Elements of Infrastructure and Seismic Hazard in the Central United States

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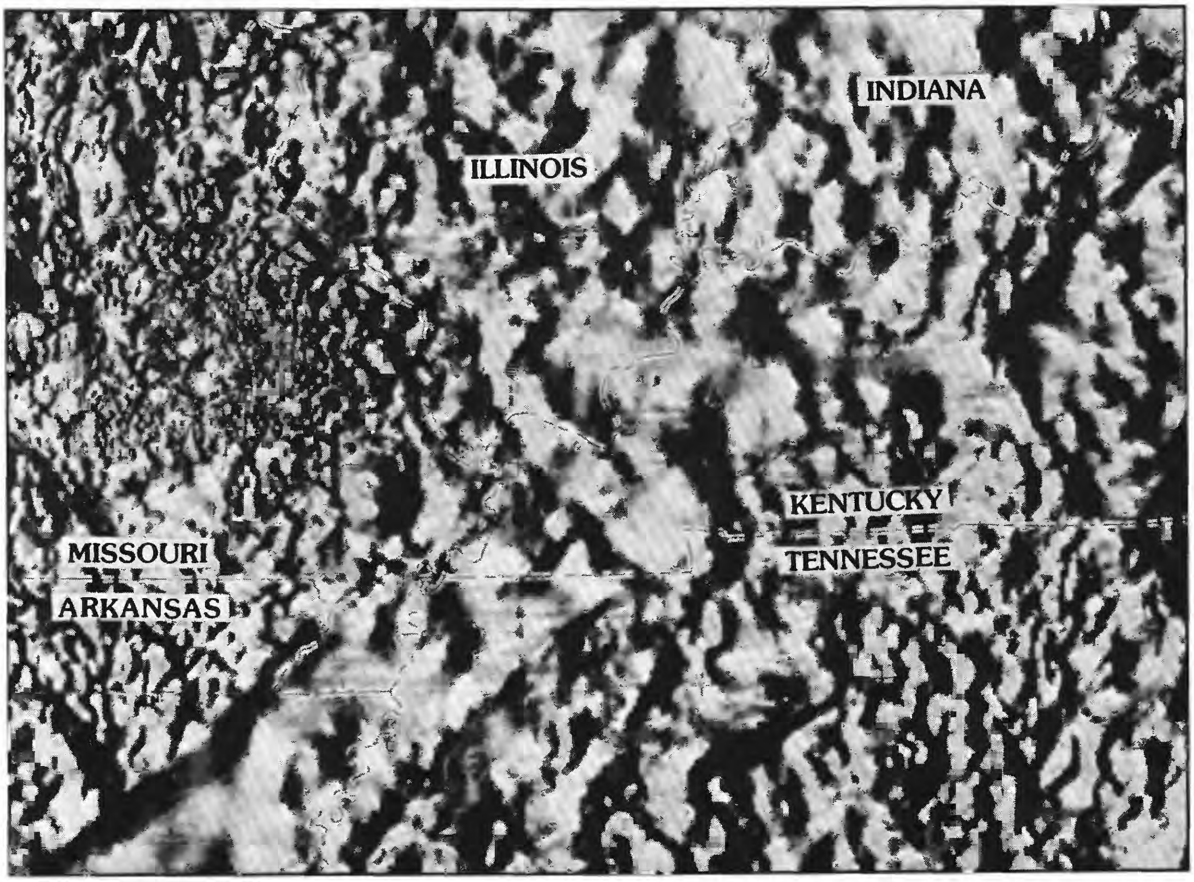

Cover. Gray, shaded-relief map of magnetic anomaly data. Map area includes parts of Missouri, Illinois, Indiana, Kentucky, Tennessee, and Arkansas. Illumination is from the west. Figure is from *Geophysical setting of the Reelfoot rift and relations between rift structures and the New Madrid seismic zone*, by Thomas G. Hildenbrand and John D. Hendricks (chapter E in this series).

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Compiled by Russell L. Wheeler, Susan Rhea, *and* Arthur C. Tarr

INVESTIGATIONS OF THE NEW MADRID SEISMIC ZONE
Edited by Kaye M. Shedlock *and* Arch C. Johnston

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PLATES

ELEMENTS OF INFRASTRUCTURE AND SEISMIC HAZARD IN THE CENTRAL UNITED STATES

Compiled by Russell L. Wheeler, Susan Rhea, *and* Arthur C. Tarr

ABSTRACT

Three maps of the central third of the conterminous United States show selected elements of seismic hazard and societal infrastructure (plates 1–3, in pocket). Hazard elements shown are locations of historical damaging earthquakes, main areas underlain by geologic units that could liquefy or amplify ground shaking, and estimated isoseismals from a surface-wave-magnitude (M_S) 7.6 earthquake, which is hypothesized to occur anywhere in the New Madrid seismic zone of southeast Missouri and adjacent States. Infrastructure elements shown are large urban areas; limited-access highways; railroads; main pipelines carrying crude oil, petroleum products, and natural gas; large dams; and nuclear power plants and fuel-cycle facilities.

Spatial relations shown on the map and results obtained by others suggest that the types of economic impacts from large earthquakes in the New Madrid seismic zone might vary with distance from the zone. The largest contributions to total losses in and near the seismic zone might come from damage to the electric-power-supply and highway systems. However, other large losses might occur far from the seismic zone because of damage to natural gas pipelines that supply the populous Upper Midwest and Northeast.

INTRODUCTION

Recent estimates of seismic hazard in the United States east of the Rocky Mountains indicate that, in the aggregate, hazard in the East might be comparable to the hazard in California (Johnston and Nava, 1985; Beavers and Uppuluri, 1990; Nishenko and Bollinger, 1990; Sibol and others, 1990). The New Madrid seismic zone in the central Mississippi Valley dominates hazard in the Eastern United States—during the winter of 1811–12, the zone produced the largest earthquakes known to have occurred in the East or in geologically similar regions worldwide (Fuller, 1912; Nuttli, 1973; Johnston and Kanter, 1990; Johnston, in press). The seismic zone continues to have the highest level of seismicity in the Eastern United States (Nuttli, 1979; Engdahl and Rinehart, 1988; Hamilton and Johnston, 1990). Accordingly, many maps and reports have addressed the seismic hazard in the central Mississippi Valley and environs (for example, Heyl and McKeown, 1978; McKeown and Pakiser, 1982; Hamilton and Johnston, 1990).

These maps (plates 1–3) are the first in a planned series that will contribute to the continuing effort (Wheeler and others, 1992). Future maps in the series will show geologic, seismologic, and other scientific information that are useful in assessing hazard and that contribute to the eventual understanding of earthquake generation. However, the focus of this first group of maps is on elements of society's regional infrastructure that might be damaged by large earthquakes in the central Mississippi Valley. The maps are aimed at (1) geographers, engineers, and others who have the expertise to test and extend our suggestions about the impacts of earthquakes on society in the Central United States, and (2) technically trained officials in Federal, State, and municipal agencies who are charged with assessing and mitigating the threats posed to society by natural hazards. Our intent is to stimulate both groups of specialists to collect more detailed cultural and engineering data than we present here, to describe and model them, and thereby to characterize society's vulnerability to New Madrid seismicity more surely than we can here. Our digital data are available on request to aid them.

The maps complement an extensive report on national infrastructure that was published when our work was nearly complete (Applied Technology Council, 1991). The report, known as ATC-25, is aimed particularly at engineers. It estimates economic losses for eight different hypothetical earthquakes in various parts of the conterminous United States. Thus, ATC-25 has a sharper focus but a larger study area than the maps presented here. However, our maps show more detail in the Central United States because of their larger scale and use of color. The loss estimates in ATC-25 provide abundant quantitative support for many of the inferences that we draw from spatial relations shown on plates 1–3.

Plates 1–3 have two main limitations. First, our focus is on the region, not on localities or municipalities within it. Many of our data sets involve too much geographic information for us to show details at the 1:2,500,000 scale of the maps. Indeed, we omitted many data sets because of this scale limitation. Because of the small map scale and the limited resolution of our data, the maps should not be used for detailed or local assessments, although they can provide a regional context for such assessments. Second, the map area includes part of Canada, which is outside the region at risk from likely earthquakes in the central Mississippi Valley. Few of our data sets could be easily extended into Canada, so we show only large urban areas there.

SEISMIC HAZARD

The New Madrid seismic zone is about 50 km (30 mi) wide and stretches along and near the Mississippi River from about lat 35°N., at Memphis, to about lat 37°N., at the junction of Missouri, Illinois, and Kentucky (Nuttli, 1979). The hazard posed to society by the seismic zone takes several forms in addition to ground shaking (Hamilton and Johnston, 1990). The plates identify large areas where geologic conditions might foster liquefaction of soft, water-saturated sediments or amplification of ground motion (Quaternary units are shown in yellow on plates 1–3, and older Cenozoic and Mesozoic units are shown in green). The plates do not show other geologic aspects of seismic hazard, such as faults that rupture the ground surface, either because they are unlikely to occur in the map area or because their areas of likely occurrence are small or scattered. East of the Rocky Mountains, dramatic fault scarps rarely form, even from large earthquakes. Most of the map area is too far from coasts to be threatened by seismically generated tsunamis, although local damage could be caused by seiches in lakes, reservoirs, or large rivers. However, uplift or subsidence could distort level lines or cause local inundation. Steep slopes or bluffs are subject to landsliding and related movements if shaken strongly (Jibson and Keefer, 1988).

We represent two different aspects of the regional hazard from ground shaking itself (plate 1). First, we show hypothetical isoseismals, which demonstrate the likely distribution of damage from a large earthquake in the New Madrid seismic zone. We chose an earthquake of a size that is used for emergency-planning purposes. Second, we show epicenters for all damaging earthquakes known to have occurred in the map area. Most of these past earthquakes are smaller than the hypothetical planning earthquake, so they are less damaging but more frequent and more widely distributed geographically.

HYPOTHETICAL ISOSEISMALS

We require some measure of earthquake effects to represent the regional impact of a hypothetical large earthquake in the New Madrid seismic zone. The two main approaches to representing earthquake impact are through intensity and measures of ground shaking; the latter include acceleration, velocity, and spectral ordinates. Near-surface geology strongly affects the shaking at a site, so prediction and mapping of ground shaking values that are expected from a hypothetical earthquake require digitized geologic maps. These have not yet been made in sufficient detail for our large map area, so we cannot represent measures of ground shaking. However, intensity reflects total damage caused by all durations and all frequencies of shaking and includes the effects of site geology. Intensity and isoseismals have been used to plan emergency responses and to estimate potential loss (Central United States Earthquake Preparedness Project, 1985; O'Rourke and others, 1992). Therefore, we use hypothetical isoseismals to represent the potential impact of a large New Madrid earthquake.

The hypothetical isoseismals show the estimated distribution of Modified Mercalli intensities that might be expected from a recurrence anywhere in the New Madrid seismic zone of an earthquake with surface-wave magnitude, M_S, of 7.6. Earthquakes much larger than $M_S = 7.6$ occurred in the seismic zone during the winter of 1811–12 (Fuller, 1912; Street, 1982; Nuttli, 1973, 1983). However, earthquakes as large as those of 1811–12 are estimated to recur only every 550 to 10,000 years (Russ, 1979; Johnston and Nava, 1985; Nishenko and Bollinger, 1990; Saucier, 1991; Wesnousky and Leffler, 1991). Earthquakes of $M_S = 7.6$ probably occur more frequently and, therefore, are more germane to most hazard assessments. Accordingly, a hypothetical earthquake with $M_S = 7.6$ is about the size used in planning emergency-response efforts for the region (Central United States Earthquake Preparedness Project, 1985).

The hypothetical isoseismals were produced empirically by Algermissen and Hopper (1985), using the observed intensity distributions of two smaller earthquakes that occurred in the New Madrid seismic zone, one in 1895 at a latitude of about 37.0°N. and the other in 1843 at a latitude of about 35.5°N. (Nuttli, 1979). The main advantage of these isoseismals is that they are based on observed damage distributions of actual earthquakes. Therefore, the isoseismals show details that would be expected from our understanding of attenuation and amplification, similar to the tongue of high intensities that extends northwestward from the seismic zone up the Mississippi River. The isoseismals also show unexpected features that are not understood and so would not be predicted theoretically, such as the wide tongue of high intensities stretching southeastward across the Appalachian bedrock into Georgia. The main disadvantage of the empirical isoseismals is that Algermissen and Hopper (1985) drew them by assuming that isoseismals change value but not shape or spacing as magnitude changes. For example, the observed isoseismals for the 1895 earthquake were converted to isoseismals for a hypothetical earthquake about one magnitude unit larger by increasing the values of the observed isoseismals one intensity unit. The 1843 shock was treated analogously. Recent findings call this assumption into question (Sibol and others, 1987; Bollinger and others, 1991; Hanks and Johnston, 1992). The isoseismals cannot be tested against an actual earthquake of about M_S 7.6 because the Central United States has had no historical shocks between about M_S 6.8 and 8.4 (Hopper, 1985; Johnston, in press).

We digitized the Algermissen-Hopper isoseismals from a photographic original at a scale of about 1:6,670,000. The isoseismals shown here reproduce those of the original only to within 5–10 km (3–6 mi) on the ground because the original shows the isoseismals as thick lines and because the original is at a smaller scale than these maps. However, the inaccuracies involved in digitizing at a scale smaller than that of these maps are probably less than the uncertainties involved in generating the isoseismals in the first place.

An alternative set of hypothetical isoseismals might be produced with the theoretical method of Evernden and others (1981) and Evernden and Thomson (1985). Using their method, isoseismals for a specified earthquake at a specified place are calculated in two steps. First, the seismic energy that reaches the bedrock beneath a particular site is calculated from the distance to the rupture zone and from an attenuation factor, k, which varies regionally. Evernden (1975) estimated k from the rates at which intensity decreases with distance, assigning $k = 1$ over most of the map area and $k = 1.25$ in the more attenuating post-Paleozoic rocks and sediments of the Mississippi Embayment and nearby coastal plains. Second, estimating the energy that reaches a site requires calculating the amplification of shaking by soft rock, sediments, and soil that overlie hard bedrock. Amplification can be as little as zero on granitic or metamorphic bedrock, or as much as three intensity units on Quaternary alluvium that is saturated with water up to the ground surface (Evernden and others, 1981).

The main advantage of the Evernden method is that it is based on a theoretical understanding of several factors that influence intensity. However, the method has two temporary disadvantages that preclude our applying it to the New Madrid seismic zone. First, to include ground conditions accurately would require digitizing geologic maps over the entire map area in more detail than has yet been done. Second, the Mesozoic and Cenozoic strata that fill the Mississippi Embayment thicken southward across the New Madrid seismic zone. In the north, the relatively attenuating Mesozoic and Cenozoic strata form a thin layer over relatively less attenuating rocks. Seismic energy radiated by earthquakes occurring there is likely to be less attenuated than for more southerly earthquakes, so hypothetical isoseismals for such a northern earthquake should encompass large areas. In contrast, in the south, the attenuating strata are thicker, so hypothetical isoseismals should be smaller. Trial calculations by Evernden demonstrate how sensitive the hypothetical isoseismals are to the location of the boundary between the regions of $k = 1$ and $k = 1.25$ (J.F. Evernden, oral and written commun., 1992). The research necessary to determine how best to represent the boundary is outside our scope here. Accordingly, we show only the hypothetical isoseismals of Algermissen and Hopper (1985) on plates 1–3.

PAST DAMAGING EARTHQUAKES

Plate 1 shows epicenters of 25 earthquakes selected from the catalog compiled under the auspices of the Electric Power Research Institute (EPRI) (Johnston, in press). The EPRI workers compiled, analyzed, and characterized all damaging earthquakes worldwide that occurred in stable continental interiors that are geologically similar to North America east of the Rocky Mountains (Coppersmith and others, 1987). Their definition of "damaging earthquake" is one having a moment magnitude, **M**, of 5.0 or greater, and we follow their definition. Smaller shocks can cause localized damage but, in stable continental interiors worldwide, earthquakes with **M** = 5.0 typically cause intensities of VI or greater over about 3,000 km^2 (Johnston, in press). Intensity VI is the threshold for superficial damage, such as cracked plaster and chimneys and broken windows, but it generally does not involve structural damage to well-built ordinary buildings (Wood and Neumann, 1931).

Johnston (in press) listed 33 additional earthquakes with **M** between 4.0 and 5.0 that are known to have occurred in the map area. However, a histogram of numbers of earthquakes plotted against magnitude indicates that several earthquakes with **M** between 4.5 and 5.0 and many between 4.0 and 4.5 have probably gone unreported or undetected (R.L. Wheeler, unpub. result). Accordingly, we consider the set of 25 earthquakes with **M** at least 5.0 to be complete. Their geographic distribution is a reasonable representation of where one might expect most damaging earthquakes to occur over the next few decades. The most likely locations are in and near the central Mississippi Valley and southern Illinois, where half of the known damaging earthquakes in the map area have occurred.

LIQUEFACTION

Liquefaction of young, water-saturated sediments in the map area could damage structures by causing flow landslides, lateral spreads, loss of bearing capacity, and differential settling (Obermeier, 1985). Obermeier and Wingard (1985) mapped parts of seven States in the central Mississippi Valley that could undergo widespread liquefaction if shaken at Modified Mercalli intensity IX or higher. Localized liquefaction is common at intensity VIII, and isolated instances of liquefaction have been observed at intensity VII (Wood and Neumann, 1931; Stover, 1984, p. 21–22). Thus, a great earthquake similar to those of 1811–12 would cause widespread, severe liquefaction, but smaller earthquakes, which are more likely to occur throughout the map area, could also cause liquefaction of lesser intensity over smaller areas.

The materials most susceptible to liquefaction within and near the central Mississippi Valley are alluvium of late Pleistocene and Holocene age, whereas pre-Pleistocene strata are lithified enough so that they are probably not liquefiable (Obermeier, 1989). Older Pleistocene alluvium might have intermediate susceptibility to liquefaction (Obermeier and Wingard, 1985). The liquefaction hazard in the map area as a whole is concentrated in four types of localities. First, the largest contiguous area of liquefaction hazard is underlain by alluvium in the wide flood plain and terraces of the Mississippi River from southernmost Illinois southward (Obermeier, 1985; Saucier and Snead, 1989). Second, scattered hazard comes from similar sediments in flood plains and terraces of smaller rivers and streams throughout the map area (Obermeier, 1985; Munson and Munson, 1991; Obermeier, Bleuer, and others, 1991; Obermeier, Munson, and others, 1991). Third, much smaller liquefaction hazards within the central Mississippi Valley arise from upland loess, lacustrine silts, and some dune sands, where they are saturated with water (Obermeier, 1985; Obermeier and Wingard, 1985). Fourth, widespread Quaternary marine and near-marine deposits along the Atlantic and Gulf of Mexico Coastal Plains might also be liquefiable to varying degrees, with higher susceptibilities in near-coastal deposits that are younger than 240 ka (Obermeier and others, 1990; Amick and others, 1990; Amick and Gelinas, 1991).

We show the Quaternary deposits along the Mississippi River and both Coastal Plains, digitized from the 1:2,500,000 map of King and Beikman (1974). The focus of the maps is the central Mississippi Valley, so we ignore isolated exposures of strata that are older than Quaternary except in southeastern Missouri and northeastern Arkansas (plates 1–3). Because of the small scale of plates 1–3, we ignore the comparatively small hazard posed by saturated loess, silts, and dune sands. We do not show the narrow threads of Quaternary alluvium that extend partway up many rivers and large streams, partly because most of the threads would reduce to single lines at our map scale and partly because we do not know how far upstream the alluvium extends along each river or stream. For more detailed studies than ours, the upstream limit of alluvium could be determined directly for areas covered by large-scale geologic maps that show stream alluvium. For other areas, the upstream limit could be estimated from 1:24,000 topographic maps that show the upstream limit of flat-bottomed stream valleys.

STRONG-MOTION AMPLIFICATION

Seismic shaking is often amplified at sites on soft sediments or young, partly lithified, sedimentary or volcanic rocks compared to shaking at hard-rock sites (Rogers and others, 1985). Regression models of seismic strong motion show that thickness of the sediments and partly lithified rocks is an important variable tending to increase amplification (Campbell, 1987). Theoretical analyses indicate that the low-velocity sediments and partly lithified rocks cause amplification, especially where they directly overlie high-velocity hard rock (Kanai, 1983, p. 96–102; R.L. Wheeler, unpub. results). Hereafter, we refer to sediments and partly lithified rocks as the "amplifying strata."

These results and regional stratigraphic information indicate that hard rock in the map area consists of mostly Precambrian metamorphic and igneous rocks of the craton, the overlying Paleozoic platform sedimentary rocks, and the Precambrian and Paleozoic rocks of the Appalachian and Ouachita orogens that are thrust upon the cratonic and platform rocks from the southeast and south, respectively. The overlying amplifying strata consist of Quaternary alluvium in river and stream valleys and Mesozoic and Cenozoic sediments and variously lithified sedimentary rocks that lap onto the hard rocks from the Atlantic Ocean and Gulf of Mexico. This choice of the boundary between hard rock and amplifying strata is consistent with velocity logs from wells in the New Madrid seismic zone. The logs show that the greatest downward increase in velocity takes place across the Mesozoic-Paleozoic contact. Analogy to velocities measured in soft California sediments (Campbell and others, 1979; Lew and Campbell, 1985) leads us to expect another large downward increase in velocity across the contact between Quaternary alluvium and partly lithified Tertiary strata. We conclude that seismic shaking is likely to be amplified at sites on Mesozoic and Cenozoic sedimentary rocks and especially on water-saturated Quaternary alluvium.

Accordingly, we show the inland contact of Mesozoic and Cenozoic coastal-plain strata, which was digitized from the 1:2,500,000-scale geologic map of King and Beikman (1974). For simplicity, we ignore isolated outliers of Cretaceous strata, small inliers that expose underlying hard rock, and local deposits of Quaternary alluvium along streams. The inland contact of Quaternary deposits bounds the main areas of saturated sediments, as described in the section on liquefaction. Along the northwest side of the Mississippi Embayment, Quaternary sediments extend farther northwest than the underlying Tertiary and Mesozoic rocks and directly overlie hard rock. Thus, the two inland contacts identify the main parts of the map area in which seismic shaking is likely to be amplified.

INFRASTRUCTURE

The elements of society that could be at risk from a large earthquake can be classified as critical and non-critical structures, population, and lifelines. Critical structures include those that are so essential to public well-being and safety that they must remain at least partly operational during and after an earthquake (Applied Technology Council, 1978). Examples include nuclear power plants, large dams and bridges, hospitals, some communications centers, transportation links through which relief would flow, and command centers for emergency-response efforts. Any list of types of critical structures can vary with the context; for example, Manrod and others (1981) defined critical industrial facilities as not only those that could release harmful substances if damaged, but also those whose damage could cause unacceptable financial loss to the owners. In contrast, non-critical structures include residences, other small buildings, and non-essential transportation and communication facilities for which alternatives are readily available. Critical and non-critical structures may be mapped as points and, as explained later, many types tend to concentrate with population in urban areas.

Lifelines, on the other hand, form networks within and between urban areas. Lifelines include transportation, pipeline, electric-power, and telecommunication networks (Central United States Earthquake Preparedness Project, 1985; Building Seismic Safety Council, 1987, p. 1; Applied Technology Council, 1991, p. 1). Lifelines carry and supply "people, goods, information, energy, water and waste" (Eguchi and others, 1990, p. 875). Lifelines differ from non-critical facilities located at single points in three ways (Eguchi and others, 1986). Lifeline networks can cover large areas, so they can be exposed to seismic hazard at many places. Lifelines comprise many interconnected components, many of which must survive an earthquake in order for the lifeline to continue functioning. Lifelines must continue to provide service with little or no interruption, unlike most buildings, which need not be usable after an earthquake as long as they do not collapse during it.

Plates 2 and 3 show large urban areas, main lifelines that connect and supply them (pl. 2), and selected critical structures (pl. 3). The urban areas represent concentrations of people and structures and local distribution or collection networks of regional lifelines. A theme that runs through several later discussions of single infrastructure elements is that much of U.S. society is tightly interconnected and sustained by large, fast, long-distance flows of information, fuels, and commerce. The flows have enlarged steadily with time (Smith, 1987) and presumably so has society's dependence on them. Many of the flows cross or pass near the New Madrid seismic zone. Hence, damage to elements of the Central U.S. infrastructure by large earthquakes in the zone could have far-reaching and complex social and economic impacts outside the region. Also, the economic loss from the earthquakes could exceed the immediate cost of physical damage to structures and lifelines by including the longer term cost of disruptions and resulting inefficiencies in society's operations.

For example, the Applied Technology Council (1991) estimated the cost of physical damage from an M_S 7 to 8 earthquake in the New Madrid seismic zone to be at least \$3.4 to \$11.8 billion. They estimated the longer term economic loss to be at least \$4.9 to \$14.6 billion, for a total loss of at least \$8.3 to \$26.4 billion. They suggested that the estimates might be low because their analysis required simplifying assumptions and because effects from landsliding were ignored because of lack of data. Loss estimates are highly uncertain, especially for long-term economic effects, because of a paucity of data and proven methodologies in a young specialty (Development Technologies, Inc., 1992).

URBAN AREAS

The map area shown on plates 1–3 is large, including part or all of 27 States and one Canadian Province. At the scale of the maps, we cannot show individual elements of infrastructure where they are densely clustered. Instead, as proxies, we map centers of large urban areas, naming them after their largest cities. The populous urban areas represent the centers of large concentrations of elements at risk—clusters of critical and large non-critical structures, and nexuses of lifelines of all kinds; thus, the map does not show these components separately.

For example, telecommunications networks are typically organized as hierarchies of nodes and links (Foss, 1981). The links comprise comparatively resilient buried and aerial cables and microwave towers. Cables are being replaced with towers, which withstand earthquakes well (Faynsod, 1987). The most vulnerable network components are the buildings at the nodes, which house main toll centers and local switching offices. The switching and transmission equipment inside the buildings are particularly vulnerable to buckling, swaying, shifting, and toppling (Shinozuka and others, 1984). In addition, during the Loma Prieta, California, earthquake of October 18, 1989, the most common problems with communications networks stemmed from emergency-power supplies that were unreliable because of infrequent use (Benuska, 1990). Even where low levels of shaking caused little damage, many generators, starting batteries, and fuel supplies did not work properly. The local switching offices of telecommunications networks must be close to centers of demand to minimize costs. Also, the sizes and numbers of switching offices in an area increase with the numbers of nearby users and the transactions between them. Thus, large urban areas serve as proxies for dense concentrations of the most vulnerable components of telecommunications networks.

Electric power systems provide another example. These systems comprise power-generating plants, high-voltage long-distance bulk transmission lines, substations, and low-voltage local distribution lines. The larger system components are shown on maps obtained from the Regional Reliability Councils of the North American Electric Reliability Council (NERC). Generating plants, many of them about 1,000 MW in size, are geographically dispersed so that many are far from concentrations of demand in urban areas. Also, the coal-fired plants common in the East have been little tested by seismic shaking (Schiff, 1981). However, electric-power grids tend to have redundancy so that a damaged plant might be bypassed (Beavers and others, 1986). Bulk transmission lines respond well to seismic shaking because their towers are designed to withstand similar shaking from winds, although locally towers can be damaged by landslides, liquefaction, or subsidence (Schiff, 1981, 1984). The NERC maps show that the higher voltage bulk transmission lines mostly connect large urban areas. The most vulnerable components of electric-power systems are substations, even in moderate shaking, because ceramic insulators are brittle, heavy equipment is tall and can shift or topple, damaged transformers cannot be bypassed as other components can, and many spare parts are scarce (Schiff, 1981, 1984, 1985, 1989; Benuska, 1990). Networks of local distribution lines lack the redundancy of the long-distance components of the power system (Schiff, 1981). The NERC maps show that substations and local distribution lines in the map area are concentrated in urban areas at centers of demand. Therefore, at the scale of plates 1–3, urban areas can serve as proxies for concentrations of the most vulnerable components of electric-power systems; the plates do not show the power system separately. Indeed, damage to electric-power systems is likely to produce the largest part of the overall economic impact from large earthquakes nationwide (Applied Technology Council, 1991).

Some components of transportation lifelines that connect urban areas are concentrated in or near the urban areas. The largest and busiest commercial airports are an example. In 1965, air traffic in the area covered by plates 1–3 was concentrated at large urban areas, whether measured by numbers of flights, numbers of passengers, or numbers and locations of airports. Since 1965, many airlines have abandoned routes to smaller cities, so the urban areas can continue to serve as proxies for locations of the largest, busiest airports in the map area. Accordingly, the plates do not show airports separately.

The Loma Prieta earthquake showed that modern airports are vulnerable to seismic shaking (Benuska, 1990). Liquefaction damaged runways built on fill or soft soil. Lack of emergency generators at small airports slowed resumption of their operations until external power was restored. Damage to windows and unanchored equipment in control towers could have restricted the airports' participation in emergency-response operations. However, as with the urban areas themselves, as of 1965, only a few commercial or military airports were in or near the New Madrid seismic zone (U.S. Geological Survey, 1970). Therefore, a large earthquake in the zone might have little impact on national air traffic.

The Loma Prieta earthquake also produced extensive damage to port facilities around San Francisco Bay from liquefaction and settlement (Benuska, 1990). Similar effects in the soft, water-saturated sediments along the Mississippi River at Memphis and St. Louis could hinder response and recovery in both urban areas (Central United States Earthquake Preparedness Project, 1985). The river extends the length of the New Madrid seismic zone and normally would be a convenient means of bulk transport of supplies and equipment into and between urban areas. However, if high-capacity roads and railroads were damaged by shaking and liquefaction in the seismic zone, perhaps the port facilities would also be damaged and would be unavailable to provide alternative access to the damaged areas. Plates 1–3 do not show port facilities separately from urban areas.

Emergency-response resources might provide another example of concentration into urban areas. We expect that the numbers of emergency-response personnel and the numbers and sizes of response facilities increase with the population of an urban area. However, the strength of the association with population is likely to vary with the particular kind of emergency-response resource. For example, most of the area covered by plates 1–3 has long been densely settled, at least since the 1960 census (U.S. Geological Survey, 1970). Therefore, police and fire protection are likely to be more or less ubiquitous, mimicking population density (Applied Technology Council, 1991). Doctors and medical clinics might follow the population density less uniformly, having higher per capita concentrations within urban areas than between them. Comparison of census data to hospital locations obtained from the National Disaster Medical System (Anonymous, 1990) shows that large hospitals with many acute-care beds are strongly concentrated into and near the largest cities, although acute-care beds may also be concentrated in teaching hospitals in smaller urban areas with large universities (Anonymous, 1990). Specialized medical facilities, such as trauma centers, might be still more concentrated into the largest urban areas, especially if they use helicopters to increase their service radius. Thus, different emergency-response services might follow different patterns of concentration, but, overall, we expect their main concentrations to be in large urban areas. Therefore, plates 1–3 do not show concentrations of emergency-response resources separately from urban areas.

Perhaps emergency-response facilities and personnel are concentrated into large urban areas even more than population density indicates. Berry and Kasarda (1977, chap. 16) examined three kinds of social systems and found that, for each kind of system, the percentage of administrative personnel increased with system size. They examined Colorado school systems, Wisconsin communities with populations from 2,500 to 25,000, and nations in which most workers are not employed in agriculture. They considered three classes of administrative personnel. For each kind of system, the number of administrative workers engaged in communications was the most strongly associated with system size. Next most strongly associated was the number of professional and technical specialists who inform, advise, and support managers. Least strongly associated with system size was the number of managers themselves. Communication, specialized management, and certain professional and technical specialists are important components of an emergency-response system, so the findings of Berry and Kasarda (1977) lead us to suggest that emergency-response facilities and personnel might have higher per capita concentrations in larger urban areas. If so, then the capacity for emergency response to seismic disaster might be more concentrated geographically than is the general at-risk population.

The choice of how small an urban area to map is complex. The 1989 Rand McNally road atlas identifies 268 "urbanized areas" (their term) within the map area. The atlas shows "urbanized areas" as orange polygons but does not define the term. "Urbanized areas," hereafter called urban areas, typically include one or more large cities and perhaps nearby cities and other named places that presumably are integrated with the large cities economically and socially if not administratively. We obtained 1990 census data for the populations of 268 urban areas. Census lists show that we have included all named places with populations larger than 50,000. We estimated an urban area's population as that of either (1) the main city or cities that dominate the area or (2) the county or counties that enclose it. We chose between these two population estimators after examining the atlas for: density of named places surrounding the urban area but within the enclosing county or counties, numbers of intersecting Interstate highways, numbers of Interstate interchanges, and presence of beltways. For urban areas that span a large river or a State boundary, these map criteria sometimes led us to add the population of a city in one part of the urban area to the population of a county in the other part. The map criteria and various histograms of population led us to conclude that an urban area begins to stand out above the densely settled regional background at a population of 200,000–300,000.

Forty-two urban areas in the area shown on plates 1–3 have populations larger than 200,000. We show these 42, classified by population as larger than 200,000, 500,000, or 1,000,000. State capitals are also likely to be command centers for disaster response, so we identified those within the mapped area, including 11 capitals with populations smaller than 200,000. Thus, we mapped 53 large urban areas and State capitals in all.

HIGHWAYS

We show only limited-access highways because they can carry heavy traffic at high speeds over long distances. Therefore, their economic and social impacts are likely to be large, widespread, and sensitive to delays. For example, most limited-access highways are parts of the Interstate highway network, and the long-term social impact of building the Interstates over the last third of a century is widely recognized. In addition, the Interstate network has become an important national economic lifeline and has helped trucks to compete with railroads in freight hauling (Garrett, 1988).

The highway network shown here (pl. 2) was digitized by others from various sources at a scale of 1:2,000,000 and was current in 1980 (U.S. Geological Survey, 1990). We included all roads coded as Interstate or limited-access highways, including those built or under construction as of 1980 but not those that were merely proposed at the time. Comparison to the 1989 Rand McNally road atlas shows few changes since 1980. Nearly all changes that we made were additions of limited-access roads, both free and toll, that were not already in the digital data. We assumed that this scheme captured all high-speed, high-capacity roads with at least four lanes. The atlas also shows numerous other four-lane divided highways to which access is unlimited. We omitted these highways because they are likely to be congested by slow, heavy, local traffic and to have comparatively easy access to detours around damaged parts of the road network. In addition, the large map area and small map scale led us to omit two kinds of short sections of limited-access highway as being of only local importance. First, we deleted numerous short sections that are in the digital data but are isolated from the main network of limited-access highways. Second, the atlas shows many short sections that are parts of beltway networks in urban areas. If these short sections were not in the digital data already, we added only the longest of them.

Damage to a transportation network causes physical loss or direct damage, consisting of repair and replacement costs, and also user loss or indirect economic loss, resulting from the system's inability to supply or service users (Oppenheim and Anderson, 1981; Applied Technology Council, 1991). Physical loss to the highway network from earthquakes in the Eastern United States is likely to include shaking damage to bridges and liquefaction damage to bridge piers and roadbeds built on young sediments, especially at river crossings (Cooper, 1981). User loss can be more widely spread and is harder to estimate (for example, Kawashima and Kanoh, 1990; Applied Technology Council, 1991; Development Technologies, Inc., 1992). If physical loss is light, as for a moderate-intensity earthquake, the economic resources of the surrounding user community might be sufficient to repair or replace the physical losses quickly, thereby limiting total user loss and allowing prompt restoration of pre-disaster patterns of travel, commerce, and other usage.

However, a large earthquake in the densely urbanized Eastern United States could cause severe physical losses to the highway network over a large area. Immediately after the earthquake, the physical losses are likely to hinder emergency-response efforts (Schiff, 1981; Central United States Earthquake Preparedness Project, 1985; Benuska, 1990). Later, the aggregate physical loss might be large enough to strain the regional or national economic community so that restoration of the physical losses would be slowed. All the damaged infrastructure elements would compete for funds available for repair and rebuilding, and some of these funds might be diverted to help maintain society's operation in the face of inefficiencies caused by physical losses. Under these conditions, the user loss could be widespread and long-lasting (Federal Emergency Management Agency, 1990). Indirect user losses could affect communities far from any physical loss, for example through diversion of their tax payments to pay for the network damage, through decrease in the ability of the damaged region to contribute to the regional or national economy because of difficulty in moving raw materials and finished goods through the damaged network, and through generally higher transportation costs imposed by diversions around the damaged parts of the network. Indeed, user loss from damaged highways is estimated to be second only to that from damaged electric-power networks (Applied Technology Council, 1991).

The ability of a transportation network to minimize user loss after undergoing physical loss depends partly on its redundancy and congestion (Oppenheim and Anderson, 1981; Oppenheim and Hendrickson, 1987), which operate against each other. Thus, in the densely urbanized northeastern part of the area covered by plates 1–3, a comparatively dense network of limited-access highways and multi-lane, unlimited-access roads provides alternatives to damaged routes. However, many parts of the regional network are congested, so excess capacity might be too small to absorb the rerouted users easily. In that case, we would expect congestion and user losses from delays to spread more widely than physical losses. In contrast, the more sparsely settled northwestern part of the area covered by plates 1–3 has fewer high-capacity, high-speed highways, but it also has much lower congestion overall. Accordingly, users might be rerouted around damaged primary highways along secondary roads. Alternatively, if secondary roads in the northwestern part of the mapped area are few or have limited capacity, the highway network would have little redundancy, and physical damage to its primary components might cause widespread, prolonged user loss. Finally, even if secondary roads are abundant and uncongested, local features such as bridges, steep slopes that might slide, dams upstream from a road, and trees that could fall across a road can increase physical and user losses in ways difficult to anticipate without local surveys (Allen and Drnevich, 1990).

These considerations lead us to expect that user losses from seismic damage to the highway network should be largest, most prolonged, and most widespread if physical losses occur where urban areas are large and close together, where several limited-access highways converge, or where heavily used highways cross large geographic barriers such as the Mississippi, Missouri, and Ohio Rivers. Plate 2 shows that converging highways and river barriers are both present in the New Madrid seismic zone. The mapped highways form a comparatively dense network north and south of the zone, but few mapped highways cross large areas east and especially west of the zone. Only Interstate 55 crosses the zone itself, extending north from Memphis along the full length of the seismic zone, with connections to similar highways only in its northern part by bridges across the Mississippi River. The closest alternative route shown on plate 2 is through Nashville, more than 250 km (150 mi) to the east. However, of the six mapped highways that converge on Nashville, one comes from Memphis, where it might be damaged by an earthquake, and three come across the hilly northwest Appalachian Mountains, which probably would slow trucks. Thus, the New Madrid seismic zone contains a bottleneck, and a large earthquake anywhere in the zone might disrupt highway traffic between the Central Gulf Coast and the Upper Midwest.

Smaller State and Federal highways provide alternate routes around the potential bottleneck. However, a New Madrid earthquake of M_S 7 or 8 could produce 30 to 60 percent damage to all these roads throughout an area spanning 100 to 200 km from west to east and lower damage levels over an area about twice as wide (Applied Technology Council, 1991). The secondary roads might not be able to provide redundancy for damaged limited-access highways either because the secondary roads were damaged themselves or because they were congested by diverted traffic.

RAILROADS

We show all railroads without distinction, both primary lines and others of more limited capacity (pl. 2). The network shown on plate 2 was digitized by others at a scale of 1:2,000,000. The digitized network was current in 1979 (U.S. Geological Survey, 1990), but the geographic observations contained in the next paragraph also apply to the railroad network as it existed on May 15, 1991 (Railroad Information Service, 1991).

The network is likely to have considerable redundancy with which to absorb and adjust to damage from large earthquakes. Physical loss in a transportation network interrupts service, causing user loss (Oppenheim and Anderson, 1981; Oppenheim and Hendrickson, 1987). Redundancy in the network can decrease the user loss, for example by providing alternative routes to damaged parts of the network. We infer likely redundancy in the railroad network because it is several times as dense as the mapped highway network, with few places being farther than about 50 km (30 mi) from the nearest railroad. Railroads are more or less uniformly distributed throughout the mapped area, except in three subareas. First, eastern Kentucky and central Tennessee have about half the railroad density typical of the rest of the mapped area. Both States have normal railroad densities to the west of the low-density regions, closer to the Mississippi River. Second, most of southern Missouri and northern Arkansas have about one third the normal railroad density, although density is normal within 75–125 km (50–80 mi) of the Mississippi River. Third, western Pennsylvania, Ohio, Indiana, and Illinois have two to three times the normal railroad density, with density especially high near Chicago. These observations indicate that the railroad network might have much different redundancy in Illinois and Indiana than in the four States to the southwest. The railroad network might have a bottleneck in and near the New Madrid seismic zone analogous to that in the network of limited-access highways. The areas over which railroads could be damaged by an M_S 7 to 8 New Madrid earthquake are similar to the estimated damage areas for highways (Applied Technology Council, 1991)

Over areas smaller than that mapped here (pl. 2), the protection provided by redundancy in the railroad network varies with factors that we cannot evaluate. First, in contrast to the seismic performance of highway bridges, that of railroad bridges is poorly understood (Pauschke, 1990). Second, congestion dilutes the protection offered by redundancy (Oppenheim and Anderson, 1981). However, readily available alternatives, for example from trucks operating along the dense network of secondary roads that permeate the map area, can reinforce the protection of redundancy. Third, railroads have been losing passengers to cars, buses, and airplanes since the 1920's, and they have lost freight business to trucks traveling on Interstate highways since the 1950's (Smith, 1987; Garrett, 1988). Freight trackage decreased by one third from 1916 to 1980 as railroad companies merged and abandoned trackage (Smith, 1987; Garrett, 1988). Thus, the railroad network that we show (pl. 2) surely contains some stretches that are no longer usable.

The limited-access highways might be able to provide redundancy for earthquake-damaged principal railroads. The Congressional Research Service (1977, map 18) mapped primary railroads as they existed in 1974. This subset of the whole railroad network shows different spatial characteristics north and south of about lat 38°N. In the southern part of the mapped area, Interstate highways mostly follow primary railroads that connect large cities. In the northern part, the railroad network is several times as dense, with Interstates tending to follow primary railroads but also crossing the large areas between them. Railroads and Interstate highways might undergo similar kinds of physical damage from earthquakes, mostly caused by shaking of bridges and damage to bridge supports and roadbeds from liquefaction, subsidence, and landsliding, especially at river crossings (Cooper, 1981; Pauschke, 1990). Collocated highways and railroads could be damaged together. Thus, any redundancy that Interstate highways and primary railroads could provide for each other is more likely in the northern part of the mapped area than in the southern part.

Seismic damage to railroads is unlikely to have a widespread impact on energy supplies. The only fuel that moves mostly along railroads in the Eastern United States is coal (Beavers and others, 1986; Cuff and Young, 1986). Most railroad-borne coal moves either short distances within and near the producing States in the northeast part of the map area or overseas from Virginia, Kentucky, and West Virginia (Congressional Research Service, 1977, maps 2–6; Cuff and Young, 1986). About half as much coal from the Eastern United States moves by water as by rail, and a much smaller amount is transported by truck (Beavers and others, 1986). The main domestic coal users in the East are electric-power utilities, and they typically stockpile coal against supply interruptions (Beavers and others, 1986; Garrett, 1988). Therefore, the likely redundancy of the railroad network itself, the large distances between most coal movements and the New Madrid seismic zone, any excess capacity in the river transportation network, and coal stockpiles will all act to minimize the impact of seismic damage to railroads on coal supplies.

PIPELINES

One quarter of the energy consumed annually in the United States moves north and northeast from Texas, Oklahoma, and Louisiana to support the densely populated East (Beavers and others, 1986). Most of the energy moves by pipeline in the form of crude oil, petroleum products, and natural gas (Congressional Research Service, 1977, map 19; Smith, 1987).

We digitized the main pipelines of the oil, gas, and products networks from maps published at about 1:3,530,000 (PennWell Publishing Company, 1982, 1983, 1984, 1988, 1990a, 1990b). We omitted the dense collecting networks in the producing States of Texas, Louisiana, Kansas, and Oklahoma for legibility and because these States are mostly outside the likely damage areas of even the largest earthquakes expected to occur in the central Mississippi Valley (Algermissen and Hopper, 1984, 1985). We show only the largest diameter pipelines in each network (pl. 2) because these lines dominate the flow patterns throughout the network and would cause the greatest disruptions if they were damaged. Comparison of the PennWell maps with published State maps (Meents, 1977; Anonymous, 1982; Miller, 1983; Burroughs and Crawford, 1987) shows that the pipeline routes on the PennWell maps are slightly generalized for legibility, especially where pipelines are abundant in urban areas and in producing or refining districts.

We show crude-oil pipelines with diameters of at least 12 inches (pl. 2), consistent with the maps of the Congressional Research Service (1977) and the discussion of Beavers and others (1986). Our selection of individual pipelines matches that of Beavers and others (1986) except that we include a few 12- to 24-inch lines that extend from Missouri northward into Minnesota and eastward through Kentucky. We include the three large pipelines near the New Madrid seismic zone that were modeled by O'Rourke and others (1992). We omit a few short 12- to 30-inch lines in Ontario, western New York State and Pennsylvania, Mississippi, Alabama, and western Florida because they are largely isolated from the main part of the crude-oil network.

The Congressional Research Service (1977) termed "major" those petroleum-products pipelines with diameters of 10 inches or larger. The network of major lines is widespread, but more than 70 percent of the products flow through a few large lines southeast of the Appalachian Mountains (Beavers and others, 1986). The rest of the flow moves through a dense network of major lines northwest of the Appalachians. We simplify the dense network because of its complexity and because it carries less than 30 percent of the total flow, so we show (pl. 2) only the pipelines described and mapped by Beavers and others (1986). Most of the omitted lines are between Pennsylvania and Missouri.

The Congressional Research Service (1977) distinguished natural-gas pipelines with diameters of at least 24 inches from narrower lines. Gas flow is concentrated along 11 pipeline routes that extend northeast up the Mississippi Valley and two routes that extend up the southeast side of the Appalachian Mountains, with a typical route containing three individual pipelines, 20–42 inches in diameter (Beavers and others, 1986). We show as single lines (pl. 2) the main routes mapped by Beavers and others (1986). In addition to these 13 main routes, we show four pipeline routes omitted by Beavers and others (1986) but that, by 1990, each contained two or three 20- to 30-inch pipelines (pl. 2) (PennWell Publishing Company, 1990b). One route trends east from Louisiana through Florida, and three spread north and east from northeastern Kansas to Chicago and Minnesota. However, we omit a few short, large-diameter lines in the dense networks of collection lines in the gas fields of western Pennsylvania, Ohio, and West Virginia, and we omit a few distribution lines in and between the large urban areas that are scattered across the northern part of the mapped area.

The maps and text published by the Congressional Research Service (1977) show that the three pipeline networks have different geographic distributions and flow patterns. From data of Cuff and Young (1986) and Smith (1987), we infer that these flow patterns persisted through at least the middle 1980's. Pipelines carry nearly all the crude oil north and northeast from the Gulf Coast up the Mississippi Valley and northeast from Texas to refineries. An additional two-thirds as much oil enters the Northeast by ship as imports to the refineries of Philadelphia and New Jersey. Nearly all of the petroleum products also move north and east by pipeline, although large volumes move by river and intracoastal and transoceanic tankers. Products pipelines from Texas and Louisiana are more widely dispersed geographically than are the crude-oil pipelines. The single largest pipeline volume of petroleum products moves up the Eastern Seaboard, thereby largely avoiding the Mississippi Valley. In contrast to oil and products, natural gas moves almost entirely through pipelines and through the largest number of pipelines, but the gas network is the most tightly concentrated geographically. Most gas pipelines are grouped into a narrow belt that connects Texas and Louisiana along the Mississippi Valley to urban areas between Illinois and the Boston-Washington urban corridor. In fact, this northeastward flow of gas was the largest single bulk flow of energy in the Nation as of 1974. A single main pipeline route carries a smaller amount of gas up the Eastern Seaboard.

Thus, a substantial part of the East's energy supplies passes through pipelines that cross or pass near the seismically active central Mississippi Valley. In addition, nearly half the northeastward flow of crude oil moves through pipelines intersecting near Patoka, Ill. (Meents, 1977; Beavers and others, 1986). The Patoka intersection is in a zone of scattered small to large earthquakes that stretches north from the New Madrid seismic zone into southern Illinois and southwestern Indiana (Nuttli, 1979; Langer and Bollinger, 1991; Obermeier, Munson, and others, 1991; Munson and Munson, 1991).

The pipeline networks consist chiefly of collection facilities at the southwest ends, distribution facilities at the northeast ends, and pipelines and pumping stations in between, where seismic hazard is greatest. The pumping stations could be affected directly by shaking, liquefaction, lateral spreading, or landslides, and they could be affected indirectly by disruption of their remote power sources or damage to their emergency batteries. However, if the pipeline itself is not ruptured, damage to a few pumping stations need not interrupt flow because nearby stations can maintain flow at reduced rates (Beavers and others, 1986; Ariman and others, 1990).

In contrast to pumping stations, damage to any part of a pipeline can interrupt flow along the entire line. Pipelines in the mapped area are unlikely to be broken directly by fault offsets because earthquakes rarely rupture the ground surface in the East. Usually, earthquakes elsewhere do not damage pipelines through shaking or bending. Instead, most damage occurs through axial compression caused by liquefaction, subsidence, lateral spreading, or large landslides (Nelson and Baron, 1981; Ariman, 1984; O'Rourke and McCaffrey, 1984; Ariman and others, 1990). Pipelines can fail by shortening even where permanent ground deformation is extensional (O'Rourke and Lane, 1986). Unburied or shallowly buried pipelines can buckle like beams and lift off or out of the ground, often without rupturing or otherwise interrupting flow. In contrast, deeper buried or larger diameter pipelines are more likely to shorten as thin shells by wrinkling along a single circumference with consequent rupturing and interruption of service (Ariman, 1984; Yun and Kyriakides, 1986; Ariman and Lee, 1990). Finally, shaking can have a long-term effect on corroded pipelines by increasing the number and frequency of leaks, accelerating aging, and permanently increasing maintenance costs (Isenberg, 1986). Ruptures and leaks in crude-oil or products pipelines can pollute ground water and streams, whereas damage to gas lines is more likely to cause fires (Beavers and others, 1986). Damage of all types is most likely at river crossings where slopes are greatest, pipelines commonly have curved shapes, and liquefiable sediments are thickest and most abundant (O'Rourke and McCaffrey, 1984; Ariman and others, 1990). Most pipeline damage at river crossings results from landsliding and lateral spreading. Indeed, Beavers and others (1986) and Ariman and others (1990) did not expect welded steel pipelines to fail except at large landslides or lateral spreads. At these places, older pipelines that might not have been welded to modern standards pose a particular threat (O'Rourke and McCaffrey, 1984). A New Madrid earthquake of M_S 7 to 8 could break pipelines as far as 100 to 200 km northwest or southeast of the seismic zone, with each pipeline possibly being broken at several places over several hundred kilometers of its length (Applied Technology Council, 1991).

The three energy-transportation networks differ in their sensitivity to disruption (Beavers and others, 1986). Crude oil and petroleum products, being mostly liquids at room temperatures and pressures, can be stored to some extent in the Northeast as cushions against interruptions or fluctuations in supplies. However, there is little gas storage capacity there (Beavers and others, 1986; Cuff and Young, 1986), and the tight geographic concentration of gas pipelines in the central Mississippi Valley provides few alternative routes from the Gulf Coast to the Northeast. Also, in the middle 1980's nearly half the residential natural-gas customers in the Nation were in the densely populated States between Massachusetts and Missouri. The possible user loss from earthquakes that rupture natural gas pipelines in the New Madrid seismic zone is large and widespread.

The connectivity between the strands of a complex network influences the degree to which flows can be shunted from a damaged part of the network onto alternative paths. Connectivity of the North American pipeline networks is unclear (Beavers and others, 1986). For example, the PennWell maps show that ownership of each pipeline network is scattered among many companies; the pipeline owners are likely to be in competition. An indicator of competition is that, even among the largest pipelines, several routes contain two or more pipelines of different ownership. Plate 2 shows examples near Nashville for natural gas pipelines, near Chicago, St. Louis, and Des Moines for crude oil, and near Little Rock for petroleum products. Therefore, even if the equipment were in place to allow connectivity at a pipeline intersection, multiple ownership could raise financial, legal, and procedural barriers to making the connection.

We can indicate connectivity only indirectly on plate 2. The PennWell maps show pumping stations along all pipelines, color coded by pipeline ownership. Some intersecting pipelines of the same kind have pumping stations that coincide within the apparent resolution of the PennWell maps, and we take that coincidence to indicate possible connectivity. Some of the maps show transfer points between intersecting pipelines, so connectivity there is at least likely. In general, where pipelines of the same kind intersect far from a large market, we have connected them on plate 2 (for example where seven large crude-oil lines meet at Patoka, Ill.). Where lines of different ownership intersect near a large city, we have left a small gap at the site of the change in ownership (for example, crude-oil lines near Chicago and St. Louis).

Finally, excess capacity in a pipeline network might provide some protection against damage to a few lines in the network, much as it does in a transportation network. Excess capacity in pipelines that carry liquids could be realized by pumping at higher velocities, whereas gas-carrying pipelines could be pumped at higher pressures. However, excess capacity is likely to vary with the age and design of pumps, pipelines, and related equipment. Available excess capacity will also vary with the pumping velocities and pressures already in use, and these vary with the selling prices of the pumped fluids. Thus the protection provided by excess capacity has inherent uncertainties and fluctuates with time.

DAMS

Dams are critical structures, partly because of their expense but mostly because of the deaths and destruction that sudden dam failures can cause downstream. For example, Jansen (1980) summarized recorded dam failures and their often disastrous consequences worldwide since 1219. Worldwide, earthquakes have caused only a small fraction of known dam failures or damaging accidents, and most of the dams were small (Ambraseys, 1960; Chopra, 1968; Jansen, 1980; Committee on the Safety of Existing Dams, 1983). Two hundred eighty-five large U.S. dams failed or were damaged through 1979, but earthquakes damaged only three and caused none of the failures (Committee on the Safety of Existing Dams, 1983). Nonetheless, the large potential consequences of an earthquake-caused dam failure within the mapped area justify representing dammed impoundments on plate 3.

We used dam and reservoir characteristics that others had digitized from the nationwide compilation of Ruddy and Hitt (1990). The compilation was current as of January 1, 1988. The digitized compilation summarizes 799 reservoirs and controlled natural lakes within the mapped area (pl. 3) that have normal capacities of at least 5,000 acre-feet (6×10^6 m^3). Normal capacity is "the total storage space, in acre-feet, below the normal retention level, which includes dead storage but excludes flood control or surcharge storage" (Ruddy and Hitt, 1990, p. 11). The Committee on Safety Criteria for Dams (1985) recommended using the "normal full pool" (p. 129) for dam safety evaluations, and we use the normal capacity as the corresponding volume measure. Ruddy and Hitt (1990) compiled their data as a contribution to mapping surface-water development, so they excluded sedimentation ponds, tailings ponds, and other mining or industrial impoundments because most are off streams and do not affect stream flow. Some of these off-stream impoundments could pose a local threat if their dams were shaken, but most are likely to be small so their aggregate threat should also be small. For example, Ruddy and Hitt (1990) reported that reservoirs larger than 5,000 acre-feet contained about 98 percent of the Nation's usable storage capacity.

The dams and associated impoundments vary widely in age, size, and purpose. Nearly all predate the 1980's, but most were built in this century (Ruddy and Hitt, 1990). About half impound less than 25,000 acre-feet (31×10^6 m^3) of water. Among these smaller dams, recreation was the most common reason for construction, followed by improving the water supply. The most common reason for building the larger dams, which impound more than 25,000 acre-feet, was to control floods, followed by power generation, navigation, recreation, and water supply. From these purposes, we infer that the economic and social impact of the failure of a large dam is likely to last longer and reach farther from the physical damage of the resulting flood than would the impact of the failures of several small dams with the same total normal capacity.

Dams vary widely in setting. Large dams could threaten the largest areas, but large dams tend to be far from cities where land is cheaper (Raphael, 1956). In contrast, a few small reservoirs on the edges of towns or cities have failed and killed tens to thousands of people (Jansen, 1980). The size of the flood from a failed dam depends on the inflow to the reservoir, the outflow from it, the reservoir size and shape, and the channel geometry downstream (Land, 1980). Infiltration tends to decrease the flood volume downstream, but volume can increase if the flowing water incorporates loose material from its channel (Costa, 1985; Costa and Schuster, 1988). The amount of human devastation that might be caused by a dam failure depends strongly on the population and development downstream from the dam and on the degree of warning (Costa, 1985).

Dams vary in construction type and the most likely modes of failure. Dams less than 15 m (48 ft) tall are overwhelmingly of earth-fill or rock-fill construction (Costa, 1985). Among dams taller than 15 m, earth-fill and rock-fill dams are somewhat more common than concrete or masonry dams in western Europe and the United States, but a fill dam is slightly more likely to fail in these regions (Committee on the Safety of Existing Dams, 1983). Among concrete and masonry dams, gravity dams are the simplest and most common type; they tend to fail by overturning or sliding on their foundations (Committee on the Safety of Existing Dams, 1983). The behavior of concrete gravity dams during seismic shaking is complicated by, for example, the likelihood of coupling between dam and reservoir water, which depends on the fundamental frequencies of the dam and the water mass (Chopra, 1968). Concrete arch dams are the most complex and highly engineered. Fill dams can fail because of excessive seepage or structural instability of the slopes or foundations, any of which can be complicated by other factors such as fissuring from differential accelerations, differential settling, or overtopping by waves generated by landslides or seismic seiches (Newmark, 1965; Committee on Safety of Existing Dams, 1983; Costa, 1985). Because the age, size, purpose, setting, type, and failure mode of dams varies so much, we make only the following generalizations.

Three lines of argument indicate that all the dams in the digitized data set could be hazardous if they fail during seismic shaking. A fourth line of argument indicates that dams whose impoundments have normal capacities greater than about 25,000 acre-feet probably place proportionately more people and economic value at risk than do the smaller dams. Therefore, plate 3 shows all dams with normal capacities of at least 5,000 acre-feet but distinguishes those with impoundments larger and smaller than 25,000 acre-feet.

First, a survey of past dam failures indicates that dams impounding more than about 5,000 acre-feet of water could be hazardous if they fail during shaking. Jansen (1980) summarized 41 dam failures or damaging accidents and their consequences. Sixteen of the failed dams caused deaths or severe destruction, and descriptions of these failures contain estimates of the normal capacity or of the water volume released in the flood. We use normal capacity and volume released interchangeably because the definition of normal capacity given previously approximates the water volume likely to be released if a dam breaches down to its foundation when holding its typical amount of water. Jansen's (1980) descriptions indicate that a dam failure that causes deaths or severe destruction is likely to remove a large part of the dam down to its foundation. These fatal or severely destructive failures involved impounded reservoirs of all sizes. Six of the failed dams impounded fewer than 5,000 acre-feet, but five of the six were of an age or poor construction that likely are not representative of present dams in the mapped area, and the sixth failure involved movement on an underlying fault, a condition that is atypical of the mapped area. The next smallest impoundment was 6,300 acre-feet (7.8×10^6 m^3), which was released when a Spanish dam failed in 1959. Thus, if we show dams impounding more than 5,000 acre-feet, we are likely to include the dams whose failure would threaten death to people or severe destruction to property.

Second, documented failures of landslide dams also constrain the size of the smallest impoundment likely to present a danger in the map area. Costa and Schuster (1991) summarized characteristics of 493 landslide dams around the world. Most eventually failed, and 24 of the failures are known to have caused deaths, severe destruction in downstream settlements, or floods or debris flows severe enough that we infer they would have been fatal had they flowed through settlements. The failure mechanism is known for 107 of the landslide dams. Ninety-seven failed by overtopping alone and another five by overtopping combined with another process. Only one failure was partial. Thus, we assume that failing landslide dams typically fill completely, and then breach to their bases similar to engineered dams, releasing the entire impounded volumes. Therefore, we treat the impounded volumes as roughly equivalent to normal capacities.

The volumes of lakes impounded behind the landslide dams just before failure is known or estimated for 13 of the 24 fatal or severely destructive failures. The volumes range from 2,026 to 551,000 acre-feet (2.50×10^6 to 6.79×10^8 m^3). However, the only impounded volume smaller than 5,000 acre-feet was in southern Chile, so settlement patterns and warning conditions at this failure might not represent those in the mapped area. Thus, the record of landslide dams worldwide contains little or no evidence that impoundments smaller than 5,000 acre-feet are likely to threaten lives in the mapped area. We conclude that the landslide-dam data are consistent with our decision to show only dams impounding at least 5,000 acre-feet (pl. 3).

Third, we further assess the cutoff at 5,000 acre-feet by considering peak discharges of the floods produced by failures of constructed and natural dams. Costa and Schuster (1988, fig. 12) compiled information on failures of earth-fill and rock-fill dams and failures of natural dams formed by landslides, moraines, and glaciers. They plotted the peak discharges of the resulting floods as a function of the potential energy of the impounded water before failure. Peak discharge increases more or less linearly with potential energy for a given type of dam. Costa and Schuster (1988) fitted a straight line to the high-discharge side of the cloud of plotted points, as a conservative estimator of the largest peak discharge to be expected for a given potential energy. We calculated potential energies for a range of normal capacities from 5,000 to 500,000 acre-feet and used Costa and Schuster's (1988) straight-line estimator to convert the energies to predicted peak discharges. We estimate that failure of a dam with a normal capacity of 5,000 acre-feet could produce a peak discharge as large as 7,000 m^3/s (250,000 ft^3/s).

Jansen (1980) gave estimated peak discharges for seven of the 16 dam failures that caused deaths or severe destruction. The two smallest peak discharges were 1,130 and 1,700 m^3/s (40,000 and 60,000 ft^3/s) from dams that failed in 1864 and 1874. These dams were too old to represent those now in the mapped area. The five other peak discharges ranged from 8,500 to 35,000 m^3/s (300,000 to 1,200,000 ft^3/s), all of which exceed the 7,000 m^3/s that could be discharged by failure of an impoundment containing 5,000 acre-feet. Thus, if we show the locations of all dams impounding at least 5,000 acre-feet we will probably include all dams posing a threat of death or severe destruction in the mapped area.

Fourth, we consider storage ratios as a way to divide dams into those that are relatively more and less dangerous in the mapped area. The storage ratio of a reservoir is roughly the ratio of its capacity to the annual runoff of the dammed stream. In general, larger streams have larger floods, and settlements along a stream are likely to be best prepared to withstand floods typical of that stream. If both generalizations are valid in the mapped area, then the failure of a dam with a large storage ratio might be more likely to generate a flood for which downstream communities are unprepared than would the failure of a dam with a small storage ratio. The larger the storage ratio, the greater the potential for death or severe destruction in the event of a dam failure. In particular, we wonder whether there is some normal capacity that separates large dams with large storage ratios from small dams with small storage ratios.

The digitized data set contains storage ratios and normal capacities for 43 of the 799 dams in the mapped area. Of these 43 dams, 30 of all sizes have storage ratios of 0.4 or less. If these dams failed while holding their normal amount of water, they would release floods less than half the size of the annual flows of the streams that they impound. The remaining 13 dams are large, and they could release much larger floods in proportion to the annual flows of their streams. These dams have normal capacities of at least 18,000 acre-feet (22×10^6 m^3), and 10 of the 13 have storage ratios between 1.0 and 8.5 and normal capacities of at least 71,000 acre-feet (88×10^6 m^3). From these considerations and for convenience, we choose 25,000 acre-feet as the approximate boundary between large dams whose failure could produce a larger and more dangerous flood than thus far experienced on their streams and small dams capable only of producing floods more in line with historical experience on their streams. We emphasize that, although such a boundary does appear to exist, its location at 25,000 acre-feet is uncertain because the value is based on storage ratios from only five percent of the dams in the mapped area (pl. 3).

Having divided the dams into those larger and smaller than 25,000 acre-feet (pl. 3), we speculate about whether some parts of the mapped area might have unusually high potentials for fatal or severely destructive flooding if earthquakes were to break dams. Both size classes are nearly ubiquitous in the map, area except in Florida and along the Gulf and Atlantic Coasts. However, the larger dams are most abundant in three areas: in the southwestern part of the mapped area, from Louisiana to eastern Kansas; in densely settled western Pennsylvania and eastern Ohio; and in and near the southern Appalachians, from northern Alabama and northern Georgia to Kentucky. The latter area includes the dams of the Tennessee Valley Authority. The smaller dams are most abundant in two areas: in eastern Oklahoma and eastern Kansas, and in the densely populated region from Illinois to Pennsylvania. Few dams of either size are within 100 km (60 mi) of the New Madrid seismic zone, except to the north in southern Illinois. Dams of both sizes are abundant in seismically active southern Illinois. They are also abundant in southwestern Indiana, where damaging historic earthquakes are unknown but where recent geologic evidence indicates the possibility of large prehistoric earthquakes (Obermeier, Munson, and others, 1991; Munson and Munson, 1991). Thus, taken together, dams might be less susceptible to earthquake damage than transportation and energy-supply lifelines, both of which cross the New Madrid seismic zone. What threat there is to dams might be concentrated more in southern Illinois and southwestern Indiana than in the New Madrid seismic zone.

NUCLEAR FACILITIES

Nuclear power plants and related facilities are critical structures because they concentrate large amounts of radioactive material at single sites. Severe seismic damage to a nuclear facility might release some of the radioactive material, contaminating surrounding areas. Accordingly, plate 3 shows locations of 44 large nuclear facilities that are regulated by the Nuclear Regulatory Commission (U.S. Geological Survey, 1988). These facilities consist of 37 nuclear electric-power plants, six uranium fuel-cycle facilities, and one low-level waste storage facility at Barnwell, S.C. The list of 44 facilities was current in January, 1988. We digitized their locations from a 1:7,500,000 map (U.S. Geological Survey, 1988).

Plate 3 does not show nuclear facilities of the Departments of Defense or Energy. Also, it does not show non-power reactor sites because their power outputs indicate that they contain much smaller amounts of radioactive material than do the power reactors (U.S. Geological Survey, 1988). The non-power reactors generate less than 10 MW each, whereas a typical power reactor generates about 1,000 MW per unit, and some sites contain two or three units.

Most of the 44 large nuclear facilities are clustered in two parts of the mapped area (pl. 3), which are farther than 300 km (190 mi) from the New Madrid seismic zone. One cluster stretches across the densely urbanized northern part of the mapped area, from Iowa to Pennsylvania; and the other is in and southeast of the Tennessee Valley Authority power system (pl. 3). Three nuclear power plants are about 300 km from the seismic zone: the Callaway plant in central Missouri, the Arkansas plant in central Arkansas, and the Browns Ferry plant in northern Alabama. The only facilities within 300 km of the seismic zone are two uranium fuel-cycle facilities, in eastern Missouri and southern Illinois.

SUMMARY AND DISCUSSION

Much of U.S. society is tightly interconnected and sustained by large, fast, long-distance flows of information, fuels, raw materials, finished goods, and food. The flows move along the interconnected strands of lifeline networks such as limited-access highways, railroads, and pipelines. Some of the pipelines cross or pass near the New Madrid seismic zone, and spatial relations on plate 2 indicate that several lifeline networks appear to have bottlenecks there. The clearest example of a bottleneck, noted by several previous workers, is in the network of large natural-gas pipelines that cross the seismic zone in a tight cluster to supply much of the energy used in the Northeast and Upper Midwest (pl. 2). Limited-access highways, railroads, and crude-oil pipelines form more widely spread networks but might also have bottlenecks at or near the seismic zone (pl. 2).

Large urban areas, large dams, and nuclear facilities are mostly distant from the New Madrid seismic zone (pl. 3). However, a diffuse cluster of large dams is in southern Illinois and southwestern Indiana, where damaging earthquakes are less common than in the New Madrid seismic zone but are still more common than in other parts of the Central United States.

The immediate physical losses and the longer term economic losses of lifeline damage from moderate to large earthquakes in the New Madrid seismic zone could reach $10 to $20 billion in the Central United States (Applied Technology Council, 1991; Development Technologies, Inc., 1992). Development Technologies, Inc. (1992) concluded that these losses could have a severe but probably not a devastating impact on national financial and insurance industries. However, the estimates do not include losses to critical structures or to urban areas with their abundant non-critical structures and local lifeline networks. Losses to critical structures and urban areas might exceed those to lifelines (Central United States Earthquake Preparedness Project, 1985).

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