Tennessee, by Sharma and Kovacs of Purdue University (USGS open file report no. 80-914, a very good reference relating to this project's vulnerability analysis) shows areas within Memphis which may be susceptible to liquefaction. (Figure 2-8) This information was used by USGS to supplement its own analysis for Memphis.

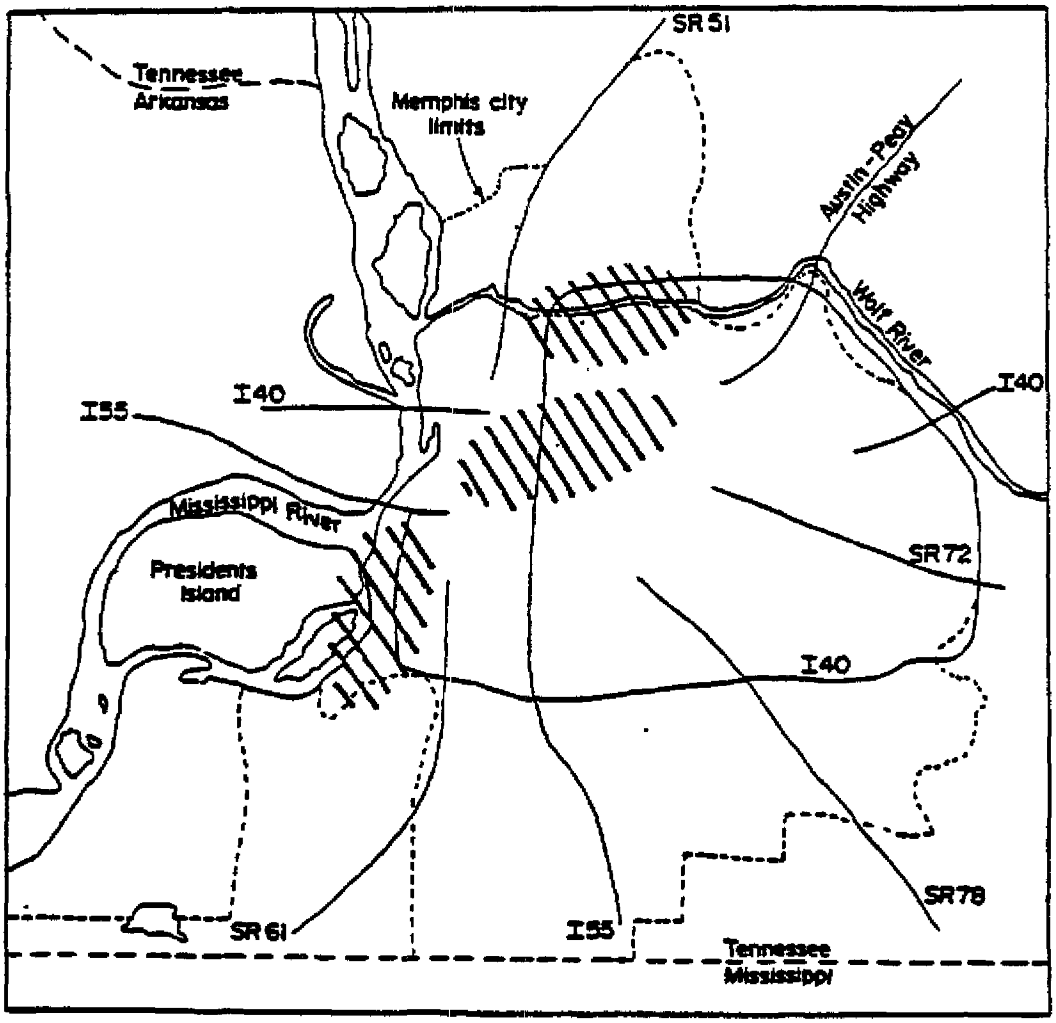
Although no similar reports exist for the other five cities, USGS compiled available relevant information to produce ground shaking and soils behavior estimates. Areas thought to be subject to adverse soils behavior were designated with higher estimates of MMI values to reflect the higher levels of structural damages expected from such conditions. As discussed later in this section, census tracts were overlaid upon these areas, within the city limits of the six cities, and an MMI level of ground shaking was assigned for each census tract.

2.3 Damage Probabilities - Fragility Curves

2.3.1 Background

Damage and failure of a structure is principally due to the shaking of the ground. In an earthquake, vibration develops in a structure, and its response level is often significantly greater than the level of shaking in the ground. For low levels of vibration, structural damage is minor or does not occur at all. At larger levels of vibration, structural damage becomes more significant and failure more likely.

The actual damage that will be inflicted on a structure by a particular level of ground shaking is uncertain because of (1) design and construction variations, (2) variability in material properties,



Shaded areas indicate zones where soils may be susceptible to liquefaction for earthquakes with Modified Mercalli Intensity greater than VII.

Liquefaction Potential microzonation map for Memphis, Tennessee

Reference 31

FIGURE 2-8

(3) uncertainty regarding precise structural response to earthquake-induced vibration, and (4) uncertainty regarding the exact level of ground shaking that will cause a structure to fail. However, it is possible to define an acceptable range of ground shaking over which structural failure can occur. Within this range, the assessment of the likelihood of failure increases from a probability of zero (i.e., no chance of failure) to a probability of one (i.e., certain failure).

The relationship which describes the probability of failure at various levels of ground shaking is known as a "fragility" curve. Fragility curves were used in this study, in conjunction with estimates of the severity of ground motion intensity, to predict the probability that a structure will fail and the degree of damage that it is likely to sustain.

2.3.2 Fragility Curve Description

A fragility curve can be used to represent failure of a specific structure, a structural system, or a generic type of structure. In this study, fragility curves were developed for 16 structure types (or structural systems) (Table 2-2). The fragility curves were prepared in two basic formats: one format which describes the probability of failure for "all" structures of a given type (e.g., all bearing wall buildings), and a second format which describes the probability of failure for "good" structures, "average" structures or "bad" structures of a given type (e.g., good bearing wall buildings, average bearing wall buildings, or bad bearing wall buildings).

For this study, if a specific structure or group of structures

TABLE 2-2
STRUCTURE TYPES

1-5/Story shear wall buildings

6/Story shear wall buildings

Bearing wall buildings

Wood frame buildings

Pre-engineered metal buildings

Tilt-up buildings

Pre-cast buildings

Electrical switchyard equipment

Emergency power units

Water/sewage plants

Power plants

Earth dams

Highway bridges

Major bridges

Cylindrical storage tanks

Elevated tanks

could be distinguished as either good (i.e., significantly better than average), average, or bad (i.e., significantly worse than average) in terms of anticipated seismic performance, then the corresponding "good", "average", or "bad" fragility curves were used to determine the likelihood of failure. On the other hand, if a structure of a given type could not be distinguished as good, average or bad in terms of anticipated seismic performance, then the "all"-structure fragility curve was used to determine the likelihood of failure.

Traditionally, fragility curves assume a structure to be in one of two possible states: completely failed or not failed. For some structure types, such as electrical switchyard equipment, this two-state modeling accurately represents observed failure patterns. However, for most structures, and especially buildings, damage is observed to occur in varying degrees from no damage to collapse.

To describe multiple damage states for buildings (and other structure types), fragility curves were developed for this study which quantify the probability of reaching one of five damage states: nonstructural, slight structural, moderate structural, severe structural and collapse. These five damage states are described in Table 2-3. For non-building structures such as bridges, tanks, etc., only the moderate structural, severe structural and collapse damage states were used since nonstructural and slight structural damage, where system usage is not impaired, is not of interest to this study. As mentioned previously, for structures such as electrical switchyard equipment, which respond with either no damage or complete failure, a single damage state (i.e., collapse) was used.

TABLE 2-3
DAMAGE CATEGORIES

Response Level		Damage Category	Extent of Damage in General	Suggested Post-Earthquake Actions
Required	0	No Damage	No Damage	No Action
Elastic	I	Slight Non-structural Damage	Thin cracks in plaster, falling of plaster bits in limited parts.	Building need not be vacated. Only architectural repairs needed.
Inelastic (yielding of some elements)	II	Slight Structural Damage	Small cracks, in walls, falling of plaster in large bits over large areas; damage to non-structural parts like chimneys, projecting cornices, etc. The load carrying capacity of the structure is not reduced appreciably.	Building need not be vacated. Architectural repairs required to to achieve durability.
Inelastic (general yielding)	III	Moderate Structural Damage	Large deep cracks in walls; widespread crack of walls, columns, piers and tilting or falling of chimneys. The load carrying capacity of the structure is partially reduced.	Building needs to be vacated, to be reoccupied after restoration and strengthening. Structural restoration and seismic strenthening are necessary after which architectural treatment may be carried out.
Inelastic (ultimate yielding of some main elements)	IV	Severe Structural Damage	Gaps occur in walls; inner or outer walls collapse; failure of ties to separate parts of buildings. Approximately 50% of the main structural elements fail. The building takes a dangerous state.	Building has to be vacated. Either the building has to be demolished or extensive restoration and strengthening work has to be carried out before reoccupation.
Inelastic (ultimate yielding of all main elements)	V	Collapse	A large part of whole of the building collapses.	Clearing the site and reconstruction.

2.3.3 Fragility Curve Development

The fragility curves were based on combining calculations, engineering judgement, and damage data from past earthquakes. A detailed description of the procedures, assumptions, sources of damage data, etc., which were used to determine the fragility curve for each structural type, is given separately in Appendix A. A brief summary of the process is described below.

In essence, two separate approaches, one based on calculations and one based on damage data, were used to determine the fragility parameters for each curve. The first approach relied upon calculations (and engineering judgements) to develop fragility parameters for specific geometrics, materials, etc. which were deemed to best represent the characteristics of structures found in the Mississippi Valley region. The second approach relied upon the analysis of damage data from past earthquakes. Damage data was taken directly from survey reports of specific earthquakes (e.g., the 1964 Alaska Earthquake, the 1971 San Fernando, CA, Earthquake, and the 1979 Imperial Valley, CA, Earthquake) or extracted from damage studies by others. The two approaches were conducted in parallel and composite fragility parameters were developed by subjective weighing and combination of the individual results. In this manner, the fragility curves represent structures specific to the Mississippi Valley, but calibrated by the general patterns of observed earthquake damage.

2.3.4 Fragility Curve Illustration

Figures 2-9 and 2-10 exemplify the fragility curves developed for this vulnerability analysis. Figure 2-9 contains "all" structure

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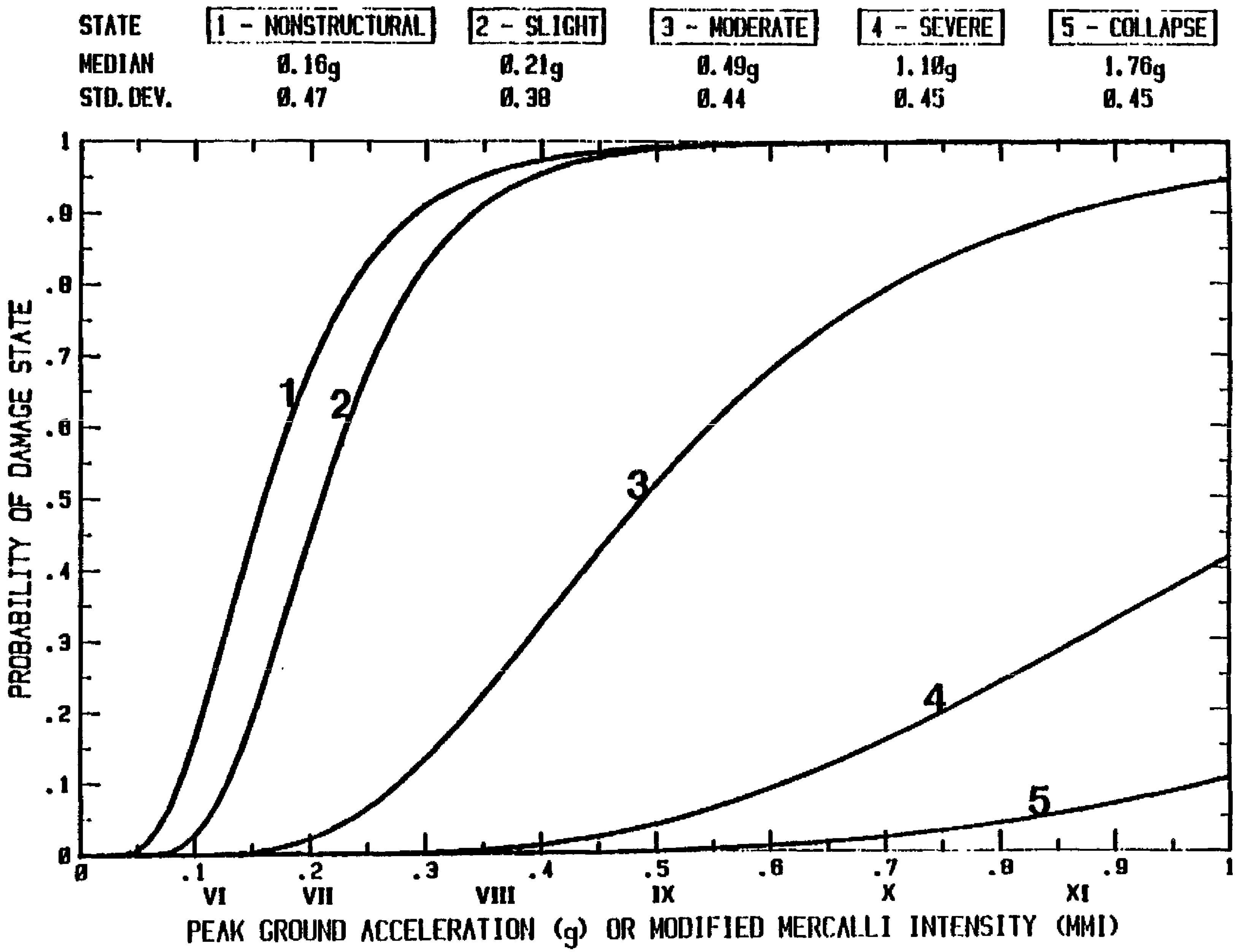
fragility curves for wood frame buildings while Figure 2-10 depicts "good"-, "average"- and "bad"-structure fragility curves, also for wood frame buildings. For each damage state in Figure 2-10, a shaded region between upper- and lower-bounds is used to represent the range of possible fragility values for "good" to "bad" wood frame buildings.

The meaning of the fragility curves may be illustrated by examining values extracted from the slight structural damage fragility curve shown in Figure 2-9.

For an earthquake intensity of MMI VI, it is almost certain that only nonstructural damage would occur to a typical wood frame building. Therefore, the probability of slight structural or greater damage at MMI VI is approximately 0.0. For an earthquake intensity of MMI XII, it is almost certain that structural damage to a wood frame building would be at least slight. Therefore, the probability of slight damage at MMI XII is approximately 1.0. At intermediate earthquake intensities, the probability of at least slight damage is greater than 0.0 and less than 1.0. As another example, at MMI VII, the probability of at least slight damage is 0.45. This means that if a wood frame building is subjected to an MMI VII 100 times, it is expected that slight structural, or greater, damage would occur on 45 of those occasions. From another viewpoint, if one had 100 wood frame buildings of unknown quality that were all subjected to an MMI VII, then one might reasonably expect that 45 of the buildings would suffer at least slight structural damage.

At any given level of intensity each fragility curve provides a relative measure of the likelihood of reaching or exceeding each

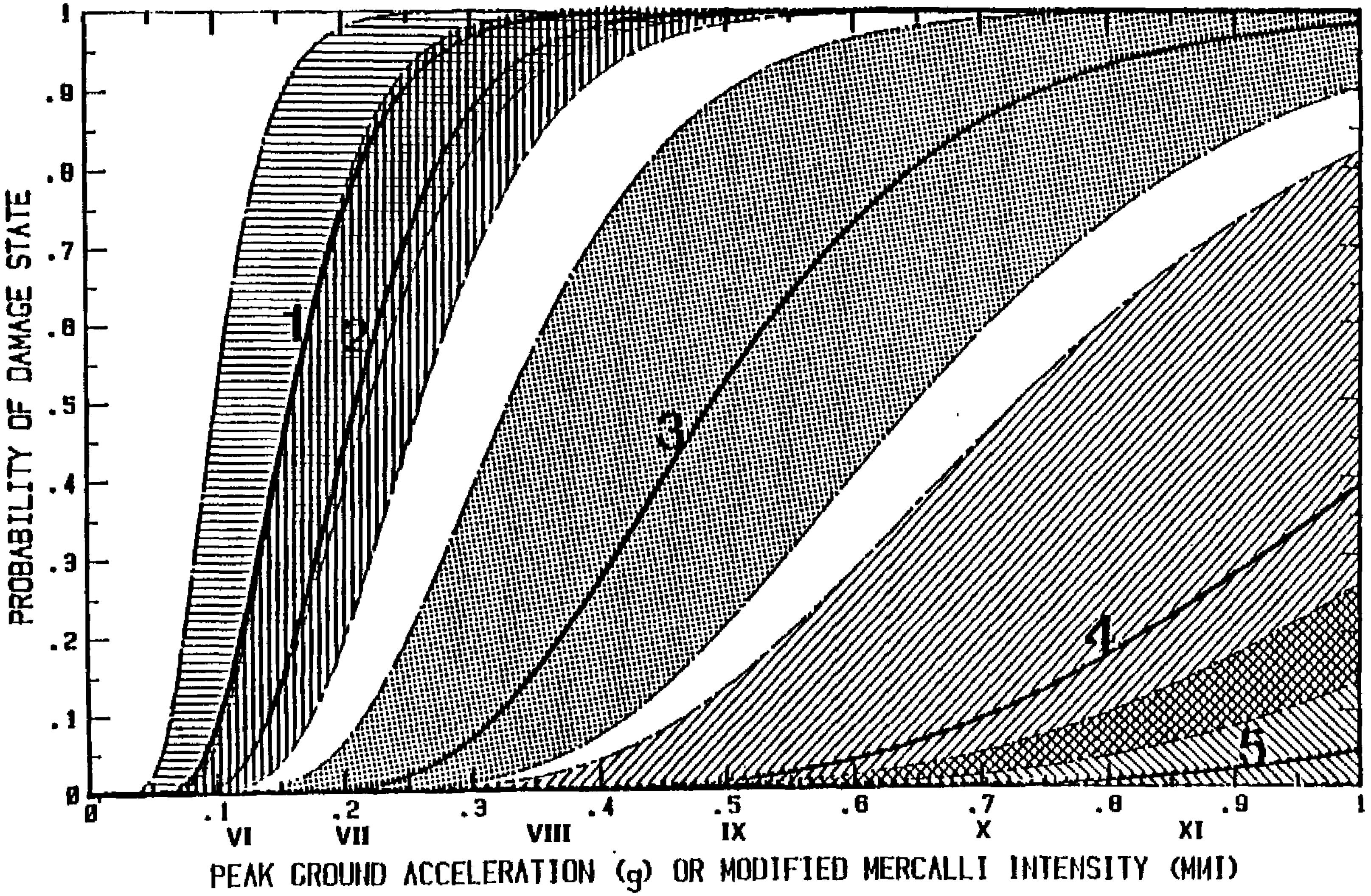


STATE	1 - NONSTRUCTURAL	2 - SLIGHT	3 - MODERATE	4 - SEVERE	5 - COLLAPSE
MEDIAN	0.16g	0.21g	0.49g	1.10g	1.76g
STD. DEV.	0.47	0.38	0.44	0.45	0.45

STRUCTURE TYPE : ALL WOOD FRAME BUILDINGS

FIGURE 2-9

STATE	1 - NONSTRUCTURAL	SLIGHT	3 - MODERATE	4 - SEVERE	5 - COLLAPSE
MEDIAN	0.16g	0.21g	0.49g	1.10g	1.76g
RANGE	0.10-0.22g	0.16-0.26g	0.33-0.65g	0.73-1.45g	1.24-2.49g
STD.DEV.	0.34	0.31	0.33	0.34	0.34



STRUCTURE TYPE : MEDIAN, UPPER AND LOWER BOUND WOOD FRAME BUILDINGS

FIGURE 2-10

damage category (i.e., likelihood of moderate structural damage is greater than that of severe structural damage, likelihood of slight structural damage is greater than that of moderate structural damage, etc.). For example, a wood frame building of unknown quality (i.e., Figure 2-9) and earthquake intensity MMI VIII, has a:

0.95 probability of at least nonstructural damage,
0.91 probability of at least slight structural damage,
0.23 probability of at least moderate structural damage,
0.01 probability of at least severe structural damage,
0.00 probability of collapse.

The nature of the information contained in the "good"-, "average"-, and "bad"-structure fragility curves is the same as the "all"-structure fragility curves, except a range of values, rather than a single value, is given for each damage state. For example, a wood frame building of known quality (i.e., Figure 2-10) and subjected to an earthquake intensity of MMI VIII, has:

0.60 probability of at least moderate damage, if it is a "bad" wood frame building,
0.16 probability of at least moderate damage, if it is an "average" wood frame building,
0.03 probability of at least moderate damage, if it is a "good" wood frame building.

A range of values was used for each damage category in order that the structure's quality, if known, could be used in the assessment of vulnerability to damages.

2.3.5 Comparison of Fragility Curves' Probabilities and Coalinga Damage Data

On May 2, 1983, at 4:42 p.m. a moderate (Ms = 6.5) earthquake struck near Coalinga, California. The duration of strong shaking was about 10 to 15 seconds. Intensity was between MMI VII and MMI IX.

This event is of particular relevance to the Mississippi Valley earthquake impact study, since many of the older masonry and wood frame buildings of Coalinga are similar in design to buildings found in the Mississippi Valley. That is, these structures were not designed for seismic forces. As a result of the Coalinga event, most older structures, which lacked adequate seismic design, were severely damaged or collapsed. In fact, damage to the older buildings in the center of the town was so severe that the entire area was eventually razed.

Immediately following the Coalinga earthquake, the Earthquake Engineering Research Institute dispatched a reconnaissance team under the leadership of Prof. Haresh Shah of Stanford University to survey the damage. The results of the team's preliminary survey of 139 buildings are given in Tables 2-4 and 2-5 and are derived directly from the preliminary report on damage to the Coalinga commercial district[1]. The pertinent damage ratios given in Table 2-4 for bearing wall (masonry) and wood frame structures were extracted from this table, expressed in a cumulative form and compared to the corresponding fragility curve probability. Table 2-4 and Table 2-5 show this comparison for bearing wall and wood frame buildings,

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[1]. Shah, h.c., et al., "Preliminary Survey of Damage to the Commercial District" Coalinga Earthquake of May 2, 1983, "Earthquake Engineering Research Institute Reconnaissance Report, May 5, 1983.

TABLE 2-4
COMPARISON OF COALINGA DAMAGE FRACTIONS AND FRAGILITY CURVE PROBABILITIES FOR BEARING WALL BUILDINGS

Structure Description	Damage State	Observed Damage[1] Coalinga		Fragility Curve Probability[2]	
		Damage Ratio Range	Fraction Damaged	MMI=VIII	MMI=IX
"Bad" Bearing Wall (40 old or poorly constr., unreinforced masonry buildings)	Collapse	60-100%	0.75	0.75	0.92
	Severe	30-100%	0.93	0.93	0.98
	Moderate	10-100%	1.00	1.00	1.00
	Slight	0-100%	1.00	1.00	1.00
"Good" Bearing Wall (31 newer brick - or reinforced masonry buildings)	Collapse	60-100%	0.06	0.02	0.06
	Severe	30-100%	0.10	0.05	0.19
	Moderate	10-100%	0.39	0.55	0.84
	Slight	0-100%	1.00	0.82	0.95
"All" Bearing Wall (total population of 71 buildings)	Collapse	60-100%	0.45	0.28	0.45
	Severe	30-100%	0.56	0.41	0.59
	Moderate	10-100%	0.73	0.85	0.95
	Slight	0-100%	1.00	0.96	0.99

[1] Data taken from Shah etal.

[2] Probabilities are taken from Bearing Wall fragility curves (Appendix A).

TABLE 2-5
COMPARISON OF COALINGA DAMAGE FRACTIONS AND FRAGILITY CURVE PROBABILITIES FOR WOOD FRAME BUILDINGS

		Observed Damage Coalinga[1]		Fragility Curve Probability[2]	
Structure Description	Damage State	Damage Ratio Range	Fraction Damaged	MMI=IX	MMI=X
"Bad" Wood Frame (33 older residences on cripple walls)	Collapse	60-100%	0.00	0.00	0.00
	Severe	30-100%	0.52[3]	0.02	0.13
	Moderate	10-100%	0.88	0.60	0.90
	Slight	0-100%	1.00	0.99	1.00
"Good" Wood Frame (28 newer, commercial buildings	Collapse	60-100%	0.00[4]	0.00	0.00
	Severe	30-100%	0.04	0.00	0.00
	Moderate	10-100%	0.14	0.03	0.22
	Slight	0-100%	1.00	0.85	0.98
"All" Wood Frame (total population of 61 buildings)	Collapse	60-100%	0.00[4]	0.00	0.00
	Severe	30-100%	0.30[3]	0.01	0.04
	Moderate	10-100%	0.54	0.23	0.52
	Slight	0-100%	1.00	0.91	0.98

[1] From Shah et al.

[2] Probabilities are taken from Wood Frame Building fragility curves (Appendix A).

[3] Although often a total loss (i.e., 60-100% damage), no wood frame structures collapsed. Therefore, these structures are considered to be severely damaged.

[4] The building which collapsed due to collapse of a neighboring masonry building is excluded from the sample population.

respectively. The conclusions reached are discussed below.

In general, very good agreement is found between the fraction of bearing wall or wood frame buildings which were observed to have suffered a particular level of damage and the probability of reaching that damage level which is given by the appropriate fragility curve. For instance, identical values were found for the damage experienced by old or poorly constructed, unreinforced masonry buildings and the probabilities predicted by the "bad" bearing wall fragility curves at MMI VIII. This close agreement between observed damage and predicted value is particularly significant, since this structure type (i.e., unreinforced masonry) is very common to the Mississippi Valley and, therefore, figures dominantly in this earthquake vulnerability assessment.

2.4 Estimates of Structural Damages

The estimation of damage to structures and systems within the six cities was performed utilizing a variety of approaches. Major factors in determining the approach for a particular analysis were the type and level of detail desired, and the quantity, quality and availability of the information required to perform the selected analysis.

2.4.1. Damage Estimates for Buildings and other Structures

Damage estimates served three basic purposes in this study. The first was to support casualty estimation. The methodology for this work, described in sub-section 2.5, uses the determined damage state for a structural category to provide a basis for estimating the exposure of individuals to risk of death or injury requiring hospitalization. A second use of damage estimates was to project the probable availability of structures or systems, such as highway and rail bridges, and of "critical facilities" (i.e., hospitals, electric substations, etc.). The third was the estimation of restoration and replacement costs.

This study relied heavily upon fragility curves for estimating damage to structures. This methodology was discussed earlier in subsection 2.3. The application of fragility curves to structures is appropriate to the goals and requirements of this study and was invoked for virtually all estimates performed for the numerous categories of structures examined.

Damage estimates were performed using fragility curves whenever possible. In addition, some analyzed items (such as utility distribution networks) required subjective assessments for their investigations. These damage assessments utilized, in addition to fragility curve assessments, the subjective judgement of subject matter experts (experienced engineers and architects practicing in the study area) to obtain vulnerability.

2.4.2 Damage Estimates for Highways and Railways

The primary objective of the damage assessment for highways and railways was to determine the likelihood that major land transportation routes would be available for emergency response. A second objective was to estimate the probable extent of overall damage to highway and railway structures.

To determine probable route availability, the highway and railway networks in the six study areas were divided into sections, and a survival probability was calculated for each section. A section of highway or railway was defined as a link in the network of major routes, such that each section began and ended at a juncture with a section of another major route. Survival after an earthquake was defined as the absence of structural damage which would render a section impassable. Damage that would make a section impassable was defined to include severe damage to or collapse of supporting structures and the collapse of overpassing structures.

The damage assessment was limited to structural damages that would be caused by ground shaking. In some areas of poor soils, however, damages to roadbeds, pavements and railroad tracks could also be incurred as a consequence of liquefaction, landslides or other ground failure. Probable damages of the latter type could not be assessed, since sufficiently detailed data on soil conditions were not available. Nevertheless, for emergency planning purposes, it should be assumed that roads and railroads along river banks and on alluvial deposits in the areas of highest earthquake intensity would very likely suffer damages to roadbeds and pavements or tracks as a result of ground failure.

Data Gathering and Processing

Bridge inventory data were obtained from the FEMA resource data base for highway bridges and from data provided by railroad companies. In some cases, supplemental data were requested and obtained directly from state highway & railroad departments. Because of the large number of structures involved and because the data were only for the major highway and railway routes in the six cities, the analyses were limited to those major routes. For a few major routes for which inventory data were not available, bridge locations were determined to the extent possible from maps that were available.

The inventories included supporting structures as well as overpassing structures for each highway route and rail line. The overpassing structures were identified as supporting either a highway or a railway. Pedestrian overpasses were not included in the analysis.

The highway and railway inventory data for each of the six cities were entered into data files using a microcomputer data base management package. Prior to data entry, each structure was located on a route map to help ensure that the data base was complete. The structures in each file were sorted by route and ordered by milepoint to facilitate the division of routes into sections and the identification of the structures in each section. In general, section limits were set at the intersections of the routes included in the analysis and at city and county corporate limits. In a few cases, sections were terminated at an intersection with a route not included in the study.

In the highway networks, when routes did not intersect at grade (i.e., when one route passed over or under another and a structure was located at the intersection), the structure at the intersection was assigned to only one of the two sections terminating on the structure and to only one of the two sections terminating under the structure. In such cases, the survival probabilities of the intersecting sections to which the structure was not assigned may have been somewhat overstated.

Entry and exit ramp structures were taken into account as appropriate in each case as overpassing structures and/or as supporting structures, when permitted by the available data.

However, the data were not sufficiently detailed to permit a determination of whether nor not a damaged structure at an intersection could be bypassed via entry and exit ramps (whether supported on structures or not).

For each of the six cities, the damage assessment was carried out for the entire county in which the city is located, since probable access to a distressed area from the outside is as important as probable mobility within the area for purposes of emergency response. Since areas in the counties were not covered by the hypothetical intensity estimates provided by the USGS for the six cities, intensities were estimated on the basis of the county-wide mapping which was provided (See Fig. 2-5). In general, the prevailing intensity in each city was assumed, except in areas adjacent to locations where the USGS had identified poor soil conditions. Although perhaps not as reliable as the USGS estimates of intensity within the city limits, the extended estimates were necessary for the damage assessments in the county-wide transportation networks.

Classification of Highway and Railroad Bridges

The vulnerability of a bridge to damage from ground shaking is considered to be a function primarily of the number, height and length of spans and of the material and type of construction. For example, single-span steel structures can generally be expected to suffer much less damage than multi-span precast concrete structures. Seismic resistance is usually greater in continuous structures and in those consisting of spans connected across supporting piers than in structures in which the individual spans are not tied together.

Two fragility curves were provided for bridges: one for typical highway bridges and one for major bridges (such as high structures over wide water ways). To apply the fragility curve methodology, bridge classification schemes based on structural characteristics were developed for highway and railway bridges. Five categories were defined for classifying bridge structures according to their ability to resist earthquake damage: good, better-than-average, average, below average and poor. The classification schemes are explained in Tables 2-6 and 2-7.

The same fragility curves were applied to both highway and railway briges, except that railway bridges were considered to be more resistant than highway bridges for a given type of structure, since they carry less dead load. To account for this difference, railway bridges were classified one category higher (more resistant to damage) than highway bridges with similar structural characteristics.

Using the tables referenced above and the structural characteristics contained in the inventory data, each bridge in each section of highway and railway was classified according to its ability to resist earthquake damage.

Damage Probabilities

For each of the five categories of bridges, the probability of severe structural damage and the probability of collapse at each level of intensity were determined from the fragility curves for the typical highway bridges and the major bridges. The damage probabilities for average structures were taken from the median curves, those for the good and poor structures from the lower and

TABLE 2 - 6
HIGHWAY BRIDGE CLASSIFICATION SCHEME

Type of Construction	Number of Spans[1] (Main & Approach)	Average Span Length[2] (feet)	Classification (Ability to Resist Earthquake damage)[3]
Concrete - arch, culvert, etc.	-	30	Good
	-	30	Avg
Concrete - continuous	-	-	Avg
Concrete - other	2	-	Avg
	2	-	Avg-
Prestressed concrete - continuous	-	-	Avg
Prestressed concrete - other	2	-	Avg-
	2	-	Bad
Steel - movable span	2	-	Bad
Steel - continuous	-	60	Good
	-	60	Avg+
Steel - other	1	60	Good
	1	60	Avg+
	1	-	Avg
Timber	2	-	Avg-
	2	-	Bad

1. The number of approach spans was not provided in the data. If an approach type was indicated, two spans were added to the number of main spans.

2. If one span length was more than 180 feet, the classification was reduced by one category (i.e., Avg became Avg-, etc.).

3. If the data were insufficient, bridges were classified as Avg.

TABLE 2 - 7
RAILWAY BRIDGE CLASSIFICATION SCHEME

Type of Construction	Number of Spans (Main & Approach)	Average Span Length (feet)[1]	Classification (Ability to Resist Earthquake Damage)[2]
Unspecified arch, box, culvert, etc.	-	-	Avg+
Unspecified trestle	-	50(total)	Good
		50(total)	Avg+
Concrete - arch, box, culvert, etc.	-	-	Good
Concrete - continuous	-	-	Avg+
Concrete - reinforced	-	-	Avg+
Concret - other	2	-	Avg+
	2	-	Avg
Prestressed concrete - continuous	-	-	Avg+
Prestressed concrete - other	2	-	Avg
	2	-	Avg-
Steel or nonspecified-movable span	-	-	Bad
Steel - trestle	-	-	Good
Steel - continuous	-	-	Good
Steel - other	1	-	Good
	1	-	Avg+
Timer - trestle	-	50(total)	Good
	-	50(total)	Avg+
Timber - other	2	-	Avg
	2	-	Avg-
Masonry (stone, brick)	-	-	Avg

1. If span length was more than 180 feet, the classification was reduced by one category (i.e., Avg became Avg-, etc.).

2. If height was greater than 60 feet, the classification was reduced by one category. If the data were insufficient, bridges were classified as Avg.

upper bound curves, respectively, and those for the better-than-average and below average structures from points halfway between the median curve and the lower and upper bound curves, respectively. The damage probabilities for both severe damage and collapse are shown for the typical highway bridges and for the major bridges in Tables 2 - 8 and 2 - 9.

When determined for individual bridges, the damage probabilities are characterized by a very high level of uncertainty. They should not be used to derive definitive estimates of damage for individual structures. They were developed primarily for the preparation of damage estimates for groups of structures, such as those which are located in a section of highway or railway, to facilitate a reliable estimate of the probability that an entire section would be available for use after a major earthquake. The estimates are much more reliable in the aggregate than for individual structures.

The damage probabilities reflected in the fragility curves for the major bridges were based primarily on the structural characteristics of the main spans of such bridges. However, it was determined that the approaches to the major bridges, which are better described by the typical highway bridge curves, would usually have a greater likelihood of failure than would the main spans themselves. In such cases, even though the main span survived an earthquake, the bridge could still be made unusable because of damage to the more vulnerable approach spans. When the probability of approach structure damage exceeded the probability of damage to the main structure, the former was taken as the relevant damage probability for the major bridge in question.

TABLE 2 - 8
PROBABILITIES OF SEVERE STRUCTURAL DAMAGE AND COLLAPSE FOR TYPICAL HIGHWAY AND RAILWAY BRIDGES

Bridge Classification	Modified Mercalli Intensity (MMI) V	VI	VII	VIII	IX	X
	Probability of Severe Structural Damage					
Good	0.00	0.00	0.00	0.02	0.14	0.40
Avg+	0.00	0.00	0.00	0.03	0.22	0.51
Avg	0.00	0.00	0.01	0.05	0.31	0.63
Avg-	0.00	0.00	0.03	0.25	0.57	0.79
Bad	0.00	0.01	0.05	0.45	0.84	0.96
	Probability of Collapse					
Good	0.00	0.00	0.00	0.00	0.02	0.09
Avg+	0.00	0.00	0.00	0.01	0.06	0.19
Avg	0.00	0.00	0.00	0.02	0.11	0.30
Avg-	0.00	0.00	0.02	0.19	0.42	0.60
Bad	0.00	0.00	0.04	0.37	0.73	0.91

Source: Fragility curve for "Median, Upper and Lower Bound Highway Bridges". The probabilities for each intensity are taken at the midpoint of the corresponding PGA interval shown in Table A.2-2.

TABLE 2 - 9
PROBABILITIES OF SEVERE STRUCTURAL DAMAGE AND COLLAPSE FOR TYPICAL HIGHWAY AND RAILWAY BRIDGES

Bridge Classification	Modified Mercalli Intensity (MMI) V	VI	VII	VIII	IX	X
		Probability of Severe Structural Damage				
Good	0.00	0.00	0.02	0.09	0.23	0.37
Avg+	0.00	0.00	0.02	0.09	0.23	0.37
Avg	0.00	0.00	0.02	0.09	0.23	0.37
Avg-	0.00	0.00	0.05	0.16	0.33	0.49
Bad	0.00	0.01	0.07	0.23	0.43	0.60
		Probability of Collapse				
Good	0.00	0.00	0.00	0.01	0.05	0.11
Avg+	0.00	0.00	0.00	0.02	0.09	0.17
Avg	0.00	0.00	0.01	0.04	0.13	0.22
Avg-	0.00	0.00	0.01	0.06	0.16	0.27
Bad	0.00	0.00	0.02	0.07	0.19	0.32

Source: Fragility curve for "Median, Upper and Lower Bound Highway Bridges". The probabilities for each intensity are taken at the midpoint of the corresponding PGA interval shown in Table A.2-2.

Two types of damage were considered: severe structural damage to or the collapse of structures supporting a highway or railway, and the collapse of structures passing over a highway or railway. Either event would render a section of highway or railway impassable at the point at which it occurred. However, a distinction should be made between the consequences of fallen overhead structures and those of damaged or collapsed support structures. In general, experience has shown that the former could reasonably be cleared within one or two weeks after an earthquake by mobilizing heavy euqipment to the site, breaking up the fallen spans or pieces and removing them from the roadway or railway. In comparison, the replacement of severely damaged or collapsed support structures could easily take several months.

Calculation of Section Survival Probabilities

The first step in the calculation of survival probabilities for the different sections of highway and railway was to determine damage probabilities for each bridge structure in the sections. For each of the two postulated earthquakes, the probability of severe damage or collapse was obtained for each supporting structure in each section, and the probability of collapse was obtained for each overpass in each section. These probabilities were taken from Table 2 - 8 or 2 - 9 based on the expected intensity of ground shaking and the classification of the structure with respect to its ability to resist earthquake damage, as described above.

The next step, for each of the two earthquakes, was to calculate the probability that each individual structure would survive the earthquake (i.e., that it would incur no damage that would cause the section it supported or passed over to be unusable). In the case of pairs of parallel structures supporting a route, as are often found on highways with dual roadways and railways with double track, the survival of the pair was defined as the continued availability or survival of at least one of the two members of the pair. More than two parallel railway structures supporting a section were treated as a pair of structures. Pairs of structures passing over a route were treated as two separate structures. The survival probabilites were calculated as follows:

Type of structure	P(Survival)
Single supporting	1 - P(severe damage or collapse)
Parallel supporting pair	1 - P(severe damage or collapse of one)x P(severe damage or collapse of other)
Overpassing	1 - P(collapse)

To determine the probability that a section would survive, each structure in the section was assumed to respond to the earthquake independently of the response of the other structures in the section (i.e., statistically independent events were assumed). Each section's survival probability was then calculated as the product of the survival probabilities of all the individual structures and pairs of structures in the section. Survival probabilities were calculated in this manner for each section of highway and railway for each of the two scenario earthquakes, and the results were keyed to diagrams of the highway and railway networks in the six counties included in the study.

Presentation and Interpretation of Results

The survival probabilities calculated for the different highway and railway sections indicate the relative likelihood that the sections would be available for use after the postulated earthquakes. A survival probability of 1.0 would indicate that a section would be expected to survive an earthquake with the highest possible degree of certainty (within the limits of the analytical procedure and data used), while a survival probability of 0.0 would indicate just the opposite -- that a section would be expected with the highest possible degree of a certainty not to be passable after the earthquake.

In the traditional use of probability information, a probability of, say, 0.3 (or 30%) would indicate that a particular outcome would be expected to occur three times in ten opportunities. Applied to earthquake damage estimation, a somewhat different interpretation is appropriate, since earthquakes, being rather rare events, do not occur with sufficient frequency to make such a statement meaningful. In the present analysis, the survival probabilities should be interpreted in the aggregate. If ten sections each had a survival probability of 0.3, for example, then three of those ten sections would be expected to be available for use following an earthquake while seven would most likely be unavailable. If all sections in a city had a probability of survival of 0.5, it would be concluded that half of them would probably not be passable. It would not be possible, however, to indicate which of the sections would survive and which would not.

In the analysis of damages in an individual highway or railway network, the connectivity of the network (i.e., the numbers of sections in series and in parallel and the connections among them) is an important factor in determining how mobility and access in the network would be affected. A thorough analysis of accessibility and route availability would require that all combinations of origins and destinations of interest be specified and that the survival probabilities of all possible routes between them be determined. An alternate approach would be to simulate damages in the networks based on the probabilities of survival estimated for each section or each structure. Those approaches were beyond the scope of the present study. An attempt was made, however, to provide some indication of how mobility in the networks might be affected.

In the highway and railway network diagrams presented with the results of the analyses for the individual cities, four categories of sections are highlighted: those with survival probabilities between 0.0 and 0.25 and between 0.26 and 0.50 for an Ms=7.6 earthquake, and those with survival probabilities between 0.51 and 0.75 and between 0.76 and 1.0 for an Ms=8.6 magnitude earthquake. Sections in the former two groups (which did not occur in all cases) would be the most likely to be unusable, while those in the latter two would be the most likely to survive an earthquake. The maps provide a visual indication of the possible effects in the networks.

The section survival probabilities and the network diagrams can be used to formulate post-earthquake strategies for the movement of goods and people as well as to indicate the areas in which preparedness planning efforts should be concentrated.

As stated above, the analyses were limited to sections of major routes for which bridge data were available. Possible detours via lower category parallel routes were not considered. It should be noted, however, that even though a major route was impassable, detours via slower or lower capacity minor routes could still be available.

2.4.3 Damage Estimates for River Ports

Available information describing river port facilities in the six cities was assembled and evaluated with respect to their availability following an occurrence of either earthquake scenario.

A key factor in the damage which these facilities can be expected to sustain is their location, i.e., they are located along the bank areas of rivers. Subsurface foundation conditions in these regions are considered to be comparatively poor. Such soils are likely, due to type and high degree of saturation, to be prone to liquefaction, differential settling, slumping and sliding. These factors, combined with fragility curve application of the structures present, were used to estimate the damage to and availability of these potentially important transportation links.

A detailed discussion of these facilities is found in the general part of Section 3; discussions for the individual cities follow in the appropriate sections.

2.4.4 Damage Estimates for Airports

A combination of fragility curve application and system-specific expertise were used to assess availability of major commercial airport facilities, civilian and military, serving the six cities. Minor airports, though addressed in the general discussions portion of Section 3, were not investigated in detail. Airports were inspected by contractor field teams and the overall vulnerability of their facilities, especially of runways, was estimated by practicing professionals in airfield design.

2.4.5 Damage Estimates for Utility Systems (Electric, Water, Gas, Sewer)

General and city-specific aspects for each of these utility systems were identified and studied under the assumed estimates of ground shaking, soils failure and existing system structural features. Since utility systems are generally a chain of components, "weak link" vulnerability assessment was performed to identify and acknowledge the importance of utility-and system-specific failure prone elements. For example, the electric substation components (notable among these being porcelain insulators) typically found in the study area are especially vulnerable to earthquake induced failure. Loss of these stations cripples or inactivates an electric system. These known weak links, added to estimated additional damage to local distribution networks, generating facilities and overland long distance transmission lines, allow for better assessment of post-earthquake system availability.

A weak link for some water systems is reliance upon (electrically driven) pumps to provide pressure in the distribution system. Loss of electric power automatically inactivates such a system until standby power (if available) is connected or regular power is reestablished. Thus, even if the distribution piping system survived in good condition (a relatively unlikely event for most of the six cities) water supplied by such a system would be unavailable immediately following a general post-earthquake loss of electric power.

Fragility curve application was then performed upon those utility system component structures which were identified and surveyed by inventory teams in the six cities. Such structures included electric substations, water and sewage treatment plants and storage tanks, elevated and non-elevated. The findings of the "weak-link" systemspecific analyses were combined with those from the fragility analysis to estimate the availability of a given utility system.

This method of examining utility systems was applied to all four basic utility types for the six cities. The results of these analyses are presented both in the general discussion of study results, Section 3.6, Public Utilities, and in the individual presentations of results for the six cities.

2.4.6 Damage Estimates for Dams and Levees

The failure of earthen structures designed to retain or impound a body of water, i.e. earthen dams and levees, (the characteristic construction type in this region) is of interest in a study of this type for several reasons. The most important and immediate is the danger posed to the population from sudden flooding. Flooding also complicates relief efforts, and loss of a reservoir can mean the loss of part or all of a city's water supply.

Fragility curve application was used in combination with knowledge and evaluation of site-specific factors and structural characteristics to estimate failure potential for these earthen structures. Separate approaches were used for the two categories. The fragility curve application was primarily used for major earthen dams in or near enough to one of the six cities to be of concern. These structures are usually reasonably well-engineered (though usually not including provisions for seismic resistance) and the estimation of their behavior with this methodology is appropriate. Dams which were likely to sustain "severe" or "collapse" damage were of concern. A dam experiencing "severe" damages would dictate immediate action to alleviate a threat to downstream persons and property through both alert/warning systems and emergency repair efforts (when possible) or drawdown. Collapse-level damage is self explanatory; available information indicated that earthen dams in the study area, even under strong ground shaking, are not likely to suffer collapse-level damage.

Levees along or near major rivers and streams, while also generally well-engineered (although similar to dams often without seismic considerations) are estimated to be more prone to allowing water release than are dams. This is due to the generally great length of these facilities and the variable and poor-behaving soil upon which they are sometimes built. It is also due to the inherent engineered design features of the dam vs. the levee. These factors were combined to lead to the conclusion that levees in the project cities will probably be damaged somewhere along their length to the extent that flooding can occur behind them. This flooding is possible at the time of the earthquake, or during the recovery phase yet before repairs are made. The earthquake flooding scenario was presumed to take place with water levels in the area's rivers or streams at the "100 year flood" elevation; thus, areas inundated by a flood of this elevation were examined. Individuals living in areas flooded in this manner were presumed to be displaced and to require shelter. Since flooding could also occur after an earthquake but prior to levee repair, the shelter figures etc., are kept separate.

Estimates of the areas thusly inundated in the cities prone to such flooding were made by assuming that the earthquakes occurred when the subject stream or river was at the "100 year" flood elevation. All areas at or below this elevation, within the corporate limits of a city, were assumed to flood to that elevation. These are the zones depicted as inundated. Persons residing in these areas were designated as displaced persons requiring shelter due to flooding.

2.5 Estimation of Deaths and Injuries

An earthquake in the central United States would cause deaths and injuries (requiring hospitalization) in the six cities as a direct consequence of collasped structures and falling objects caused by the ground shaking and movement of buildings. Additional casualties would be caused by heart attacks, accidents and other incidents that occur in the panic and confusion produced by an earthquake. The methodology employed to estimate these casualties is described in Section 2.5.1. Deaths and injuries could also occur as a consequence of secondary events such as flooding or conflagration, as explained in Section 2.5.2.

2.5.1 Casualties from Structural Failure

The category of casualties from structural failure includes those caused by the collapse of buildings and other structures, by the impact of falling objects such as parapets, external masonry and glass, and by personal accidents, heart attacks and similar situations induced by an earthquake.

In this century, in the United States, earthquakes of Modified Mercalli Intensity IX or greater have produced deaths ranging from 10 to 500 persons per 100,000 population. Eliminating the extreme cases, the range falls generally between 20 and 120 dead per 100,000 population. These figures were used as an overall parameter for the estimation of casualties that would be caused by earthquakes in the New Madrid Seismic Zone in the six cities. However, the earthquakes which generated the above statistics occurred mostly in areas characterized by frequent and expected seismic activity with some degree of seismic protection already incorporated into local building codes and practices. In contrast, building codes and practices in the six cities covered by the present study generally have not been designed to enable structures to resist the forces produced by strong seismic events.

Conceptual Approach Employed

The intent of developing the casualty estimation methodology employed in this study was to formulate a quantitative technique that would reflect the important determinants of earthquake casualties and could be applied systematically in each of the six cities.

In general, the number of casualties produced by an earthquake will be determined by population density, the geographical location of the population at the time of the earthquake, the types of building construction in the affected area and the level of groundshaking from the earthquake. These factors were taken into account in this study, along with the fragility curve technique for determining probable damages to structures. The methodology varied slightly from city to city depending on the specific data available, although a similar overall approach was taken in each case, with exceptions made primarily in adjusting or improving data in the inventory file.

The primary producer of casualties was assumed to be the collapse of occupied buildings. Based on that assumption, the estimation of casualties consisted of the following steps:

-Determining the average occupancy of each inventoried building in the study area at the time of the earthquake;