LIQUEFACTION SUSCEPTIBILITY MAPPING,
ST. LOUIS, MISSOURI AND ILLINOIS

FINAL TECHNICAL REPORT

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ABSTRACT

A detailed study was performed to assess the relative liquefaction susceptibility of Quaternary deposits that exist in the greater St. Louis, Missouri and Illinois area. The study area encompasses five (5) 7.5-minute quadrangles of the highly populated, industrial, and commercial areas in the metropolitan area. Much of this area lies on unconsolidated alluvium recently deposited by the Missouri and Mississippi Rivers. The region has experienced strong ground shaking as a result of pre-historic and contemporary seismicity associated with the major neighboring seismic source areas, including the Wabash Valley Seismic Zone (WVSZ) and New Madrid Seismic Zone (NMSZ). The St. Louis region experienced strong shaking from the 1811-1812 NMSZ events, and historical reports indicate that this shaking was sufficient to induce structural damage to buildings on the alluvium of the low-lying floodplain. Therefore, of key concern for liquefaction are the nearly ubiquitous Holocene unconsolidated granular sediments of the river valley alluvium.

We employ detailed geologic mapping in conjunction with a quantitative geotechnical analysis (Simplified Procedure) to evaluate and classify the relative susceptibility to liquefaction of the Quaternary deposits. From the mapping we differentiate four primary geologic units: Artificial fill, Holocene alluvium, Pleistocene glacio-fluvial outwash, and Pleistocene loess. The results of the integrated analysis show that Holocene alluvial units are the most susceptible to liquefaction. Late Pleistocene glacio-fluvial outwash has a moderate-to-low susceptibility; the loess deposits have a very low susceptibility. Artificial fill deposits are common, and are assigned a conservative value of “very high” liquefaction susceptibility because of the difficulties associated with estimating their geotechnical properties, and thus the ability to forecast their response to seismic shaking. Since many transportation routes, power and gas transmission lines, population centers, and levee structures exist on the highly susceptible Holocene alluvium, the St. Louis region is at significant potential risk from seismically induced liquefaction and liquefaction-related ground deformation.

This research produced a series of five 1:24,000-scale maps located within the St. Louis region that depict liquefaction-related hazards, and that can be used for probabilistic risk assessments or scenario earthquake studies. The results of this study provide data needed to effectively manage liquefaction hazards in the St. Louis area, and thus will contribute to the USGS and FEMA loss reduction efforts in the central United States. Although these maps are based on detailed geologic maps and available geotechnical information, the susceptibility maps should not be considered or used as a substitute or replacement for site specific geologic or geotechnical investigations to assess local liquefaction potential.

1.0 INTRODUCTION

This technical report presents the results of a detailed study to assess the relative susceptibility of Quaternary geologic deposits to earthquake-induced liquefaction near St. Louis, Missouri. The primary goal of this research is to characterize the surface and subsurface distribution and geotechnical properties of potentially liquefiable sediments and artificial fill in and around St. Louis, Missouri and Illinois. The result of the geologic and geotechnical characterization and quantitative analysis is the construction of GIS-based, 1:24,000-scale, liquefaction susceptibility maps. The study area encompasses five 7.5-minute quadrangles (Columbia Bottom, Wood River, Granite City, Monks Mound, Cahokia) in the greater St. Louis area and surrounding communities such as Metro East, Illinois, and downtown St. Louis, Missouri (Figure 1). To avoid confusion, the study area will be referred to in this report informally as the "St. Louis region".

Much of the low-lying St. Louis region (Figure 2) is underlain by a substantial thickness (up to 125 feet) of Holocene and Pleistocene alluvial floodplain and pro-glacial outwash deposits of the Mississippi and Missouri Rivers. These unconsolidated granular materials are potentially susceptible to liquefaction during large earthquakes from nearby potentially undetected seismic sources, or possibly even more distant, larger seismic sources, such as the New Madrid seismic zone (NMSZ) (Wheeler and Perkins, 2000; Hermann et al., 1999, Atkinson and Beresnev, 2002). Regional (1:100,000 scale) hazard mapping of the St. Louis area was completed in 1995 by the Missouri Department of Natural Resources Geological Survey and Resource Assessment Division (now MGS) and shows large areas potentially susceptible to liquefaction along the Missouri and Mississippi rivers and substantial areas in the urbanized "uplands" drainages (Hoffman, 1995). Our study refines this initial study by Hoffman (1995) by incorporating more subsurface and surficial geologic data toward assessing the liquefaction susceptibility in the St. Louis area.

Previous reconnaissance studies confirmed evidence of paleoliquefaction in the region along tributaries to the Missouri and Mississippi Rivers, for example the Meramec River, a large tributary to the Mississippi River, is shown on the 1:100,000-scale hazard map of Hoffman (1995) as having variable or unknown liquefaction hazard. In contrast, field evidence for paleoliquefaction has been documented in the Meramec River sediments (Tuttle, 1999), and other drainages (i.e. Kaskaskia River, Shoal Creek; McNulty and Obermeier, 1999). However, to the best of our knowledge, no comprehensive characterization of the geotechnical properties of similar fluvial deposits, or detailed maps of liquefaction susceptibility, existed for the greater St. Louis area prior to this study. Therefore, a need existed for a more detailed study of liquefaction susceptibility to adequately characterize the hazard, and to provide information to communities for improved planning and mitigation strategies.

Liquefaction is not a randomly occurring phenomenon; liquefaction tends to be restricted to deposits with certain geologic and hydrologic conditions (Youd, 1973). Since these conditions can be identified, delineated, and mapped (e.g. Youd and Perkins, 1987), planners, federal and state agencies, and individuals can prepare for and mitigate the effects of liquefaction. For example, if local governments have information on areas of possible liquefaction susceptibility hazard, they can require that site-specific analyses be performed prior to new development and appropriate engineering mitigation be incorporated into project design.

In this report, in addition to the presentation of the liquefaction susceptibility hazard maps, we describe the methods, data, analysis and criteria used to evaluate, and then integrate, each component that are used to construct the maps. The maps of liquefaction susceptibility are based on: (1) existing and newly completed 1:24,000-scale Quaternary geologic maps for the study area; (2) evaluating geologic and

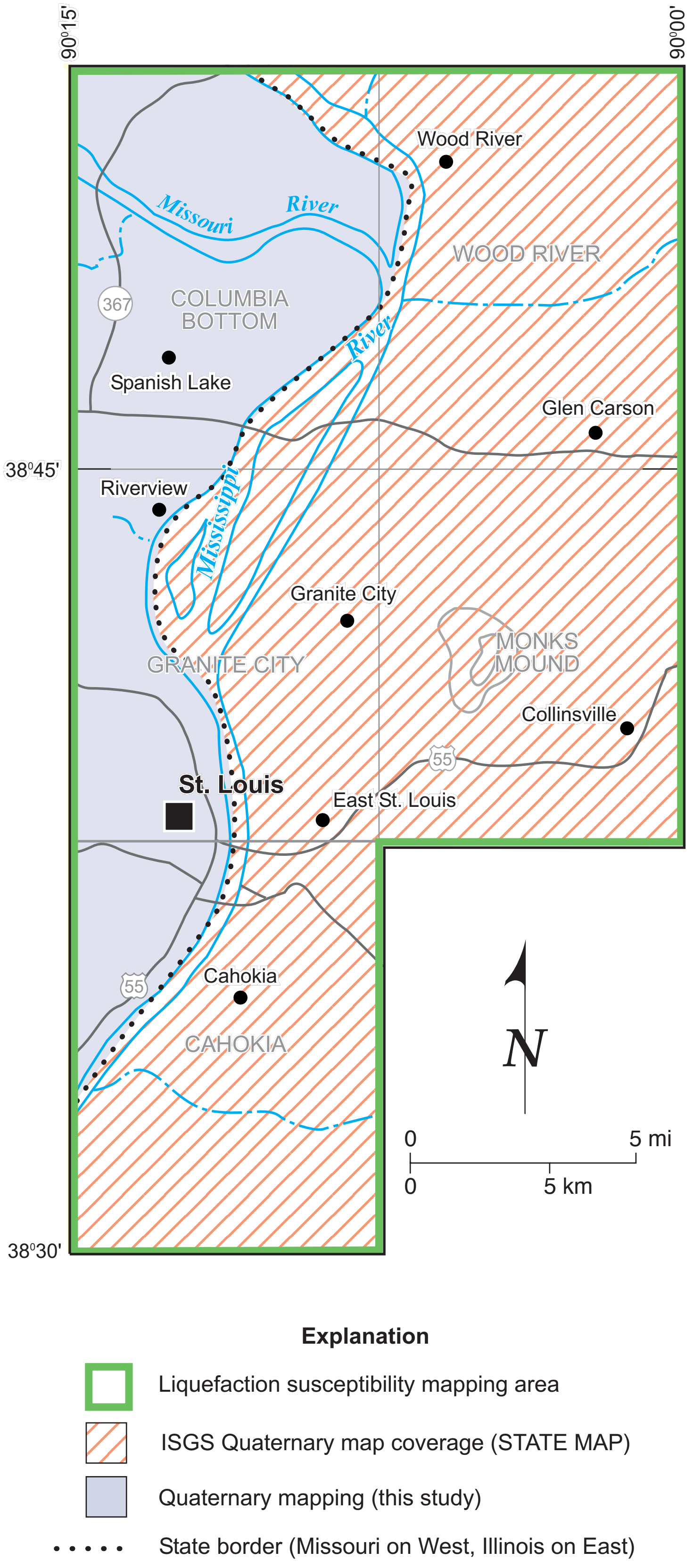


Figure 1. Location map and quadrangle index of liquefaction mapping of the St. Louis region.

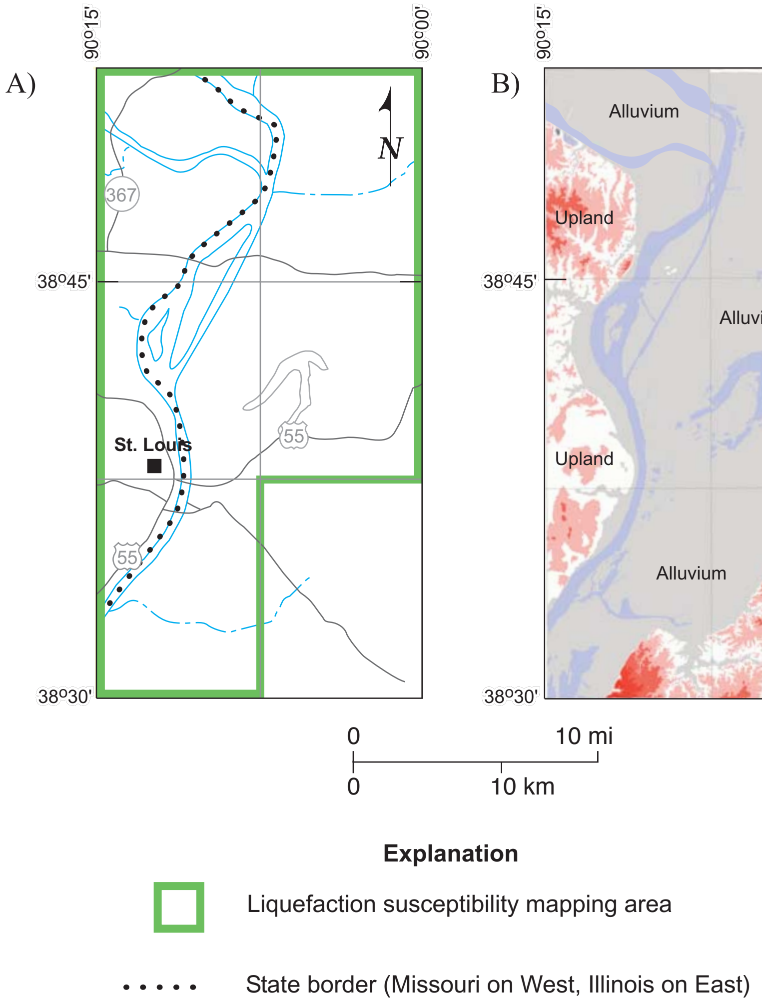


Figure 2. A) Quadrangle index of liquefaction mapping, with B) digital elevation surface. Warm tones are higher elevations; (upland); gray tones are lower elevations (alluvium).

geotechnical subsurface borehole information; (3) characterizing depth to groundwater data; (4) evaluating liquefaction susceptibility incorporating the “Simplified Procedure” devised by Seed and Idriss (1971) (Figures 3 and 4). The location and extent of surficial deposits are characterized by Quaternary geologic mapping. The subsurface deposit properties such as soil type, estimated fines content, and relative density, are characterized through borehole logs, coring logs, and Standard Penetration Test (SPT) blow count data. Regional groundwater conditions are assessed based on existing data, and a scenario depth-to-groundwater map was developed for use in the quantitative liquefaction analysis. The resultant susceptibility categories are included in the GIS map database to facilitate the use and distribution of the susceptibility maps to interested researchers, agencies, municipalities. The final 1:24,000-scale map products are delivered as hard copy and digital GIS map layers. These maps can be used to improve the assessment of liquefaction hazards in St. Louis and allow communities to better plan and mitigate the effects of liquefaction on the built environment.

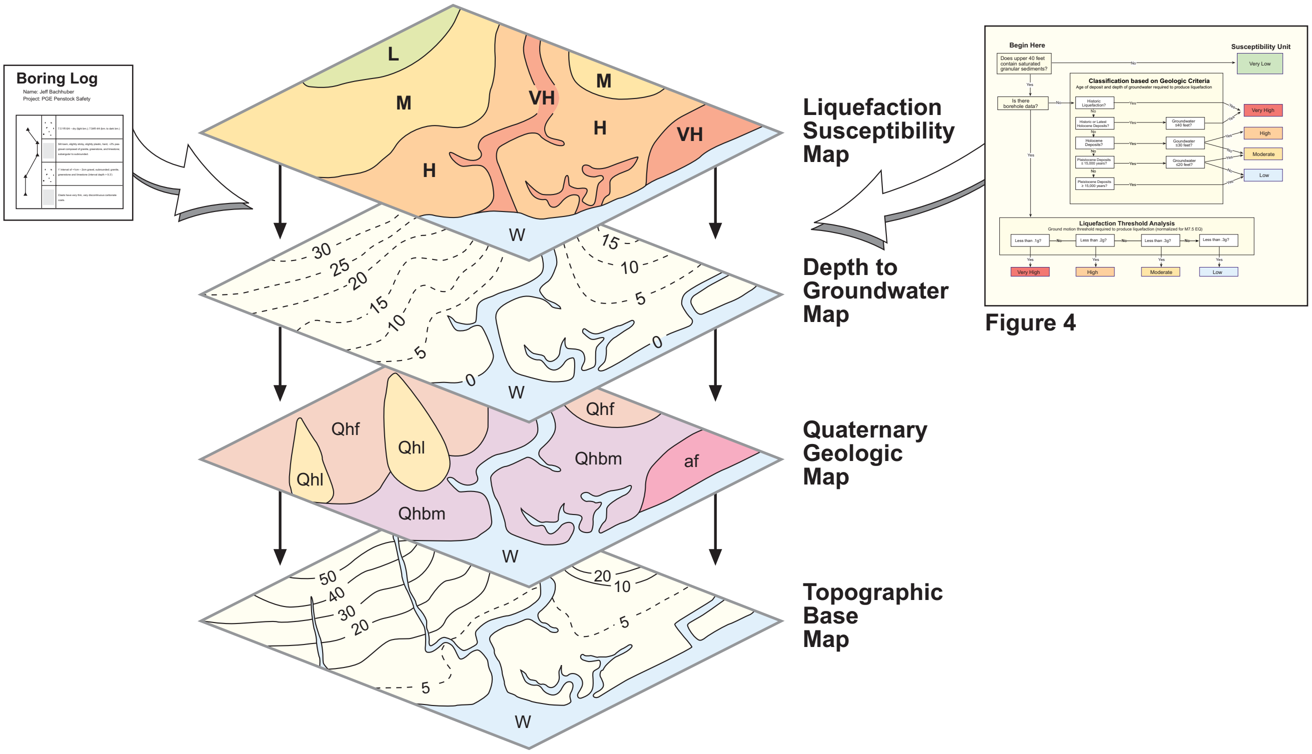


Figure 3. Data sources and integration procedures to produce a liquefaction susceptibility map.

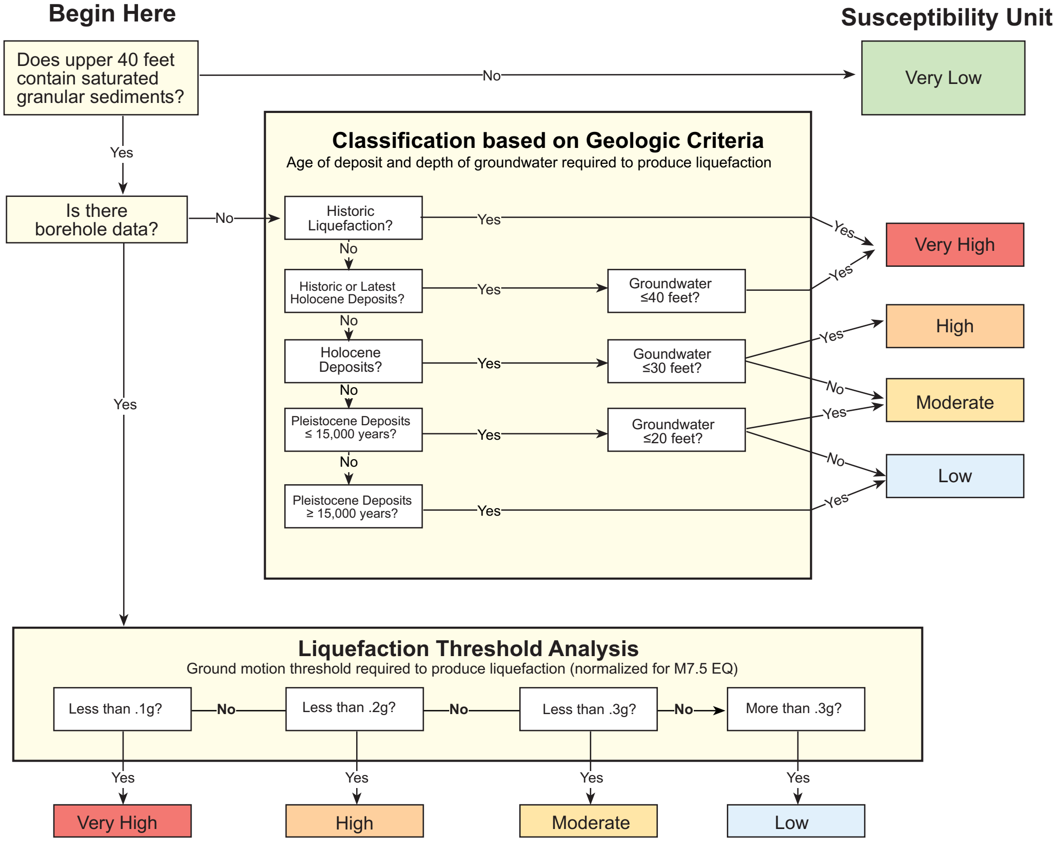


Figure 4. Decision flow chart for evaluation of liquefaction susceptibility. Flow chart developed in cooperation with California Geological Survey for Simi Valley, California, with ground motion thresholds required to produce liquefaction normalized for a M7.5 earthquake (from Hitchcock et al., 1999).

2.0 BACKGROUND

Liquefaction-related ground failures historically have caused extensive structural and lifeline damage in urbanized areas around the world. Recent examples of these effects include damage produced during the 1989 Loma Prieta, 1994 Northridge, 1995 Kobe, 1999 Izmit, and 2001 India earthquakes. These, and other historical earthquakes such as the 1811-1812 New Madrid earthquakes, show that the occurrences of coseismic liquefaction, and thus the distribution of liquefaction-related damage, is generally restricted to areas that contain low-density, saturated, near-surface (<50 feet depth) granular sediments susceptible to liquefaction, that are in regions with the opportunity for coseismic ground motions to exceed a specified threshold level. Large portions of the St. Louis metropolitan area, including extensive areas of industrial, commercial, and residential development, are underlain by granular late Pleistocene and Holocene alluvial sediments of the Missouri and Mississippi Rivers (Grimley and Lepley, 2001; Goodfield, 1965; Pearce and Baldwin, 2004; Harrison, 1997) (Figure 2). Furthermore, the St. Louis area has been expanding in terms of population and developed areas, increasing the vulnerability to loss of life and property damage into a larger geographic area. Conjunctively, a preponderance of police, fire, and emergency response stations are located within the study area, as well as key pipelines, highways, bridges, and other lifelines and infrastructure (Hoffman, 1995).

Paleoliquefaction studies in the region have shown that many of the tributaries of the Mississippi River, such as the Meramac, Kaskaskia, and Big Rivers provide exposures of earthquake-related liquefaction deformation (e.g. sand blows) interpreted to have been caused by the New Madrid 1811-1812 earthquakes, or earlier events from unknown seismic sources. According to historical accounts, St. Louis suffered considerable damage from the 1811-1812 earthquakes, including structural damage to dwellings such as cracked houses and toppled brick chimneys (St. Louis University Earthquake Center, 2004). The region has experienced other, less infamous, earthquake events (Figure 5) that were of large enough ground shaking intensity to cause structural damage, such as the:

1. January 1843 MMI VI event (estimated magnitude 6.0, northeast Arkansas source) that toppled chimneys in the area;
2. April 1917 MMI VI event (estimated magnitude 5.0, Ste Genevieve, Missouri source) that “threw horses to pavement in St. Louis” and caused damage to houses and chimneys;
3. November 1968 MMI V-VII event (estimated magnitude 5.5, southern Illinois source), that shook and moved furniture, cracked walls, and toppled chimneys (St. Louis University Earthquake Center, 2004).

2.1 Previous Liquefaction Studies

Historical and modern records clearly indicate that the region is subject to repeated strong ground shaking, and the geological conditions are sufficient for liquefaction to occur. Regional (1:100,000-scale) hazard mapping of the St. Louis area was completed by the Missouri GSRAD (Hoffman, 1995), and is a useful screening-level map of the hazard. However, this hazard mapping did not evaluate the differences in relative liquefaction susceptibility that exist due to the differences in geologic depositional environment, texture, and age. The regional liquefaction hazard mapping performed by our study predominantly relies on characterizing these criteria to relate surficial geology to liquefaction susceptibility (e.g. Youd and Perkins, 1978). Semi-empirical methods for estimating liquefaction susceptibility such as the Simplified Procedure (Seed and Idriss, 1971) are based on the site specific deposit properties and existing conditions, and provides a more quantitative evaluation of susceptibility. When regional geologic hazard mapping criteria of age, relative density, depositional environment are used as a framework for interpreting and classifying the results of the Simplified Procedure analysis, the liquefaction susceptibility is more fully characterized.

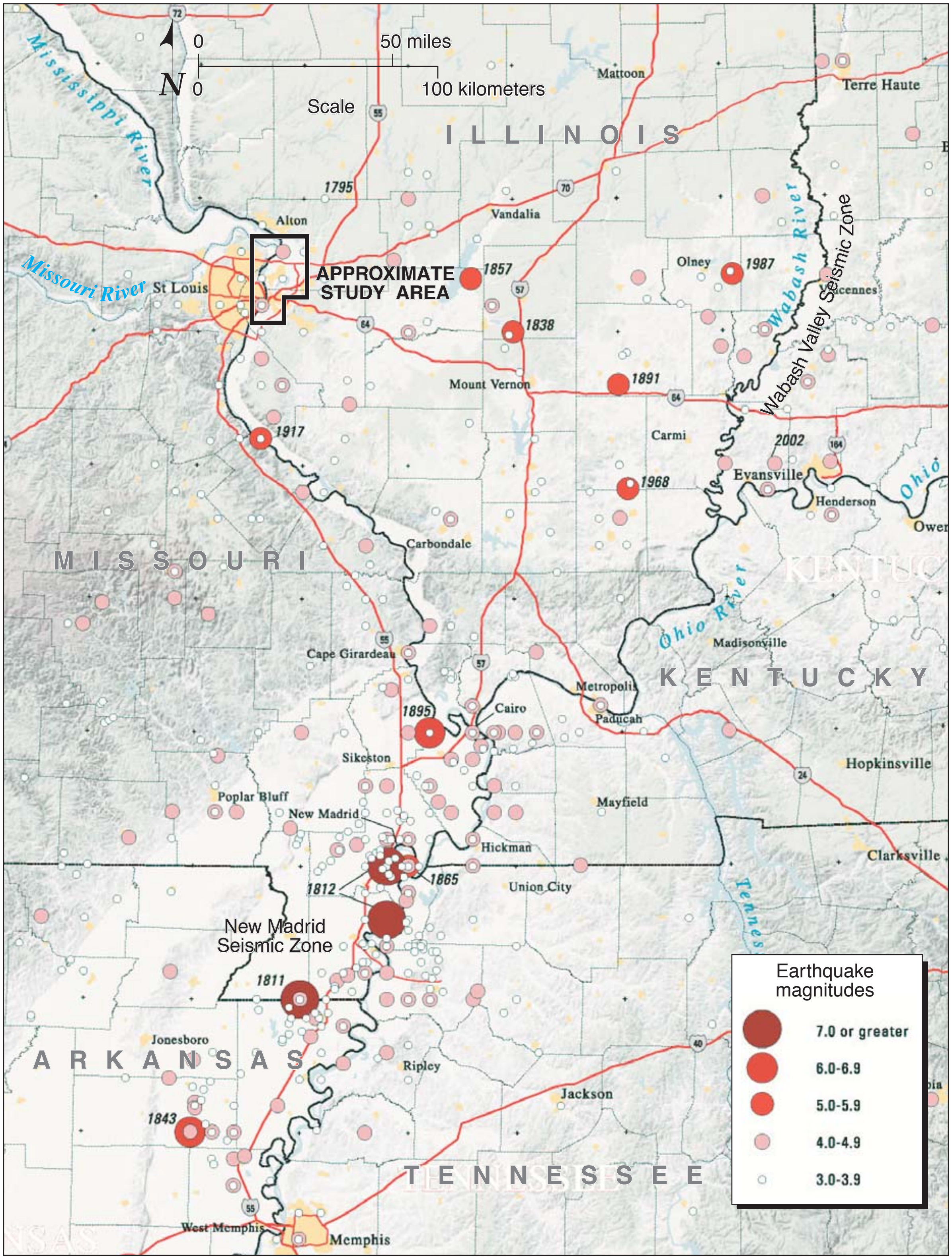


Figure 5. Regional seismicity map showing earthquakes from 1699-2002, with magnitudes above 3.0 (from Wheeler et al. 2002, USGS map I-2812).

2.2 Simplified Procedure

The Simplified Procedure is a method to estimate the liquefaction susceptibility of a deposit by relating standard penetration test (SPT) blow counts of a soil sample to earthquake-induced cyclic shear stresses, based on liquefaction case history. This method is commonly employed because of the volume of SPT data that exists from public engineering projects (e.g. bridges, highways). Other means exist to quantitatively estimate liquefaction susceptibility such as using shear wave velocity (e.g. Andrus and Stokoe, 1999), cone penetration resistance (e.g Mayne, 2000, 2001; Rix, 2001, Tinsley et al., 1985) and Becker penetration test (Youd et al., 2001). For reference, we examined the results from analyses that use alternative methods for assessing liquefaction susceptibility near, but not directly within, our study area (e.g. Mayne, 2001).

Because the Simplified Procedure has been extensively used and studied, the method has benefited from revisions and refinements that have improved the level of analysis overall (e.g. Seed et al., 1982, 1983, 1985; Robertson and Wride, 1987; Youd et al., 2001; Idriss and Boulanger, 2004). Most recently, Cetin et al. (2004) presented revisions to the Simplified Procedure that are based on updates to the case history database to include new field sites from recent liquefaction events (e.g. 1999 Kobe, Japan), a quality screening index for weighting the accuracy of reported case data, and a “Baysian” statistical analysis. The Baysian analysis performed by Cetin et al. (2004) reportedly results in empirical liquefaction relationships that have minimal bias and uncertainty as compared to the previous relationships (e.g. Youd et al., 2001). We use the recent relations developed by Cetin et al. (2004) in our liquefaction susceptibility analysis of the St. Louis region.

3.0 REGIONAL GEOLOGY

The St. Louis region includes the high-standing “uplands” area that confines and bounds the low-lying alluvial floodplain (Figure 2). This region is the location of the confluence of the Mississippi and Missouri Rivers, and was marginal to two major Pleistocene glaciations (Grimley, 2000). As a result of the glaciations, packages of till and sequences of loessal silts (e.g. Roxanna and Peoria) were deposited over areas of the St. Louis region. The more ubiquitous loessal silts are thickest proximal to the bluffs, and thin away from the bluffs and rivers (Goodfield, 1965). The silt deposits blanket nearly all of the uplands topography, and mantle some of the terrace remnants.

In the upland areas, the loess overlies Paleozoic carbonate and marine shale rocks (Harrison, 1997). The Paleozoic carbonates are known to be the source of karst dissolution (Hoffman, 1991). The bedrock typically is responsible for maintaining the generally steep bluffs of the “uplands”. However, near downtown St. Louis (Mo.), the bluff slopes are uncharacteristically gentle which makes precise delineation of the uplands difficult in this particular area.

The expansive low-lying valley floor (“American Bottoms” in Illinois, “Columbia Bottoms” in Missouri) that exists between the uplands was carved to limestone bedrock in places (e.g. Chain of Rocks), and was subsequently backfilled by late Pleistocene coarse glacial outwash deposits (Henry Formation). The Pleistocene outwash is overlain by about 60 feet of relatively finer-grained, intercalating Holocene alluvial sand (Cahokia Formation - sand facies) and overbank clays (Cahokia Formation - clay facies). The overall fining-upward sequence is interpreted to result from the change to a meandering, rather than braided, Mississippi River system during the Pleistocene-Holocene transition (Grimley and Lepley, 1999). Remnants of Pleistocene fluvial terraces exist, most notably a slackwater-environment clay 470- to 480-ft elevation that is believed to have been deposited as ice advanced across the Mississippi valley, temporarily damming it (Grimley, 2000; Goodfield, 1965). Other Pleistocene terraces, composed of coarse glacio-fluvial outwash sediment, were cut at lower elevations and exist marginal to the upland bluffs. Small streams and creeks emanate from atop the bluffs on both sides of the river, transporting sediment and water to the valley floor. Holocene alluvial fan deposits with relatively high silt content are present at the base of the bluffs. The valley floor is thus composed of alluvial fill from the Mississippi and Missouri Rivers and to a lesser degree, minor tributary creeks and local alluvial fans.

The Mississippi River is known to have been very active in the late Holocene to Recent time, meandering across the wide floodplain, carving distinctive meander scrolls and paleochannels on the modern floodplain. The following descriptions attest to the historical activity of the Mississippi River:

> *The river lost its narrow aspect at St. Louis after 1804 when a small sand bar formed near the Illinois shore near Bissell’s Point. It deflected some of the river current against the east bank, causing a wash out and subsequent widening of the river* [to the east] *as well as the creation of Bloody Island from the sand bar. This trend continued until after 1850 when dykes were built to prevent the channel from completely deserting the St. Louis* [Mo.] *side of the river.* (City of St. Louis, 2004)

And,

> *The Illinois shore was covered by a wooded island, which had been washed away by 1830. The capricious action of the river had shifted to the Illinois side to such an extent by this time that sand bars had developed into Duncan's and Quarantine Islands in the river opposite the Soulard area. The formation of Duncan's Island threatened to block off the St. Louis levee from the river channel by 1845. This was prevented by the harbor*

> *works, started by Lt. Robert E. Lee, which caused the channel to again shift to the Missouri side and which later resulted in the washing away of the two islands.* (City of St. Louis, 2004)

These accounts illustrate the naturally meandering tendency of the Mississippi River within the last centuries. This is an important process for depositing potentially liquefiable sediments (very young, unconsolidated alluvial deposits) on the floodplain. However, these accounts also document the beginning of major engineering modifications to the river system. These modifications are designed to control flooding and enhance shipping and navigation. Currently a system of levees, floodwalls, and canals are designed to protect developed areas against flooding damages or loss of real estate from lateral shifting. However, these structures occasionally exceed capacity and fail to contain the water and sediment of the Mississippi River, as in some instances during 1993.

4.0 REGIONAL SEISMICITY

The St. Louis region is characterized as experiencing relatively low magnitude earthquakes from diffuse sources that are not atypical of the central United States seismotectonic setting (Figure 5). However, the region is located near known active seismogenic source areas, such as the New Madrid seismic zone (NMSZ), the Wabash Valley seismic zone (WVSZ), and the Commerce Geophysical Lineament (CGL) that could potentially trigger liquefaction in the study area. The NMSZ (northern section) is about 170 miles (275 kilometers) south of the St. Louis region, and the WBSZ is about 150 miles (240 kilometers) east of the region. For the purposes of this study, we consider the New Madrid North Fault segment of the NMSZ, and the WVSZ as the main seismic source areas that could produce strong ground motions in the St. Louis region that could trigger liquefaction.

The north fault segment of the NMSZ is believed to have produced a large magnitude earthquake during the 1811-1812 earthquake series, and although variable as a result of the estimating technique, the estimated magnitudes (M_w) range from 7.5, 7.6, (Johnston, pers. comm., 2004), 7.2, 7.5 (Bakun and Hopper, 2004), and 7.0 (Hough, 2004), with a 7.3 (M_w) weighted mean average from five maximum magnitude estimates (Geomatrix, 2004). The WVSZ is believed to have produced an earthquake 6,000 (+- 200) years BP, with an estimated range of maximum magnitudes **M** ~7.2 to 7.3, to possibly as high as **M** 7.5 to 7.8. (Geomatrix, 2004). These earthquakes occurred prior to modern seismological instrumentation; therefore the magnitudes of the events are estimates based on paleo-liquefaction (e.g. Obermeier, 1989), paleo-seismologic investigations (e.g. Tuttle et al., 2002), MMI intensities, and interpretation of historical written accounts.

Based on the above best estimates of the ranges and magnitudes of large earthquakes produced during the Holocene by the NMSZ and the WVSZ, we selected a magnitude of 7.5 as our scenario event for the liquefaction analysis. This is appropriate because (1) this value is well represented by the magnitude distributions cited above, and (2) if the scenario event selected is larger than the lower bound (e.g Mw 7.5 vs. 7.0), this results in our liquefaction analysis being somewhat "conservative". Furthermore, strong ground motions in St. Louis modeled by Atkinson and Beresnev (2002) suggest that a magnitude 7.5 earthquake in the NMSZ can produce peak ground accelerations (PGA) ranging from 0.07g to 0.30g, which is in our considered liquefaction triggering criteria range (Figure 4). Frankel et al. (2002), and Hermann et al. (1999, 2004) indicate that the St. Louis region can expect about 0.05 to about 0.10g PGA for a 2% probability of exceedance in 50 years.

5.0 APPROACH AND METHODS

Development of seismically-induced liquefaction hazard maps are based on the development of a comprehensive GIS database of borehole data for the St. Louis region and incorporation of advances in assessments of liquefaction susceptibility as previously described (Grant and Perkins, 1994; Youd et al., 2001; Robertson and Wride, 1997, Cetin et al., 2004). While the details of the quantitative estimates vary slightly, in this study we follow the general procedure accepted by California Geologic Survey (CGS), and employed in previous liquefaction susceptibility projects such as in Boston, Massachusetts (Brankman and Baise, 2004), Simi Valley, California (Hitchcock et al.., 1996; Hitchcock et al., 1999), and the San Juan, Puerto Rico area (Hengesh and Bachhuber, 1999). The liquefaction susceptibility mapping involves four main tasks:

1. Compile and evaluate existing geologic and geotechnical data;
2. Characterize late Quaternary geologic deposits;
3. Characterize ground water depths;
4. Evaluate liquefaction susceptibility of geologic units based on 1, 2, and 3.

The relationship of these tasks to the development of susceptibility maps is schematically illustrated in Figure 3. Liquefaction susceptibility maps are constructed at a scale of 1:24,000 on these quadrangles that contain areas with conditions conducive to liquefaction (Figure 1). The methodology emphasizes the use of detailed Quaternary geologic mapping in conjunction with quantitative evaluation of subsurface information, as a basis for differentiating susceptibility classes. One advantage of this approach is that the categorization of borehole SPT data with respect to geologic map units allows for the extrapolation of data over areas where borehole coverage may be absent or lacking.

5.1 Surficial Geologic Maps

In collaboration with the Illinois State Geologic Survey (ISGS), we incorporated Quaternary geologic maps developed for the STATEMAP program (e.g. Grimley and Lepler, 2001). We used the ISGS maps for four of the five 7.5-minute quadrangles mapped as part of this susceptibility study that lie within Illinois. Our study developed the mapping of Quaternary deposits for those portions of the quadrangles that lie within Missouri (Figure 1; Plates 1, 2, and 3).

The ISGS digital GIS maps depict Quaternary surficial deposits and are based on interpretation of soil maps, digital air photos, and field reconnaissance. The surficial materials units delineated on the ISGS Quaternary geologic maps are assigned to relative age ranges (e.g. Wisconsin; 75,000-12,000 ya), and are associated with an interpreted depositional environment (e.g. abandoned channel). These criteria are consistent, in part, with our geologic mapping criteria, thus we believe the maps are suitable for use in liquefaction susceptibility mapping. For those portions of our study area that lie in Missouri, we developed new, 1:24,000-scale Quaternary geologic maps. The Quaternary deposits in Missouri are mapped in a manner consistent with established WLA criteria for use in liquefaction hazard mapping (e.g. Knudsen et al., 1997; Hitchcock and Wills, 1998; William Lettis & Associates, 1999; Hitchcock and Wills, 2000; Kelson et al., 2001). Quaternary deposits were evaluated on the basis of (1) topographic position in a sequence of inset deposits or surfaces; (2) relative ages of individual deposits; (3) depositional environment; and (4) continuity and lateral correlation with other stratigraphic units.

The ISGS Quaternary geologic maps and the Quaternary geologic maps developed in this study are similar to each other in their delineation of deposits except for the low lying alluvial floodplain areas. Our geologic mapping of the late Holocene alluvial map units are based on fluvial geomorphic frameworks of Kelson et al. (2001), and Pearce and Kelson, (2003), and differentiates units in detail based on inferred depositional environment and process (e.g. meander scrolls, natural levees), topographic expression, and cross-cutting relationships. The delineation of these map units serve to provide additional detail to the Quaternary geologic map, and adds more information about geologic and fluvial geomorphic processes.

The ISGS maps classify the Holocene floodplain alluvium as two map categories, a sand facies and a clay facies, (sandy Cahokia and clayey Cahokia, respectively). Because of this generalization, we needed to provide a context for associating our detailed Holocene map unit classifications to the ISGS map units, in order to have a consistent stratigraphic framework for evaluating and mapping the liquefaction hazard in the St. Louis region. The proposed map unit association framework was developed on the basis of similar interpreted environments of deposition, because this is one of the key geologic criteria for assessing liquefaction (e.g. Youd and Perkins, 1978). Furthermore, the proposed framework is acceptable because it is nearly impossible to distinguish our detailed map units (e.g. natural levee) in the subsurface borehole SPT samples, which is prohibitive for the liquefaction analysis. The presentation and justification for this framework is discussed in a later section.

Our geologic and liquefaction susceptibility maps were constructed in a GIS-environment at 1:24,000-scale. The use or display of the maps at scales greater than 1:24,000 is neither appropriate nor recommended, and will violate the spatial resolution of the map. Enlargement of the maps will incorrectly imply undue accuracy of the map and the susceptibility analysis. These maps should not be considered as substitute for a site specific study.

5.2 Liquefaction Susceptibility Calculations

The five quadrangles chosen for investigation in this study were selected on the basis of the concentration of industrial and commercial development and lifelines, the presence of young potentially susceptible sediments, and the availability of geologic and geotechnical data. The final liquefaction susceptibility maps integrate existing subsurface data, surficial geologic mapping, and depth to groundwater to estimate triggering peak acceleration thresholds (PGA trigger). Our approach to assigning relative levels of liquefaction susceptibility is shown in Figure 4. We analyzed the liquefaction susceptibility of surficial deposits in the St. Louis region on the basis of sediment texture, density, age, depositional environment, and groundwater conditions. These criteria govern the liquefaction resistance of a deposit (e.g. Youd and Perkins, 1987). Our quantitative analysis of liquefaction susceptibility of sediment is based on the Simplified Procedure (Seed and Idriss, 1971) and subsequent revisions (Seed et al., 1983, 1985; Youd et al., 2001; Cetin et al., 2004), wherein the Standard Penetration Test (SPT) and other data (e.g. overburden, effective overburden, texture) provide a functional means of establishing material strengths and the susceptibility to liquefaction.

The use of the Simplified Procedure is based on the relationship of the driving shear stresses exerted by earthquake strong ground motions (Cyclic Stress Ratio - CSR) to the resisting forces of the soil (Cyclic Resistance Ratio - CRR). CSR is a function of soil overburden, soil effective overburden, peak ground acceleration (a_{max}), and earthquake magnitude scaling factor (MSF) that accounts for shaking duration. The quantitative estimate of CRR is a function of soil geotechnical properties; in this case Standard Penetration Test (SPT) blow count [$(N_1)_{60}$] information. The SPT blow count measurements are an indicator of the relative density of a soil which is directly related to the resistance to liquefaction. More consolidated sediments, with high blow counts are generally less susceptible to liquefaction, and the converse is also true. This approach was reviewed and updated during a “state-of-the-science” workshop in 1998 (Youd et al., 2001).

Revisions to key coefficients of Youd et al. (2001) were introduced by Cetin et al. (2004). The revisions are based on (1) a re-screening of original and newly added empirical data quality and (2) a multidimensional “Baysian” statistical analysis of the impacts of the range in various susceptibility parameters and their effect on observed liquefaction resistance. The statistical analysis resulted in substantial changes in how the “non-linear shear mass participation” factor (r_d) is estimated. Cetin et al. (2004) assert that robust statistical analysis reduced inherent uncertainty in the liquefaction analysis, and that these new relationships are removed of inherent bias that existed in the earlier relationships. However, the premise of the deterministic Simplified Seed-Idriss approach remains the same with Cetin et al. (2004). We believe that because of the: (1) augmentation to the empirical liquefaction database, (2) data quality screening and ranking, (3) statistical analysis of the data, and (4) professional experience and judgment of the authors, that the revisions and updates are warranted and justified in their usage for liquefaction susceptibility analysis. Below is a synopsis of the changes to estimation of r_d.

5.3 Soil Rigidity Factor (r_d)

This term is sometimes called different names (e.g. “soil rigidity factor”, “non-linear shear mass participation factor”, “stress reduction coefficient”) but represents the same physical phenomenon: that a soil column experiences, and therefore responds to, cyclic shearing forces in a vertically heterogeneous fashion, that is non-linear with depth. In simple terms, the soil column does not behave as an entirely rigid body when shaken by an cyclic shear stresses caused by an earthquake. Because of this fact, calculated CSR must incorporate this term. Cetin et al. (2004) state the r_d is a function of several variables, however due to strong cross correlation among some parameters, there are four main descriptive variables: (1) depth (d), (2) earthquake moment magnitude (M_w), (3) intensity of shaking ($a_{\max}$), and (4) site stiffness (V^*_s). Increasing earthquake magnitude, site stiffness, or depth results in non-linearly increasing values of r_d, while increasing $a_{\max}$ decreases r_d.

In summary, we used a revised Simplified Procedure approach incorporating Cetin et al. (2004) r_d factor (e.g. Seed and Idriss, 1971; Youd et al., 2001; Cetin et al., 2004) to quantitatively estimate the peak ground accelerations necessary to trigger liquefaction in a unit. We used the triggering PGA’s for designated geologic units to develop relative susceptibility hazard rankings for the geologic materials for each geologic unit (Figure 4).

6.0 DATA

Three key groups of data are needed for successful evaluation of the liquefaction susceptibility of the Quaternary deposits: (1) Quaternary geologic maps, (2) subsurface borehole stratigraphic and geotechnical logs, and (3) information on the regional depth-to-groundwater. Quaternary geologic maps provide information on unit age and depositional environment. Subsurface logs are a source of information about the physical and technical properties of the units that are needed for the Simplified Procedure, such as blow counts, soil texture (e.g. USCS unit designation), fines content, and unit weights. Regional depth-to-groundwater is critical for calculating effective overburden stress in the Simplified Procedure. Input parameters for the liquefaction calculations are also needed, such as shear wave velocity, unit weights, and percent fines contents, and are largely based on published reports or on reasonable estimates from subsurface borehole data. Below we describe the sources, assumption, and limitations of our data.

6.1 Quaternary Geologic Mapping

Quaternary geologic maps used in this study are from: (1) existing Illinois State Geologic Survey 1:24,000-scale mapping that covers areas in Illinois; and (2) newly developed 1:24,000-scale Quaternary geologic mapping that covers the Missouri portion of the study area quadrangles.

For quadrangles in Illinois, we used the following existing Illinois State Geologic Survey Quaternary geologic maps developed for STATEMAP:

Cahokia Quadrangle (IL); A. Phillips, 1999;
Columbia Bottom Quadrangle (IL); D. Grimley and S. Lepley, 2001;
Granite City Quadrangle (IL); A. Phillips, D. Grimley, and S. Lepley, 2001;
Monk's Mound Quadrangle (IL); D. Grimley, A. Phillips, and S. Lepley, 2001;
Wood River Quadrangle (IL); D. Grimley and S. Lepley, 2001.

For those portions of our study area that lie in Missouri, we developed new, 1:24,000-scale Quaternary geologic maps based on: (1) review of previous, regional geologic mapping (e.g. Goodfield, 1965; Schultz, 1993; Hoffman, 1995); (2) inspection and interpretation of stereo-paired black and white 1958 aerial photographs, review of historical geographic and topographic maps of the St. Louis area (e.g. Paul, 1844; Metropolitan Sewer District, 1899); (3) inspection of modern digital air photos, soils and topographic maps; (4) analysis of subsurface boring logs; and (5) field reconnaissance. The 1958 aerial photograph set was chosen because it provides the highest quality, 1:24,000-scale, stereo-paired images available that pre-date the modern urban conditions. Quaternary deposits were evaluated on the basis of: (1) topographic position in a sequence of inset deposits or surfaces; (2) relative ages of individual deposits; (3) relative degree of soil profile development; and (4) continuity and lateral correlation with other stratigraphic units.

6.1.1 Illinois State Geologic Survey (ISGS) Quaternary Mapping

The reader is referred to the original reports and documentation for each quadrangle for a detailed explanation of the map criteria, map units, and Quaternary depositional history of the mapped quadrangles (e.g. Philips, 1999; Phillips et al., 2001; Grimley et al., 2001, and Grimley and Lepley 2001a, 2001b): The descriptions, explanations, and interpretations of map units for the ISGS quadrangles are as written for the Wood River quadrangle (Grimley and Lepley; 2001b). We used the ISGS map unit descriptions to develop our stratigraphic framework for the correlation of the final liquefaction susceptibility map; therefore we describe the ISGS map units for Illinois as:

Qd – Disturbed ground (Holocene). Artificially emplaced fill or removed earth; sediment of various types. Includes man-made materials in major highways, landfills, sand and gravel pits, and levee fills.

Qcu – Cahokia Formation, upland facies (Holocene). Silt loam with some silty clay and sand, occasional gravel; gray to brown, may contain organic or man made debris. Alluvium from channels tributary to the main valley. Contains significant eroded and re-deposited loess material.

Qcf – Cahokia Formation, fan facies (Holocene). Silt loam with occasional thin sand beds; brown, weakly stratified, and soft. Alluvium deposited by distributary channels; includes much re-deposited loess, and some deposits from interpreted mud flow events.

Qcc – Cahokia Formation, clayey Mississippi Valley facies (Holocene). Silty clay loam, silty clay, and silt with occasional fine sand lenses; gray to brown, some thin red lenses, massive to well-stratified, soft to stiff. Abandoned channel fill and backswamp alluvium deposited in the floodplain of the Mississippi River.

Qcs – Cahokia Formation, sandy Mississippi Valley facies (Holocene). Very fine, fine, and medium sand, with some coarse sand and gravel and some silt and clay layers; light brown to gray, stratified, loose to soft. Point bar and channel alluvium of the Mississippi River. This unit can be difficult to distinguish from Henry Formation (Qh) in subsurface logs. Generally recognized by relatively finer grain sizes, lower blow counts, and shallower depths.

Qce – Cahokia or Equality Formation, undifferentiated (Holocene to Pleistocene). Silty clay to silt with some fine sand; gray to brown, massive to stratified, stiff. Fine-grained alluvium and/or lake deposits found at the east edge of the floodplain, deposited by Mississippi River backflooding.

Qe – Equality Formation (Pleistocene). Silty Clay to silt with some fine sand; gray to brown to pinkish-brown, massive to stratified, stiff. Lake deposits laid down by backflooding of the Mississippi River during glacial episodes.

Qh – Henry Formation (Pleistocene). Medium to coarse sand with gravel and some fine sand; fine sand where exposed near surface; light brown to gray. Glacial outwash deposits of the Mississippi River that are primarily buried by post-glacial Cahokia alluvium. Occurs as terrace remnants at the edge of the valley floor. This unit can be difficult to distinguish from sandy Cahokia alluvium in subsurface logs. It is generally recognized by relatively coarser grain sizes (medium sand to gravel), abruptly higher blow counts (e.g. ≥ 50), and deeper encountered depths.

Qpr – Peoria and Roxanna Silts (Pleistocene). Silt to silt loam; yellow-brown to gray to pinkish brown; massive with some dark organic layers, friable. Loess deposited during glacial times. Preserved mainly in the topographically high-standing areas.

Qg – Glasford Formation (Pleistocene). Pebbly silt loam to loam diamicton with common sand and silt bodies; olive to gray; weathered brown in the upper sections; typically massive and dense. Till and ice-marginal sediment. Occurs primarily in the subsurface, with few map exposures.

6.1.2 Quaternary Mapping Performed for this Study

The surficial geology in the St. Louis region is dominated by deposits that were formed as a result of several repeated ice advances and retreats in the Quaternary. We recognize four areally extensive deposits, from oldest to youngest: late Pleistocene eolian loess material (as much as 40 feet thick) derived from various sources (e.g. Grimley, 2000; Goodfield, 1965), late Pleistocene coarse-grained glacio-fluvial valley train outwash (about 100 feet thick), Holocene fine- to medium-grained floodplain alluvium (about 50-60 feet thick), and artificial fill (variable thickness).

The glacio-fluvial deposit is interpreted to be a relatively high-energy of deposition (e.g. braided stream) due to the coarse texture of the deposit, and the depositional proximity to the ice margin. The late Pleistocene outwash deposits are exposed at the surface as terrace remnants at the base of the bluffs.

During the Holocene, the Mississippi River evolved to a more meandering-type stream, with lower overall depositional energy as the ice retreated and discharge and sediment load characteristics changed. Lateral migration of the Mississippi and Missouri Rivers and relatively frequent overbank flooding characterizes the late Holocene fluvial system, with distinct sand facies associated with the former channel and bar deposits (e.g. meander scrolls), and clay facies associated with overbank deposition of fines (e.g. crevasse splays). These late Holocene deposits are mapped based on relative position, topographic expression, and inferred depositional environment. However, the subdivided fluvial units are difficult to differentiate in subsurface borehole logs.

Artificial fill is also an extensive surficial map unit, because it is an unconsolidated Quaternary deposit. The fill, therefore, is subject to the effects of strong ground shaking induced by earthquakes. We classify fill as either engineered or “non-engineered”. This refers to the overall method and nature of emplacement technique. Engineered fill for roads tends to be designed for stability and therefore tends to be of suitable material for construction, and tends to be compacted to a calculated amount. This is usually the case for highway or interstate embankments. We do not have engineering or borehole records that substantiate this interpretation and delineation. Therefore, our mapping of engineered artificial fill based on topographic expression and should be considered subjective, at best. As seen in subsurface boring logs, non-engineered fill is usually composed of a mixture of natural materials and foreign debris (bricks, glass, wood, ash). Typically, non-engineered fill is not compacted, and tends to have highly variable blow counts, suggesting vertical heterogeneity. We infer that this material was used to construct the artificial levees that exist on the floodplain, or as heterogeneous reclamation and fill material under urbanized areas. Generally, non-engineered artificial fill underlies populated areas (e.g. downtown St. Louis), and may or may not be liquefiable depending on site-specific conditions beyond our ability to differentiate, given the regional quadrangle-based mapping of this study.

Quaternary geologic mapping in the area of the original settlement of St. Louis is difficult due to pre-aerial photography cultural modification. The settlement was established in late 1763 by Pierre Laclede Liguest, near present day Jefferson National Expansion Memorial Park. Historical maps, drawings, and reports document the original conditions, but can be difficult to reconstruct because referenced landmarks (e.g. buildings, street intersections) may no longer exist, or have been renamed or relocated. Very early maps commonly lack sufficient geographic control or accuracy to be used for other than illustrative purposes. Written reports commonly are unclear in the language, thus making interpretation and reconstruction of described landforms difficult. Early settlers used the bedrock that comprised the bluffs to the east as local quarries for house building stone (City of St. Louis, 2004), which degraded already gentle bluff slopes. A description of the original settlement site is described as:

> *Laclede and his band of traders landed at what is now the foot of Walnut Street* [in November, 1763]. *Here was a high limestone bluff rising about forty feet above the Mississippi, sloping back in two or three terraces to the west and extending about two miles along the riverfront. The bluff and the ceceding terraces were covered by a growth of timber extending irregularly west as far as present day Fourth Street…A small creek flowed into the river below the selected site, it traversed a wooded valley across the prairie from the east. Affording a place for the erection of a mill and dam, the creek later*

> *was called Mill Creek, and formed Cheauteau's Pond. Its valley marked the south edge of the bluff along the riverfront.* (History of St. Louis).

This description of the landscape is clearly different from that seen today. As described earlier, the activity of the Mississippi River in the 1800's was a general trend of lateral migration eastward. Upon examination and comparison of Paul's (1844) map and the modern topographic maps, it is apparent that the western boundary of the Mississippi River had substantially shifted eastward near Jefferson National Expansion Memorial Park, thus sub-aerially exposing the alluvial sediments, which were subsequently covered by artificial fill. We note that during the 1800's the Mississippi River migrated eastward, leading to deposits of large sand bars along the main channel (e.g. Duncan's Island). We infer that this shift in the river position exposed the alluvium (now a terrace), which was subsequently developed for the expanding town. We map this deposit as artificial fill (Qaf) over alluvium (Qht1), to depict the materials at the surface and the unconsolidated Quaternary deposits beneath.

Delineation of Quaternary terraces Qht1 and Qht2 (Plates 2, and 3) is based largely on inspection and interpretation of 2-foot topographic contours (St. Louis Metro Sewer, 1899), modern topographic maps, relative geomorphic position, and limited subsurface borehole data. It is possible that Qht1 and Qht2 may be a single alluvial deposit, rather than two distinct cut-and-fill deposits, with two surfaces cut on top as the Mississippi River meandered and slightly incised the deposit. We do not have sufficient subsurface geologic information across the two map units to compare the deposits. In the area of Riverview, and downtown St. Louis, historic and modern small creek channels (e.g. Mill Creek, Harlem Creek, and Maline Creek) emerge from the higher elevations to flow along, and across, the Qht1 and Qht2 terraces. Because the creek channels cross-cut the mapped terraces, they must therefore be younger than the terraces.

Geologic maps by Goodfield (1965), Schultz (1993), and Hoffman (1995) depict extensive areas of (non-engineered) artificial fill that presumably overlies alluvial surfaces adjacent to the Mississippi River. Boring logs and subsurface soundings indicate that the non-engineered artificial fill is composed of a variety of materials such as cinders, bricks, wood, re-worked and locally sourced sand and silt, gravel and rubble. The geotechnical properties of these deposits, and their expected response to strong ground shaking, are unknown, and are likely to be highly variable from one area to another due to the non-uniform manner of fill emplacement and source materials.

Engineered artificial fill deposits (Qafe) are interpreted from modern topographic maps as distinct alterations to the landscape contours (e.g. highway and railroad berms). We do not have information to directly assess the method of emplacement or characterize the material properties. Because these fill deposits were emplaced sometime after the 1950s and because they generally serve to support interstate travel loads, we assume that they were constructed using modern engineering principles (e.g. compaction), and will therefore behave differently than non-engineered fill. Additionally, we mapped artificial fill deposits that were presumably placed to create small ponds and lakes, and to allow for urban development (i.e. fill prisms for buildings). The composition of these fill materials is unknown. Thus, our interpretation and classification of engineered fill based on topographic map inspection may not necessarily reflect the actual conditions in the field, and should be viewed with caution. The delineation of artificial fill is consistent with mapping produced by ISGS (e.g. Grimley and Lepley, 2001) and mapping for liquefaction evaluations in the San Francisco Bay area (e.g. Knudsen et al., 1997), San Juan, Puerto Rico (Hengesh and Bachhuber, 1999), and Ventura County (Hitchcock, 1999).

Map Units for Quaternary Geologic Maps in Missouri

Map Units (Informal)

Qaf – Artificial fill. Artificially emplaced, clays, silts, sands, or gravel in various relative quantities, with or without a heterogeneous mixture of cinder, glass, brick, wood fragments, ash, "rubble". This unit has variable thickness and extent where it occurs in flat, urbanized areas adjacent to the Mississippi River. This unit also represents deposits composing the levees that are constructed on the floodplain between the Mississippi and Missouri Rivers, and on the Columbia Bottom wildlife refuge area.

Qafe – Engineered artificial fill. Artificially emplaced mixture of native or imported soil material, loose to dense. This unit is mapped where alterations to natural topography can be observed (e.g. berms, interstate fill prisms). This unit is differentiated from Qaf on the assumption that it is generally, but not necessarily, machine compacted to a given dry density, although this is uncertain.

Qhb – Channel bar (Holocene). Fine to medium sand, silty sand to clayey sand, some intercalated clay layers, stratified, loose to medium dense. Alluvial deposit of the Mississippi and Missouri Rivers, constructed in the lateral or medial portion of the channel from bedload transport and accretionnary processes.

Qhs – Marsh or backswamp deposit (Holocene). Clays and silts, silty clay to clayey silt with minor sand component; massive to stratified; some organic detritus; soft to stiff. Alluvial deposit from slackwater conditions, typically occurring in relatively low topographic areas such as abandoned channels or swales between the bluffs and the natural levees of a floodplain.

Qhnl – Natural levee deposit (Holocene). Sandy silts to clayey silt, with occasional fine sand lenses; soft to stiff. Alluvial deposit constructed from channel overbank events that results in the development of topographic ridges that are highest proximal to the channel bank, and are aligned parallel to the channel course.

Qhcs – Crevessase splay (Holocene). Silty clay to clay, with minor very fine sand component; soft, vertically stratified. Alluvial overbank event occurring due to breaches or cracks (i.e. crevasses) in natural levee deposits.

Qhms – Meander scrolls (Holocene). Fine to medium sands, with some silt and clay layers; stiff, laterally and vertically sorted. Alluvial deposit constructed as a channel migrates, and the old position of a point bar is preserved topographically as an arcuate system of ridge and swales referred individually to as scroll bars.

Qhch – Channel (Holocene). Fine to medium sand, silty sand to clayey sand, with some granule and pebble content; typically well sorted; loose to dense. Alluvial deposit of the channel bed material.

Qhal – Tributary alluvium (Holocene). Fine to coarse sand, silty clay to slightly sandy clay, silt containing shells and roots; gray; loose. Alluvium from channels draining the uplands, tributary to the Mississippi and Missouri Rivers. The silt content is from locally re-worked and re-deposited loess.

Qhf – Alluvial fan (Holocene). Predominantly clayey silt, thin layers of fine to medium sand; gray to brown; soft. Alluviual deposit from distributary channels draining the uplands. The silt content is from locally re-worked and re-deposited loess.

Qht1 –Terrace (Holocene). Fine to medium sand with traces of gravel, with lenses of silty clay to clay in the upper section; grey; stiff to medium dense. Limestone is at about 80 feet below ground surface, and is veneered by a thin gravel-cobble layer. Alluvial deposit from Mississippi River, exposed by abandonment and incision during post-glacial times, this surface is inset about 6 feet into Qt2.

Qht2 –Terrace (Holocene). Sandy silt, silt with fine sand lenses, fine sand, localized clay layers near the top of the section; tan; very loose to medium dense; poorly sorted. Alluvial deposit from Mississippi River. This unit overlies limestone bedrock, whose surface deepens toward the river (13' depth to 60' depth).

Qhtu – Undifferentiated Terrace (Holocene). Sandy silt to silty clay; soft to stiff; stratified. Alluvial deposit from upland channels tributary to the Mississippi and Missouri Rivers.

Qpt3 – Lacustrine Terrace (Pleistocene). Sandy clay to sandy silt, clay with some coarse sand; gray to brown; very soft to medium stiff. Lacustrine deposit created by damming of the Mississippi River from advancing ice (Goodfield, 1965).

Qptd – Deer Plain Terrace (Pleistocene). Fine to coarse sand with gravel lenses, fine sandy clay, clayey silt; brown to yellowish-brown; stratified; soft to stiff (Goodfield, 1965). Fluvial terrace deposited from glacial outwash, occurs as an isolated remnant along the bluffs near Columbia Bottom Road.

Qpl – Peoria and Roxana Loess -undifferentiated (Pleistocene). Silty to clayey silt, tan to brown to pinkish-brown to yellowish-brown; usually massive; some limonite nodules and staining; terrestrial gastropods common (Grimley and Lepler, 1999).

Qpmc – Mill Creek Till (Pleistocene), not exposed at surface. Sand and gravel with cobbles, clay, and silt in various proportions, minor to occasional lignite; brown to gray; very stiff. Glacial till and ice marginal sediments, occurs primarily as an aerially restricted deposit in the subsurface.

6.1.3 Correlation of Map Units

Because the Quaternary geologic classification framework used for mapping deposits differs across the state boundary, the map units were correlated for internal consistency during the liquefaction susceptibility analysis. Our correlation of stratigraphic map units for the study area is shown in Table 1. This proposed stratigraphic correlation is primarily based on similar-interpreted depositional environment of each map unit. The ISGS maps three geologic deposits on the study area floodplain: (1) Cahokia alluvium (sand facies), (2) Cahokia alluvium (clay facies), and (3) artificial fill. We combined our map units, as appropriate, to conform to the more generalized classification scheme used by ISGS. For instance, clayey Cahokia facies are interpreted to have been deposited by overbank flood processes. Thus, we aggregate natural levee and crevasse splay deposits in this category. Also aggregated into this category are marsh (backswamp) deposits because of the finer grain sizes of the deposit, and the inferred relatively low energy depositional environment. This proposed stratigraphic correlation is reasonable because: (1) the generalized stratigraphic scheme of ISGS encapsulates our more detailed geologic units; and (2) the ISGS mapping scheme implies a depositional environment that also is captured by our mapping.

Table 1. Stratigraphic Correlation of Map Units

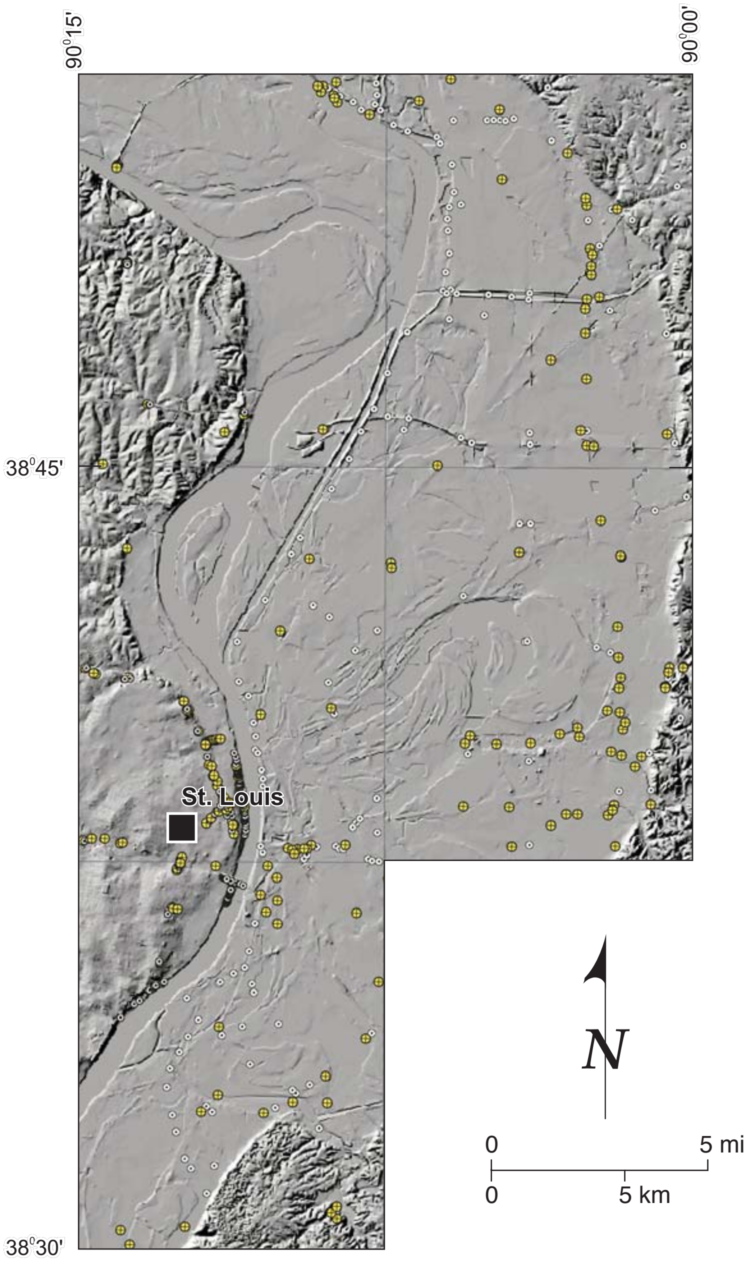
Unit Symbol (This study)	Map Unit (This study)	ISGS Unit Symbol	Classification	Relative Age
Qhaf	Artificial fill	AF	Disturbed ground	Recent
Qhafe	Artificial fill (engineered)			
Qhs	Marshes (backswamp)	Qcc	Clayey Cahokia	Holocene
Qhcs	Crevasse splay			
Qhnl	Natural levee			
Qhb	Channel bars	Qcs	Sandy Cahokia	
Qhch	Abandoned channels			
Qhms	Meander scrolls			
Qht1,Qht2,Qhtu	Fluvial terraces			
Qhal	Tributary alluvium	Qcu	Upland Cahokia	
Qhf	Alluvial fans	Qcf	Fan Cahokia	
Qpt3	Lacustrine terrace	Qe	Equality Formation	Late Pleistocene
Qptd	Deer Plain terrace	Qh	Henry Formation	
Qpl	Loess	Qpr	Loess	

6.2 Subsurface Boreholes

Subsurface borehole information used in this study was collected from various sources in differing formats. The bulk of our SPT data was provided by the ISGS database compiling data from bridge and highway structures on the alluvial floodplain and some of the adjacent upland areas. The spatial location provided for each borehole is as accurate as possible (D. Grimley, pers. comm.); however, some original hardcopy records only included location information at Township, Range, and Section resolution (e.g. no quarter section resolution). Because of this fact, instances occur where multiple boreholes are plotted at the same spatial coordinate (e.g. the center of the Section).

We also obtained subsurface geologic and geotechnical subsurface information from the Missouri Department of Transportation (MoDOT). Data was photocopied from the Log of Test Borings (LOTBs). These data are primarily located along major interstates, highways, and overpasses (Figure 6). The data included SPT results and shallow auger or push core soundings. Recent LOTBs include grain size distribution analysis and Atterberg limits for finer-grained samples. The boreholes were hand plotted onto our basemap for digitization into GIS database. If a site map showing borehole locations was included with the file, we used the included map to plot the boreholes. If the LOTBs were referenced to the MoDOT stationing coordinate system, we plotted the boreholes based on the description of the location on the log header, and by relative distance along station. We estimate these hand plots to be accurate within about 250 to 500 feet.

Reports and data were collected from various environmental investigation/remediation sites near the Mississippi River edge in Missouri (e.g. URS, 2001; Burns and McDonnell, 1994; Bechtel, 1990; IT Corporation, 2002). These data include limited SPT data, and generally are sounding and groundwater monitoring well information. Most of the SPT data are shallow (e.g. 20-30 feet), and



Explanation

⊕ Boreholes with SPT blow count data

⊙ Boreholes with only stratigraphic logs

Figure 6. Borehole location map.

predominantly encounter only artificial fill deposits. No information is included with these logs to estimate either the fines content of the fill, overall USCS classification, or unit weight. Therefore, this reduced the number of SPT samples we could include from this data source.

We obtained additional subsurface stratigraphic information from the Corps of Engineers, St. Louis District, for portions of the downtown St. Louis floodwall in Missouri, and for a portion of the levee at the Chain of Rocks Canal. Both data sets lacked SPT information, but were used to assess the character and extent of the underlying subsurface deposits. The stratigraphic data from the floodwall soundings were plotted on our map based on engineering-scale general plan and profile diagrams.

Subsurface borehole coverage is sparse for the Columbia Bottom quadrangle when compared to coverage in the adjacent areas in Illinois (Figure 6). Typically, the deposit of a subsurface SPT sample is correlated to a surficial geologic map unit (e.g. Knudsen et al., 1997; Hitchcock and Wills, 1998). In this way, the results of the Simplified Procedure can be extended to represent those geologic map units that lack subsurface borehole information. Because we have developed a stratigraphic correlation between units in Illinois with deposits in Missouri (Table 1), we rely on the results of the borehole analysis from Illinois deposits to infer susceptibility for similar mapped deposits in Missouri where subsurface data is lacking.

6.3 Groundwater

Depth-to-groundwater (DTW) is an important variable in the Simplified Procedure for liquefaction evaluation, because it is used to calculate effective normal stress exerted on a sample. We constructed a scenario DTW map for the study area (Figure 6), based on a synthesis of published maps and reports, groundwater well data, and encountered free water levels in borehole logs.

Missouri

Depth-to-groundwater data for the Missouri portion of the study area were compiled from three different sources: (1) USGS national well station data, (2) Missouri GSRAD digital information base (MEGA), and (3) boring logs if groundwater was encountered during drilling. It appeared that there were duplicated data between the USGS and MEGA data based on their spatial proximity and identical DTW values. These duplicate data were removed. The limitation with using this data for constructing a scenario DTW map is that the groundwater levels were recorded in different years for each boring, and also at different seasons of the year, and is therefore not temporally consistent. We constructed DTW contours for the alluvial areas based on review of the well data and reasonable hydro-geologic assumptions. We assigned the low-lying floodplain areas a DTW range of 0-10 feet. Our field visit to the Columbia Bottom Conservation area (April, 2004) confirmed nearly saturated soil conditions. For those alluvial areas that are urbanized, we assigned a DTW value of 11-20 feet (Figure 7). This is a reasonable estimate based on encountered free water in boreholes and groundwater elevation maps in environmental reports.

Groundwater aquifers in the uplands are generally restricted to the Paleozoic carbonate basement rocks. Groundwater level data in the higher-elevation loess-covered uplands area is scattered and sparse, at best. In the uplands area, DTW is on the order 60 feet, is highly variable. However, the limited well data indicate that while DTW can exceed 100 feet, it only rarely is less than 40 feet. Because liquefaction susceptibility is very low when the upper 40 feet of sediment is not saturated (Figure 4), we simply characterize the upland areas as having DTW of greater than 40 feet.

Illinois

DTW Depth-to-groundwater for potentially liquefiable sediments in Illinois was derived from the potentiometric surface map from Kohlhase (1987). This map shows the approximate elevation of the potentiometric surface from November, 1985, and clearly demonstrates the presence of drawdown cones.

These cones have persisted in time and space (e.g. Collins and Richards, 1986; Schicht and Buck, 1995), as a result of ground water pumping for industrial usage and public consumption. Schicht and Buck (1995) show that groundwater pumping has decreased though time since its peak of nearly 110 mgd in 1956, compared to an estimated 58 mgd in 1990. They also show that groundwater elevations recovered somewhat as a result of the reduction in pumpage. Overall, the Kohlhase report (1987) estimates a higher potentiometric surface elevation than recently measured in 1990. This is partly due to higher stage elevations of the Mississippi River in November of 1990 compared to November 1985. We believe it is appropriate to use the highest historical groundwater elevations of Kolhase (1987) for liquefaction susceptibility evaluation, because this provides a "conservative" (e.g. more susceptible) estimate of the hazard (e.g. Hitchcock et al., 1999, 2000; Knudsen et al., 2000). Additionally, we believe that the groundwater pumping from the Illinois aquifer sediments will continue to persist due to industrial and public needs; therefore the Kohlhase (1987) map represents relatively realistic present-day conditions. As a simplification, we assume that the potentiometric surface map from Kohlhase (1987) represents unconfined water table elevations, even though the aquifer is considered mostly a leaky confined aquifer. This results in a slightly conservative analysis, since the potentiometric surface is generally above, or equal to, the water table.

We digitized the Kohlhase (1987) potentiometric surface map, and assigned elevation attribute values to the contour lines. We converted the groundwater surface elevations to depth-to-groundwater (DTW) values, by intersecting the digitized groundwater contours with digital land elevation data (10-meter cell size). Subtracting land surface elevation from potentiometric surface elevation yields a DTW value at each intersection point. These DTW data points were interpolated and used to construct DTW map with ten-foot contours (Figure 7). This process for deriving depth-to-groundwater provides an estimated value only. The sources of uncertainty that contribute to possible error in our data include (1) the interpolation of the original potentiometric map, (2) the interpolation of the source land surface elevation file (up to 2 meters), and (3) the interpolation used in the creation of the DTW map (e.g. using land surface elevation instead of top of casing). We know that there are some errors in this method because some calculated DTW points produced negative depth to groundwater values, which would represent artesian conditions.

6.4 Shear Wave Velocity

Shear wave velocity is a variable that is used in the calculation of the coefficient r_d for the Simplified Procedure. We used shear wave velocities for our geologic map units based primarily on values obtained by B. Bauer (ISGS), cited in Hermann and Akinci, (2004), and to a lesser degree Pugin et al. (2002), Mayne and others (2002), Atkison and Beresnev (2002), and MoDOT (2004). It should be noted that the values used in this study are estimates based on averages that represent a wide range of values in the soil column. Generally, for unconsolidated sediments, as the average shear wave velocity of a unit increases, the resistance of that unit to liquefaction decreases. Using values from the higher bound of a velocity range would produce a more conservative result (higher apparent liquefaction hazard).

For the liquefaction calculations, we largely used the values listed in Hermann and Akinci (2004) because (1) those data are specific to our geologic units of interest, and (2) they are within the range of values determined by other investigators working in the same or similar geologic units (Table 2). We used the University of Missouri-Rolla (2004) velocity data for Artificial Fill units. As a note, Atkinson and Beresnev (2002) cite higher shear wave velocities for alluvium near Memphis as compared to St. Louis, which could represent a fundamental property that controls causes different site response to strong ground shaking (e.g. liquefaction).

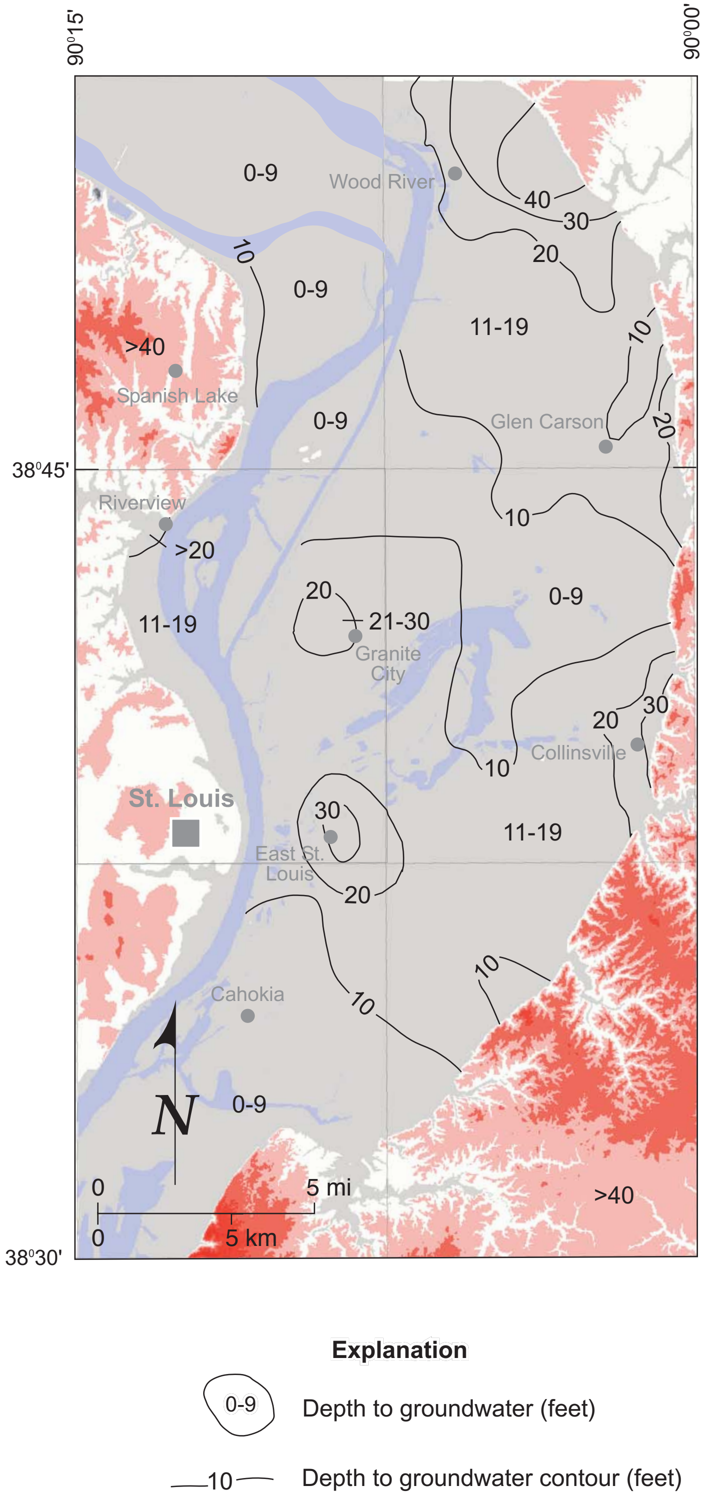


Figure 7. Map of scenario depth-to-ground water used in liquefaction analysis; ten-foot contours. Modified from Kohlase, 1987. Base map is a digital elevation model. Warm tones are higher elevations (uplands), gray tones are lower elevations (alluvium).

Table 2. Estimated Shear Wave Velocities

	Estimated shear wave velocity (m s^{-1})				
Geologic Formation	**Hermann and Akinci (2004)**	**Pugin et al. (2002)**	**Mayne et al. (2002) †**	**UMR (2004)**	**Used**
Artificial fill*	x	x	x	215-245	230
Clayey Cahokia	200-230*‡	150-200*‡	150-200*‡	~180	200
Sandy Cahokia			220	~230	230
Upland Cahokia	x	x	x	x	200
Fan Cahokia	x	x	x	x	200
Henry Formation	200	x	x	x	230
Equality Formation	175	x	x	x	175
Loess	200	x	x	x	200
Till	365	x	x	x	365

† Tested Meramec river alluvium, ‡ values increase with depth, * undifferentiated units, x no data

7.0 RESULTS

We collected about 5,800 SPT sample data from over 200 boreholes that were drilled in the St. Louis region to assess the texture and relative density of the Quaternary subsurface deposits. These data allowed a subsurface sampling of the stratigraphic units that compose the bulk of the valley alluvial fill. Each soil sample with SPT blow count data was assigned to an ISGS map unit category (e.g. Sandy Cahokia, Henry Formation), to group the data for the liquefaction analysis. The Simplified Procedure shows the relationship between cyclic stress ratio (CSR) and SPT $(N_1)_{60}$ value for each map unit (Figure 8). Each plot shows the recorded SPT $(N_1)_{60}$ versus the expected cyclic stress ratio (CSR) from a 7.5 magnitude earthquake, with liquefaction threshold curves. We used 0.10g, 0.20g, and 0.30g as scenario values for maximum ground acceleration in the St. Louis region (a_{max}). A soil sample is considered to be susceptible to liquefaction if it lies above (to the left) of the threshold curve, and not susceptible if it lies beneath the curve. Peak ground acceleration values needed to trigger liquefaction (PGA trigger) for a map unit are estimated by inspection of the plotted ($(N_1)_{60}$, CSR) pairs, in relationship to the triggering threshold curve. The values of PGA trigger resulting from the Simplified-Procedure borehole analysis, in conjunction with geologic knowledge of the map unit's age (aging effects) and depositional environment (texture and relative density) lead to the susceptibility rating values.

7.1 Artificial Fill

Artificial fill underlies most of the low-lying urban areas and is used to construct levee features. Our subsurface investigation shows that there is considerable variation and complexity in the nature, extent, composition, and geotechnical properties of the artificial fill deposits throughout the St. Louis region (e.g. glass, brick, cinders, ash, wood, rubble, with/without sand or silt). This complexity limits our ability to accurately anticipate the response of this deposit to earthquake-induced strong ground motions. There were SPT data we could not include in the analysis because the log of materials information was not sufficient to estimate unit weights or fines content of the fill. For the samples we could analyze, the Simplified Procedure indicates a PGA trigger of 0.20g (Figure 8a). Because we do not have SPT data for the levee structures, the relative density (i.e. blow counts) of the levee material is not accurately known. Based on inspection of available Army Corps boring logs, the Chain of Rocks canal material is composed largely of low hydraulic conductivity silts and clays, and could, but not necessarily, potentially be resistant to liquefaction as a result of higher fine contents. Thus, the liquefaction susceptibility of the artificial fill likely ranges from Low (e.g. silty-clay fill) to Very High (e.g. rubble and urban detritus, loosely piled fine sand and silt). Therefore, artificial fill should be conservatively considered to be Very High until shown otherwise by site-specific studies.

7.2 Artificial Road or Rail Embankment Fill

This map unit is inferred to have been emplaced in accordance with modern engineering principles and practices (e.g. compaction ratios, dry densities), based on the relative recency of construction, and the volume of earth moving, filling, or grading needed to produce the engineered berms observable on 1:24,000-scale topographic map. In Missouri, the road prisms typically overlie areas of relatively deep groundwater (e.g. loess-capped uplands), and are also elevated about the pre-existing ground elevation. Therefore, we consider these units to be of Moderate susceptibility to liquefaction based on their inferred engineering characteristics (e.g. Hengesh and Bachhuber, 2004); however, site-specific geotechnical studies should be performed to fully and accurately characterize the liquefaction susceptibility of this deposit.

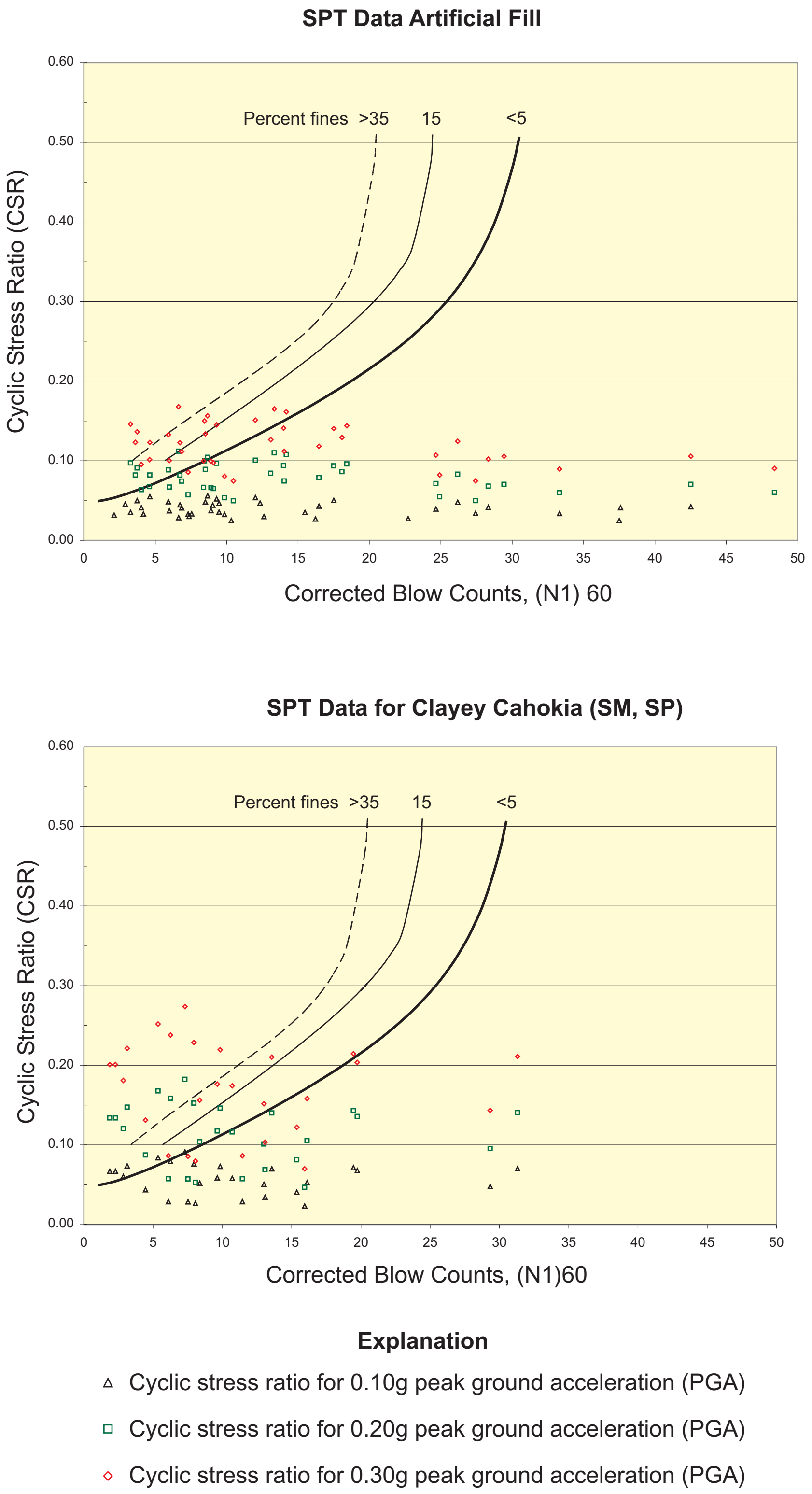
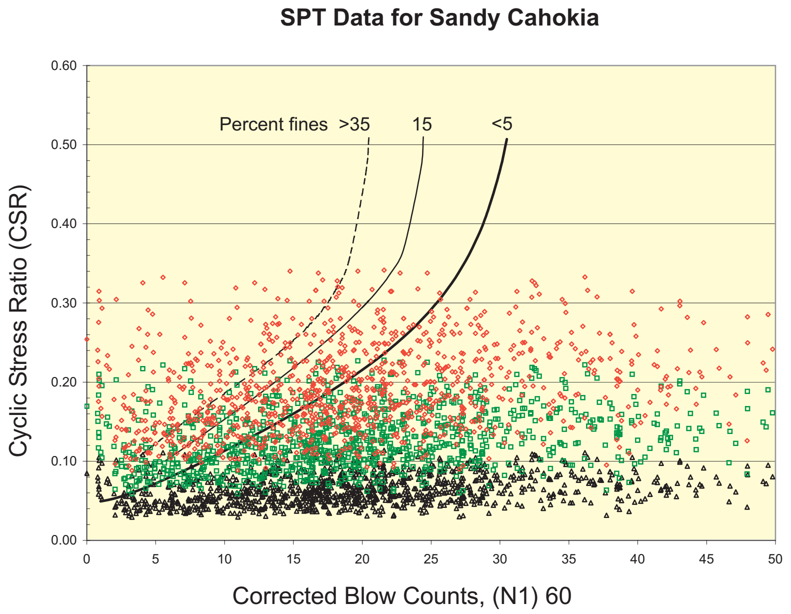
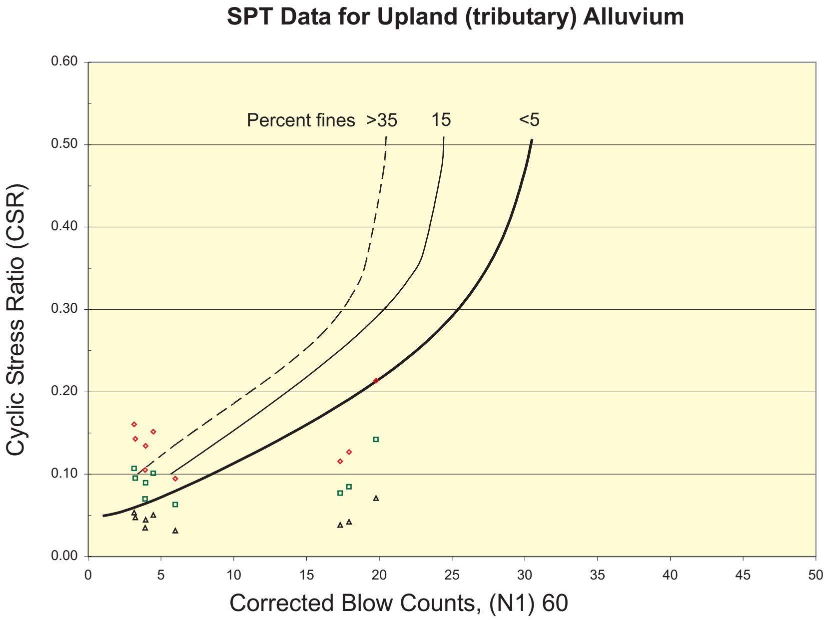


Figure 8a. Simplified Procedure plots of standard penetration test data within liquefiable geologic map units. Lines represent Simplified Procedure threshold curves for liquefaction, with respect to fines content.





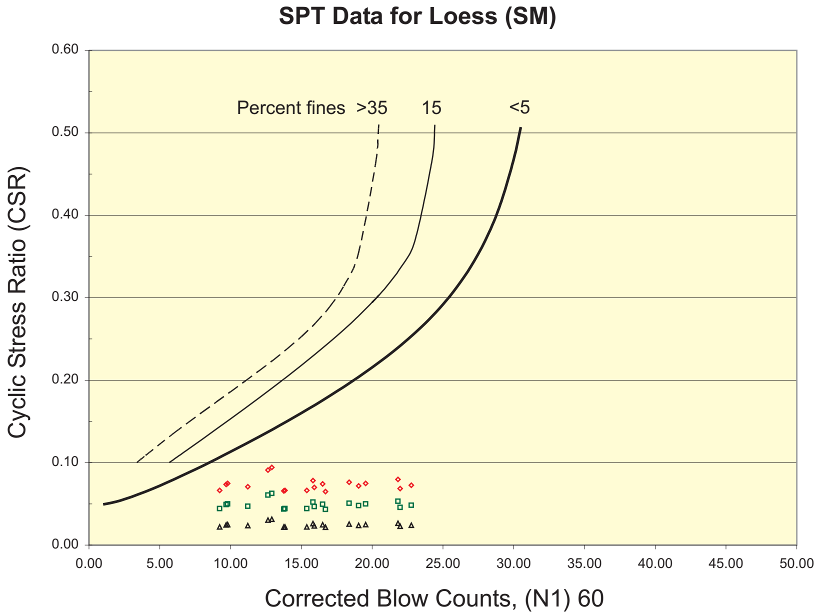
Explanation

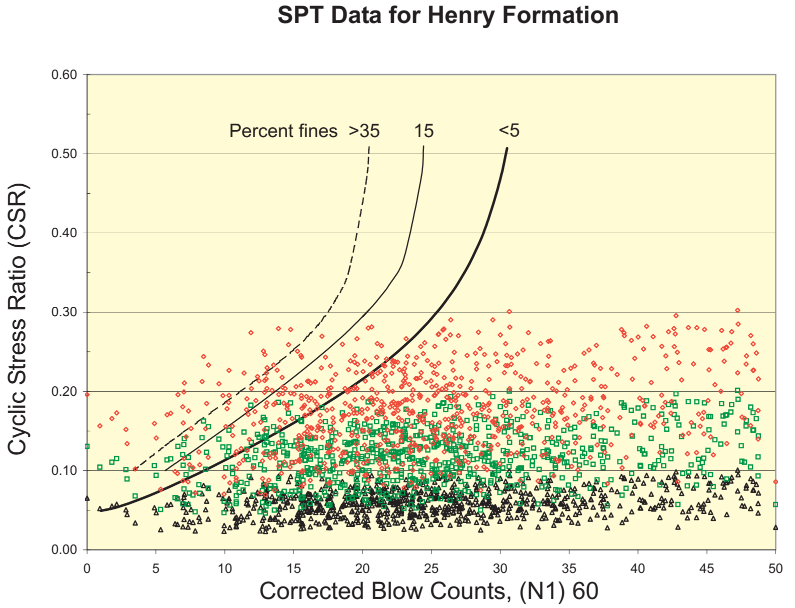
△ Cyclic stress ratio for 0.10g peak ground acceleration (PGA)

□ Cyclic stress ratio for 0.20g peak ground acceleration (PGA)

◇ Cyclic stress ratio for 0.30g peak ground acceleration (PGA)

Figure 8b. Simplified Procedure plots of standard penetration test data within liquefiable geologic map units. Lines represent Simplified Procedure threshold curves for liquefaction, with respect to fines content.


SPT Data for Loess (SM)


SPT Data for Henry Formation

Explanation

△ Cyclic stress ratio for 0.10g peak ground acceleration (PGA)

□ Cyclic stress ratio for 0.20g peak ground acceleration (PGA)

◇ Cyclic stress ratio for 0.30g peak ground acceleration (PGA)

Figure 8c. Simplified Procedure plots of standard penetration test data within liquefiable geologic map units. Lines represent Simplified Procedure threshold curves for liquefaction, with respect to fines content.

7.3 Sandy Cahokia

This late Holocene granular sediment typically would be considered Very High liquefaction susceptibility based on screening-level analysis, because it generally meets the liquefaction criteria of age, texture, depositional environment, and saturation (e.g Youd and Perkins, 1979). However, the results of the Simplified Procedure analysis indicate this unit as High susceptibility to liquefaction, with an estimated PGA trigger of 0.18g (Figure 8b). This somewhat milder susceptibility rating suggested from the Simplified Procedure is not un-reasonable, based on the fact that Cahokia alluvium is a poor groundwater source due to its low specific yields (Schict and Buck, 1990). Low specific yield is linked to aquifer porosity, which is a function of void ratio. Seed and Idriss (1971, p. 1250) state that "...the susceptibility of a given soil to liquefaction will be determined to a high degree by its void ratio or relative density." In other words, low void ratios of a unit are associated with relative resistance to liquefaction. In this light, and in conjunction with the results of the Simplified Procedure, we assess the sandy Cahokia alluvium as High susceptibility to liquefaction.

7.4 Clayey Cahokia

As noted in a previous section, this is a cohesive deposit, mostly comprised of silty clay, clayey silt, with some intercalated sandy silt / sandy clay (SM / SC). The overall high fines content of the unit makes it relatively resistant to liquefaction, but within the deposit are interspersed lenses of coarser grained textures, due to its depositional environment (e.g. alluvial overbank sequences). The sandy silt lenses, capped by low permeability silty clays, could produce elevated pore water pressures when subjected to cyclic stresses from earthquake shaking, and could be a source of liquefaction phenomenon such as sand dikes or sand boils. The Simplified Procedure analysis (Figure 8a) indicates an estimated value of 0.10g for the PGA trigger for the SM units (~15% FC), with the $N_{1,60}$ blow counts corrected to a clean sand value (Youd et al., 2001; Cetin et al., 2004). Based on the criteria matrix (Figure 4), this unit would be classified as High susceptibility. However, because we know that the overall texture of the geologic unit is fine and relatively cohesive (much greater than 35% FC), it is generally not prone to liquefaction. Yet, because this unit contains minor occurrences of liquefiable sandy layers (although they are not substantially thick or laterally extensive) we assess this unit to be of Moderate liquefaction susceptibility.

7.5 Upland Cahokia

These sediments are young alluvial sands intercalated with overbank silts and clays. The estimated triggering PGA for the sandy layers in this map unit is 0.18g (Figure 8b), which classifies this map unit as High susceptibility to liquefaction. Because the deposit is geologically young, composed of generally loose, stratified alluvium, and the estimated PGA trigger of less than 0.20g, we assign a susceptibility of High to this unit.

7.6 Fan Cahokia

As described in previous section, this unit has a large silt and clay component due to the re-working and redeposition of silty (loess) materials (e.g. Grimley and Lepley, 1999), whose high fines content (>50%) provide cohesion to the soil. Inspection of borehole stratigraphy confirms that fine-grained sediments are ubiquitous in these deposits. Additionally, groundwater conditions are encountered in these map units are about 20 – 30 feet below ground surface. Therefore, based on the high percent of fines content (cohesion) and lack of sand units encountered in the boreholes, but overall loose and unconsolidated nature of the deposit (based on blow counts), we assign a susceptibility of Moderate hazard to this map unit.

7.7 Henry Formation

This late Pleistocene outwash-derived sand and gravel unit is mapped as isolated terrace remnants that exist at the base of the bluffs, near the distal edges of the modern floodplain. The unit is encountered in boring logs primarily at depths of about 30 to 50 feet below ground surface, but is shallower where exposed near the surface, and deeper where buried beneath Holocene alluvium. Beneath 50 feet (15 meters), the samples are not considered liquefiable based on the increased overburden pressures (e.g. Brankman and Baise, 2004; Hengesh and Bachhuber, 1999). About 70% of the Henry Formation samples are shallower than 50 feet below ground surface. Figure 8c shows the results of the Simplified Procedure for SPT samples of the Henry Formation that are only in the upper 50 feet of soil column. The estimated PGA trigger for this unit is less than 0.30g, suggesting a moderate susceptibility. However, there are an abundance of data points representing $N_{1,60}$ values greater than 30 that are consequently considered non-liquefiable. Because this is a late Pleistocene deposit (i.e. more resistant due to age) with relatively high overall blow counts (dense condition), we classify this map unit as Low susceptibility to liquefaction.

7.8 Equality Formation

The Equality Formation, also a late Pleistocene deposit, consists of fine grained sediments (predominantly clays) that are interpreted to have been deposited in slackwater (lacustrine) conditions. As such, we consider the deposit to be cohesive, and therefore generally not susceptible to liquefaction. The Simplified Procedure analysis is not appropriate to apply to this unit due to the preponderance of clay. We assess this unit to be Very Low susceptibility, based on age and cohesion.

7.9 Loess

The loess deposits in the Mississippi valley have a complex history of deposition (e.g. Leigh, 1994; Grimley, 2000; Goodfield, 1965). There are essentially two late Pleistocene loess formations in the study area: the Peoria Silt and the Roxanna Silt. The Roxanna Silt lies stratigraphically beneath the Peoria Silt (and is therefore older), and has a somewhat higher clay content compared to the Peoria Silt (Grimley and Lepley, 1999). However, the units can be difficult to discern from one another in the field or in borehole logs. Therefore, we did not make an attempt to distinguish the individual silt units, and informally lump them together as the same deposit for the Simplified Procedure analysis. The subsurface borehole logs indicate the interpreted loess deposits are largely silt with a clay to silty clay component, suggesting fines content of about 85%. The grain size distribution analysis indicates the Peoria Silt as about 25% clay (mostly montmorillonite and illite), 70% silt, and rarely more than 5% sand (Goodfield, 1965, Appendix D). In addition Grimley (2000) presents a very thorough description of the Peoria and Roxanna Silts, and indicates that while the percent illite (< 2μm) content in the Peoria Silt varies through depth, and ranges from about 35 to 55 percent. The Simplified Procedure analysis of SPT samples in relatively sand rich layers (e.g. "sandy loam", SM) encountered in the interpreted loess unit are shown on Figure 8c, with blow counts corrected for fines content. The results indicate that the loess should not experience liquefaction even at greater than 0.30g PGA. The Peoria Silt (loess) deposit mantles the entire St. Louis region except for the modern, low-lying floodplain, and some low elevation terrace remnants and alluvial valleys. Occurring mostly atop the bluffs, this unit is typically above the groundwater table. Therefore, due to the high fines content, very high estimate triggering PGAs of the sandy layers (>0.30g), low likelihood of saturation, and the overall age of the deposit, we evaluate this unit as Very Low susceptibility to liquefaction. This susceptibility classification for loess is corroborated by the liquefaction hazard map of Shelby County (Van Arsdale and Cox, 2000).

7.10 Till

There is relatively sparse occurrence of till units in the geotechnical boring logs, indicating that the till has limited sub-aerial extent and vertical thickness in our study area. It is generally encountered about 100 – 125 feet below ground surface, well below liquefaction depths. The till is rarely exposed at the surface, and occasionally at the near-surface. Analyzing this data using the Simplified Procedure illustrates the caution warranted when assessing the liquefaction susceptibility of units that exist at such depths. The extreme values of CSR on the plot are most likely due to the disproportionate ratio of overburden (σ_{vo}) to effective overburden (σ'_{vo}) that results from the relatively deep samples and relatively shallow groundwater values used in the analysis. The estimated PGA trigger for this unit is 0.05g; clearly not a reasonable result for Pleistocene age, indurated material. We consider this unit to have a Very Low susceptibility to liquefaction based on its age (Pleistocene), its fine-grain sedimentary matrix that supports sand and larger clastics, overall high raw blow counts (e.g >50 blow per foot), and its depth.

8.0 DISCUSSION

Our final liquefaction susceptibility maps for the St. Louis region depict a range of hazard levels for the study area, due in large part to the various ages, depositional environments, and physical properties of the unconsolidated sediments (Figure 9; Plates 4, 5, 6, 7, 8). As with many regional studies, certain assumptions and generalizations were necessary in order to perform the analysis. We made assumptions regarding the following physical properties and conditions of the geologic deposits: the shear wave velocities of each map unit, the unit weight and percent fines content of the soils, and saturated thickness of the deposit. These parameters can vary spatially, both over large areas and within one map unit in a single borehole. We used estimated shear wave velocities (V_s) specific to the map units in question (Table 2). However, the shear wave velocities used for each map unit represents an average of the ranges measured, and can therefore be a source of uncertainty. The unit weights and percent fines content of the samples used in the Simplified Procedure are estimates based on the soil description in the log of boring. Previous liquefaction studies (e.g. Brankman et al. 2004, Hengesh and Bachhuber, 1999), indicate that this is a reasonable and common generalization for liquefaction maps of this type. Furthermore, we generalized and simplified the regional groundwater conditions. Because the water table elevation fluctuates naturally, and because local pumping conditions can change (e.g. Schicht and Buck, 1985), the scenario depth-to-groundwater values used in this study may not match instantaneous static water level measurements, and may therefore introduce a level of uncertainty to the analysis by inaccurately reflecting the effective overburdens. To temper this uncertainty, we made a concerted effort to develop a scenario depth-to-groundwater map that is based on modern conditions. Ultimately, site specific studies should be performed to fully assess and verify the full ranges in variation of these properties.

Comparison of our liquefaction susceptibility maps to susceptibility hazard maps closer to the NMSZ in the Memphis-Shelby County area (e.g. Van Arsdale and Cox, 2000) show key differences that need to be discussed. First, and most important, the liquefaction susceptibility maps of Memphis-Shelby County were derived in a slightly different manner than ours. Regional, screening-level maps of liquefaction hazard near Shelby County were developed by Hwang et al. (1999). These maps indicate liquefiable conditions if the following criteria are met: (1) if there is sand present at depths less than 20m, (2) water table depth less than 10m, and (3) SPT blow counts less than 20. The criteria are reasonable; however the result is a binary (yes/no) map of 700 m by 900 m grid cell resolution, and does not reflect the current geotechnical state-of-practice level of detail (e.g. cyclic stress ratios). Van Arsdale and Cox (2000) recognize the fact that detailed delineation of the surficial geology is critical to interpreting the potential seismic hazard, and include this component in their liquefaction susceptibility mapping. They base their liquefaction susceptibility classification scheme more heavily on geologic criteria (e.g. Youd and Perkins, 1978), and use the Hwang et al. (1999) liquefaction analysis as a cross-check of their liquefaction mapping. The Van Arsdale and Cox (2000) maps have the advantage of calibrating their map unit susceptibility to known liquefaction occurrence, based on field exposures. The observation and identification of prior liquefaction occurrence typically leads to a classification of “Very High” susceptibility for that particular map unit in which liquefaction occurred. In contrast, we have not found maps or reports that document or describe paleo-liquefaction features, such as sand boils, in the alluvium in our study area. This does not necessarily mean that no liquefaction occurred in the St. Louis region as a result of repeated strong ground shaking; rather, it should be interpreted that compelling evidence either for the occurrence or for the absence of liquefaction features is not forthcoming. Van Arsdale and Cox (2000) state that while the Mississippi River alluvial sediments in Shelby County likely experienced some degree of liquefaction from the 1811-1812 NMSZ earthquakes, because the uppermost deposits post-date 1811-1812, the liquefaction features potentially associated with this event are likely either eroded or buried. This probably holds true in our study area as well; that the post-1812 erosion and deposition of shallow alluvial sediments by the meandering of the Mississippi River removed or buried liquefaction features on the floodplain.

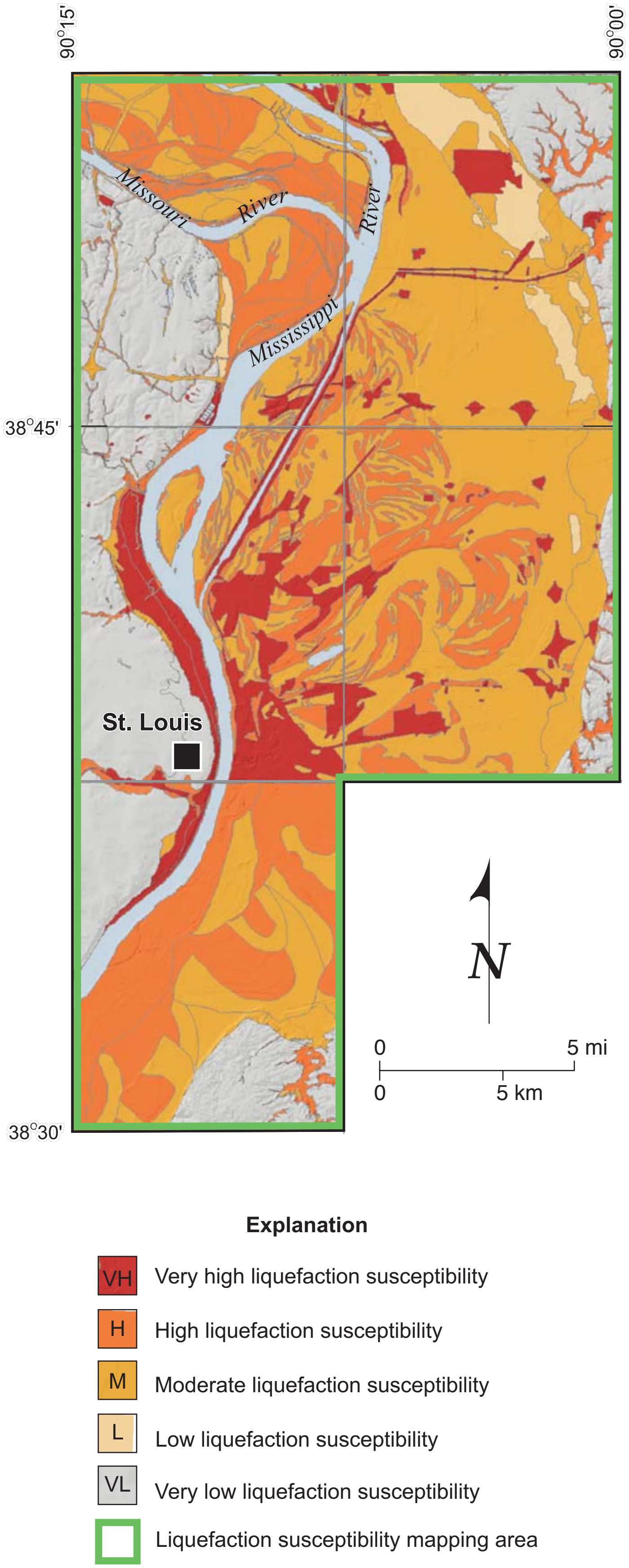


Figure 9. Regional liquefaction susceptibility map, see Plates 4-8 for 1:24,000-scale susceptibility maps.

The liquefaction susceptibility maps of Shelby County (Van Arsdale and Cox, 2000) show an overall higher relative seismic hazard of the major river valley alluvium, indicated by areas that are classified as "Very High" susceptibility to liquefaction. In contrast, our analysis indicates that the major river valley alluvium (e.g. Sandy Cahokia facies of the Mississippi and Missouri Rivers) have a "High" susceptibility to liquefaction (Figure 7). There are several possible reasons why these analyses do not show a consistent level of seismic hazard. First, the borehole analysis used for the Shelby County liquefaction maps (Van Arsdale and Cox, 2000) differs from our approach, by using the Hwang (1999) binary (yes/no) screening-level results based on borehole sample criteria. Our study used estimates of triggering PGA based on the Simplified Procedure. Second, there was no differentiation of alluvial depositional facies in the Memphis-Shelby County Quaternary geologic maps (e.g. channel sand vs. overbank fines). Although the alluvium is recognized as having different depositional environments, processes, and different grain size distributions (e.g. Van Arsdale and Cox, 2000), these units are considered as one during the liquefaction analysis. We differentiate these units because the clay deposits tend to have very low blow counts, yet tend to be cohesive and not prone to liquefaction. These clay facies can comprise a substantial thickness in deposits within the upper 15 m of soil column. Furthermore, an overall higher relative liquefaction hazard for Shelby County as compared to the St. Louis region may not be unreasonable based solely on the distance from the seismic event, and the resulting stronger ground motions nearer the seismic source. Shear wave velocity values for "alluvial sediments" near Memphis are estimated as 360 m s^{-1} (cited in Atkinson and Beresnev, 2002; *cf*. Wen and Wu (2001)) as compared to values near 230 m s^{-1} used for sandy Cahokia alluvium. Increasing shear wave velocity in unconsolidated sediments during the analysis generally acts to increase the estimated liquefaction susceptibility. This estimated difference in physical properties of the sediments could potentially control where and whether or not seismically-induced liquefaction occurs.

Other factors that may contribute to lower overall liquefaction susceptibility ratings not directly incorporated into our analysis include (but are not limited to) thinner overall alluvial sediment thicknesses in the St. Louis region as compared to the Shelby County area. The St. Louis region lies north of the Mississippi Embayment, and therefore has a thinner amount of unconsolidated overburden above the bedrock. Atkinson and Beresnev (2002) indicate that this difference in overburden thickness would affect the ground motion responses (e.g. peak accelerations and frequencies) between Memphis and St. Louis, for the same scenario earthquake, because of differences in energy amplification and attenuation that are a function of the soil column properties.

9.0 CONCLUSIONS

We analyzed the Quaternary geologic, subsurface geotechnical, and hydrologic conditions of the unconsolidated deposits in the St. Louis region to produce 1:24,000-scale liquefaction susceptibility hazard maps (Plates 4, 5, 6, 7, 8). The results of these analyses incorporate qualitative geologic criteria (e.g. Youd and Perkins, 1987) and quantitative geotechnical criteria (e.g. Seed and Idriss, 1971). The liquefaction hazard maps show non-engineered artificial fill deposits are very high susceptibility; the Holocene sandy Cahokia alluvium and the upland (tributary) alluvium are high susceptibility; the Holocene clayey Cahokia alluvium and alluvial fan deposits are moderate susceptibility; late Pleistocene Henry Formation is low susceptibility; late Pleistocene Equality Formation and Peoria loess are very low susceptibility. The liquefaction susceptibility of artificial fill units are the most difficult to accurately assess, because of their highly variable and complex compositions and properties. Therefore, we assign a conservative value of "very high" for artificial fill interpreted to be non-engineered, and a conservative value of "moderate" for engineered artificial fill such as road embankments. The results of our susceptibility hazard mapping indicate that large portions of the St. Louis region can be vulnerable to liquefaction-related phenomenon resulting from earthquake strong ground shaking.

9.1 Acknowledgements

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11.0 INFORMATION DISSEMINATION

As part of item G.3 Final Report and Dissemination, we have accomplished the following during our research efforts:

- Presentation at St. Louis Seismic Hazards Working Group committee meeting (April, 2004)
- Presentation at Geological Society of America, Central US Section Meeting
  Pearce, J.T., and Baldwin, J.N., (2004). Liquefaction susceptibility mapping St. Louis, Missouri and Illinois: [abs] Geological Society of America North-Central Section Meeting Abstracts with Programs
- Borehole information exchange with Jim Palmer, MSGSRAD.
- Project Annual Summary submittals to NEHRP
- Additionally, we have disseminated this report and the accompanying liquefaction susceptibility maps to academics and practitioners in the area via CD.