle with the center at the source, and the radius equal to the distance from the source to the site, the site will be within the plume if it sits anywhere along the arc defined by the intersection of this circle and the plume. Since the width of the plume, and hence the length of this arc, varies with the distance from the source, the probability of the site being located within the plume varies with distance from the source. Hence, this probability will depend on three factors; the parameters that define the plume (semi-axes a and b), and the distance, d, from the site to the source of the plume.

The probability, P, that the site will be located along the arc located within the plume is the ratio of the arc length, S, to the circumference of the circle whose radius is equal to the distance from the source to the site:

$$P=\frac{S}{C}=\frac{2\theta d}{2\pi d}=\frac{\theta}{\pi}$$

where Theta, measured in radians, represents the angle between the plume axis and a line connecting the source to the site.

Population Data

1980 census data was obtained for all enumeration districts in the five county Los Angeles Basin area; Los Angeles, Orange, Riverside, San Bernardino, and Ventura Counties. In these five counties, a total of 10,370 enumeration districts represent 11.5 million people. For each enumeration district, the population count is associated with a representative geographic point location.

COMPUTER MODELLING

A computer program was developed to determine the overall risk of exposure, from aggregated information collected during the first six steps of the risk assessment methodology. Program "Plume" was designed to take the collected data as input, and output the number of people exposed to hazardous chemicals in a given earthquake event.

A probabilistic approach was used to develop Program "Plume". The general procedure used to calculate population exposure at a given site from a given hazardous materials source, for a given earthquake event is as follows:

1) Based on the ground shaking intensity (MMI) at the hazardous materials source, calculate the probability of failure in each failure mode for each facility component. Also note the resultant plume size if failure occurs in each component.

2) For each population center, calculate the distance from hazardous materials source to the population site.

3) For each component at the source facility, check whether the population site could be located within the resultant plume if failure occurs.

4) If the population site is within the plume's extent, calculate the probability that the plume will form over the site.

5) Aggregate these probabilities for all components at the source to find the total probability of exposure at the population site for release at this source.

These values may be aggregated such that the total exposure of each site from all sources is produced. In our example, the exposure is further aggregated to the County level.

RESULTS

The computer analysis yielded the number of people exposed to hazardous materials in each of the five counties, as a result of each scenario earthquake. Only Los Angeles and Orange Counties were found to be affected by possible hazardous materials releases from the listed 22 sources within Los Angeles County. As a result of a Magnitude 7.0 earthquake on the Newport-Inglewood fault, 133,000 people in Los Angeles and Orange Counties would be exposed to hazardous materials released from the 22 subject sources. (1.8% of the population in Los Angeles County, and 0.03% of the people in Orange County). These 133,000 people are dispersed throughout more than 3000 enumeration districts. Of these 3000 enumeration districts, only 1% have more than 500 people affected, 90% have fewer than 100 people affected, and 40% have fewer than 10 people affected. The maximum number of people exposed at any one site is approximately 1400.

From these same sources, a total of 20,763 people would suffer exposure to hazardous materials following a M 8.3 event on the San Andreas fault. (0.3% of the population in Los Angeles County, and 0.01% of those in Orange County). The stricken population would be distributed among 2,860 enumeration districts. Of these districts, 99.9% would have fewer than 100 people affected, and 81.5% would have fewer than 10 people affected. The most affected at one site would be only 211 people.

From the smallest of the three events, the Whittier-Narrows simulation, only 6660 people (0.09% of the people in Los Angeles County, and less than 0.01% in Orange County) would be affected by the hazardous materials release. 1800 enumeration districts would be affected; 99.7% of these would have fewer than 25 people affected, and 75% would have fewer than 5 people affected. The largest number of people affected by the release in any one enumeration district is 57 people.

For the event presenting the greatest threat to population, the Newport-Inglewood event, the locations of the 20 enumeration districts with the greatest number of people affected by hazardous releases have been identified, and are plotted in relation to the potential sources in Figure 3. Each of these districts has more than 500 people affected, and the total number of people affected within these districts comprises 12% of the overall number of people affected by hazardous releases in this event.

CONCLUSIONS

The threat of hazardous materials release exists wherever hazardous materials are stored. Earthquake-induced releases are a very real possibility. Based on the 22 sources identified for this study, the most serious releases would occur not in the largest postulated earthquake, but in the earthquake causing the strongest ground shaking at the hazardous materials sources. This earthquake, the Magnitude 7.0 Newport-Inglewood event, would cause ground shaking of at least intensity VIII at all but two of the studied sources. In contrast, the M 8.3 San Andreas event causes MMI VIII or more at only 4 sites. This type of information would be useful in the planning efforts of local communities. If a community could identify those facilities likely to be in areas of strong ground shaking in postulated earthquakes representative of the local seismic hazard, they could concentrate mitigative efforts on these facilities.

One of the most serious hazardous materials threats is presented by the storage of large quantities of chlorine in areas expected to suffer strong ground shaking. Chlorine is stored in vessels as large as 90-ton rail cars, whose failure plumes can extend over 7 miles. The identification of chlorine as the more serious threat enables users to address this risk by concentrating efforts in improving performance of existing vessels, developing smaller safer vessels, or perhaps relocating storage facilities.

The failure models developed for use in this study are based on conservative assumptions regarding failure thresholds. Even with these conservative assumptions, the largest total expected population affected in any of the three scenarios is 132,000 or less than 2 percent of the total population of Los Angeles County. These estimates, however, do not include risks that may result from failure of chemical facilities in counties other than Los Angeles, or from chemicals other than ammonia or chlorine. A more complete analysis of risk must include these other facilities and chemicals.

FUTURE DIRECTIONS IN RESEARCH AND APPLICATION

There are various types of research that would make this methodology more widely applicable. Some are widely explored, such as improved seismic hazard assessments, while others are specific to this type of analysis. Possibilities for this type of research include developing an extensive library of plume patterns for a wide variety of hazardous chemicals, and developing additional chemical facility models and failure curves.

To further explore the benefits to the planning efforts of a local jurisdiction, the completion of a smaller scale, detailed risk assessment including a more extensive inventory of chemicals and sources, tied to the development of detailed response and evacuation plans, would be the next logical step in the development of this methodology.

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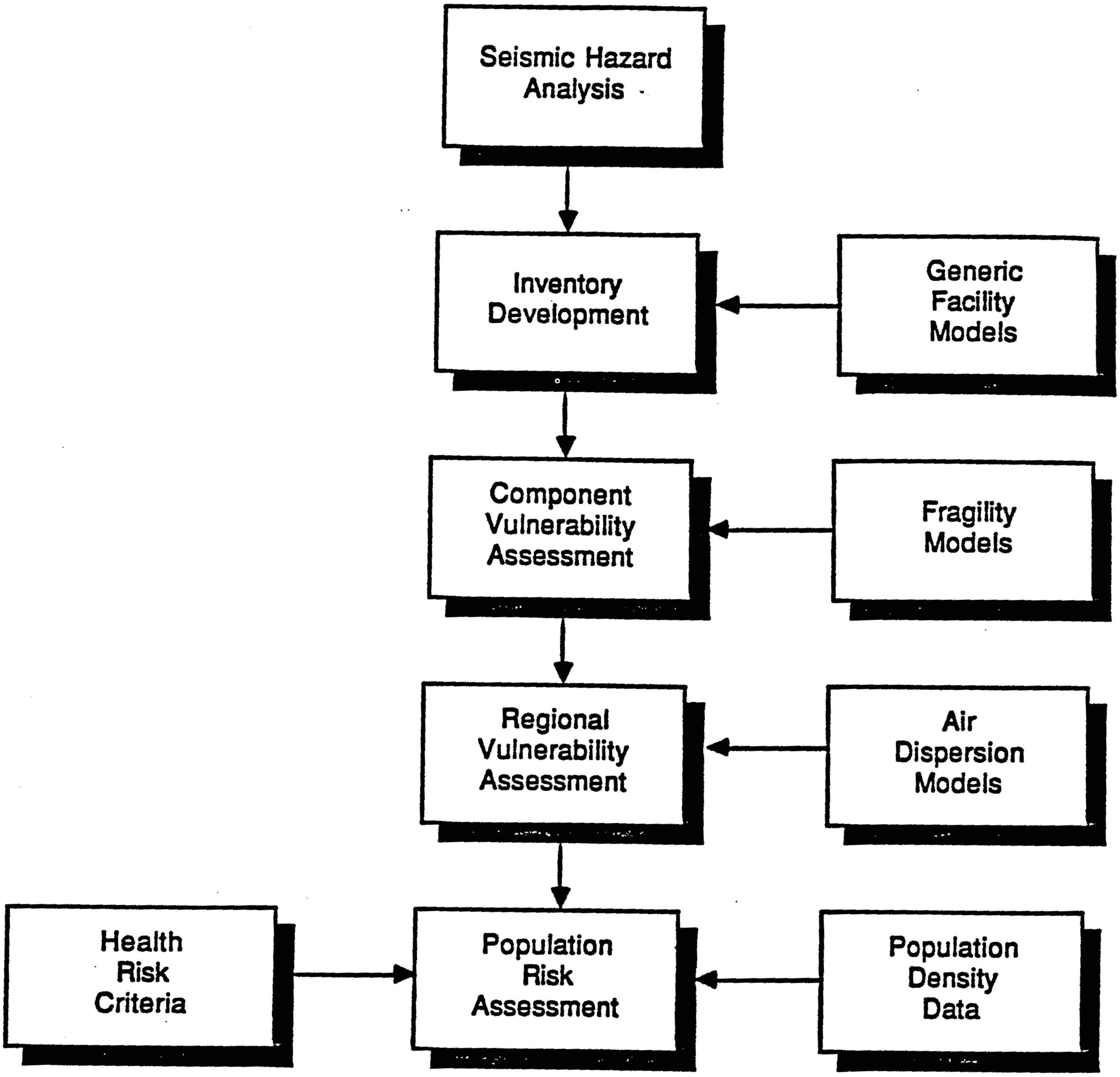
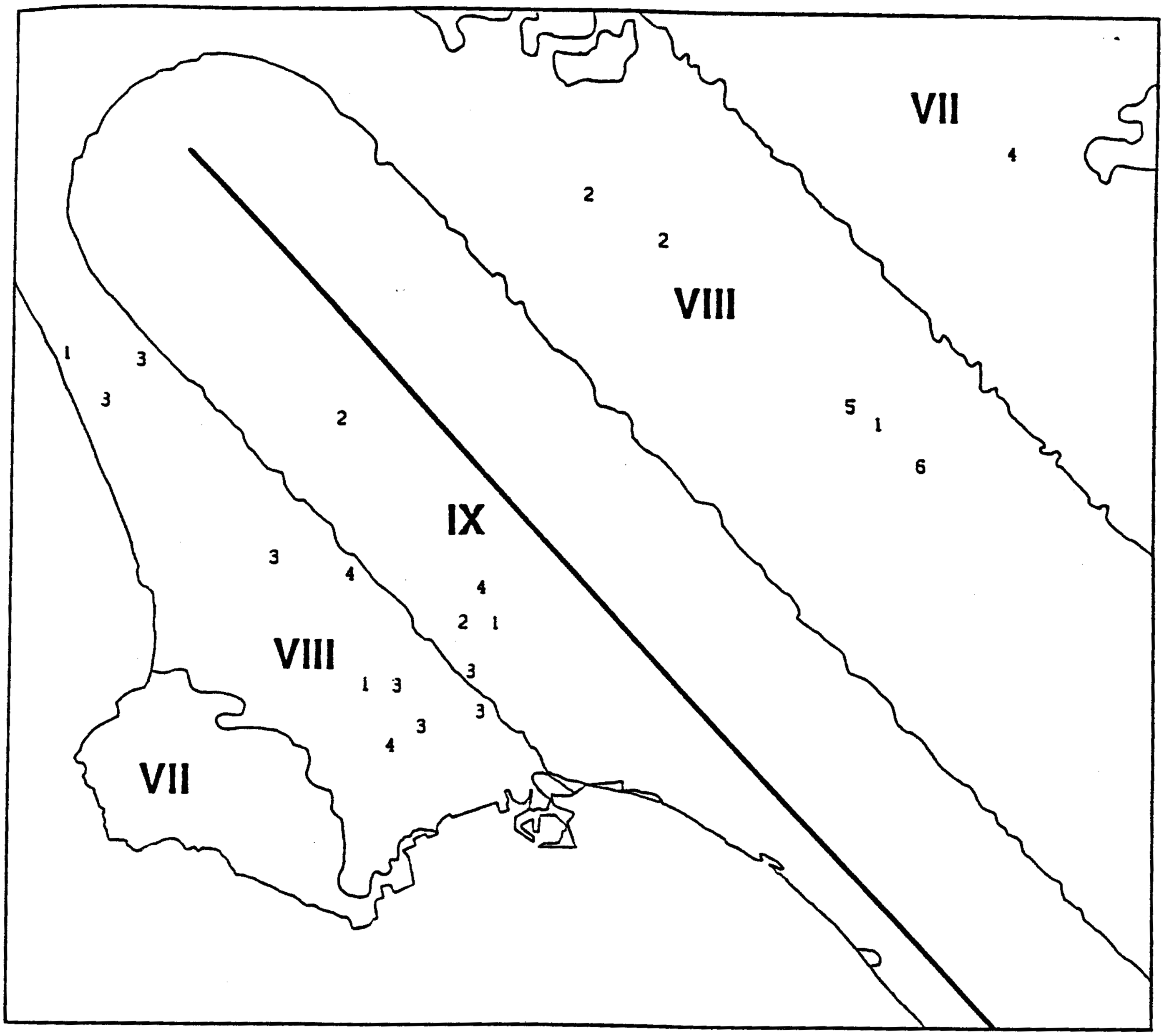


Figure 1. Methodology for Risk Assessment of Hazardous Materials Release During Earthquake



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EXPLANATION

1 Chlorine Storage

2 Chlorine Processing

3 Chlorine Storage and Ammonia Processing

4 Chlorine Storage and Ammonia storage

5 Chlorine Processing and Ammonia Storage

6 Ammonia Storage

0 4.5 9.0

SCALE IN MILES

Figure 2. Seismic Hazard Map (Modified Mercalli Intensity) for a Magnitude 7.0 Earthquake on the Newport-Inglewood Fault with Site Locations

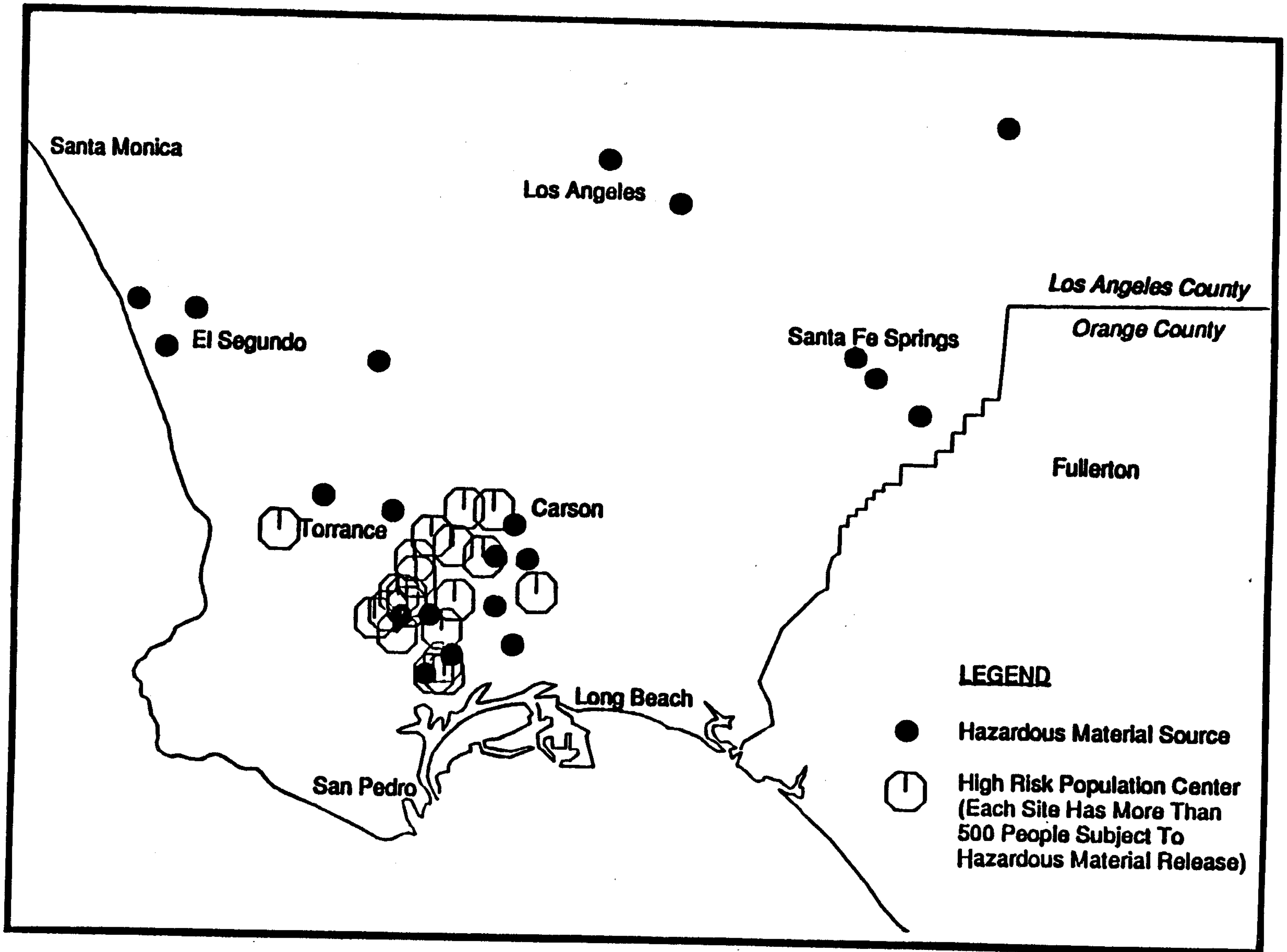

Figure 3. Population Centers with High Risk Potential from Hazardous Materials Release During a Magnitude 7.0 Earthquake on the Newport-Inglewood Fault