Final Technical Report March 2004

SHEAR WAVE VELOCITY DETERMINATION OF UNLITHIFIED GEOLOGIC MATERIALS AND PRODUCTION OF SOIL AMPLIFICATION MAPS FOR PROJECT IMPACT COMMUNITY AREAS IN THE CUSEC REGION

External Grant Award Number 01-HQ-GR-0195

Robert A. Bauer, Coordinator CUSEC State Geologists, Illinois State Geological Survey, Champaign, Illinois 61820

Telephone (217)244-2394 FAX (217) 244-2785 bauer@isgs.uiuc.edu

Element I. Products for Earthquake Loss Reduction
Element II. Research on Earthquake Occurrence and Effects

Keywords: Geologic Mapping (Surficial Deposits), Regional Seismic Hazards, Mitigation, Information Transfer

Technical Abstract

Surficial materials overlying the bedrock surface can either amplify (most commonly) or deamplify the bedrock ground motions by the time they reach the ground surface where manmade structures are built. Therefore, to better estimate the shaking and damage that may occur to manmade structures during an earthquake, it is necessary to modify the bedrock motions with soil amplification values. The Central U.S. Earthquake Consortium State Geologists are producing soil amplification maps for communities based on existing and newly collected borehole geologic descriptions and shear wave seismic velocity information. These soil amplification maps, at a scale of 1:24,000 (1 inch = 2,000 feet) are produced for FEMA's Earthquake Loss Estimation Program (HAZUS) for use by the communities to estimate and mitigate their earthquake losses.

The soil amplification maps are based on geologic maps, at a scale of 1:24,000, that were specifically made for this project or used existing maps that were modified with new data. The new geologic base maps are also useful to these communities for other hazards outside of the use for estimating earthquake losses. Arkansas Geological Commission completed work on the community of West Memphis; the Kentucky Geological Survey completed work on the community of Louisville and the Missouri Geological Survey completed work on Poplar Bluff, Missouri. Several workshops have been completed in Evansville, Indiana; Cape Girardeau, Missouri and Owensboro, Kentucky. These workshops included agencies; community officials and private consultants. The workshops reviewed the production of the geologic maps and collection of shear wave velocity information for the production of the soil amplification maps that may be used in HAZUS (an earthquake loss estimation program). Background information on earthquake activity and potential earthquake impacts in the region are also presented.

NON-TECHNICAL SUMMARY

The Central U.S. Earthquake Consortium (CUSEC) State Geologists gathered information on the local geologic and material properties of the soils in the Communities of West Memphis, Arkansas; Louisville, Kentucky; and Poplar Bluff, Missouri. This effort has produced soil amplification maps based on the NEHRP classification for how much the soils will amplify earthquake ground motions from earthquakes. The geologic information gathered is used to first produce geologic maps of the materials resting on the bedrock of these communities at a scale of 1:24,000 or 1 inch = 2,000 feet. The geologic maps, along with measurements of the soil's properties, are used to classify the various soils as to how much they would amplify earthquake ground motions. The amplification maps can be used in the Federal Emergency Management Agency's earthquake loss estimation program (HAZUS) to better estimate the amount of damages a community may expect from various earthquakes. Workshops on how the soil amplification maps were produced and how they may be used have been completed in Evansville, Indiana; for the State Departments of Transportation in the Midwest; and at Owensboro, Kentucky and Cape Girardeau, Missouri. Also during this contract period, measurements on the properties of various geologic units were performed throughout the CUSEC states to add to measurements previously reported.

Investigations undertaken

The Central U.S. Earthquake Consortium (CUSEC) State Geologists gathered information on the local geologic and material properties of the soils in the Communities of West Memphis, Arkansas; Louisville, Kentucky; and Poplar Bluff, Missouri. This effort has produced soil amplification maps based on the NEHRP classification for how much the soils will amplify earthquake ground motions from earthquakes. The geologic information gathered is used to first produce geologic maps of the materials resting on the bedrock of these communities at a scale of 1:24,000 or 1 inch = 2,000 feet. The geologic map, along with measurements of the soil's properties, are used to classify the various soils as to how much they would amplify earthquake ground motions. The amplification maps can be used in the Federal Emergency Management Agency's earthquake loss estimation program (HAZUS) to better estimate the amount of damages a community may expect from various earthquakes. Workshops on how the soil amplification maps were produced and how they may be used have been completed in Evansville, Indiana; for the State Departments of Transportation in the Midwest; and at Owensboro, Kentucky and Cape Girardeau, Missouri. Also during this contract period, shear wave velocity measurements were performed in various geologic units throughout the CUSEC states to add to measurements already reported.

The report of work performed by each state is presented below. Also presented are the technology transfer projects performed in each state.

Alabama Geological Survey

The Geological Survey of Alabama redesigned that part of the Survey's website that relates to earthquakes in order to provide new, updated educational material and links on earthquakes, particularly for the central and the southeastern United States. Material is presented in a user friendly and attractive manner that facilitates public access to earthquake-related information.

Maps show the distribution of known earthquakes in Alabama and are kept current. Records are posted on historical earthquakes in the state, and emphasis is placed on recent large seismic events in Alabama. Links are also provided to CUSEC, the US Geological Survey, Center for Earthquake Research and Information (University of Memphis) and other earthquake-related research groups. Special focus is on making available educational materials on earthquakes, their cause, their prediction, and their study, as well as on current efforts to limit damage from earthquakes in the eastern United States.

Arkansas Geologic Commission

The Arkansas Geologic Commission mapped the West Memphis Quadrangle which is a very rapidly developing region that has Interstate 55 cutting directly through it. Local officials were receptive to the mapping work. They coordinated with the Urban Hazard Mapping Project in the Memphis area.

Geology:

Haley, et al (1976) mapped the regional geology in the West Memphis area for the Geologic Map of Arkansas and delineated two Holocene units: a Stream Overbank deposit and a Channel Meander deposit. McFarland (1998) described the Stream Overbank unit as alluvial deposits of small streams, the overbank deposits of major streams, or older meander belt deposits of major streams, and the Stream Overbank units as representing the more recent channel meanders and current flood plain deposits of significant streams. Both units were indicated to be of variable thickness (Haley, personal communication)

Saucier (1994) made a more detailed map of the region in his Geomorphology and Quaternary Geologic History of the Lower Mississippi Valley. The surface geology of the West Memphis 7.5' Quadrangle used in this report is adapted from the Saucier report (Plate 6, 1:250,000 scale) with slight modifications (Figure 1). Saucier recognized three types of Holocene deposits: Backswamp (floodbasin) deposits (Hb); Point bar/meander belt (meander scroll) deposits of the Mississippi River meander belt 1 (Hpm1); and, deposits of abandoned channels (neck and chute cutoffs) of the Mississippi River (Hchm). He described the units thus:

> Backswamp (Hb): A well-drained swamp deposit that "consists of firm to stiff, mostly gray and black clays and silty clays with thin silt laminations and frequent burrows. Organic matter is abundant both as woody fragments and scattered small particles. Bedded organics in the form of peat layers or zones of compacted leaf litter are infrequent… Well drained swamp deposits typically exhibit color mottling (grays, browns, buffs), abundant ferruginous and calcareous nodules and staining, and slickensides resulting from shrink and swell associated with periodic wetting and drying."
>
> Point Bar/meander belt (Hpm1): "The top stratum of a point bar ridge consists of a few feet of gray or tan, oxidized, silty or sandy clay or silty sand. Below the top stratum is a thick, coarsening downward sandy substratum that constitutes the "typical"" point bar deposits. …all areas exhibit a typical vertical sequence that grades downward from a well-sorted, fine and medium sand to medium and coarse sands with gravel. …the sands contain thin layers of pebble-sized gravels, frequent thin lenses of macerated plant material, layers of heavy mineral concentrations, and wood fragments of all sizes. Other materials observed include armored mudballs, reworked freshwater shells, and even bone fragments. In point bar sequences, fine-grained, cohesive deposits occur mainly in the topstratum and upper part of the substratum as either very thin clay drapes (Generally less than an inch thick) or as swale filling. Small swales may contain only a few feet of silty or sandy clay, clayey sand, or silty sand unconformably overlying clean sands, whereas the larger, deeper swales (a hundred or more feet wide and perhaps thousands of feet long) may contain several tens of feet of soft, gray clays, organic clays, or clayey silts."
>
> Abandoned Channels (Hchm): "Two major lithologic units are present in most abandoned channels… The sand wedge or plug portion of a channel filling that forms mainly in the arms of a cutoff during early stages consists predominantly of cross-bedded, fine to medium sands and silty sands. They closely resemble and often cannot be differentiated

from point bar deposits at comparable depth; however, near the transition into the overlying clay plug, they are often interlayered with silts and silty sands. This situation reflects the stage in channel filling in which slack-water sedimentation alternates with flood stage sedimentation. The overlying fine-grained or clay plug sediments are what most people regard as abandoned channel deposits. These consist predominantly of very soft to medium gray, slightly organic, silty clays and clays. …they lack color mottling and nodules except in the uppermost portions of channels that are essentially filled. …Most sequences … exhibit distinct layering with beds generally not more than a few inches thick… (they look like lacustrine deposits). Clay sequences are frequently interrupted by thinner, planar layers of silts and fine sands that mark flood events. Clay plugs are less well developed in chute cutoffs. Most chute filling consists of cross-bedded silty sands and fine to medium sands with gravel lenses and layers at depth that resemble sand wedges in neck cutoffs. Those clay plugs that do occur contain relatively large amounts of silt and sand layers with clays and silts."

Soils:

The surface soils of the West Memphis Quadrangle (Gray and Ferguson, 1974) area are described as one of four basic types: Sharkey-Tunica association (poorly drained, level and gently undulating, clayey soils on slack-water flats), Sharkey association (poorly drained, level and gently undulating, predominantly flooded, clayey soils on slack-water flats), Dundee-Dubbs association (somewhat poorly drained and well-drained, level and gently undulating, loamy soils on old natural levees), and Alligator-Sharkey association (poorly drained, level and gently undulating, clayey soils on slack-water flats). A soil map was not produced for this report as these soils descriptions represent only the top 60 to 80 inches (1.5 to 2 meters) of the area's surface materials and these materials are not expected to behave significantly different to seismic loads than the underlying materials.

Static water level:

Schrader (2001) mapped the potentiometric surface of the alluvial aquifer in the West Memphis area. He indicated that the regional potentiometric surface ranged from just under an elevation of 190 feet in the southern part of the quadrangle to just over an elevation of 200 feet in the northern part of the quadrangle (Figure 2). Surface elevations in the West Memphis Quadrangle are typically 205 to 225 feet above mean sea level. A review of 143 alluvial water well drilling logs in and around the West Memphis Quadrangle indicated that the static water level averages about 17 feet (5.2 meters) below the local surface with a range of 5 to 32 feet (1.5 to 9.7 meters). The water well data did not indicate a systematic variation of the static water level as suggested by Schrader's map and formed no obvious pattern with respect to the various units delineated by either Haley or Saucier.

Suballuvial Surface:

The configuration (elevation) of the suballuvial surface in feet above mean sea level is taken from Saucier (1994) (Figure 3). This map indicates that the entire West Memphis sheet area has over 30 meters of Holocene deposits of one of the types listed above (geology). The suballuvial surface is considered to be the buried Pleistocene-Holocene stratigraphic contact (Saucier, 1994). It marks the shift from predominately braided stream, glacial outwash deposition to meandering stream deposition.

Standard Penetration Resistance Tests:

The Arkansas Highway and Transportation Department provided records on Standard Penetration Tests (SPT) conducted in the Mississippi Embayment including eight that were conducted in the West Memphis Quadrangle area (Figure 4). This data set (Table 1) was restricted to the southern part of the quadrangle; however, the results of these tests conform to the general pattern of similar Standard Penetration Tests observed in the northeast Arkansas region east of Crowley's Ridge. In all cases there is a surficial layer of silty clay 35 to 64 feet thick with a Standard Penetration Test blow count of generally less than 10, overlying a sandy sequence extending to a depth of at least 66 to 101.5 feet with blow counts averaging more than 30. The entire sequence tested by these penetration tests appears to be composed of Holocene deposits.

Soil Amplification Potential

The NEHRP (National Earthquake Hazards Reduction Program) seismic amplification class of the upper 30 meters of the surficial materials is based on the average shear wave velocity of those materials. When shear wave velocity determinations are not available other engineering parameters such as Standard Penetration Tests may be used to indicate the general NEHRP Site Class (FEMA 222A, 1994). Street et al., (2001) suggested that the shear wave velocity for the Mississippi River Valley in the West Memphis area is less than 360m/s and gave the area a NEHRP Site Class of D. They stated that a few places in the embayment were borderline Site Class E (shear wave velocity <180m/s). They also indicated that larger ground motion amplification should be expected in the alluvial materials of northeastern Arkansas than upland areas of western Tennessee regions mapped as the same Site Class.

It is the NEHRP procedure that any soil column that has lost bearing strength under seismic loads in the past is fully capable of doing so in the future and therefore should be considered Site Class F irrespective of shear wave velocity values. Liquefaction features have been noted in similar deposits in the Mississippi Embayment both north and south of the West Memphis region (Fuller, 1912; Haydar Al-Shukri, personal communication). Bauer et al., (2001) showed the West Memphis Quadrangle area as NEHRP Site Class F based on this observation and historical accounts of liquefied deposits near epicenters of the events of 1811-12. Under these considerations the entire West Memphis quadrangle is given a NEHRP Site Class F designation in this report.

Illinois State Geological Survey

The Illinois Geological Survey has completed a map of the Carbondale, Illinois Township area showing the geology, soil amplification and soil period map in the previous grant 99-HQ GR 0086. This contract period we collected shear wave velocity measurements using three different methods throughout the state. The methods were surface shear wave survey, downhole measurements in cased boreholes and the use of a shear cone with a push technology probe. Measurements were taken in 7 cased boreholes in northeastern Illinois (Table 2) and one in central Illinois. Most of these are 200 to 300 feet deep. In the Wabash River Valley near Vincennes, all three methods were used with 12 surface shear wave surveys, 5 shear cone sites and 1 cased borehole (Table 3); making an interesting comparison between the results of the methods. Downhole measurements in cased boreholes were also performed in Central (Table 4) and Southern Illinois (Table 5).

Methodology of Surveys

Surface shear wave surveys - The surface shear wave surveys were performed by using a linear array of geophones at 5 to 10 foot intervals and a 10 foot offset. The energy source was an 8 pound hammer striking an end of a wooden 4x4 inch post held down by the weight of a vehicle. Equipment used was a Geometrics Strataview recorder with Mark Products L-28, 8 Hz horizontal geophones. Using this method produced an average shear wave velocity value for "one layer" or with the wider spacing of geophones, produced average values for "two layers". Estimated error in velocities is about 2.5 to 5 percent.

Borehole shear wave surveys - Borehole shear wave surveys were performed by using a 2 inch diameter PVC cased borehole with a 3 component Geostuff geophone. Shear wave velocity measurements are taken every 4 feet. Recording was performed with the Geometrics Strataview and Model BHG-2, (3) 14-Hz geophones with orthogonal orientations. It uses a wall clamp with a motor-driven steel spring. Several boreholes where ISGS ran downhole and surface shear wave surveys we also had downhole surveys performed by the Indiana Geological Survey and was provided the average shear wave velocity.

Cone shear wave velocity surveys - A 3 component (3-axis) shear wave geophones were mounted within 1.25 inch diameter soil sampler for push technology rods. Rods were pushed 4 feet and horizontal energy input was with an 8 pound hammer striking a short 4x4 inch wooden post with a metal cap. The short post had spikes through it coupling it with the ground and the post/block was weighted with one tire of a vehicle. We found that a short post under one tire produced a much cleaner signal compared to a long post under both tires of one axis of a vehicle. Recording was performed with the Geometrics Strataview and model GS-14-L3, 28 Hz Geo Space Corporation geophones.

Results

A comparison of the shear wave velocities for the three methods used in the Vincennes Quadrangle (Table 3) shows the shear cone method to have overall higher values than the surface and downhole measurements. This alluvia valley sediments have a silty clay capping material over thick medium to dense sands. The range and average in shear wave values for these materials is shown in Table 6. The most consistent reading between techniques was in the Cache River Valley where measurements were taken in one, uniform thick silt layer. The values were identical between the surface and downhole measurements (Table 5).

Indiana Geologic Survey

The geologic map and soil amplification map of Evansville, Indiana was completed in the grant 99-HQ GR 0086. A workshop sponsored by the Southwestern Indiana Disaster Resistance Community Corporation with support from the Indiana Emergency Management Agency was conducted on October 17, 2001. Representatives of City of Evansville, Vanderburgh County and the private sector attended the workshop to discuss the data and procedures used to produce the soil amplification map and to show how it can be used. The workshop included representatives of the USGS who discussed the national hazard mapping program and present information on the seismic hazards in the area. The approximately 60 people attending the workshop had many questions ranging from the basic principles to Graphic Information System use of local information in loss estimation programs.

Also a presentation was made on the Graphic Information System (GIS) mapping products of earthquake emergency routes and bridge inventory to the Central U.S. Earthquake State Transportation Task Force members in Indianapolis, Indiana on Nov. 14-15, 2001. The GIS maps were produced by ISGS for the task force to coordinate their earthquake emergency routes between states for mutual aid in the event of an earthquake event. Also it was demonstrated how this information can be used in earthquake loss estimation programs to produce earthquake related exercises and to estimate damages immediately following an earthquake event. Also USGS representatives presented information on earthquake impacts in the area and also went through a list of questions that the Task Force had supplied from their members.

In April 2003, the Indiana Geological Survey produced the Evansville Seismic Hazard Geographic Information System. This covered the Indiana parts of four 1:24,000 scale quadrangles of Evansville North and South, Newburgh and Daylight. This product has the shear wave velocity borehole locations, shear wave velocity profiles, unit description and geotechnical properties. This information was used to produce the NEHRP classified soil amplification maps for these quadrangles.

During the summer of 2003, the Indiana Geological Survey performed shear wave velocity measurements using surface seismic refraction methods. These 8 measurements were performed at 7 Purdue University farm sites across the state of Indiana (figure 5). Table 7 shows the average shear wave velocity information and general material description for the sites.

Kentucky Geologic Survey

This report summarizes the effort to assess potential seismic hazards in the Louisville Metropolitan Area using available geologic, hydrologic, topographic, and geotechnical data. Although there are some faults mapped in and around the Louisville metropolitan area, there is no evidence suggesting the faults are seismogenic- meaning that they are capable of creating a strong earthquake. The most significant earthquakes affecting the area were the series of 1811-1812 earthquakes in the New Madrid Seismic Zone 200 miles to the west. Earthquakes in other seismic zones, such as the Wabash Valley Seismic Zone in the tri-state area of Illinois, Indiana, and Kentucky (120 miles to the west), may also affect the Louisville area, but earthquakes from the New Madrid Seismic Zone will have the dominant impact in terms of seismic hazards.

Earthquake-related hazards can be created by local geologic, hydrologic, and topographic conditions. Three phenomena generally will be induced by strong ground motion during earthquakes under certain local conditions: (1) amplification of ground shaking by a “soft” soil column; (2) liquefaction of water-saturated sand, silt, or gravel, creating areas of “quicksand;” and (3) landslides, including rock falls and rock slides, triggered by shaking, even on relatively gentle slopes.

Two maps, ground motion amplification and liquefaction, were produced by this project for the Louisville metropolitan area; one for illustrating ground motion amplification and the other depicts liquefaction potential.. Although landslides could be triggered in some limited localities during a strong earthquake, landslide hazard will be minimal because the estimated low level of shaking and relative low variation of topography in Louisville area. The earthquake-induced landslide hazard, therefore, was not assessed in this project.

The maps, in combination with the ground-motion hazard maps, such as Street and others (1996) and Frankel and others (1997 and 2002), can be used to develop a variety of hazard mitigation strategies such as seismic risk assessment (HAZUS99), emergency response plans, and land-use planning.

For Louisville, Street and others (1996) estimated that a peak ground acceleration (PGA) of about 0.1g could be expected in the next 500 years. This would be the same peak acceleration you would feel if your car was bumped from behind while waiting for a traffic light. The United States Geological Survey (USGS) also estimated a similar ground shaking level for Louisville area that could be expected in the next 2,500 years (Frankel and others, 1997 and 2002). This level of ground motion (~0.1g PGA) has been used for policy decisions such as building code and highway bridge seismic designs.

Study Area and Local Geology

Louisville, the largest metropolitan area in Kentucky, is located in north central Kentucky along the Ohio River. The area chosen for this project are three adjacent 7.5 minute U.S.G.S. topographic quadrangles (New Albany, Louisville West, and Lanesville) and includes downtown Louisville and the majority of the Louisville Metropolitan Area as defined by the U.S. Census Bureau.

The topography of the area is characterized as being in the Outer Bluegrass Physiographic region (McGrain And Currens, 1978). The eastern portion has rolling to hilly terrain, the central and northern parts are flat with little relief (except adjacent to major drainage), and the southwestern corner is situated in the knobs region. Highest elevation is along the knobs (790 feet) and the lowest are along the Ohio River floodplain (435 ft).

The surficial geology is relatively simple in the study area. The bedrock, consisting of Silurian, Devonian and Mississippian siltstone, limestone, shale, and dolomite, is exposed in the east and northeast part of the study area. Quaternary, consisting of Pleistocene terrace deposits, loess and eolian sand, outwash, and lacustrine deposits, and Holocene alluvium, covers most of the study area. Holocene alluvium concentrates along the Ohio River and small streams (Figure 6). There are also some artificial fills mapped in the area.

Many places in the Louisville metropolitan area are underlain by unconsolidated deposits, especially along the Ohio River (Figure 6). Therefore, the secondary seismic hazards related to local geology , ground-motion amplification, liquefaction potential, and landslide/rockfall potential, must be a concern for the Louisville area.

Procedures

For the relative seismic hazard assessment, the unconsolidated young soils are important. Characterization of the distribution and thickness of these soil units (Quaternary) in the study area was accomplished using existing geologic maps, geotechnical subsurface investigations, and water well data plus collecting surface SH-wave data,. Geotechnical investigations were mainly conducted along road right-of-ways and the Ohio River by the Kentucky Transportation Cabinet and the US Army Corps of Engineers. SH-wave refraction techniques (Wang and others, 1998; Wang and others, 2000) were used to determine subsurface geologic materials and average shear-wave velocity for mapped stratigraphic units. New SH-wave data were collected at 15 sites (Figure 7). SH-wave data were processed on a personal computer using the commercial software package SIP by Rimrock Geophysics, Inc. (version 4.1, 1995). To process the data, refraction for each layer were identified, and then first-arrival times were picked and used to generate a shear-wave velocity model for the profile surveyed.

Ground shaking amplification

Soils and poorly consolidated sedimentary rocks overlying bedrock near the surface can modify bedrock ground shaking caused by an earthquake. The physical properties, spatial distribution, and thickness of geologic materials above bedrock can influence the strength of shaking by increasing or decreasing it or by changing the frequency of shaking. The method used to evaluate these modifications was developed by the Federal Emergency Management Agency (FEMA) (Building Seismic Safety Council, 1994) as NEHRP recommanded provisions for seimic regulations, called NEHRP methodology. This method was adopted in the 2000 version of the International Building Code and the International Residential Code (International Code Concil [ICC], 2000). These two codes were adopted by the Commonwealth of Kentucky and became *the 2002 Kentucky Building Code* and *the 2002 Kentucky Residential Code*.

The NEHRP methodology defines six soil categories that are based on average shear-wave velocity, Standard Penetration Test (SPT) value, or undrained shear strength in the upper 100 ft (30 m) of the soil column (Table 8). The six soil categories are Hard Rock (A), Rock (B), Very Dense Soil and Soft Rock (C), Stiff Soil (D), Soft Soil (E), and Special Soils (F). Category F soils are very soft soils that require site-specific evaluation. The ground motion amplification ranges from none (Hard Rock/A), to high (Soft Soil/E and F).

Liquefaction

Liquefaction is a phenomenon in which shaking of a saturated soil causes its material properties to change so that it behaves as a liquid. In qualitative terms, the cause of liquefaction was described very well by Seed and Idriss (1982): "If a saturated sand is subjected to ground vibrations, it tends to compact and decrease in volume; if drainage is unable to occur, the tendency to decrease in volume results in an increase in pore water pressure, and if the pore water pressure builds up to the point at which it is equal to the overburden pressure, the effective stress becomes zero, the sand loses its strength completely, and it develops a liquefied state."

Soils that liquefy tend to be young, loose, granular soils that are saturated with water (National Research Council, 1985). Unsaturated soils will not liquefy, but they may settle. If an earthquake induces liquefaction, several things can happen: (1) the liquefied layer and everything lying on top of it may move downslope; (2) the liquefied layer may oscillate with displacements large enough to rupture pipelines, move bridge abutments, or rupture building foundations; and (3) light objects, such as underground storage tanks, can float toward the surface, and heavy objects, such as buildings, can sink. Typical displacements can range from centimeters to meters. Thus, if the soil at a site liquefies, the total damage resulting from an earthquake can be dramatically increased from that caused by shaking alone.

Liquefaction hazard potential was first evaluated based on the age and engineering properties of the geologic unit and hydrologic conditions. Youd and Perkins (1978) found that the liquefaction potential for different sediments is related to age and depositional environment. Table 9 summarizes the liquefaction potential for several continental deposits (Youd and Perkins, 1978). Based on the ages of soils, only Holocene alluvium has moderate to high susceptible to liquefaction in the Louisville area.

A further evaluation was performed for the Holocene alluvium based on the average shear-wave velocity. Andrus and Stokoe (1997) found that soils with a shear-wave velocity of less than 200 m/s have high liquefaction potential. However, the estimated ground-shaking would be moderate (~0.1g PGA) in the Louisville area. A moderate liquefaction hazard was assigned to the Holocene alluvium.

Based on the surficial geologic mapping, SH-wave data, geotechnical subsurface investigations, and water well data, four major soil units and bedrock were identified and characterized (table 9).

Based on the average shear-wave velocities and thickness of the soil units (table 10) and the

NEHRP methodology (table 8), a ground motion amplification map for the Louisville metropolitan area was generated (figure 8). The ground motion amplification map assigns NEHRP/UBC soil types, based on average shear-wave velocity for the upper 30 m of the soil column, to hazard categories as follows: (1) none (B type soil); (2) low (C type soil); (3) moderate (D type soil); and (4) high (E type soil).

Liquefaction hazard assignments for each geologic unit based on age, depositional environment, and average shear-wave velocity are listed in Table 10. The liquefaction potential hazard map for the Louisville area is illustrated on Figure 9. As depicted on the map, areas with moderate liquefaction susceptibility, comprised of Holocene alluvium, are concentrated along the Ohio River and major stream valleys.

Technology transfer

On April 22, 2002 the Kentucky Geologic Survey arranged a workshop in Owensboro, Kentucky for state and local officials, consultants and the public concerning earthquakes in the area or events that may impact the area; mapping of soils for soil amplification; and the results of a HAZUS run with default soil data and with detail soil amplification maps. Seventy-five people attended the workshop and several consultants requested electronic soil amplification maps and other seismic shaking computer program information.

Missouri Geologic Survey

The geologic map and soil amplification map of Cape Girardeau was completed in the grant 99-HQ GR 0086. During this contract, geologic mapping and shear wave velocity measurements were performed on 4 quadrangles (Poplar Bluff, Rombauer, Harviell and Hanleyville 7.5' quadrangles) that covered the city of Poplar Bluff. This work produced a soil amplification map for these 4 quadrangles.

Earthquake damage is related to the intensity of shaking or ground motion generated by an earthquake. Usually, the only earthquake ground motion information readily available for an area is the bedrock ground motions. The estimated bedrock ground motions for a variety of earthquake conditions are available in map or tabular form from the U. S. Geological Survey (http://eqhazmaps.usgs.gov/). The surficial material overlying the bedrock surface can either amplify (most commonly) or deamplify the bedrock ground motions by the time they reach the ground surface where man-made structures are built. Therefore, to better estimate the shaking and damage that may occur to man-made structures during an earthquake, it is necessary to modify the bedrock motions with soil amplification estimates. This map is intended to serve that need. Specifically, this map is intended to be used with Federal Emergency Management Agency's (FEMA) Hazards U. S. (HAZUS) computer program for earthquake loss estimation. Together they can give a more refined estimate of earthquake damage based on six classes of soils versus the one soil class provided as default soil amplification data in HAZUS. The map can also be used by a variety of users to get a general idea of where potential damage is likely to be greater or lesser, based on the soil class. Use of the map to evaluate individual specific sites is not recommended as the resolution of the source data is not sufficient to pin-point the location of boundaries and unit characteristics. Individual sites need to be evaluated with site specific subsurface investigations.

The CUSEC State Geologists has organized geologists from the Geological Surveys in the Midwest to gather and use information on "soil" properties to produce maps showing where unconsolidated geologic material (material resting on top of bedrock) will amplify earthquake ground motions. Individual state geological surveys produced their own state's soil amplification maps from existing geologic maps which represented either 3-dimensional surficial material to various depths or surficial data which was extrapolated in the third dimension by geologists familiar with the area. In some cases, geologists produced new geologic working maps of the areas. This mapping effort is designed to support the City of Poplar Bluff, Missouri and its participation in FEMA's disaster resistant community program, which uses the HAZUS computer program for earthquake loss estimation.

It has been shown that the amount of amplification of "soil" is correlated to its shear wave velocity. Based on this relationship, a classification has been put forward in the 1997 NEHRP Recommended Provisions for Seismic Regulations for New Buildings and Other Structures and is used in the 1997 Uniform Building Code (UBC) and the 2000 International Building Code (IBC), which classifies the upper 100 feet or 30 meters of "soils", by its average shear wave velocity. In the Midwest, the state geological surveys have worked together to produce maps that offer a consistent use of this soil amplification classification based on measured shear wave velocity values of Midwest "soils."

The 1997 NEHRP classification system, summarized in Table 8, is referred to as the Site Class and it contains six categories identified as A, B, C, D, E and F. It is in essence a combination of two separate classification systems. Classes A, B, C, D and E are based on the average shear wave velocity of all materials to a depth of 100 feet or 30 meters. The average shear wave velocity associated with classes A through E is given in Table 8. Class F is based on identifying soils requiring site-specific evaluation and is not related to the shear wave velocity of those soils. These F soils include: 1) soils vulnerable to potential failure or collapse under seismic loading such as liquefiable soils, quick and highly sensitive clays and collapsible weakly cemented soils, 2) peats and/or highly organic clays over 10 feet (3 meters) thick, 3) very high plasticity clays over 25 feet (8 meters) thick, and 4) very thick soft/medium stiff clays over 120 feet (36 meters) thick. Rather than shear wave velocity, this different evaluation is performed to identify class F soils.

This map showing the classification of soils for amplification induced by earthquake ground motions is a derivative or interpretative map based on existing surficial geology maps of the Poplar Bluff, Rombauer, Harviell and Hanleyville 7.5' quadrangles. The surficial materials or "soils," all the loose material above bedrock, in the four 7.5' quadrangles were mapped as a part of a Missouri Geological Survey Program project partially funded by a US Geological Survey STATEMAP grant in 1999 and 2000 (Figure 10). Three of those maps are available from the Missouri Department of Natural Resources' Geological Survey and Resource Assessment Division as open-file maps, OFM-00-366-GS, OFM-00-370-GS, and OFM-00-360-GS (Middendorf, 2000a & b and Baker, 2000). An open-file map of the Harviell 7.5' quadrangle is not currently available. Refer to those maps for a description of the map units and how the mapping was conducted.

The surficial geology map units were reinterpreted to classify them based on the 1997 NEHRP Site Classes and to determine their susceptibility to amplifying earthquake ground motions input by the underlying bedrock surface. With the generous assistance of the Missouri Department of Transportation (MoDOT), new shear wave velocity data were collected at 18 sites in areas where alluvium exists in the four-quadrangle area (Figure 11). The seismic cone penetrometer test (SCPT) equipment used by MoDOT is not appropriate for use in the upland areas where gravelly residuum exists. The Kentucky Geological Survey/University of Kentucky (KGS/UK) also generously assisted by collecting shear wave velocity data at 10 sites in the four quadrangle map area (Table 11). The KGS/UK uses a surface geophysics technique employing shear waves, which can be used in all settings. The University of Missouri - Rolla (UMR) was also contracted to provide shear wave velocity data for 40 sites in the four-quadrangle area. The UMR surface geophysics technique used Rayleigh waves and the spectral analyses of surface waves (SASW), which can also be used in all settings. Multiple tests were run at many of the 40 test sites using the different investigation techniques in order to compare the methods, their effectiveness, their results and their efficiency. A total of 58 shear wave velocity tests were run at the 40 different sites.

All of these shear wave velocity data were then averaged by map unit and correlated to the existing surficial geology map units (Table 12). For each test site, each layer of surficial material has a shear wave velocity value and a thickness value. The average shear wave velocity, to a depth of 100 feet or approximately 30 meters, for the entire stack of surficial material layers was determined by using the formula presented in FEMA 302, 1997 NEHRP Provisions. Based on this average shear wave velocity, the surficial material unit at the site was assigned the NEHRP/UBC soil classification of A, B, C, D or E. The procedure was facilitated by constructing a series of spreadsheets. The shear wave velocity and thickness data for the sequence of materials was entered and then the spreadsheet calculated the average shear wave velocity for the stack. The individual test site average shear wave velocities for all sites in the same surficial geology unit were then averaged to obtain an average shear wave velocity for the surficial geology unit. The unit average was then assigned a NEHRP/UBC soil classification of A, B, C, D or E. Areas on this map (Figure 12) are classified F due to their surficial material unit's potential to liquefy or fail due to ground shaking and not according to shear wave velocities. Therefore geologic settings that have saturated sands or have evidence of past liquefaction are assigned the classification F.

Technology Transfer

Workshop on earthquake impacts, effects and mapping of soil for amplification in Owensboro, KY April 2002 and Cape Girardeau, MO Oct 2002. Poster presentations were made in Lexington, KY April 2002 SE-GSA, Champaign, IL April 2002 Environmental Horizons, Nashville Aug 2002 CUSEC Annual, Denver Sept 2002 - WSSPC, Nashville Jun 2003 CUSEC Annual and a presentation at the FHWA Ground Motion Workshop in Collinsville, IL Feb 2003.

Summary

The Central U.S. Earthquake Consortium (CUSEC) State Geologists have presented workshops on the information gathered on the local geologic and material properties of the soils in the Disaster Resistant Community of Evansville, Indiana; to the State Department of Transportation officials in the Midwest; and state and local officials, consultants and the public in Owensboro, Kentucky and Cape Girardeau, Missouri. The geological information is first used to produce geologic maps of the materials resting on the bedrock at a scale of 1:24,000 or 1 inch = 2,000 feet. The geologic map, along with measurements of the soil's properties, is used to classify the various soils as to how much they will amplify earthquake ground motions. The amplification maps can be used in the Federal Emergency Management Agency's earthquake loss estimation program (HAZUS) to better estimate the amount of damages a community may expect from various earthquakes. This work entailed gathering all existing borehole information, "drilling" new holes for stratigraphy, measuring shear wave velocity and producing new maps of the "soils" and their thickness. The average shear wave velocity is calculated for the total column of "soil" and used to produce a map classifying the soils as to how much they will amplify earthquake ground motions. The soil amplification maps and the background information used are being presented in workshops in the communities, along with how the earthquake loss estimation program can be used for preparation, recovery and mitigation. Presentations to Evansville, Cape Girardeau and Owensboro used default and detailed soil amplification maps to show how new data impacts the estimates in using the HAZUS loss estimation program.

In addition to the NEHRP classified soil amplification maps produced for West Memphis, Poplar Bluff and Louisville, shear wave velocity measurements were performed through the CUSEC states using three different methods; down cased boreholes, shear cone and surface refraction/reflection. At some locations all three methods were used at the same place. Values of shear wave velocity differed between methods except for one location that had uniform geologic materials.

References

Andrus, R.D., and Stokoe, K.H., 1997, Liquefaction resistance based on shear wave velocity: Report to the NCEER Workshop on Evaluation of Liquefaction Resistance (9/18/97 version), Jan. 4-5, Salt Lake City, Utah.

Baker, Harold W., 2000, Surficial Material Geologic Map of the Poplar Bluff 7.5' Quadrangle, Butler County, Missouri, Missouri Department of Natural Resources, Geological Survey and Resource Assessment Division, Rolla, MO, OFM-00-366-GS

Bauer, R. A., Kiefer, J., Hester, N., 2001, Soil amplification maps for estimating earthquake ground motions in the Central US: Engineering Geology 62, pp. 7-17.

Building Seismic Safety Council, 1994, NEHERP recommended provisions for seismic regulations for new buildings, 1994 edition, Part 1: Provisions: Federal Emergency Management Agency Publication FEMA 222A / May 1995, 290 p.

Federal Emergency Management Agency (FEMA), 2001, HAZUS®99 Estimated Annualized Earthquake Losses for the United States, FEMA 366.

FEMA 222A, 1994, NEHRP recommended provisions for the development of seismic regulations for new buildings, 1994 edition, Part 1 – provisions, Federal Emergency Management Agency, 290 pp.

Frankel, A., Mueller, C., Barnhard, T., Perkins, D., Leyendecker, E. V., Dickman, N., Hanson, S., and Hopper, M., 1997, National 1996 Seismic Hazard Maps: U.S. Geological Survey, Open-File Report 97-131.

Frankel, A., Petersen, M., Mueller, C., Haller, K., Wheeler, R., Leyendecker, E.V., Wesson, R., Harmsen, S., Cramer, C., Perkins, D., and Rukstales, K., 2002, Documentation for the 2002 update of the national seismic hazard maps: U.S. Geological Survey Open-File Report 02-420, 33 p.

Fuller, M. L., 1912, The New Madrid Earthquake: U. S. Geological Survey Bulletin 494, p. 119.

Gray, J. L. and Ferguson, D. V., 1974, Soil Survey of Crittenden County, Arkansas: U. S. Department of Agriculture Soil Conservation Service in cooperation with the Arkansas Agricultural Experiment Station.

Haley, B. R., et al, 1976, Geologic Map of Arkansas: Arkansas Geological Commission.

International Code Council, 2000, International Building Code.

McFarland, John David, 1998, Stratigraphic Summary of Arkansas: Arkansas Geological Commission Information Circular 36, 39 p.

McGrain, P., and Currens, J.C., 1978, Topography of Kentucky, Kentucky Geological Survey Series X, Special Publication 25.

Middendorf, Mark A., 2000a, Surficial Material Geologic Map of the Rombauer 7.5' Quadrangle, Butler and Stoddard Counties, Missouri, Missouri Department of Natural Resources, Geological Survey and Resource Assessment Division, Rolla, MO, OFM-00-370-GS

Middendorf, Mark A., 2000b, Surficial Material Geologic Map of the Harviell 7.5' Quadrangle, Butler County, Missouri, Missouri Department of Natural Resources, Geological Survey and Resource Assessment Division, Rolla, MO, OFM-00-360-GS

National Research Council, Commission on Engineering and Technical Systems, Committee on Earthquake Engineering, 1985, Liquefaction of soils during Earthquakes: Washington, D.C., National Academy Press, 240 p.

NEHRP Recommended Provisions for Seismic Regulations for New Buildings and Other Structures, 1997 Edition, Part 1: Provisions (FEMA 302), Building Seismic Safety Council of the National Institute of Building Sciences.

Saucier, Roger T., 1994, Geomorphology and Quaternary Geologic History of the Lower Mississippi Valley: Vol. I, II, U. S. Army Engineer Waterways Experiment Station.

Schrader, T. P., 2001, Status of water levels and selected water-quality conditions in the Mississippi River Valley Alluvial Aquifer in eastern Arkansas, 2000, U. S. Geological Survey Water-Resources Investigations Report 01-4124.

Seed, H.B., and Idriss, I.M., 1982, Ground motions and soil liquefaction during earthquakes: Earthquake Engineering Institute Monograph Series, 134 p.

Street, R., Z. Wang, I Harik, and D. Allen, 1996, Source Zones, Recurrence Rates, and Time Histories for Earthquakes Affecting Kentucky, Research Report KCT-96-4, Kentucky Transportation Center, University of Kentucky, Lexington, Kentucky.

Street, R., Woolery, E. W., Wang, Z., Harris, J. B., 2001, NEHERP soil classifications for estimating site-dependent seismic coefficients in the Upper Mississippi Embayment: Engineering Geology 62, pp. 123-135.

Wang, Z., Madin, I.P., and Street, R.L., 1998, Shear-wave velocity and soil classifications for communities in Oregon: Proceedings of the 8th International IAEG Congress, Vancouver, British Columbia, Canada, September 21-25, 1998, p. 149-154.

Wang, Z., R. L. Street, E. W. Woolery, and I. P. Madin, 2000, SH-Wave Refraction/Reflection and Site Characterization, Use of Geophysical Methods in Construction (Geotechnical Special Publication No. 108), Proceedings of Sections of GEO-Denver 2000, ed. By S. Nazarian and J. Diehl, ASCE, Reston, Virginia, p. 126-140.

Youd, T.L. and D.M. Perkins, 1978, Mapping Liquefaction-Induced Ground Failure Potential, Journal of the Geotechnical Engineering Division, ASCE, Vol. 104, No. GT4, p433-446.

Figure 1 Geologic map of West Memphis 7.5 degree quadrangle. Geology adapted from Saucier (1994).

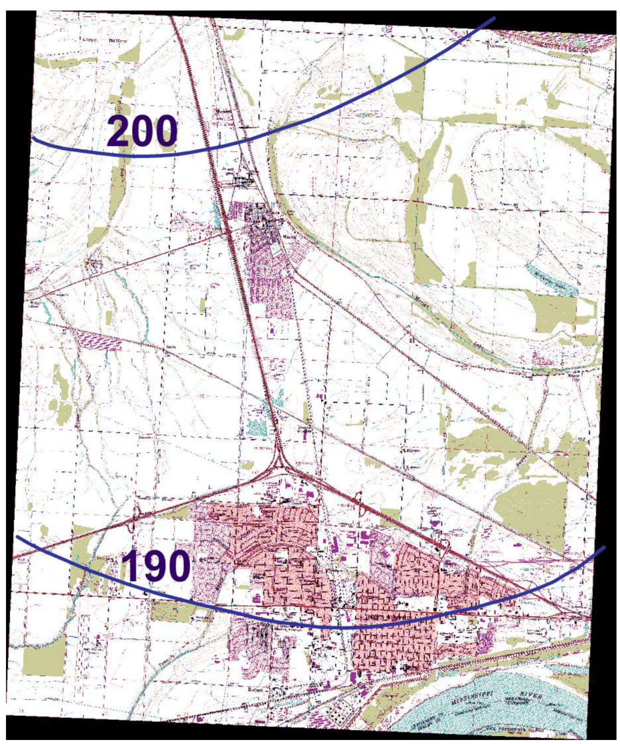

Figure 2 Elevation in feet of potentiometric surface of alluvial aquifer (after Schrader, 2001).

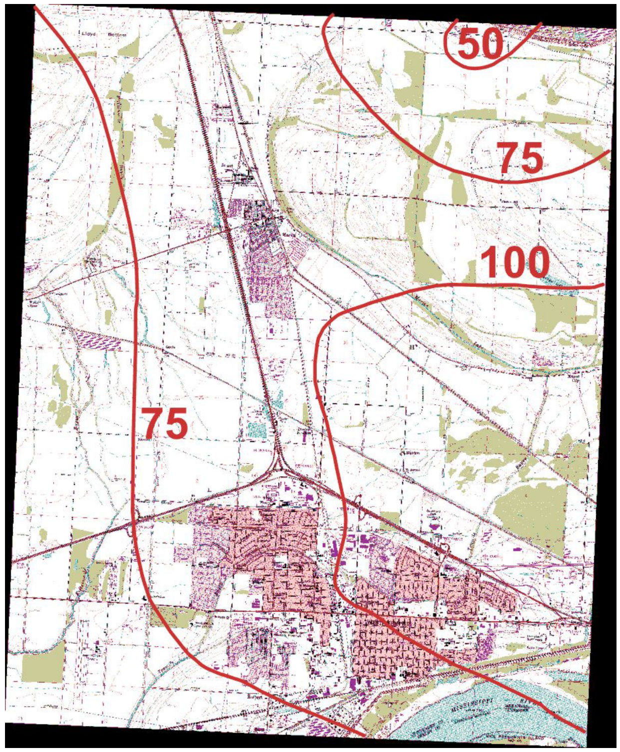

Figure 3 Elevation in feet of suballuvial surface (after Saucier, 1994).

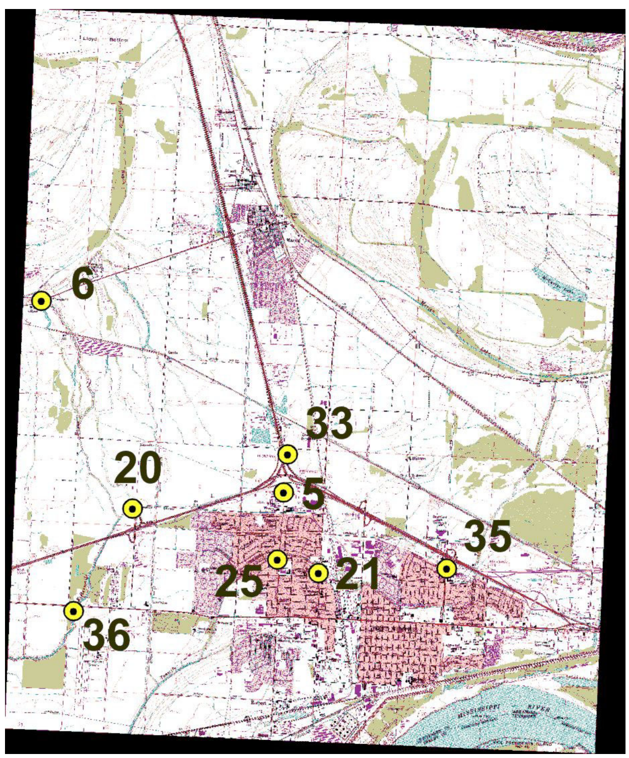

Figure 4 Location of Arkansas Highway and Transportation Department Standard Penetration Test sites.

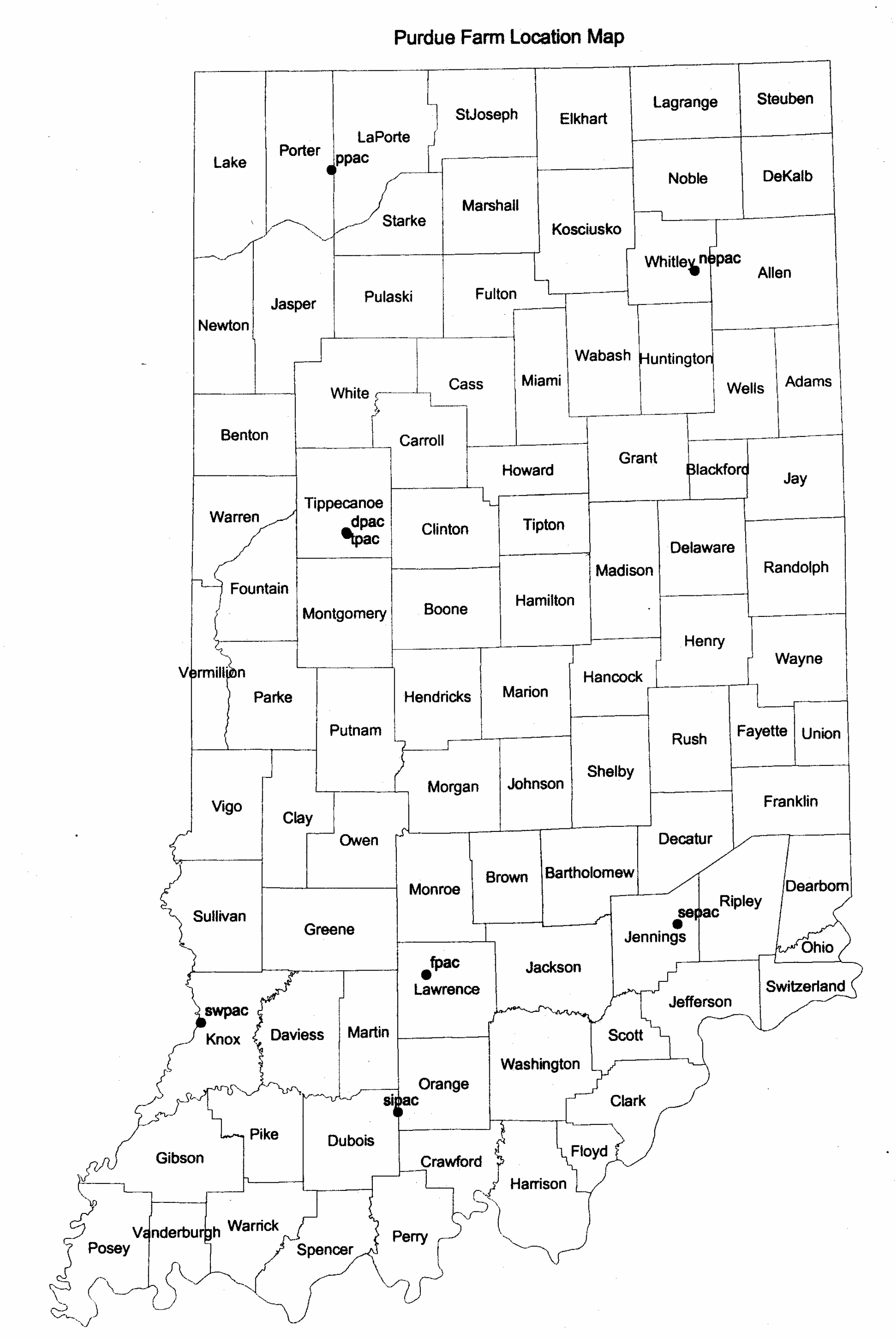

Figure 5. Location of downhole shearwave velocity measurements on the 7 Purdue University farms in Indiana. Site IDs cross reference with measurement results shown in table 7.

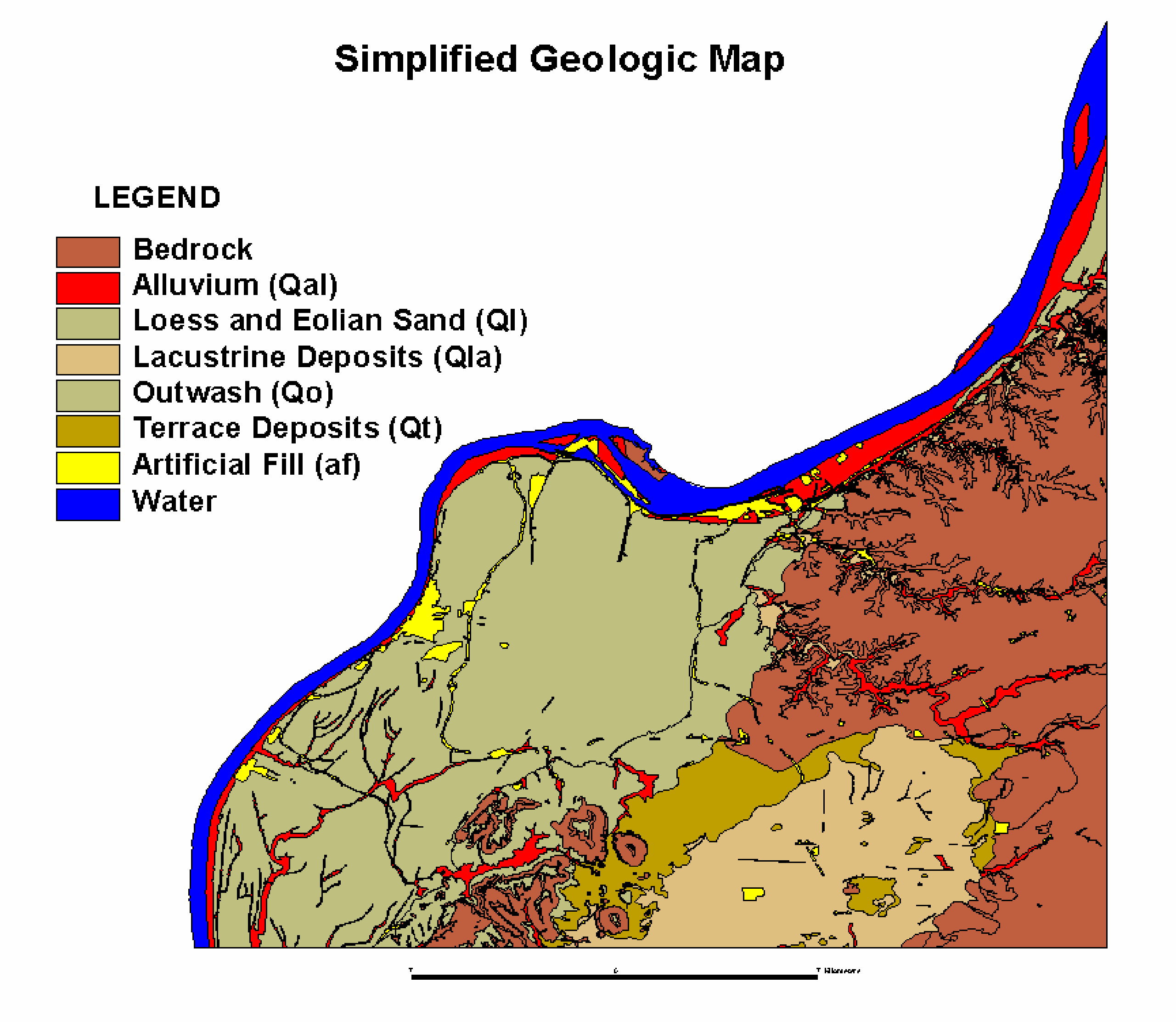

Figure 6. Surficial geology of the Louisville, Kentucky area.

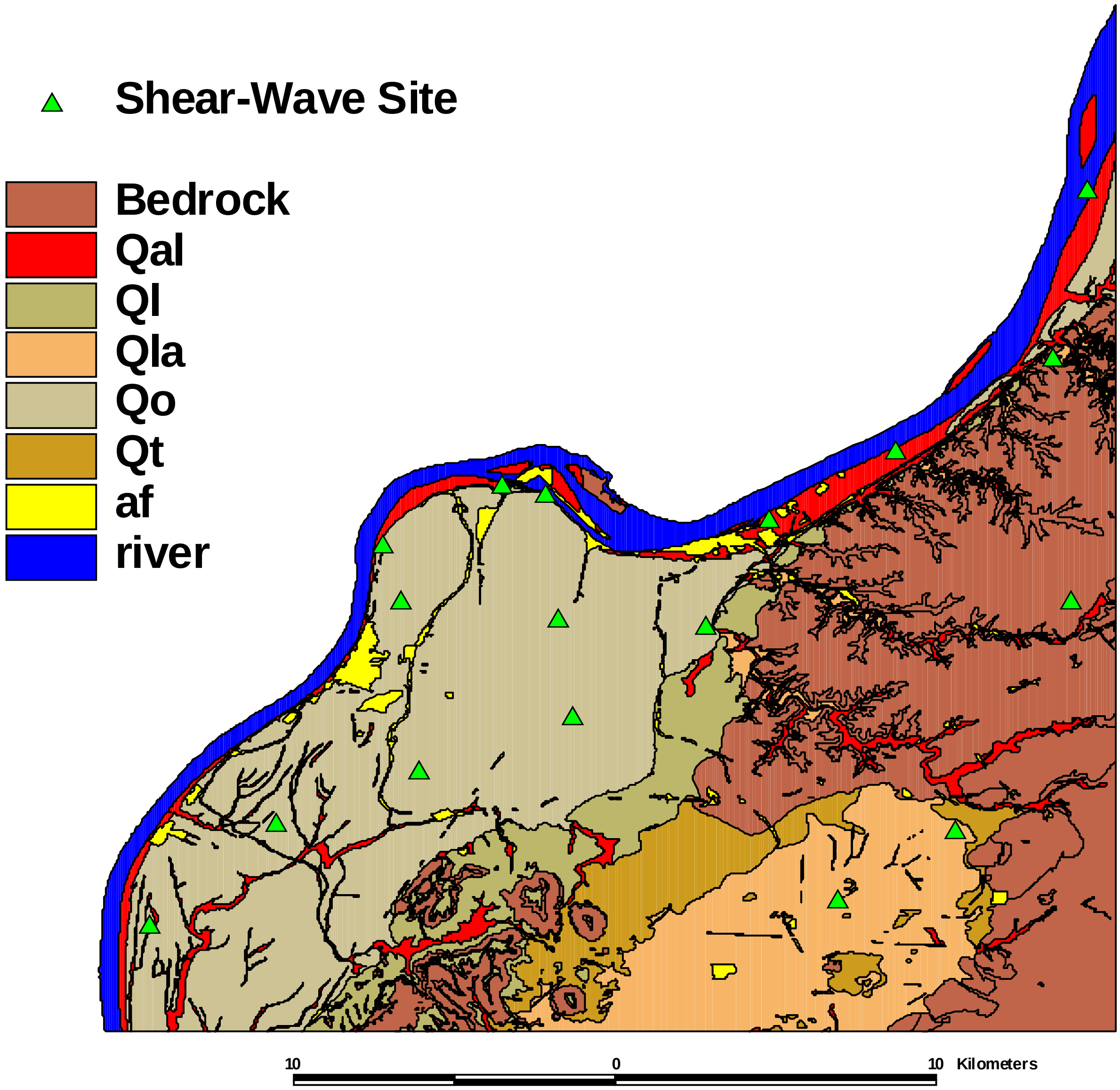

Figure 7. Location of 15 shear wave velocity measurement sites in relation to surficial geology.

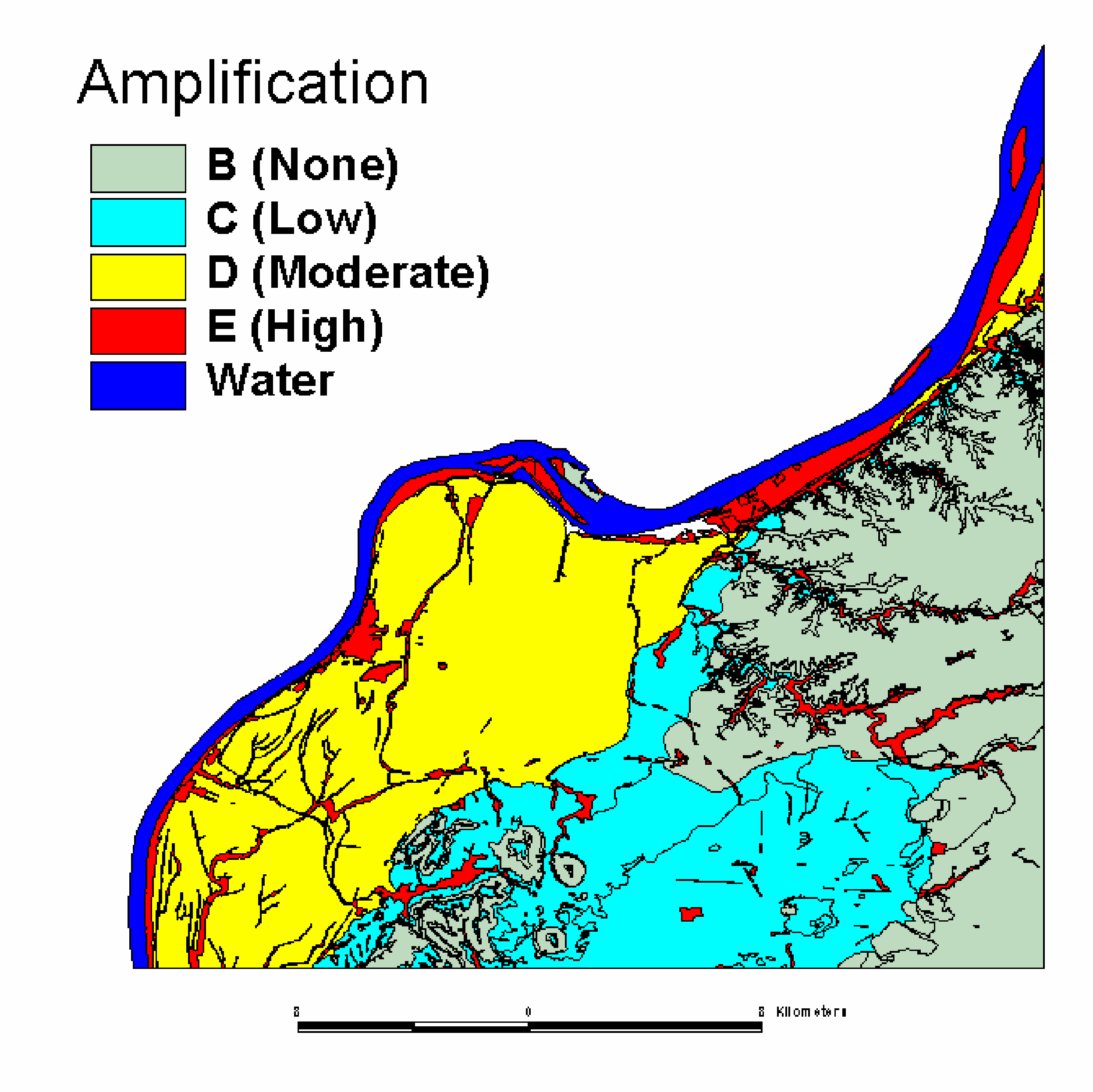

Figure 8. Soil amplification map of Louisville, Kentucky area.

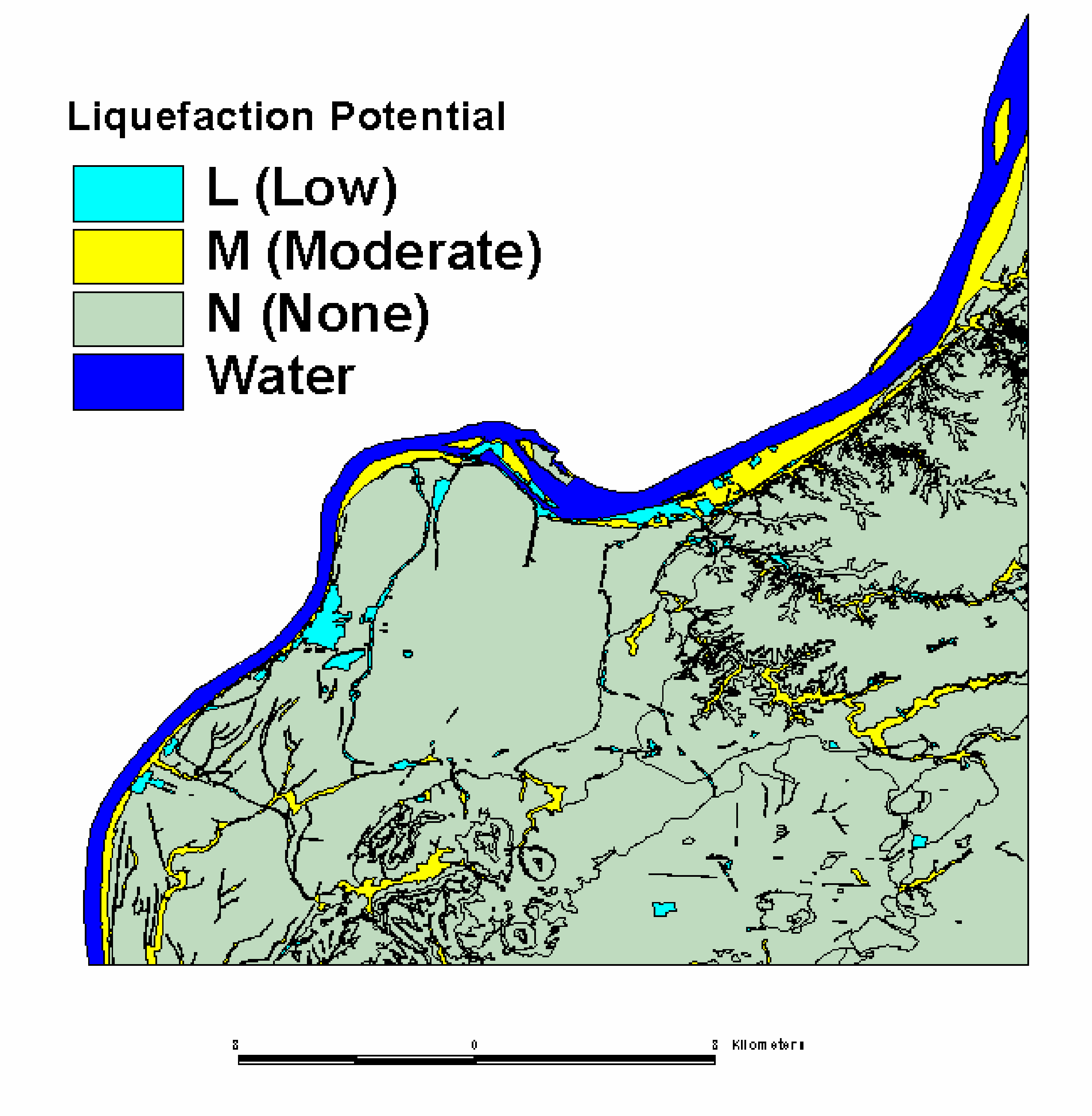

Figure 9. Liquefaction potential map of the Louisville, Kentucky area.

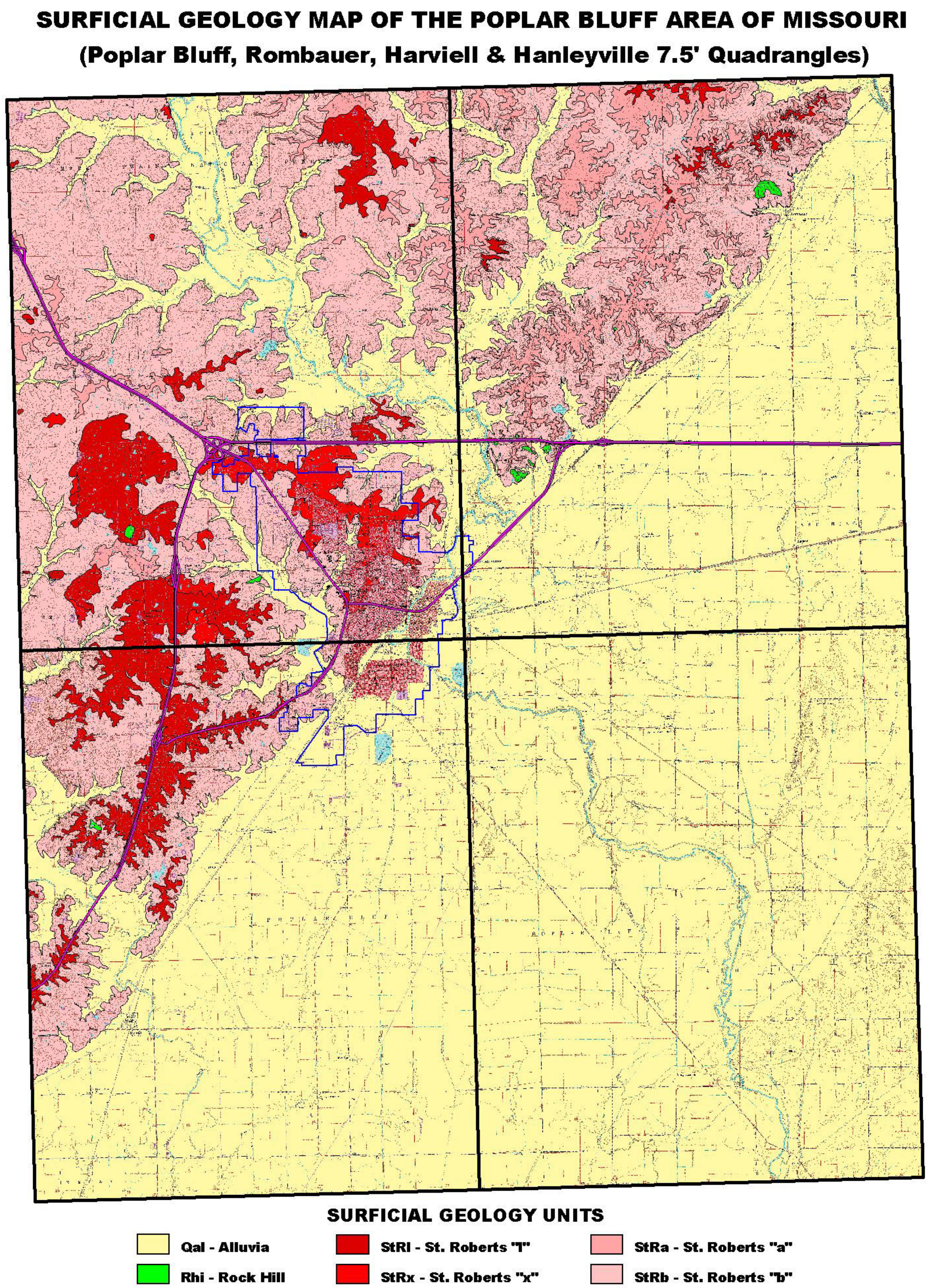

Figure 10. Surficial geologic map of the Poplar Bluff, Missouri area.

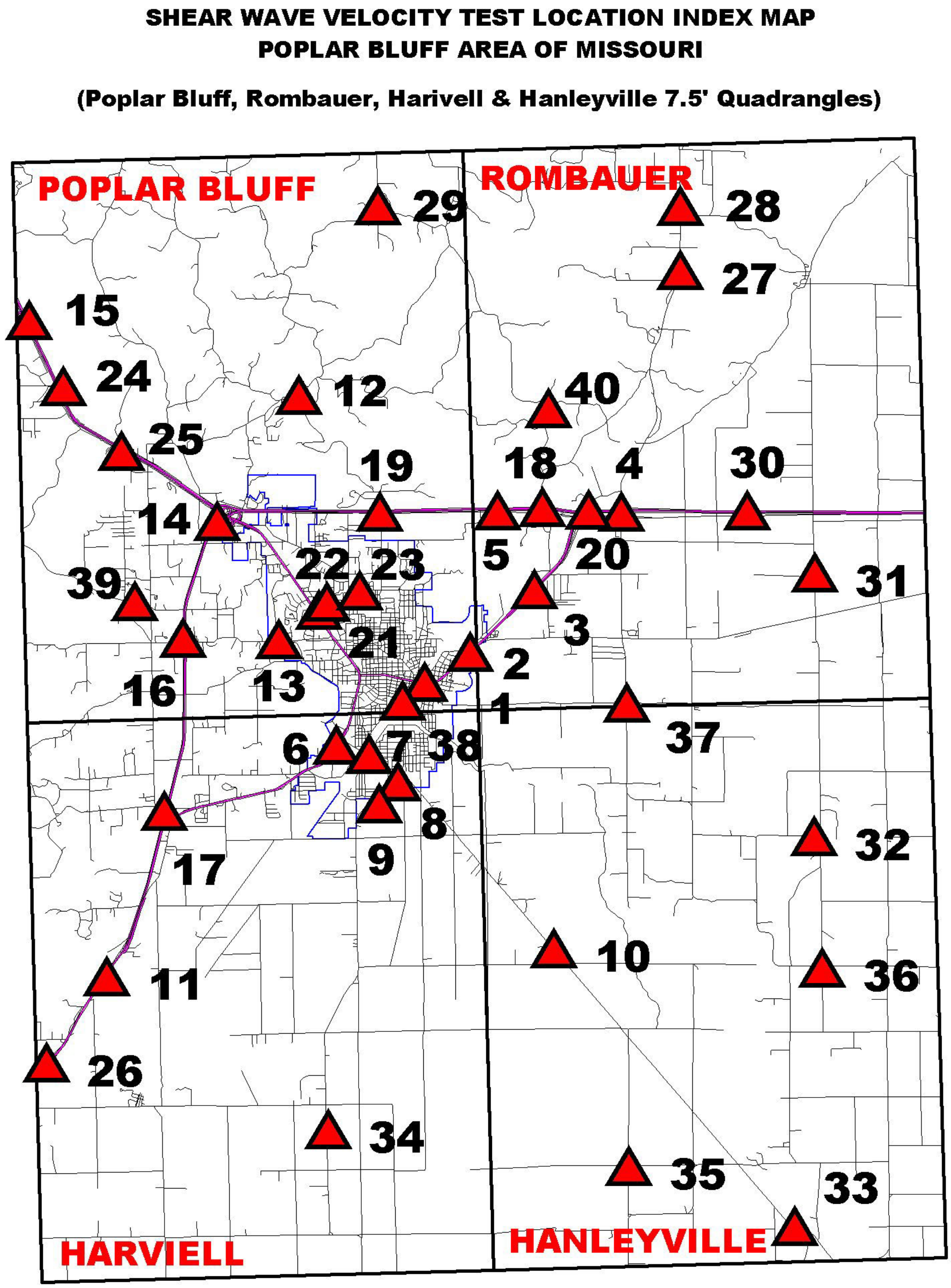

Figure 11. Map of Poplar Bluff, Missouri area showing location of site where shear wave velocity measurements were taken.

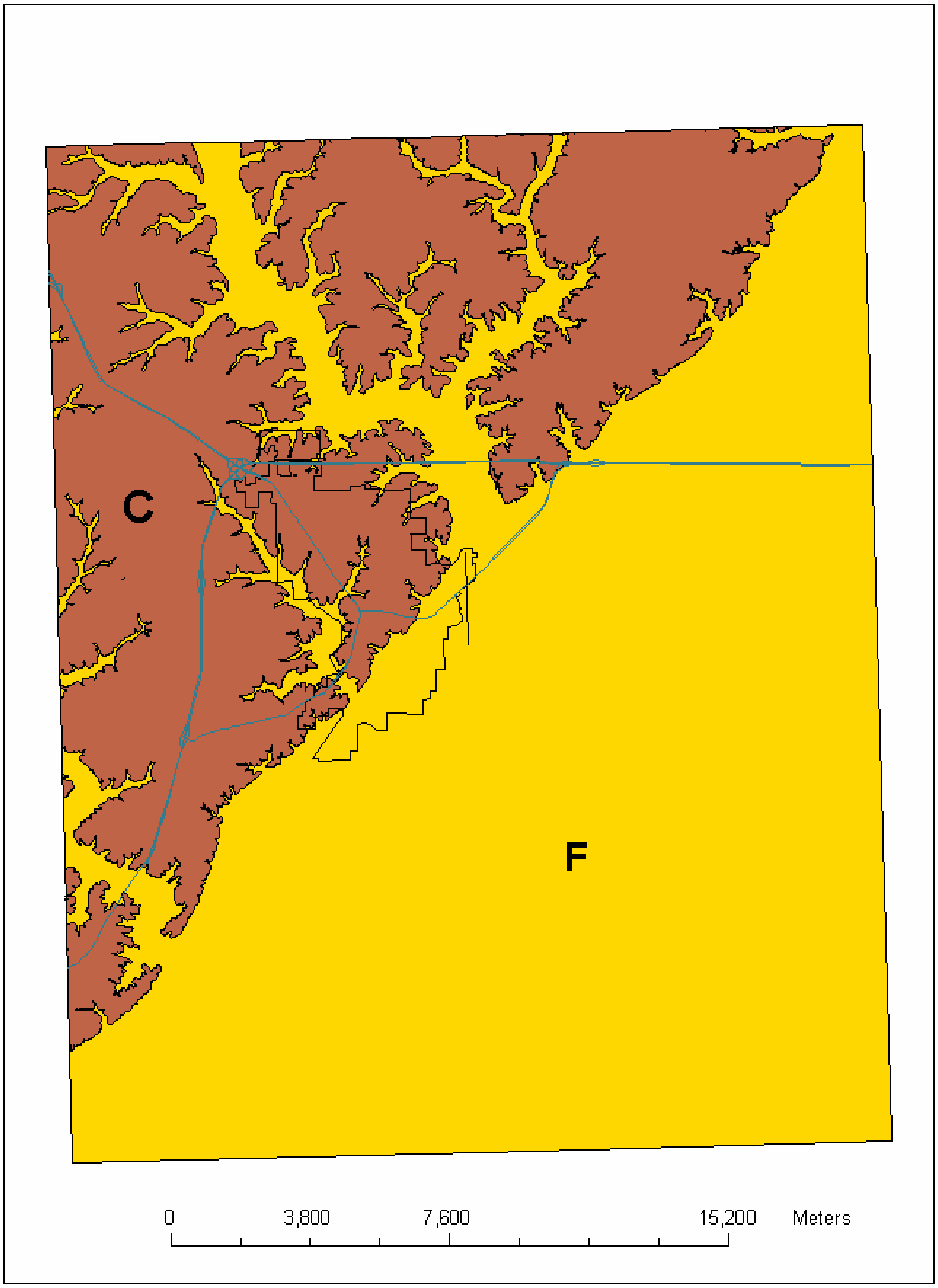

Figure 12. NEHRP soil classification based on shear wave velocities and geologic materials.

Table 1. Borehole information for West Memphis, Arkansas quadrangle.

Borehole Number	Depth below Surface (feet)	Lithology	SPT blow counts (N)
#5	0.0 – 50.0	Clay, silty, trace of fine sand, soft to medium stiff	N = 3 to 7 (av. = 5.4)
	50.0 – 76.5	Sand, medium dense to dense	N = 24 to 36
#6	0.0 – 45.0	Clay, silty, trace of sand, soft to medium stiff	N = 3 to 16 (av. = 5.7)
	45.0 – 66.5	Sand, trace of gravel, dense	N = 33 – 48
#20	0.0 – 35.0	Clay, silty, trace of sand, very soft to medium stiff	N = 0.75 to 6 (av. = 4.2)
	35.0 – 85.0	Sand, gravel, medium dense to dense	N = 20 to 47 (av. = 32.1)
#21	0.0 – 55.0	Clay, silty, trace of organic material and sand, very soft to soft	N = 0.67 to 4 (av. = 2.7)
	55.0 – 85.0	Sand, trace of lignite, medium dense to dense	N = 23 to 43 (av. = 33.0)
#25	0.0 – 45.0	Clay, silty, some sand, soft to stiff	N = 3 to 16 (av. = 6.8)
	45.0 – 101.5	Sand, traces of gravel, clay, and lignite, soft to dense	N = 4 to 39 (av. = 24.3)
#33	0.0 – 41.5	Clay, silty, sandy, trace of gravel and organic material, medium stiff to stiff	N = 5 to 10 (av. = 8.1)
	41.5 – 66.5	Sand, Gravel, trace of lignite, dense to very dense	N = 40 to 68 (av. = 54.0)
#35	0.0 – 64.0	Clay, silty, soft to medium stiff	N = 2 to 7 (av. = 5.7)
	64.0 – 71.5	Sand, lignitic, trace of gravel	N = 39
#36	0.0 – 50.0	Clay, silty, very soft to medium stiff	N = 0 to 8 (av. = 4.1)
	50.0 – 76.5	Sand, some silt and clay, very stiff to dense	N = 18 to 44 (av. = 36.8)

Table 2. Downhole shear wave velocity measurements in boreholes in northeastern Illinois.

	Antioch Quad 1		Antioch Quad 2		Grayslake Quad 1		Grayslake Quad 2	
	Meters/Sec	N	Meters/Sec	N	Meters/Sec	N	Meters/Sec	N
Clay					306	9		
Cobbles								
Gravel					286	7		
Gravel/Sand								
Sand	455	23	359	9	248	7	448	22
Sand/Gravel								
Sandy Silt								
Silt	480	8	542	28	416	26		
Till	465	34	433	33	283	2	492	37

	Grayslake Quad 3		Fox Lake Quad		Wauconda Quad	
	Meters/Sec	N	Meters/Sec	N	Meters/Sec	N
Clay						
Cobbles					486	6
Gravel			1,079	8		
Gravel/Sand					272	6
Sand	417	2	509	33	388	3
Sand/Gravel					328	4
Sandy Silt					350	5
Silt			582	6		
Till	389	32	553	10	316	13

Table 3. Three different shear wave velocity measuring techniques for sites in the Vincennes quadrangle in Illinois. Measurements are in the Wabash River Valley alluvium.

Site	Average from Borehole Vs (m/s)	Average from Surface Seismic (m/s)	Average from Shear Cone (m/s)
1	199	206	
2		207	
3		221	294
4		262	
5		215	
6		238	308
7		225	
8		248	329
9		237	297
10		252	
11		203	125
12		219	

Table 4. Average shear wave velocities measured in Allerton Park by Monticello, Illinois using a cased borehole.

Formation/type	Average Shear wave velocity (m/s)			
	N	Minimum	Average	Maximum
Wedron Group Clays	16	279	393	565
Glasford Sand	8	228	321	426
Glasford Till	9	446	734	999
Banner Sand	30	332	448	595

Table 5. Average shear wave velocities in two cased boreholes in lacustrine silts in the Cache River Valley.

Site	Average shear wave downhole Meters/sec	Average shear wave surface Meters/sec
Cache West – Lacustrine Silt	173.87	173.73
Cache East – Lacustrine Silt	174.53	176.02

Table 6. Range and average of shear wave velocity values for silty clay overbank deposits and thick medium to dense sands in the valley.

		Average Shear Wave Velocities (m/sec)		
	N	Minimum	Average	Maximum
Alluvium clay	6	99	161	229
Aluvium sands - med to dense	6	207	263	297

Table 7. Average P and S wave velocity measurements taken in cased boreholes on 7 Purdue University farms in Indiana.

Site	Vp Average (m/s)	Vs Average (m/s)	Layer Description
nepac	1,817	406	Silty clay loam (till)
swpac	2,061	1,018	Loess
tpac	2,017	481	Loam till
ppac	2,152	443	Silt loam till
sipac	2,283	757	Loess/residuum
fpac	2,989	1,453	Loess/Terra Rossa
dpac	3,840	2,050	Loam till
sepac	4,234	2,289	Loess/thin loam till

Table 8. NEHRP soil classification by shear wave velocity and material properties.

Soil Type	Soil Name	Average Soil Properties for Top 30 m (100 feet)		
		Shear-wave Velocity,Vs (m/s)	Standard Penetration Test, N (blows/foot)	Undrained Shear Strength s_u (kPa)
S_A	Hard Rock	>1,500	-	-
S_B	Rock	760 to 1,500		
S_C	Very Dense Soil and Soft Rock	360 to 760	>50	>100
S_D	Stiff Soil	180 to 360	15 to 50	50 to 100
S_E	Soft Soil	<180	<15	<50
S_F	Soil Requiring Site-specific Evaluation			

Table 9. Liquefaction potential related to type of continental deposits by Youd and Perkins (1978).

Age	**Geologic Unit**	**Average Shear-Wave Velocity (m/s)**	**Average Thickness (m)**	**Liquefaction susceptibility**	**Equivalent units**
Holocene	Channel and Floodplain Alluvium	100-200	5-20	moderate	Qal
Pleistocene	Lacustrine Deposits	160-275	3-5	none	Qla
Pleistocene	Glacial Outwash	250-600	5-25	none	Qo
Pleistocene	Loess and Eolian Sand	(170-300)	(3-5)	none	Ql
Pleistocene	Terrace Deposits	(170-300)	(3-5)	none	Qt
	Bedrock	>820	--	none	--

Table 10. Liquefaction potential by type of deposit and age of deposit.

Type of deposit	**Likelihood that Cohesionless Sediments, When Saturated, Would Be Susceptible to Liquefaction (by Age of Deposit)**			
	<500 yr	Holocene	Pleistocene	Pre-Pleistocene
River channel	Very high	High	Low	Very low
Flood Plain	High	Moderate	Low	Very low
Alluvial fan and Plain	Moderate	Low	Low	Very low
Lacustrine and playa	High	Moderate	Low	Very low
Colluvium	High	Moderate	Low	Very low
Talus	Low	Low	Very low	Very low
Tuff	Low	Low	Very low	Very low
Residual soils	Low	Low	Very low	Very low

Table 11. Shear wave velocity measurements in Poplar Bluff, Missouri using reflection/refraction by Kentucky Geological Survey.

KGS	MGS	Layer1			Layer2			Layer3 (weathered) Vs (m/s)
		Vs (m/s)	Thick. (m)	Unit	Vs (m/s)	Thick. (m)	Unit	
1	32	220	21.5	Dune Sand	250	15.3	Alluvium	Not measured
2	27	177	3.0	Surficial materials	581		Residuum	Not measured
3	5	362	27.5	Alluvium/fill				Not measured
4	25	230	1.0	Surficial materials	380		Residuum	Not measured
5	19	258	0.5	Surficial materials	462		Residuum	Not measured
6	15				490	2.0	Residuum	710
7	13	364	12.0	Alluvium/fill				Not measured
8	21	281	0.5	Surficial materials	410	9.0	Residuum	752
9	17				576		Residuum	Not measured
10	6	116	1.0	Surficial materials	190	11.5	Alluvium	656

Notes: Residuum and bedrock are difficult to be separated because there is no clear velocity interrupt between the units. Layer 3 is assumed to be the bedrock (weathered).

Table 12. Results of shear wave velocity measurements by two difference methods by 3 different groups for the Poplar Bluff, Missouri sediments.

	UMR			KGS/UK			MoDOT			ALL TESTS		
	No. Vs Tests	Average of Vs Tests Only SM to 30 m or < (m/s)	Average Soil Site Class Only SM to 30 m or <	No. Vs Tests	Average of Vs Tests Only SM to 30 m or < (m/s)	Average Soil Site Class Only SM to 30 m or <	No. Vs Tests	Average of Vs Tests Only SM to 30 m or < (m/s)	Average Soil Site Class Only SM to 30 m or <	No. Vs Tests	Average of Vs Tests Only SM to 30 m or < (m/s)	Average Soil Site Class Only SM to 30 m or <
SURFICIAL MATERIALS MAP OF MISSOURI - 1982 Unit												
Alluvium - Creek	3	243	D	2	339	D	3	171	E	8	240	D
Alluvium - Embayment	11	219	D	0			8	191	D	19	207	D
Alluvium - River	2	226	D	1	362	C	2	170	E	5	231	D
Alluvium - River & Embayment	5	247	D	0			4	179	E	9	217	D
Sand Dune & Alluvium - Embayment	1	252	D	1	228	D	1	313	D	3	264	D
Quaternary/Tertiary Residuum	1	508	C	0			0			1	508	C
Residuum	18	436	C	6	524	C	0			24	458	C

Table 132. Continued

	UMR			KGS/UK			MoDOT			ALL TESTS		
	No. Vs Tests	Average of Vs Tests Only SM to 30 m or < (m/s)	Average Soil Site Class Only SM to 30 m or <	No. Vs Tests	Average of Vs Tests Only SM to 30 m or < (m/s)	Average Soil Site Class Only SM to 30 m or <	No. Vs Tests	Average of Vs Tests Only SM to 30 m or < (m/s)	Average Soil Site Class Only SM to 30 m or <	No. Vs Tests	Average of Vs Tests Only SM to 30 m or < (m/s)	Average Soil Site Class Only SM to 30 m or <
STATEMAP												
Surficial Geology Unit 1 Name												
Alluvia	22	231	D	4	317	D	18	190	D	44	222	D
Rock Hill	1	508	C	0			0			1	508	C
St. Roberts "a"	3	527	C	1	473	C	0			4	513	C
St. Roberts "b"	12	424	C	4	521	C	0			16	448	C
St. Roberts "l"	1	379	C	0			0			1	379	C
St. Roberts "x"	2	401	C	1	588	C	0			3	463	C