U.S. Earthquake Hazards: Real but Uncertain in the East

To most residents of the eastern United States, destructive earthquakes are solely a California phenomenon. They are wrong. Major earthquakes have struck the East, and it must be assumed that they will strike again. Damaging quakes may seem to be an unlikely possibility to many because the last one occurred in 1886, near Charleston, South Carolina. That one killed 60 people, caused extensive damage in and around Charleston, and was felt as a strong shaking as far away as Chicago.

The Charleston quake was not the only major one in the East. During the winter of 1811–1812, the first of three major earthquakes that winter centered near New Madrid in far southeastern Missouri caused potentially damaging ground shaking over 600,000 square kilometers, an area 20 times larger than the equivalent area for the great San Francisco quake of 1906. Another major earthquake occurred off Cape Ann, Massachusetts, in 1755, probably less than 100 kilometers from downtown Boston.

Many researchers and policy-makers have become increasingly concerned about the danger of underestimating their own ignorance of the problem. This concern has been particularly evident in recent attempts to determine the legal design requirements of nuclear power plants in the East. The proceedings have been somewhat muddled because, unlike the reasonably straightforward situation in California, no one knows what causes earthquakes in the East, where they may occur in the future, or how large they may be when they do occur. Participants on both sides of the debate admit that current federal regulations covering seismic risk assessment are awkward, if not totally inadequate, when applied to the peculiar and poorly understood earthquakes in the East. Changes in the regulations can be expected following a planned reevaluation of present criteria, but researchers are only just beginning to make sense of eastern seismicity.

The increasing awareness of possible seismic hazards in connection with nuclear plants has pointed up the problems of applying federal siting regulations and helped accelerate the study of eastern seismicity. For example, doubts were raised in recent years concerning the seismic safety of proposed plants at North Anna, Virginia, and Indian Point, New York (60 kilometers from New York City). At North Anna, the first sign of possible trouble was the uncovering of a fault (a break between adjacent blocks of rock) during excavation for the reactor foundation. To be considered a danger, a fault must still be active or have been active in the recent geologic past. In California, most faults are associated in some way with the continuing movement of the Pacific Ocean crust and part of the California coast to the northwest. If part of a fault binds, stress builds up, and an earthquake will result when the fault suddenly snaps free. Thus, many faults in California remain active.

No such crustal movement has occurred on the East Coast. Still, the East is riddled with faults. Their discovery in an excavation does not surprise geologists. According to the theory of plate tectonics, the African continent slammed into the coast of what is now North America about 375 million years ago, pushing up the Appalachians in the process. The opening of the present-day Atlantic Ocean about 200 million years ago pulled the same rocks apart. Today, the resulting faults do not feel the strong forces that created them initially and many are buried beneath much sediment, but federal regulators must still decide if movement along them can cause a significant earthquake.

At North Anna, that question was answered in the negative by resort to the Nuclear Regulatory Commission's geologic criteria for fault capability. A "capable fault" can be one which has exhibited "movement at or near the ground surface at least once within the past 35,000 years or movement of a recurring nature within the past 500,000 years." Geologists can determine the age of fault movement by noting its effect on rocks and sediments of different ages. The NRC found the North Anna fault to have been long inactive, and seismological monitoring confirmed that only very low-level activity occurs in the area and is not associated with the fault.

The NRC's geologic criteria cannot be applied readily to the Indian Point area. There, too, a fault passes beneath one of the three reactor units, but it may be part of the well-known Ramapo fault system, a branch of which passes within 1 kilometer of the reactors. Nicholas Ratcliffe of the City College of New York has mapped the surface traces of the Ramapo system. He has determined a minimum age of fault movement of 150 million years. The problem with demonstrating any more recent movement is that most of the rocks in the area date from the opening of the Atlantic and are thus too old to throw any light on more recent fault movements.

Another means of demonstrating the capability of a fault that is allowed by NRC regulations involves the use of instruments to show that "macroseismicity" is associated with a particular fault. The term macroseismicity is not defined by the regulations and is taken by various geologists to mean anything from at least a quake of magnitude 3 (felt by some people) to one of magnitude 6 (typically causes slight damage to buildings). In any case, at the time of the NRC seismic safety hearings for Indian Point in 1976, no fault in the East had been associated with specific seismic events of any size and the data available at that time for the Ramapo system were poor. The hearing board was unanimous in concluding that the capability of the Ramapo had not been demonstrated.

Since the hearings, Yash Aggarwal and Lynn Sykes of Lamont-Doherty Geological Observatory believe that they have demonstrated unequivocally that the Ramapo system is seismically active. Their approach was to show instrumentally that small earthquakes are now occurring on the fault itself. They have located the foci, or the points of the initial rupture of rock, for about 10 microearthquakes of magnitude 1.5 to 2.9 (the magnitude scale is a logarithmic measure of seismic wave amplitudes). The foci fall on a plane that extends at an angle from the surface trace of the Ramapo to the southeast. This is consistent with the geologic evidence observed at the surface. They also determined the direction of slippage between adjacent sides of the fault during some of the quakes. The direction inferred from these focal plane solutions coincides with the general northeast-southwest direction of the Ramapo system.

In addition, Aggarwal and Sykes have estimated that there is a 5 to 11 percent probability that a reactor unit at Indian Point will experience an earthquake equaling or exceeding the largest quake previously expected. Their prediction is an extrapolation from microearthquakes, which often cannot be felt, to earthquakes of magnitude 5 and greater, sizes

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Fig. 1. Map of the earthquake hazard to be expected from ground shaking, developed by S. T. Algermissen and David Perkins of the U.S. Geological Survey from the historic seismic record. Seismic hazard is depicted as accelerations due to ground shaking (in terms of a percent of the earth's gravity) that have only a 10 percent probability of being exceeded in 50 years. Although the hazard in the East is lowered by the relative infrequency of large earthquakes, the total area in the East that has experienced destructive ground shaking at some time in the last 250 years is actually greater than that in the West.

at which buildings begin to be damaged. Only three such damaging quakes, of uncertain location, have been reported in the New York–New Jersey area in the last 250 years. A key step in their extrapolation is the choice of the ratio of larger quakes to smaller quakes. The best estimate of this value for the Ramapo area was one calculated for all of New York and New Jersey, although in general it does vary with location. The resulting probability is ten times higher than that estimated earlier by NRC seismologists using other methods. Aggarwal and Sykes concede that their estimate may be uncertain by a factor of 2 to 3, but they stress that, in their view, the presence of microseismicity on the Ramapo makes it all the more probable that the larger historical quakes also occurred on such faults. Therefore, the Ramapo system is likely to be capable of generating larger quakes.

Extrapolations aside, no one knows whether large earthquakes inevitably follow small ones in the East as is often the case in the West. For that matter, it is not known whether large quakes will again occur at Charleston, New Madrid, or Cape Ann. The peculiar seismic nature of the East is partly to blame. In California, seismologists can assume that a lack of large quakes on a section of historically active fault foretells a future rupture of the fault. The steady driving force of plate tectonics ensures that there will eventually be motion along the fault. In the East, even the largest historical shocks have not broken the ground to form the fault traces typical of California. Neither the driving force responsible nor the potential for further movement along these subsurface faults is known.

The first tentative steps toward understanding the generation of major historical quakes are now being taken. For example, recent studies of the New Madrid area suggest an association between its large historical quakes, present-day seismicity, and an apparent subsurface fault. Drawing on historical records of the time, Otto Nuttli of St. Louis University estimates that the 1811–1812 quakes had magnitudes of 7.2, 7.1, and 7.4; that is, they were all at least several times larger than the destructive San Fernando quake of 1971. There, the damage amounted to $1 billion and 62 people died. The destructive capacity of any one of the New Madrid quakes was actually much greater than a comparison of these magnitudes might suggest. Earthquakes of equal magnitude can cause more damage in the East than in the West because their seismic energy is transmitted more efficiently by the rocks they pass through. Nuttli has calculated that their transmission is up to ten times more efficient in the East.

Another measure of destructive potential is intensity at a given location, as is now measured by the Modified Mercalli Scale. This scale rates the way people feel a quake and the kind of damage it does on a scale of I (unnoticed) to XII (catastrophic). Nuttli rates the intensity at the center of the first New Madrid quake as X (disastrous, many buildings destroyed) and in the Memphis area as IX (ruinous, houses begin to collapse). Intensities of VI (strong, some damage from falling objects) were felt out to about 800 kilometers, whereas the same intensity extended no more than about 80 kilometers from the center of the San Fernando quake.

The characteristics of the low-level seismicity observed in the New Madrid area today suggest that it is occurring on the same fault or system of faults along which the 1811–1812 quakes occurred. A team from St. Louis University, headed by William Stauder, has used a seismometer network to determine the geographical locations, or epicenters, of the small quakes in the vicinity of the historical quakes. Most of the epicenters lie near one of two lines that intersect near the Missouri-Tennessee border. Fault plane solutions for several moderate-sized events, as well as for some composite groups of events, indicate a mixture of both vertical and horizontal movement in the same direction as the two lines of epicenters, according to Robert Herrmann of St. Louis.

Herrmann points out that one leg of the apparent fault system is a possible candidate for the source of the 1811–1812 shocks. If it is a fault, it is long enough to have stored all the energy released during those quakes. Also, progressive breaks from the southwest to the northeast along this fault would explain historical reports of a similar progression of epicenters.

Despite the St. Louis team's feeling that they have probably located the still active fault responsible for the 1811–1812 quakes, that fault could not be considered capable under the NRC regulations. Those quakes produced no "movement at or near the ground surface." With no fault identified in a regulatory sense, the rules say that the observed seismicity cannot be directly related to it.

When a particular fault cannot be shown to be capable (none in the East ever has been), NRC regulations allow the level of seismic hazard to be determined by the use of the "tectonic province" method. In this approach, nearby historical earthquakes are grouped into geologically defined tectonic provinces, regions "characterized by a relative consistency of the geologic structural features contained therein." The greatest earthquake intensity expected at a given site would result from having the largest historical quakes occur at the point within its province nearest the site. The use of the tectonic province method has brought complaints of manipulation, or "geological gerrymandering," of province boundaries in order to keep large quakes as far as possible from proposed nuclear power plants. In support of this contention, the Indian Point hearing board noted that the NRC staff had used different arrangements of tectonic provinces in New England in determining the maximum intensities for different sites. As in the case of demonstrating fault capability, the unusual nature of seismicity in the eastern United States complicates this type of hazard assessment.

In the East, seismic activity does not always coincide with regional sets of geologic structures. In the Southeast, Gilbert Bollinger of Virginia Polytechnic Institute and State University has included 90 percent of the activity noted in the historical record within three seismic zones, two of which cut across regional geologic structures. His southern Appalachian seismic zone does follow the Appalachians from northern Alabama to western Virginia. The central Virginia zone is contained within but trends across the structural grain of the Piedmont plateau that parallels the Appalachians. The South Carolina–Georgia zone cuts across both the coastal plain and the Piedmont. In the Northeast, a Boston-Ottawa seismic zone has been proposed by a number of workers. It runs from offshore of Massachusetts, across the Appalachians, and into Canada. Thus, as the Indian Point hearing board noted, groupings of seismic activity in the East often form "seismotectonic" zones rather than the tectonic provinces specified by NRC regulations.

An underlying problem with anticipating the destructiveness of eastern earthquakes is the lack of a comprehensive theory for their generation. The plate tectonic theory adequately explains the cause of quakes along plate boundaries, as in California, but not within a plate. The eastern United States is actually in the middle of the North American plate, which extends from the Mid-Atlantic Ridge to the Pacific Coast. Its earthquakes occur without the large relative movements of the earth's crust that are so evident in the fence-bending antics of California quakes. Even so, they must still result from the buildup of stress and its sudden release as the rock fails.

Sykes has suggested that intraplate quakes are also linked to plate motions, both past and present. According to his model, broad zones of weakness in the crust were created in the distant geologic past by the opening and closing of ocean basins. Since then, the stresses that formed these zones subsided, eliminating the initial seismic activity. Eventually, different processes created new stresses, usually of a different type and from a new direction. These stresses reactivated the zones of weakness, according to Sykes, producing the seismicity observed today.

Sykes believes that there are many examples throughout the world that support his model. On the East Coast, he points out that the apparent Boston–Ottawa zone, which includes the epicenter of the Cape Ann quake, forms a landward extension of the New England Seamount Chain, a string of old submerged volcanoes off the continental shelf. This alignment and the chemical composition of rocks in New England suggest to Sykes that the two features are a single zone of crustal weakness that once allowed magma to rise to the surface. Now, under new stress, it is giving slightly and producing earthquakes. He also sees a connection between the Blake Fracture Zone, an inactive submarine fault formed during the opening of the Atlantic, and the South Carolina–Georgia seismic zone.

Charleston Studies

Studies around the Charleston area, conducted largely by the U.S. Geological Survey, have shown this explanation of intraplate seismicity to be a possible but not yet a required mechanism for the observed activity. So far, investigators have identified a close association between the location of the 1886 shock and present-day seismicity. Both may in turn be related to possible massive intrusions of rock from the mantle beneath the Charleston area, which could be related to the Blake Fracture Zone.

Bollinger and T. R. Visvanathan of the University of South Carolina searched historical records for an indication of the forthcoming large quake of 31 August 1886. During the 50 years before, there were no discernible differences between the frequency of reported quakes in South Carolina and in the surrounding states. No shocks greater than intensity V (rather strong, widely felt) seem to have occurred between 1698 and the day of the Charleston quake, which was intensity X.

Ninety-two years later, the seismic activity in the Charleston area has still not returned to its pre-1886 level, according to Arthur Tarr of the USGS in Denver. The present-day seismicity is concentrated along a line running northwest-southeast near the center of highest intensity during the 1886 quake. A single focal plane solution as well as a composite solution indicate slippage along the same line formed by the epicenters. The stress causing the slippage appears to be a compressive force from the northeast, which is generally consistent with a stress being created by a push from the Mid-Atlantic Ridge, Tarr says. Unfortunately, the situation does not appear to be that simple, he adds. A pocket of activity near the town of Bowman, South Carolina, 100 kilometers northwest of Charleston, does not appear to be related in a simple way to the activity near Charleston. Although it lies on an extension of the line of Charleston activity, there is now no activity between them. In addition, focal plane solutions for the quakes around Bowman indicate a different direction for the stress causing them than for those near Charleston.

A possible explanation for these and other small isolated areas of seismicity is the amplification of stress by relatively small geologic structures within the crust. Geophysical surveys of the Charleston area indicate that current seismic activity is closely associated with a number of anomalous physical properties of the crust. Timothy Long of the Georgia Institute of Technology and J. W. Champion of Chevron Oil Company believe that an intrusion of mantle-like rock, revealed in gravity surveys of the area, may have been capable of increasing the general levels of stress and triggering the 1886 quake. Martin Kane of the USGS in Denver has noted that similar gravity anomalies also appear near but never directly below the epicenters of six other major eastern earthquakes, including the New Madrid and Cape Ann events. The Bowman activity is also near a gravity anomaly, but there are also anomalies scattered about the area that show no unusual seismic activity.

If some intrusive structures really can affect seismicity, they may differ in some way from those that cannot, allowing their detection before a major quake. It is generally supposed that the intrusions could concentrate stress around their edges because their rigidity differs from that of the surrounding rock. David Campbell, also of the USGS in Denver, has calculated that, in order to achieve a high concentration of stress, an intrusive rock must be less rigid than the surrounding rock. Rock derived from the lower crust or mantle would only be less rigid if water were added to it. Thus, hydration, and possibly the proximity of an old fault or other line of weakness, may be a prerequisite to the triggering of earthquakes.

Although reactivation of old seismic sources by various means is often proposed as the underlying cause of eastern seismicity, the apparent variety and inaccessibility of these sources will require considerable time and effort to understand their workings. In the meantime, decisions concerning the location and design of vulnerable technology such as nuclear power plants will be made. A forthcoming study by the NRC is expected to clarify the application of seismic siting criteria to the East. Many researchers believe, in light of what remains to be learned, conservative design should prevail.—RICHARD A. KERR