Seismic Analysis of Relict Liquefaction Features in Regions of Infrequent Seismicity

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In regions of infrequent seismicity where strong-motion data are unavailable, seismic parameters for engineering design are commonly inferred from historical intensity data. However, historical data often prove inadequate, as demonstrated by recent studies of relict liquefaction features. In appropriate environments, seismic analysis of liquefaction features using geological and geotechnical engineering procedures provides an additional means of estimating the shaking severity of past earthquakes, including prehistoric events. The procedure first requires a search for relict liquefaction features in areas where past strong earthquakes are suspected. Geotechnical parameters are then measured at sites where liquefaction features are found, and the magnitude and peak accelerations required to produce the features are estimated. Where a thorough field search of liquefiable sediments reveals no evidence of disturbance, upper limits can still be placed on the maximum possible past ground motions. Studies to estimate past ground motions during the Holocene Epoch (the past 10,000 years) have been undertaken in the eastern and central portions of the United States. In the eastern United States, this analysis suggests that the ground motions of the Charleston, South Carolina, earthquake of 1886 were lower than those suggested by interpretation of Modified Mercalli intensity data. In the central United States, preliminary analysis of liquefaction features in southern Indiana and Illinois shows that a very strong prehistoric earthquake or earthquakes occurred in the Wabash Valley seismic zone, far from the epicentral region of the 1811–1812 New Madrid earthquakes.

The shaking levels of earthquakes have traditionally been estimated on the basis of seismic instrumentation data, historical intensity data, or measurement of fault movements. Earthquake intensity data are limited by the short historical record and are generally inadequate in regions of infrequent seismicity. Intensity data are influenced by varying factors such as soil conditions, quality of building construction, and human interpretation, so estimates of ground motions based on earthquake intensities can be misleading. A more direct means for estimating past ground motions involves measurement of fault displacement, but this method cannot be used where the locations of the causative faults are unknown or where the faults are unexposed. In addition, fault studies cannot always determine whether the movements were associated with earthquakes.

Now, though, an additional approach for estimating past ground motions has been developed by the authors' combination of geological and geotechnical engineering methodologies. Liquefaction leaves in the geologic record features such as steeply dipping sand-filled fissures (dikes), gently dipping sand-filled fissures (sills), and vented sand (sand boils or blows). Geotechnical analysis of the source sediments for these features provides a means for estimating the severity of seismic shaking. Methods that relate geotechnical parameters [Standard Penetration Test (SPT) blowcounts, shear wave velocities, etc.] to liquefaction development can be used to estimate the magnitude and peak accelerations of earthquakes required to cause liquefaction of deposits of known density. In addition, where there are different generations of liquefaction features, dating provides a means for estimating the recurrence of earthquakes large enough to cause liquefaction. This information can extend the knowledge of the seismicity of a region into prehistoric times.

Such analysis of previous seismicity is most applicable where liquefaction susceptibility has been moderate to high through time and where the susceptibility is fairly constant over broad areas. Having low susceptibility can result in limitation of liquefaction effects to such a few sites over a restricted geographic area as to make the field search extremely difficult. The settings most susceptible to liquefaction contain loose, sandy sediments at shallow depth and are saturated with a high water table (*1*). In ideal situations, this analysis has the following results: (*a*) it determines the epicentral area of previous strong (i.e., liquefaction-producing) earthquakes, (*b*) it estimates the magnitude and peak acceleration levels consistent with observed liquefaction evidence, and (*c*) it estimates the attenuation pattern of the accelerations.

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METHODOLOGY

The basic approach of the seismic analysis procedure involves the following:

1. Determining the areal extent of liquefaction and the age of the liquefaction features,
2. Determining the severity of liquefaction at specific sites,
3. Determining the liquefaction susceptibility of the soils at specific sites in terms of geologic factors and geotechnical engineering parameters, and
4. Using liquefaction prediction methods to place limits on the ground motions that would be consistent with the liquefaction evidence at each site.

Previous Liquefaction

Field searches for liquefaction relicts are conducted along drainage ditches, river banks, and other exposures having potentially liquefiable sediments. Deep (>3 m) soil exposures often allow observation of the source strata in situ and provide the opportunity to observe small liquefaction features that did not penetrate far into overlying soils. Observations at depth are important because the absence of surficial liquefaction evidence does not necessarily mean that liquefaction did not occur at depth.

The severity of past liquefaction at specific sites is determined from factors such as the size and abundance of sand blows and the widths of sand-filled dikes in a localized area (*2*). Dating of organic material buried by vented sediment, combined with archaeological and pedological data, generally allows bracketing the ages of the liquefaction features. The distribution of liquefaction effects and the ages of many individual sites are then used to develop a picture of regional earthquake activity. Sites are next selected for detailed geotechnical studies.

The absence of liquefaction features, or "negative evidence," also plays an important role in estimating past earthquake motions. An absence of features within liquefaction-prone environments suggests that the maximum past shaking levels did not exceed threshold levels. Where the location of the water table can be bounded through time and there is no evidence of cementation or lithification of potential source deposits, negative evidence can be used to place reasonably well-defined limits on the maximum levels of past ground shaking.

There is no well-defined procedure for determining the amount of outcrop that must be searched in order to conclude that liquefaction and strong shaking has not occurred previously. Uncertainty arises because of the many varying factors that affect the development of liquefaction (soil conditions, dynamic site response, stochastic attenuation of energy from the source zone, etc.). In this study, the policy used was that at least several kilometers of outcrop must be searched, even in an area suspected to be in the near field, before any statement could be made about previous severity of shaking.

Field Site Assessment and Testing of Soils

The liquefaction susceptibility of soils is usually evaluated using in situ penetration tests. The most commonly used methods involve subsurface tests, such as the SPT or cone penetration test (CPT). Other in situ data from sand cone or shear wave velocity measurements can provide supplemental information.

Because the liquefaction susceptibility of soil is estimated using present-day penetration data, it is important to consider whether soil conditions were significantly changed as a result of past ground motions. At sites of severe liquefaction, it is likely that the ground motions greatly exceeded the threshold for liquefaction, and densification occurred almost entirely throughout the source strata [see, for example, SPT data in the epicentral region of the 1811–1812 New Madrid earthquakes reported by Obermeier (*3*)]. At sites where only marginal or no liquefaction occurred, it is likely that soil conditions underwent only minor changes. To estimate the attenuation pattern of the earthquake motions, it is necessary to perform tests at sites of increasing distance from the suspected zone of energy release, preferably at sites that experienced marginal liquefaction.

Evaluation of Previous Ground Shaking

Existing liquefaction prediction methods are used to estimate the ground shaking at each site. Two well-established methods are the simplified procedure of Seed et al. (*4*) and the Ishihara (*1*) method [Figure 1 (*left* and *right*, respectively)]. Both methods predict the threshold shaking levels required to cause venting of sand at the ground surface. The Seed method relates occurrence of sand blows to peak acceleration and earthquake magnitude on the basis of SPT blowcounts. Many case

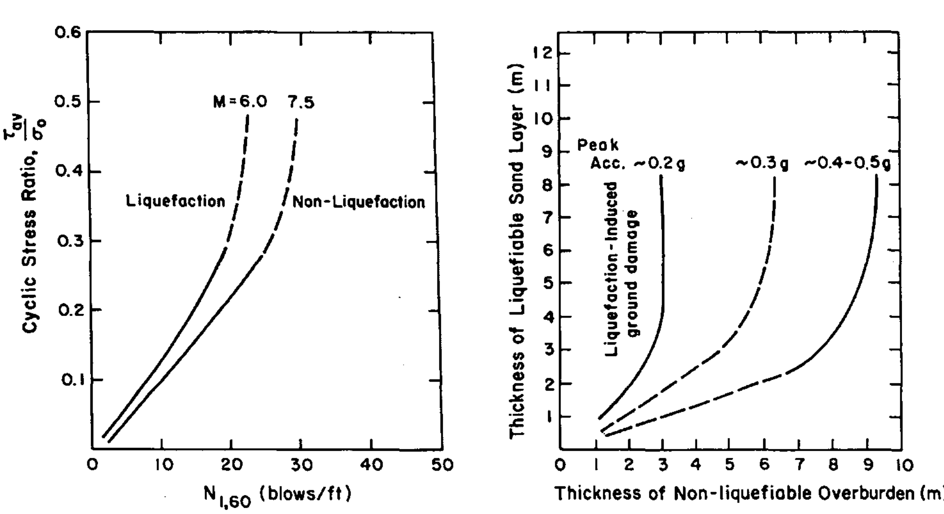

FIGURE 1 *Left:* **SPT-based liquefaction prediction curves (*4*); *right:* boundary curves to predict surface disruption [modified from Ishihara (*1*)].**

studies show this method to be reliable in matching field liquefaction behavior to earthquake ground motions [i.e., those by Holzer et al. (*5*) and Seed et al. (*6*)]. The Ishihara method relates the occurrence of sand blows to peak acceleration on the basis of the relative thicknesses of the liquefiable and nonliquefiable portions of the soil profile. This method accounts for the possibility that there is no liquefaction evidence at the ground surface because a nonliquefiable cap was too thick to be penetrated to the surface.

It is important to consider that the Seed and Ishihara methods were developed using liquefaction data collected largely in the western United States and other tectonic plate-margin areas, so application of the methods to intraplate regions such as the central and eastern United States can be questioned. However, a recent liquefaction case history from the 1988 Saguenay, Quebec, earthquake in eastern North America (*7*) suggests that the methods are applicable to intraplate regions. Also, it was noted previously that the Seed and Ishihara methods predict the threshold accelerations for sites of marginal liquefaction. At sites of severe liquefaction, where sediments mainly have densified, the Seed and Ishihara methods still can be used to determine the lower-bound level of past shaking. At sites of no liquefaction, upper-bound accelerations can be obtained.

Next, dynamic site response studies are performed [using a program such as SHAKE (*8*)] to determine motions in bedrock beneath the field liquefaction site. These studies assess whether the accelerations at each field site were likely the result of localized amplification (or deamplification) of the bedrock motions. The bedrock motions can then be compared with predictions of strength of shaking for various earthquake magnitudes, using models developed by seismologists.

Because liquefaction is sensitive to duration of strong shaking, the methods of Seed and Ishihara provide insight into possible combinations of the magnitude and duration of strong shaking of past earthquakes. Greater earthquake magnitudes (and longer durations of strong shaking) require smaller sustained accelerations to cause liquefaction. Earthquake magnitude can be estimated in some situations by using worldwide liquefaction data presented by Youd (*9*) or Ambraseys (*10*). Their data show relations between the epicentral distance to the farthest liquefaction effects for various earthquake magnitudes. To use the technique, though, their curves must be calibrated to the local seismotectonic setting because bedrock motion is the fundamental parameter. [An example of the use of this technique is discussed for the Wabash Valley by Obermeier et al. (*11*).]

The threshold shaking level at which an earthquake will produce liquefaction is a moment magnitude (**M**) 5.0 or higher (*10*). This magnitude of 5 gives an estimate of a minimum value for past ground motions in areas where liquefaction features are present and a maximum where no liquefaction is evident.

One way to assess the accuracy of the backcalculation techniques used for this study is to examine case histories in which soil conditions, field performances, and seismic loading levels are known. For instance, these techniques worked well when applied to effects of the 1989 Loma Prieta earthquake near San Francisco, California. The method successfully predicted peak accelerations at several liquefaction sites along San Francisco's waterfront during that earthquake. Details of this and other cases are given by Martin and Clough (*12*; unpublished data).

The following sections describe the application of the authors' seismic analysis technique to two areas of infrequent large earthquakes. The studies are in different stages and somewhat different approaches are being taken for each, but both are sufficiently advanced to discuss the preliminary results.

EASTERN UNITED STATES: CHARLESTON, SOUTH CAROLINA

One of the most prominent areas of seismic activity along the eastern seaboard of the United States is near Charleston, South Carolina (Figure 2). The 1886 Charleston earthquake is the largest during some 300 years of record. Recurring small earthquakes continue in the vicinity. The 1886 earthquake is estimated to have a Modified Mercalli intensity (MMI) of X within the epicentral region. Moment magnitude estimates are 7.5 to 7.7, with peak ground accelerations of 0.5 to 0.6 *g* (*13–15*). These estimates are based primarily on the long propagation distance of MMI V-VI effects and the severity of damage in the near field. The authors' estimates of possible combinations of earthquake magnitude and accelerations differ substantially from those made by seismologists, whose estimates are based on MMI values.

The source of seismicity near Charleston possibly originates from one or more deeply buried and probably intersecting fault zones, although definitive evidence strongly supporting a specific model has not yet been presented. Although the cause of the 1886 event is still speculative, recent studies have led to an improved understanding of the possible source mechanisms and ground motion patterns (*16*; P. Talwani, unpublished data).

Geologic-Geotechnical Setting

The low-lying Charleston region has a high water table and many areas of loose, fine sands, causing there to be high susceptibility to liquefaction. Of primary interest is a series of beach ridges, ranging in age from modern to as old as 200,000 to 240,000 years, that parallel the present coastline from North Carolina to Georgia (Figure 2). Deposits of fine and silty sands in these ridges have the highest liquefaction susceptibility relative to other geologic settings in the area. Liquefaction susceptibility of the ridges is not only high at many places but also relatively constant regionally (*17*). Typical soil conditions are shown in Figure 3, which shows the upper portion of the soil profile along Hollywood Ditch, a 2.8 km long drainage ditch excavated along the crest of a 130,000- to 230,000-year-old beach deposit.

Liquefaction Findings

Liquefaction effects of the 1886 earthquake were observed to be especially abundant in the sandy soils of the beach deposits. Eyewitness accounts presented by Dutton (*18*) describe a multitude of sand blows or "craterlets" up to 6 m in diameter. The features decreased in size and abundance with increasing

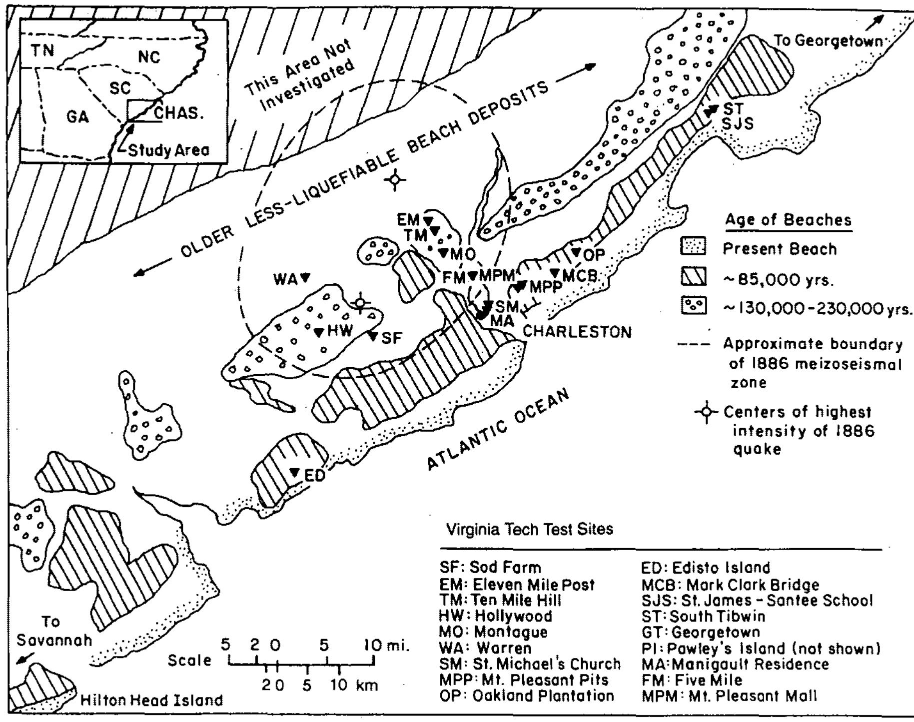

FIGURE 2 Map of coastal South Carolina showing beach deposits and test sites.

distance from the central area of strongest destruction, presumed to be the epicenter. Scattered smaller features were reported as far as 100 km from the epicentral region.

Recent field studies have led to the discovery of relict craterlets and sand dikes throughout the Charleston area (*19–21*). Many craterlets were found in the walls of drainage ditches and sand pits located within the ancient beach deposits. Dating of the craterlets showed that although many were produced by the 1886 earthquake, others were caused by prehistoric earthquakes. The evidence indicates that at least four prehistoric episodes of significant ground shaking occurred near Charleston during the last 5,000 to 6,000 years (*21*). Although this has led to an improved understanding of the seismicity near Charleston, the question remains as to the levels of ground motion that produced the liquefaction features, especially those caused by the 1886 event.

Paleoseismic Study

A paleoseismic study by Martin and Clough (*12*) has led to an estimation of the magnitude and peak accelerations of the 1886 earthquake. The study involved field reconnaissance, historical research, SPT and CPT, laboratory testing, compiling of boring logs from consulting firms, and analyses. The work focused on the properties of sediments that liquefied in the beach deposits. The locations of the test sites are shown in Figure 2.

Liquefaction analyses were carried out at each test site, and the peak ground-surface accelerations required to produce the observed liquefaction evidence were estimated. Because the sites were located at various distances from the source zone, the attenuation pattern of the earthquake motions could be estimated. Dynamic site response analyses by Martin and

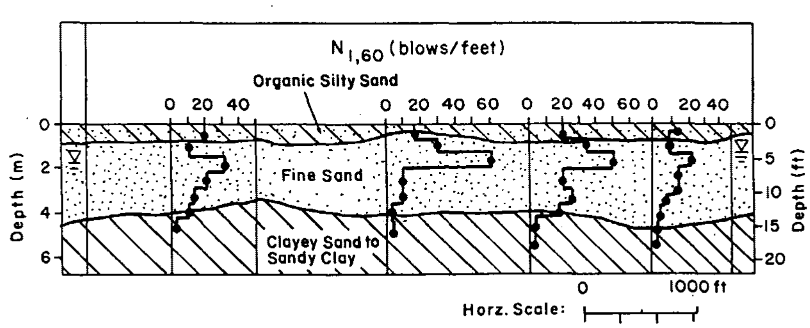

FIGURE 3 Portion of soil profile showing SPT data from Hollywood site near Charleston, South Carolina.

Clough (*12*) found that significant amplification or deamplification of the 1886 ground motions probably did not occur within the unconsolidated, near-surface (20 to 30 m depth) sediments of the beach ridges. Thus, the attenuation curve (Figure 4) developed in this study is thought to approximate the motions that occurred at the top of bedrock or semilithified material (with shear wave velocities exceeding 600 m/sec) underlying the test sites.

Estimates of peak ground acceleration are plotted versus distance from the 1886 source zone in Figure 4. The curve in Figure 4 (*top*) was developed assuming that the 1886 earthquake had a moment magnitude of 7.5. As indicated in Figure 4, the accelerations were estimated with various levels of confidence. The solid data points indicate marginal liquefaction sites at which the 1886 accelerations could be closely estimated. The solid arrows correspond to sites at which the accelerations could only be bounded. The open data points represent sites at which the accelerations could not be closely estimated. In developing the attenuation curve in Figure 4 (*top*), judgment was used in assigning different weights to the data, depending on their quality. The curve shown provides the most consistency between the estimated accelerations and the liquefaction evidence.

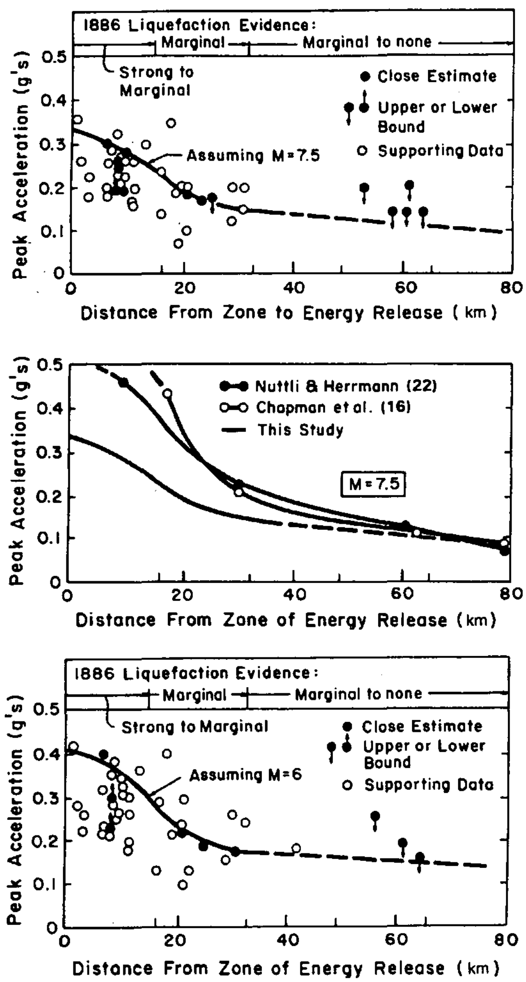

FIGURE 4 ***Top:*** **Estimated attenuation of peak accelerations assuming 1886 event of M7.5;** ***middle:*** **comparison of attenuation curve from this study with curves proposed for eastern United States for M7.5 events;** ***bottom:*** **estimated attenuation of peak accelerations assuming 1886 event of M6.**

In Figure 4 (*middle*), the attenuation curve developed in this study is compared with those proposed for the eastern United States by seismologists (*16*,*7*). Because some seismologists (e.g., M. Chapman, unpublished data) have suggested that the 1886 earthquake was significantly less than M7.5, a backcalculation analysis was also performed assuming that the 1886 event was M6. These results are shown in Figure 4 (*bottom*). Details of the Charleston study are available in a report by Martin and Clough (*12*).

Principal findings are summarized below:

1. If the 1886 Charleston earthquake was M7.5 and the duration of strong shaking was normal for this earthquake magnitude, the peak ground-surface accelerations are estimated to have been 0.35 to 0.4 *g* for the epicentral region and 0.1 *g* at distances of about 80 km beyond the epicentral region. The estimated attenuation pattern of the 1886 ground motions is similar in form, but values of acceleration are lower (especially in the near field) than those currently proposed by seismologists for M7.5 earthquakes in the eastern United States.
2. If the 1886 earthquake was M6, the methods used in this study yield peak accelerations approximately 20 percent higher than those associated with the M7.5 scenario.
3. The overall liquefaction evidence suggests that either the magnitude or the strongest accelerations of the 1886 Charleston earthquake were less than what have been conventionally suggested for this event (M7.7 and a_{max} = 0.5 to 0.6 *g*). Possibly the magnitude and shaking levels were initially overestimated by the seismological community because of the damage to buildings resulting from widespread liquefaction.
4. The authors' best estimates are that the 1886 earthquake had peak accelerations in the range of 0.35 to 0.4 *g*, with a moment magnitude no larger than 7.5 and possibly as low as 7.0.

CENTRAL UNITED STATES: WABASH VALLEY SEISMIC ZONE

The seismicity of the central United States has been largely defined by the great 1811–1812 earthquakes that occurred near New Madrid, Missouri. These earthquakes, as large as M8.3 and body wave magnitude m_b = 7.4 (*23*), represent the strongest historical ground shaking within the region. Liquefaction features from these earthquakes extended as far as 250 to 275 km from the epicenter (*24*). The only other historical account of strong shaking in this region was the 1895 Charleston, Missouri, earthquake, estimated as M6.8 and m_b = 5.6 (*23*). (Charleston, Missouri, is near the confluence of the Ohio and Mississippi rivers.)

The Wabash Valley Seismic Zone (WVSZ) is located along the lower Wabash River, where it forms the border between Indiana and Illinois (Figure 5). The southern end of the WVSZ is approximately 100 km northeast of the northern limit of the source of the 1811–1812 earthquakes, the New Madrid Seismic Zone. Records extending back approximately 200 years show that five slightly damaging earthquakes, having

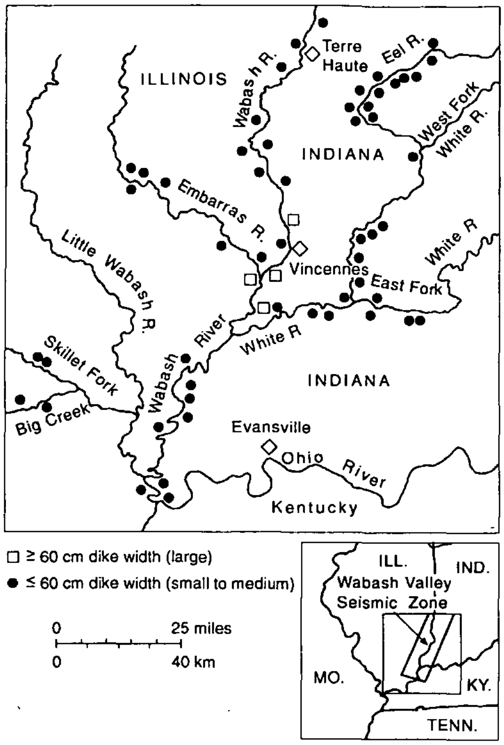

FIGURE 5 Map of lower Wabash Valley showing liquefaction sites.

estimated m_b's of 5.0 to 5.8 (M5.0 to 5.5), have occurred in and near the lower Wabash River valley (*23*). The area has long been thought capable of producing stronger than historic earthquakes. Support for the suspicion is provided by continuing seismicity and the presence of numerous faults in the Wabash region and by the proximity and suspected similar seismotectonic setting to that of the New Madrid Seismic Zone (*25*). In addition, numerous prehistoric liquefaction features have recently been discovered in the WVSZ, indicating strong prehistoric ground shaking within the region far from the 1811–1812 epicenters. Preliminary findings indicate a seismic source within or very near the Wabash Valley (*11*).

Geologic-Geotechnical Setting

Broad terraces bordering river valleys of the Wabash region are underlain by sand and gravel sediments laid down first by glacial outwash systems (about 14,000 years old) and later by the Wabash River and its tributaries. These sediments are overlain by much finer-grained flood plain and channel fill deposits of clayey silt and silty clay. The water table at most locations along the river valleys is within approximately 0.6 to 3 m of the ground surface and fluctuates with the level of nearby rivers. The setting most frequently associated with the liquefaction features is a relatively thin (1 to 4.5 m) low-permeability cap of silt- and clay-rich soil overlying a source stratum of silty-to-clean sand, gravelly sand, or in some cases, sandy gravel. Soil conditions typical of the sites investigated to date in the WVSZ are shown in Figure 6.

Liquefaction Findings

Prehistoric liquefaction features (mostly dikes and sand blows) that formed largely in source beds of sand or gravelly sand have recently been discovered throughout the WVSZ in both glacial outwash deposits and younger river deposits (*11,26*). Almost all the features appear to have been produced by a single earthquake that occurred in the region between 2,500 and 7,500 years ago, with the regional span of features apparently controlled by a single, very large earthquake. More than 200 dikes have been identified over a widespread area, including gravelly sand-filled dikes up to 2.5 m in width. The largest features have been found over an approximately 35-km-wide zone, north to south, with smaller dikes being found over a reach of at least 225 km. The largest dikes are centered near Vincennes, Indiana (see Figure 5).

Many of the soils that liquefied and flowed were either clean gravelly sands or sandy gravels. Some of the vented materials contain gravels as large as 7.5 cm in diameter. With the exception of sites investigated by Andrus et al. (*27*) following the 1983 M7.3 Borah Peak, Idaho, earthquake, the liquefaction of soils as coarse and clean as some of those in the Wabash region appears to be unprecedented. Because gravels generally have much lower liquefaction susceptibility than sands

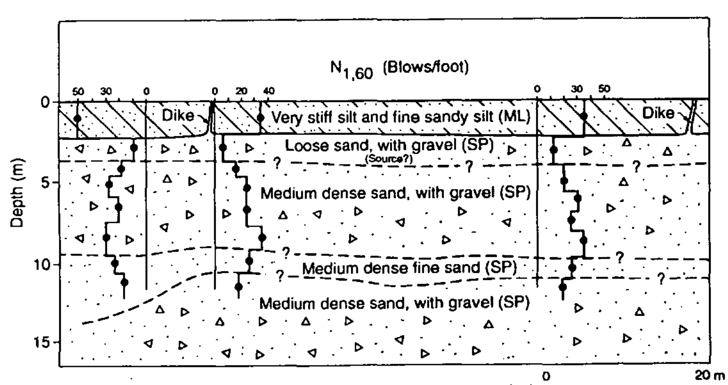

FIGURE 6 Typical soil conditions at sites where large gravelly sand dikes have been discovered in WVSZ.

(*1*), the liquefaction of the gravelly Wabash soils suggests very strong ground motions.

Paleoseismic Study

An ongoing study by the authors is designed to estimate the magnitude and peak accelerations necessary to produce the liquefaction features observed in the Wabash Valley. To date, most of the geotechnical work has been conducted at sites where the largest liquefaction effects (dikes) have been found. Preliminary estimates of the magnitude and accelerations that produced these liquefaction features have been made, and a regional site response study has been performed. On the basis of the size of the liquefaction features (widths of dikes) and the span over which dikes have been found, the authors' first estimate of the earthquake that produced the features is M7.5 (*12*). This estimate is based mainly on comparisons of the areal distribution and size of the dikes observed in the Wabash Valley with those of historic liquefaction-producing earthquakes in the central and eastern United States, using the Youd-Ambraseys curves discussed in a previous section. This magnitude of 7.5 far exceeds any earthquake occurrence in the WVSZ region during historical times.

Assuming M7.5, preliminary SPT data mainly obtained at the sites of largest dikes indicate a minimum peak ground acceleration of 0.3 *g* within a 25-km radius of the epicentral area (assuming that the epicenter is at the center of the region of largest dikes). The 0.3 *g* value represents the threshold acceleration for liquefaction at these sites, although the large size of the dikes shows that liquefaction much exceeded incipient development. At a distance of approximately 100 km from the apparent epicentral area, a lower-bound peak acceleration of 0.1 *g* is indicated. It is suspected that the upper-bound accelerations far exceed these values, although upper-bound estimates will not be possible until testing is performed at sites having either marginal or no evidence of liquefaction.

CONCLUSIONS

The shaking levels of earthquakes have been traditionally estimated on the basis of fault studies, seismic instrumentation, or historical intensity data. However, in regions where the rate of seismic activity is low, traditional methods are often of limited use. An alternative approach is to do geotechnical analysis at sites of past liquefaction. Geotechnical correlations developed between modern earthquakes and occurrence of liquefaction can be used to bracket the likely magnitude and acceleration levels of past earthquakes. Sites of past liquefaction thus can have an important role in the identification of seismic hazards and in the assessment of seismic risk. An overview of seismic analysis of liquefaction features is described for two studies in the eastern and central United States.

The principal conclusions are as follows:

1. Liquefaction relicts can be used with geotechnical procedures to estimate the magnitude and acceleration levels of past earthquakes and the attenuation of accelerations. In liquefaction-prone areas where no liquefaction evidence is found, the past peak accelerations can be estimated.
2. Seismic analysis of liquefaction features can be used in all regions in which liquefiable sediments are present. The method is best applied to regions in which soil conditions and liquefaction susceptibilities have been moderate to high at many places over a widespread area.
3. Seismic analysis of liquefaction features is of particular importance in regions of infrequent seismicity where the seismic sources are poorly defined. This approach provides estimates of past ground motions that are independent of those proposed by seismologists.
4. Seismic analysis of liquefaction features has been used to estimate the magnitude and peak accelerations of the 1886 Charleston, South Carolina, earthquake. The findings suggest that the accelerations were significantly lower than those conventionally accepted for this event (M7.5 to 7.7; 0.5 to 0.6 *g* a_{max}). Attenuation relationships for the accelerations of the 1886 event were also estimated from the study of liquefaction effects.
5. Ongoing seismic analyses indicate that very strong prehistoric ground shaking has occurred in the Wabash Valley, an area having no historical earthquakes exceeding M5.5. The authors' preliminary estimate of the earthquake magnitude that produced these feature is M7.5, with accelerations at least as high as 0.3 *g*.

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