E-20-G42

Non-Technical Abstract

CONE PENETRATION TESTING FOR SEISMIC HAZARDS IN MID-AMERICA

USGS Grant Award Number: 01HQGR0039 - Final Report (Feb. 28, 2002)

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Investigations Undertaken

Series of cone penetration tests (CPT) have been completed at project sites in the New Madrid Seismic Zone to evaluate the seismic ground hazards and provide supplemental geotechnical data at prior sites known to have liquefied during large earthquakes. The test locations included two sites at the Meramec River in St. Louis, three sites in Dexter MO, the Wyatt MO site, Nodena Farm AR, and three sites in the greater Memphis TN area. Most of these sites have already been mapped and noted by paleoliquefaction evidence from prior large earthquakes that have occurred in the region. Cone penetration involves soil exploration without the use of traditional drilling, boring, & sampling. An instrumented electronic steel probe is hydraulically-pushed into the ground vertically to record stress, pressure, friction, conductivity, and/or wave characteristics that are continuously monitored by a computer. This tool is used to identify layers of loose sands and silts that may be prone to liquefaction should another large earthquake shock this area of the country. This information can be used to forewarn of select sites and local areas that may be problematic for development and/or require rehabilitation for current residents.

Results

The results of the 20- to 30-meter deep soundings can be view or downloaded from our website: http://www.ce.gatech.edu/~geosys under the *in-situ research* domain. Analyses are underway to evaluate the results for various magnitude earthquake events and to backfigure the level of ground shaking caused during prior large seismic events that happened circa 1811-1812, 1450 A.D., 900 A.D., and 500 A.D.

Reports Published

1. Schneider, J.A., Mayne, P.W., and Rix, G.J. (2001). Geotechnical site characterization in the greater Memphis area using seismic cone tests. Engineering Geology, Vol. 62, Issues 1-3, pp. 169-184

2. Liao, T., Mayne, P.W., et al. (2001). Liquefaction Evaluation of Soils in the New Madrid Zone by Cone Penetration Testing, submitted to the Journal of Soil Dynamics & Earthquake Engineering, in review.

3. Zavala, G.J. and Mayne, P.W. (2001). Post-Processing of Downhole Shear Wave Velocities by Cross-Correlation Method, submitted to the Journal of Soil Dynamics & Earthquake Engineering, in review.

Cone Penetration Testing for Seismic Ground Hazards Evaluation in Mid-America

USGS Grant 01HQGR0039
Program Element: CU

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Cone Penetration Testing for Seismic Hazards Evaluation in Mid-America

USGS Grant 01HQGR0039

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Keywords: Cone Penetration Test, In-Situ Testing, Liquefaction, Seismic Ground Hazards, Shear Wave, Site Characterization, Soil Resistance

Introduction:

This report documents the cone penetration testing (CPT) conducted for the purpose of mapping seismic ground hazards and soil properties at selected sites in Missouri, Arkansas and Tennessee in the year of 2001. Prior work was reported for USGS Grant 00HQGR0025 that was more specific for seismic mapping efforts in Memphis and Shelby County, TN. The test sites have been selected and coordinated with the assistance of other USGS researchers and members of the Center for Earthquake Research & Information (CERI) and the Mid-America Earthquake (MAE) Center. In particular, the PI and his research assistants are grateful for the direction and help provided by Dr. Martitia Tuttle, Dr. Buddy Schweig, Dave Hoffman, Dr. Roy Van Arsdale, Laurel Mayrose, Steve Obermeier, Dr. Ronaldo Luna, Houda Jadi, and Dr. Paul Bodin.

Three types of soundings were conducted during the investigations, including standard piezocone (ASTM D 5778), seismic piezocone (SCPTu), and resistivity piezocone (RCPTu). The collected data have been used for site characterization and liquefaction evaluation of the subsurface materials. Field testing was conducted by Alec McGillivray, Guillermo Zavala, and Tianfei Liao of Georgia Tech.

During our contract period, we presented findings, data, and lectures of our USGS research efforts at local, national, & international conferences and workshops.

Purpose:

In these studies, a cone penetrometer system has been used to obtain both geotechnical and geophysical measurements at the same locations in order to facilitate data collection in the New Madrid Seismic Zone (NMSZ). The soundings performed during this study held a threefold purpose towards seismic ground hazard mapping: (1) delineating the presence and extent of liquefaction-prone soils, (2) obtaining shear wave velocity data for site amplification analyses; and (3) collection of forensic information on the geostratigraphy and source sands at pre-mapped paleoliquefaction sites.

Test Sites:

The test sites include: (1) Nodena Farm at Wilson, AR; (2) Hillhouse Farm at Wyatt, MO; (3) Memphis, TN; (4) Dexter, MO; and (5) St. Louis, MO. The map on the following page indicates the general location of all the soundings performed during 2001.

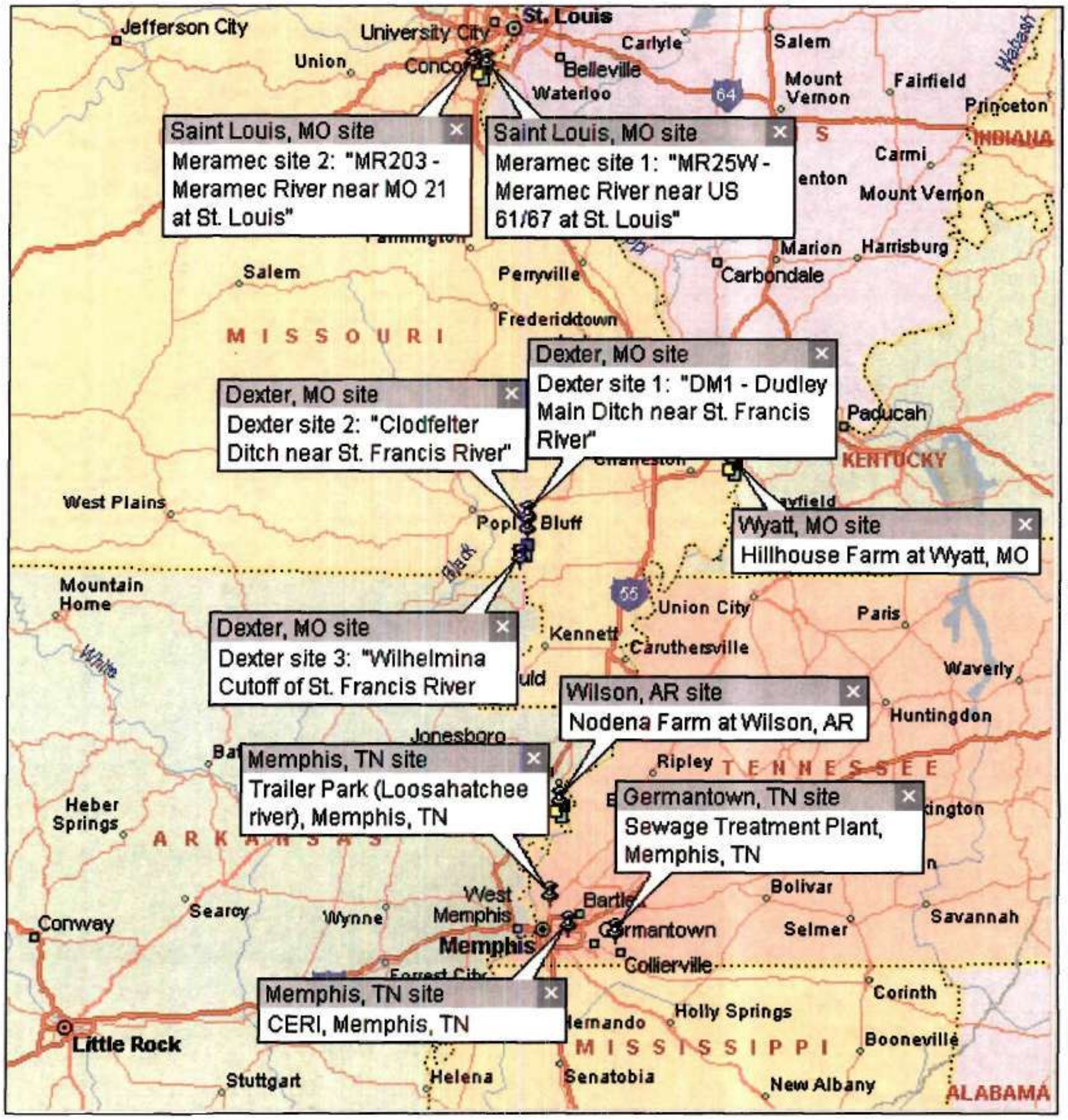


Figure 1. Map showing the location of the soundings performed during 2001

Nodena farm test site, Wilson, AR:

The Upper Nodena site is a paleoliquefaction site located northeast of Wilson, Arkansas. Archeological investigations had previously been performed to study liquefaction features (Tuttle, 1999). Four CPT soundings were performed in a linear array. The site arrangements were coordinated by Dr. Martitia Tuttle of Tuttle & Associates, Georgetown, Maine, Dr. Buddy Schweig of the USGS, and Laurel Mayrose of the University of Memphis.

Testing at CERI Headquarters, Memphis, TN:

Two seismic piezocone soundings were performed next to the 100-meter accelerometer array, which is installed at the headquarters of CERI in Memphis, TN. The soil strength characteristics and shear wave velocity obtained are necessary for analysis of the acceleration history should a seismic event occur. Dr. Paul Bodin of CERI assisted in this testing.

Soundings at CERI, Memphis, TN

Sounding	Latitude N°	Longitude W°	Depth (m)	Cone Type
CERI03	35.12366	89.93169	10.18	10 ton cone, u2, seismic
CERI04	35.12366	89.93169	21.33	15 ton cone, u2, seismic

Testing at the western Lowlands of Southeast Missouri:

Six piezocone soundings were performed at 3 different paleoliquefaction sites near Dexter, Missouri. The tests included three seismic piezocone soundings and three resistivity piezocone soundings. Previous archaeological and paleoseismological investigations were performed at these sites in the period July 1990 to 1991 and are documented in the report by Vaughn (1994). The following tables list the exact locations of the recent soundings. The test locations were selected by David Hoffman, Geologist with the Missouri Department of Transportation.

DM1 – Dudley Main Ditch near St. Francis River, Dexter, MO

Sounding	Latitude N°	Longitude W°	Depth (m)	Cone Type
DEX01	36.70038	90.13251	29.02	10 ton cone, u2, seismic
DEX02	36.70038	90.13251	19.33	10 ton cone, u2, resistivity

Clodfelter Ditch near St. Francis River, Dexter, MO

Sounding	Latitude N°	Longitude W°	Depth (m)	Cone Type
DEX03	36.65318	90.13231	30.03	10 ton cone, u2, seismic
DEX031	36.65321	90.13226	28.90	10 ton cone, u2, resistivity

Wilhelmina Cutoff of St. Francis River, Dexter, MO

Sounding	Latitude N°	Longitude W°	Depth (m)	Cone Type
DEX04	36.53725	90.17570	26.43	10 ton cone, u2, seismic
DEX05	36.53725	90.17570	26.50	10 ton cone, u2, resistivity

Testing close to Saint Louis, MO:

Four piezocone soundings were performed at paleoliquefaction sites along the Meramec River at the south side of Saint Louis, MO. The test site arrangements were made by Ronaldo Luna, Professor of Civil Engineering at University of Missouri-Rolla, David Hoffman with State of Missouri, and Houda Jadi of University of Missouri, Rolla.

Soundings at Nodena Farm, Wilson, AR

Sounding	Latitude N°	Longitude W°	Depth (m)	Cone Type
WILS02	35.60202	89.97719	21.43	10 ton cone, u2, seismic
WILS04	35.60208	89.97722	16.20	10 ton cone, u2
WILS06	35.60215	89.97715	22.93	10 ton cone, u1, resistivity
WILS07	35.60217	89.97711	16.43	10 ton cone, u2

Hillhouse farm test site at Wyatt, MO:

The Hillhouse farm is a paleoliquefaction site located in Wyatt, Missouri, just east-northeast of Sikeston, Missouri. Sand blows and other liquefaction evidence were found by previous researchers. The liquefaction features were subjected to archeological investigations, which included trenches to profile the sand dikes (Tuttle, 1999). The CPT soundings were distributed around the edge of the site. Site arrangements were made by Martitia Tuttle and Laurel Mayrose.

Soundings at Hillhouse Farm, Wyatt, MO

Sounding	Latitude N°	Longitude W°	Depth (m)	Cone Type
WYAT01	36.92609	89.15822	25.30	10 ton cone, u2, seismic
WYAT03	36.92685	89.15717	12.03	10 ton cone, u2
WYAT04	36.92706	89.15572	23.00	10 ton cone, u2, resistivity
WYAT05	36.92740	89.15610	19.63	10 ton cone, u2, resistivity

Testing in sites close to Memphis, TN:

Seismic piezocone tests were performed at a sewage treatment plant on the banks of the Wolf River near Germantown, Tennessee, and in a small housing community on the banks of the Loosahatchee River in the northwestern part of Memphis, Tennessee. The general areas are known to have experienced seismicity in the past. The testing at the Wolf River and Loosahatchee River was arranged by Roy Van Arsdale, Professor of Geology at the University of Memphis.

Soundings at Wolf River site, Germantown, TN

Sounding	Latitude N°	Longitude W°	Depth (m)	Cone Type
SWG01	35.09335	89.71093	28.58	10 ton cone, u2, seismic
SWG02	35.09333	89.71091	30.35	10 ton cone, u2, seismic

Soundings at Loosahatchee River site, Memphis, TN

Sounding	Latitude N°	Longitude W°	Depth (m)	Cone Type
TRPK01	35.23957	90.02412	14.95	10 ton cone, u2, seismic
TRPK02	35.23957	90.02412	15.05	10 ton cone, u1, resistivity

MR25W – Meramec River near US 61/67 at St. Louis, MO

Sounding	Latitude N°	Longitude W°	Depth (m)	Cone Type
MER01	38.45882	90.35043	19.75	10 ton cone, u2, seismic
MER02	38.45882	90.35043	18.68	10 ton cone, u2

MR203 - Meramec River near MO 21 at St. Louis, MO

Sounding	Latitude N°	Longitude W°	Depth (m)	Cone Type
MER03	38.46538	90.41467	12.98	10 ton cone, u2, seismic
MER04	38.46502	90.41460	13.55	10 ton cone, u2, seismic

Stratigraphy Delineation by Three-channel cluster analysis of CPT data

Delineating soil stratification is a very important step for site characterization, and very often it is the basis for the following geotechnical analysis and calculation. Since the data collected through CPT tests are functions of both soil type and soil behavior, they can be used for the delineation of soil stratigraphy. Currently two approaches are widely used in engineering practice to delineate the soil stratigraphy, which are the visual method and the soil classification charts method. With the visual method, the boundaries of the soil layers are determined through the researcher's experience, and the accuracy of this method is largely dependent on the researcher's knowledge about the properties of different soils. It is usually impossible to detect the subtle changes in the soil stratigraphy by the the naked eye. The CPT soil behavioral classification charts method is popular in engineering practice. The collected CPT data points are compared with the classification charts, and each point is classified as a particular soil type. The soil stratigraphy is then generated by grouping the data points, which are close to each other in depth and belong to similar soil types. Since CPT soundings provide hundreds or thousands of data points, the number of layers generated through this method is often overwhelming. Furthermore, the boundaries between the layers are often unreasonable and/or scattered.

Cluster analysis is an efficient statistical way to analyze the stratigraphic vertical profiling of geomaterials. It detects the inherent similarity between data sets and then groups them together. In this regard, a cluster analysis method was used for stratigraphy delineation, which is based on the three-channels of CPT data: cone tip stress (q_t), penetration porewater pressure (u_2), and sleeve resistance (f_s). For detrending these readings for depth effects, the normalized cone tip resistance is defined by $Q = (q_t - \sigma_{vo}) / \sigma_{vo}'$, normalized porewater pressure as $B_q = (u_2 - u_0)/(q_t - \sigma_{vo})$, and normalized sleeve friction resistance is given as $F_R = f_s/(q_t - \sigma_{vo}) \times 100\%$. With these normalized parameters, Robertson (1990, 1991) developed a paired set of soil behavioral charts which represent a three dimensional with the three axis being Q, B_q, and F_R respectively. Since Q, B_q, and F_R are normalized data, which have removed the effect of the overburden stress, it is reasonable to assume that the CPT data sets collected from the same type of soils should be located in the same spot in the three-dimensional system, with same value of Q, B_q, and F_R. Therefore, the soils should be more likely belong to the same soil type, if their corresponding data sets are located near each other. Based on this idea, three-channel cluster analysis groups data sets into different groups and gives the mathematically reasonable boundaries between the soil layers.

Figure 2 shows the data representation for sounding DEX04 performed at Dexter, MO, and we can see that below the depth of 7 meters, the site consists of sands, while the soils above the depth of 7 meters are mostly clay with some thin layers that are sandy or silty. Figure 3 shows the result of cluster analysis for the case that the number of layers is specified as four. As shown in Figure 3(b), the data points are drawn in the three dimensional system with the same color used to represent the corresponding layer in Figure 3(a). The cluster analysis not only detected the obvious boundary between layers, but also the subtle ones that cannot be detected easily by other methods.

Probabilistic Liquefaction Evaluation Based on Shear Wave Velocity:

The liquefaction potential calculations have been updated with a probabilistic approach for liquefaction evaluation based on shear wave velocity.

In order to evaluate the liquefaction potential, the impact on the soil from the seismic event must be known or assumed. In liquefaction analyses, the seismic loading is typically expressed in terms of the cyclic stress ratio (CSR). For the well-known simplified procedures, the cyclic stress ratio is most often expressed as (Seed & Idriss, 1971):

$$CSR = \frac{\tau_{ave}}{\sigma'_{vo}} = 0.65\left(\frac{a_{\max}}{g}\right)\left(\frac{\sigma_{vo}}{\sigma'_{vo}}\right)r_d \qquad (1)$$

where a_{max} is the peak ground acceleration, g is the acceleration of gravity, σ_{vo} and σ'_{vo} are the total and effective vertical stresses, respectively, and r_d is a stress reduction coefficient that accounts for the flexibility of the model soil column. In our work, the r_d recommendations of the NCEER Workshop on Evaluation of Liquefaction Resistance of Soils (Youd, et al. 2001) were followed. Ordinarily, a_{max} is taken from the appropriate design events for a given project (i.e., the 2%, 5%, or 10% probability earthquake; the maximum credible event for a known fault located a set distance from the site; a code based response spectrum, hazard maps, etc.).

The cyclic resistance ratio (CRR) is the threshold for liquefaction and used to compare the available soil resistance with level of ground shaking represented by the cyclic stress ratio (CSR). Currently two approaches are available to compute the CRR, one based on normalized tip stress (Robertson & Wride, 1998) and one based on normalized shear wave velocity (Andrus & Stokoe, 2000). Both are summarized in Youd, et al. (2001).

For the normalized tip stress-based method, the cone tip resistance is normalized by the effective stress (actual normalization criteria depends upon the CPT soil classification) and then corrected for the apparent fines content, which is empirically calculated from the CPT data as well. Ultimately, a normalized and corrected tip resistance is obtained and used to establish CRR. CRR is calculated by the following equation with an earthquake moment-magnitude of 7.5:

$$CRR_{7.5} = 93\left(q_{c1N,cs}/1000\right)^3 + 0.08, \qquad \text{if } 50 \le q_{c1N,cs} < 160 \qquad (2a)$$

$$CRR_{7.5} = 0.833\left(q_{c1N,cs}/1000\right) + 0.05, \qquad \text{if } q_{c1N,cs} < 50 \qquad (2b)$$

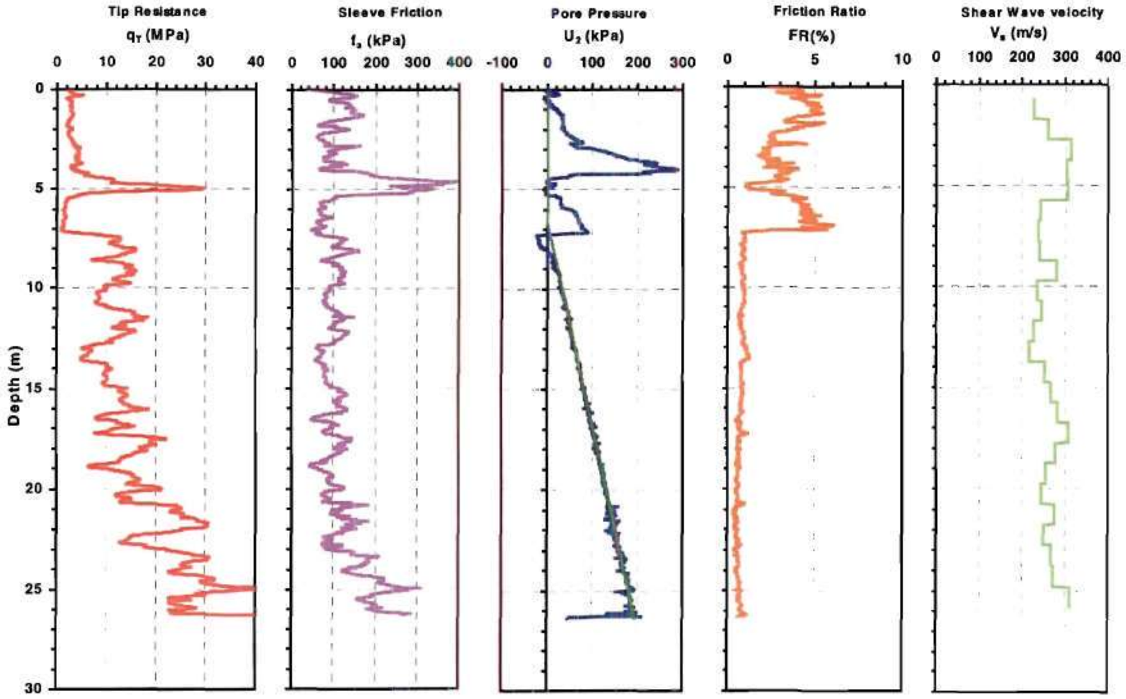
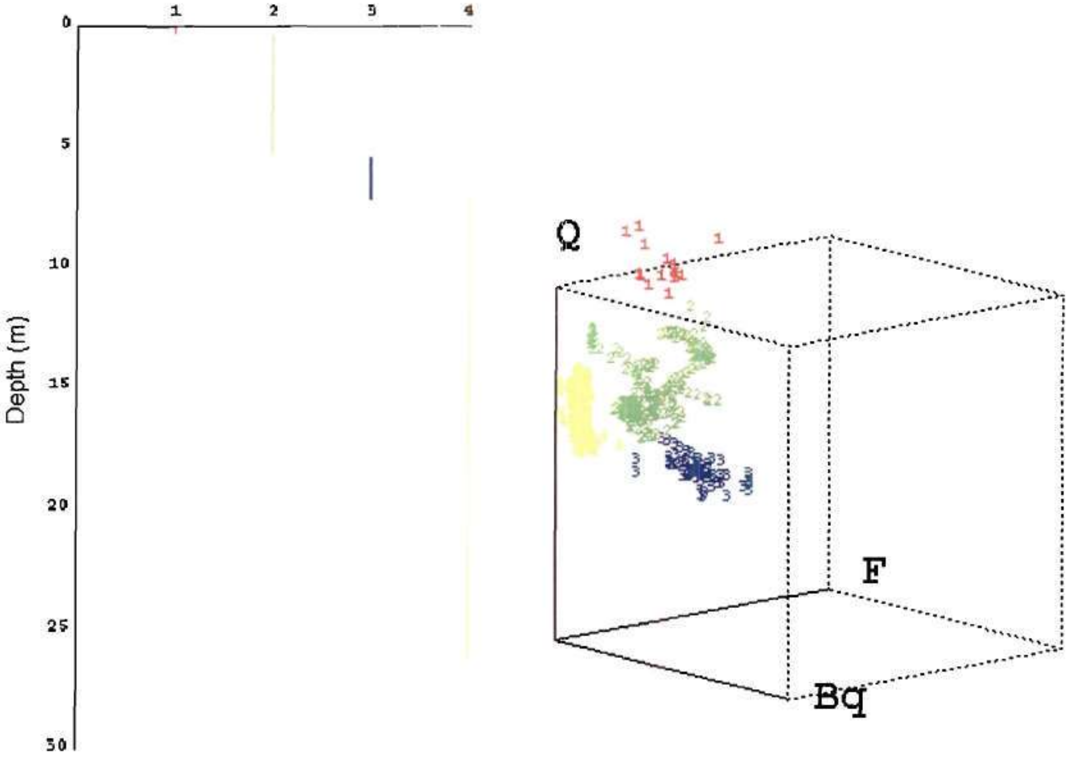


Figure 2. Representative SCPT Data of Sounding DEX04 Performed at Dexter, MO



(a) (b)

Figure 3. Result of Cluster Analysis for Sounding DEX04 Performed at Dexter, MO

where $q_{c1N,cs}$ is the clean sand equivalence of the stress-corrected cone tip resistance. As to the normalized shear wave velocity method, the shear wave velocity is normalized by the effective stress and the fines content is accounted for through the following equation with an earthquake moment-magnitude of 7.5 (Andrus & Stokoe, 2000):

$$CRR_{7.5} = a(V_{S1}/100)^2 + b[1/(V_{S1c} - V_{S1}) - 1/V_{S1c}] \tag{3a}$$

where a=0.03, b=0.9, V_{S1} is the overburden stress-corrected shear-wave velocity given by $V_{s1} = V_s / \sigma_{vo}'$, with σ_{vo}' as the effective overburden stress. The asymptotes are V_{S1c}=220 m/s for sands and gravels with the fines content FC≤5%, and V_{S1c}=210 m/s for sands and gravels with FC=20%, and V_{S1c}=200 m/s for sands and gravels with FC≥35%. A correction factor K_c can be provided for cemented and very old soils (>10,000 years) of high V_{s1} (Andrus & Stokoe, 2000):

$$CRR_{7.5} = a(K_c V_{S1}/100)^2 + b[1/(V_{S1c} - K_c V_{S1}) - 1/V_{S1c}] \tag{3b}$$

Average estimates of K_c for Pleistocene-age soils range from 0.6 to 0.8.

Both of the two approaches fall into the deterministic category, and they usually provide a calculated safety factor Fs=CSR/CRR, but the safety factors from different methods are not comparable. As an alternative and more rational approach, recent methods to the problem are now being addressed through probabilistic analyses that provide a numerical way to compare the confidence on liquefaction evaluations based on different measurements.

For the normalized tip stress, a mapping function was proposed to relate the safety factor Fs to the liquefaction probability PL based on a database of 225 CPT-based cases reported by Juang and Jiang (2000):

$$P_L = 1/\left[1 + (F_s/1.0)^{3.34}\right] \tag{4}$$

Based on the shear wave velocity, there is a similar mapping function (Juang et al, 2001):

$$P_L = 1/\left[1 + (F_s/0.72)^{3.1}\right] \tag{5}$$

where F_s = CRR/CSR. Figure 4 and 5 show the curves of CRR for different probabilities of liquefaction based on tip resistance and shear wave velocity, respectively.

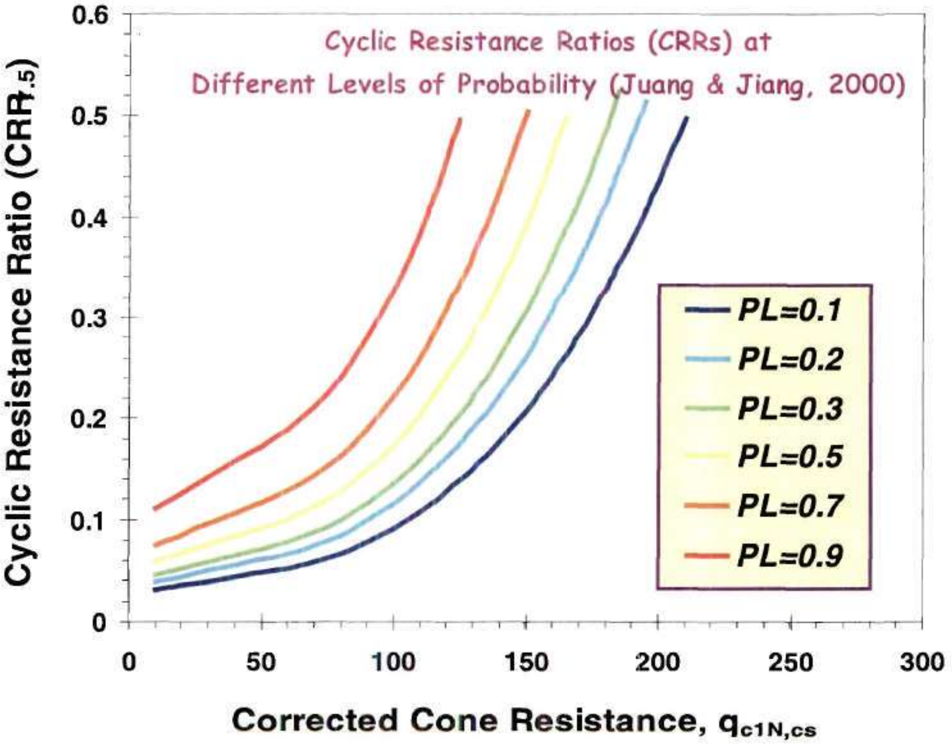


Figure 4. Cyclic Resistance Ratios (CRRs) Based on Cone Resistance at Different Levels of Probability (Juang et al., 2001)

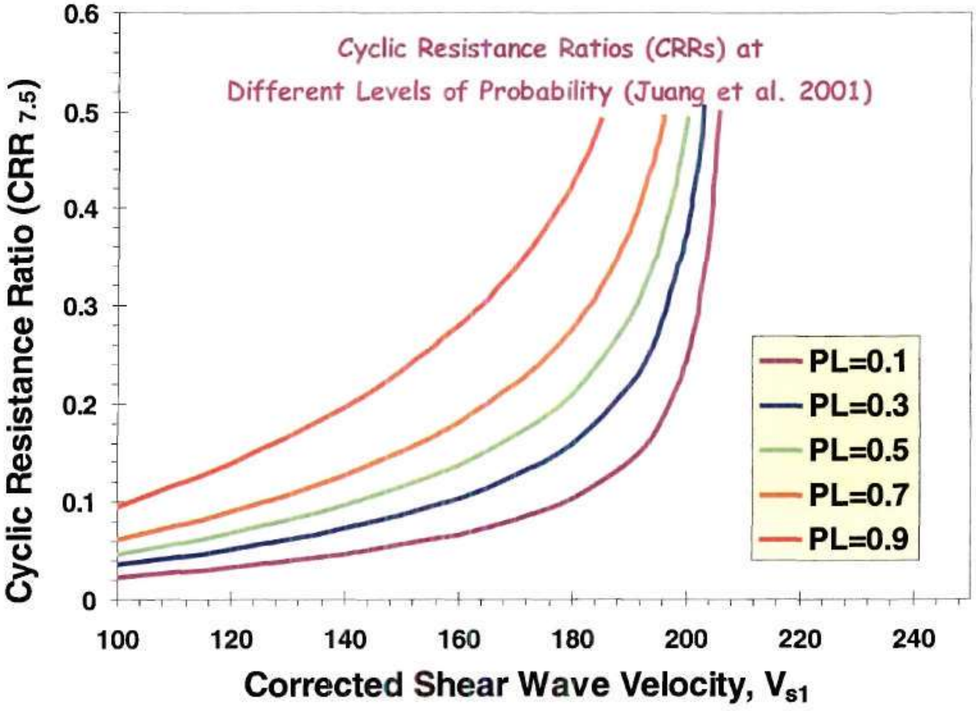
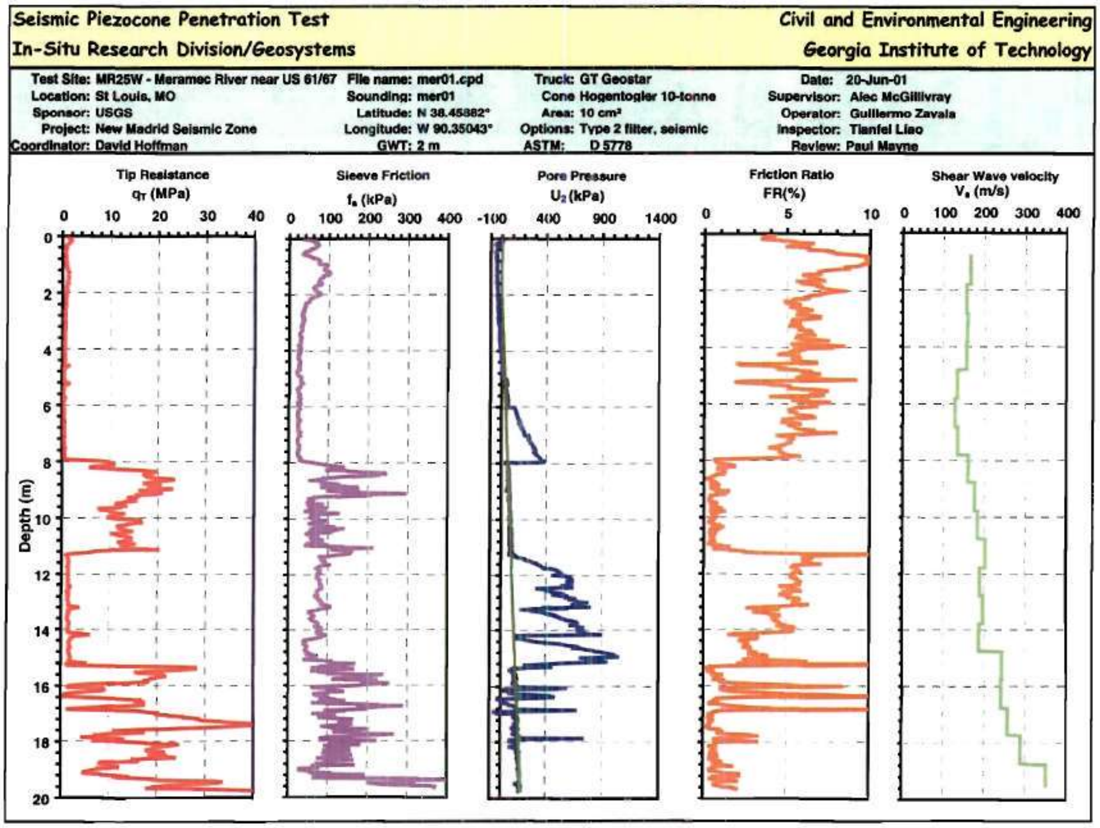


Figure 5. Cyclic Resistance Ratios (CRRs) Based on Shear Wave Velocity at Different Levels of Probability (Juang et al., 2001)

An illustration of having two sets of measurements for evaluating liquefaction potential is provided herein. Figure 6 shows the data collected for sounding MER01, which was performed along the Meramec River in St. Louis, MO. In Figure 7, the results of liquefaction analysis for this sounding, based on both the tip resistance and shear wave velocity, are presented as the different liquefaction probability versus the corresponding depth under different earthquake. According to the results of this sounding, it can be seen that though the two approaches are independent, they both detected the same regions of high liquefaction probabilities, that is, from 8m to 10m, and from 15m to 20m. They also detected the clayey layer from 11m to 15m, which has zero liquefaction probability. From this example, the analysis result, which are based on both the tip resistance and shear wave velocity respectively, agrees well to some extent, and the redundant analysis result would enhance the confidence on the conclusion about the liquefaction potential.



Seismic Piezocone Penetration Test
In-Situ Research Division/Geosystems
Civil and Environmental Engineering
Georgia Institute of Technology

Test Site: MR25W - Meramec River near US 61/67
Location: St Louis, MO
Sponsor: USGS
Project: New Madrid Seismic Zone
Coordinator: David Hoffman
File name: mer01.cpd
Sounding: mer01
Latitude: N 38.45882°
Longitude: W 90.35043°
GWT: 2 m
Truck: GT Geostar
Cone Hogentogler 10-tonne
Area: 10 cm²
Options: Type 2 filter, seismic
ASTM: D 5778
Date: 20-Jun-01
Supervisor: Alec McGillivray
Operator: Guillermo Zavala
Inspector: Tianfei Liao
Review: Paul Mayne

Figure 6. Representative SCPT Data of Sounding MER01 Performed along Meramec River in St. Louis, MO

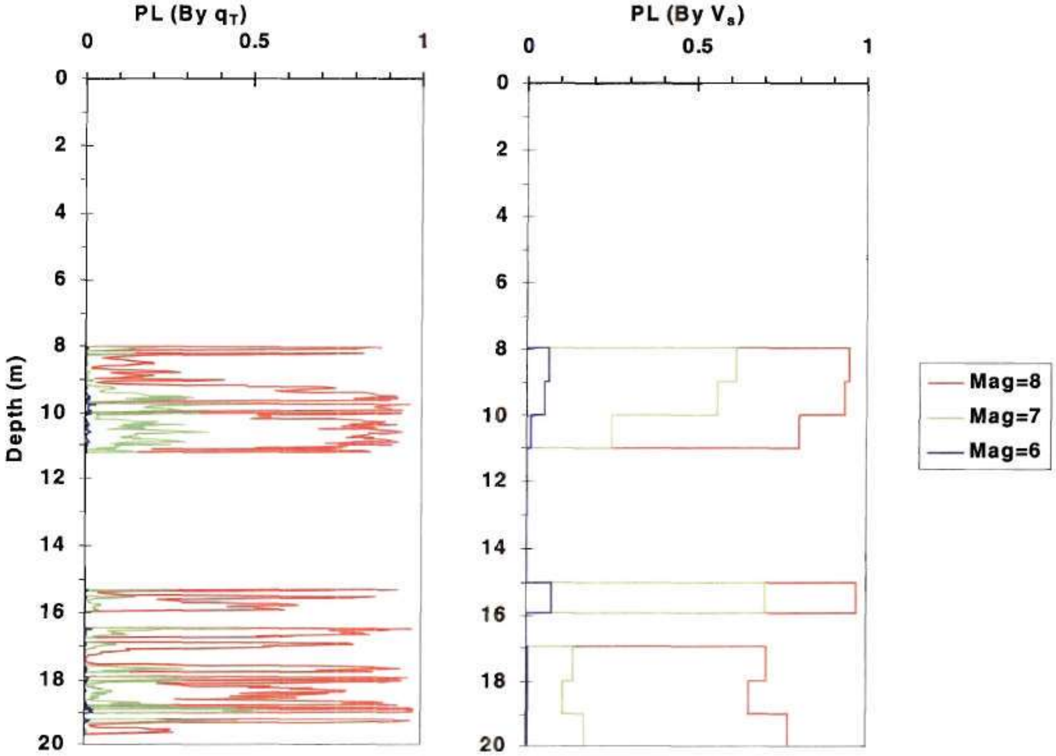


Figure 7. Results of Liquefaction Analysis by Probabilistic Approaches for Sounding MER01 Performed along Meramec River in St. Louis, MO

Shear Wave Velocity post-processing

Determination of shear wave velocity from downhole shear wave data requires obtaining a time difference between sequential waves recorded at different depths. The time difference can be obtained by various methods, such as picking first arrivals, first peaks, first troughs and first crossovers in the case of paired sets of left and right strikes. Selecting the first arrivals of shear waves from the recorded signals is a commonly-used method (Hoar and Stokoe, 1978). However, this method only uses a first point picked subjectively that can vary depending on the discretion of the operator, especially when the wave shows extraneous noise. The first arrival is not very clear and its selection could be very operator-dependent. First peak and first trough determinations are affected more by the variability of the separate impulse events during the downhole procedure, as the force-time record during impact varies with each event.

A routine method for SCPT is to use pairs of left and right strikes and follow the first crossover (Robertson et al. 1986), which can also be misleading because of baseline shifts in each record. All of the above conventional approaches (first arrival, peak, trough, crossover) suffer from reliance on a single point of the record in evaluating the time difference needed determine the shear wave velocity. Herein, an automated method based on crosscorrelation of consecutive shear waves (also using pseudo-interval data) is presented. The crosscorrelation method is superior as it matches approximately 2000 data points of individual wave trains of successive events, as compared with the conventional single point comparison used in crossover or direct arrival approaches, thus smoother and more accurate profiles of Vs are obtained. A program to process the shear wave data with this method was developed in MATLAB. After the crosscorrelation procedure was applied, visual checking of the shear wave matching was performed. In case of uniform soil the automated procedure works with no problem, but if consecutive waves have different shapes due to non-uniform soil profiles, extensive layering or other anomalies, the final wave matching should be corrected manually. These mentioned differences are caused by the reflection and refraction of the waves in the different layers. Figure 8 shows an example of shear wave matching obtained by the crosscorrelation procedure explained above, and it can be seen that complete wave matching provides a much more objective way on calculating the time delay between the readings at two depths

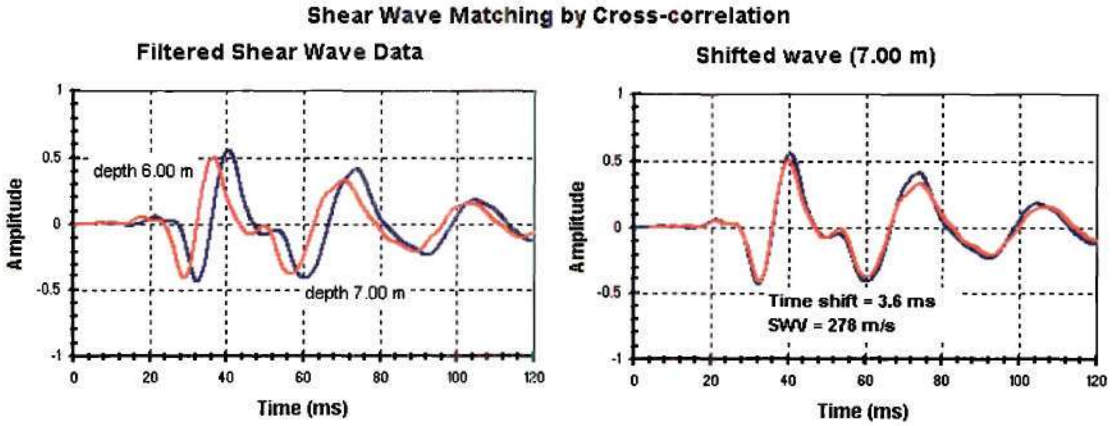


Figure 8: Shear wave matching by crosscorrelation and visual matching

Presentations & Publications:

During the past year, our USGS research program has been promoted and presented at the following events:

1. Geotechnical Earthquake Engineering in Mid-America, MAE Seminar, Dec. 7, 2000, Collinsville, Illinois.
2. New Developments in Geotechnical Site Characterization, S&ME Seminar, March 15, 2001 in Charlotte, NC.
3. Geotechnical Earthquake Engineering in Mid-America, MAE Seminar, March 15, 2001, in Memphis, TN.
4. CPT Workshop, Mobile, AL held by Southern Earth Sciences, May 4, 2001.
5. CPT Workshop by Georgia Tech given in Cape Girardeau to FHWA Midwestern Center, including MoDOT, IL DOT, MN DOT, and Univ. MO-Rolla, May 9-10, 2001.
6. Keynote Lecture at In-Situ 2001, Bali, May 24-28, 2001 (Proceedings, In-Situ Measurement of Soil Properties & Case Histories).
7. Enhanced Site Characterization - Short Course at GeoOdyssey 2001 (with Prof. James K. Mitchell), Blacksburg VA, June 7, 2001.
8. Geotechnical Investigations by Seismic Piezocone, Puerto Rican Engineers Club, San Juan, Aug. 6, 2001.

9. Geotechnical Earthquake Engineering Site Characterization by Seismic Cone, presented at the ASCE/ISSMGE Workshop held in Istanbul, Sept. 1, 2001.
10. Evaluating Seismic Ground Hazards by Seismic Cone Tests - Soil Dynamics & Earthquake Engineering Conference, Drexel Univ., Oct. 8, 2001.
11. Post-Processing of Shear Wave Data by Cross-Correlation, SDEE'01, Philadelphia, Oct. 9, 2001.
12. Geotechnical Earthquake Engineering in Mid-America, MAE Seminar, Mills House, Nov. 15-16, 2001, Charleston, SC.
13. Geotechnical Site Characterization by SCPTu, 2-day workshop to Fugro BV Offshore Engineering, Leidsheidam, Netherlands, Dec. 17-18, 2001.

Recent publications concerning our research program and funding support from the USGS include the following:

1. Schneider, J.A., Mayne, P.W., and Rix, G.J. (2001). Geotechnical site characterization in the greater Memphis area using seismic cone tests. **Engineering Geology**, Vol. 62, Issues 1-3, pp. 169-184
2. Liao, T., Mayne, P.W., et al. (2001). Liquefaction Evaluation of Soils in the New Madrid Zone by Cone Penetration Testing, submitted to the **Journal of Soil Dynamics & Earthquake Engineering**, in review.
3. Zavala, G.J. and Mayne, P.W. (2001). Post-Processing of Downhole Shear Wave Velocities by Cross-Correlation Method, submitted to the **Journal of Soil Dynamics & Earthquake Engineering**, in review.
4. Mayne, P.W. (2001). Stress-strain-strength-flow parameters from enhanced in-situ tests. Keynote lecture. **Proceedings, Intl. Conf. on In-Situ Measurement of Soil Properties and Case Histories,** Bali, Indonesia, (In-Situ 2001), pp. 27-48.

Data Availability:

The details of all CPTs performed by Georgia Tech in Mid America have been compiled into a single database. Data searches can currently be performed based on geographic location (latitude and longitude), depth, device specifications, operator, and a number of other items including the availability of seismic or resistivity data. The digital and or graphical results from the CPT field testing program are available at the following site:

http://www.ce.gatech.edu/~geosys/Faculty/Mayne/Research/index.html

These data include downhole shear wave velocity (V_s) measurements that have been collected at most of the sites at select sounding locations.

References:

- Andrus, R.D. and Stokoe, K.H. (2000). Liquefaction resistance of soils from shear wave velocity. **Journal of Geotechnical & Geoenvironmental Engineering**, ASCE, Vol. 126 (11): 1015-1026.
- Andrus, R. D and Stokoe, K.H (1997). Liquefaction resistance based on shear wave velocity. **Proceedings of the NCEER Workshop on Evaluation of Liquefaction Resistance of Soils,** Technical Report NCEER-97-0022, National Center for Earthquake Engineering Research, Buffalo, 276.
- Broughton, A.T., Broughton, J.H, and Van Arsdale, R.B. (2000). Memphis and Shelby County, TN liquefaction susceptibility mapping. **Seismological Research Letters**, Vol. 71 (1): 110.

- Chen, C.J. and Juang, C.H. (2000). Calibration of SPT- and CPT-based liquefaction evaluation methods. **Innovations and Applications in Geotechnical Site Characterization**, Geotechnical Special Publication (GSP) No. 97, ASCE, Reston, VA., 49-64.
- Hegazy Y.A. and Mayne P.W. (1998). Delineating geostratigraphy by cluster analysis of piezocone data. **Geotechnical Site Characterization**, Vol. 2, Balkema, Rotterdam, 1069-1074.
- Hoar, R.J. and Stokoe, K.H., II.(1978) Generation and Measurement of Shear Waves In Situ. **Dynamic Geotechnical Testing**, ASTM STP 654, American Society for Testing and Materials, pp 3-29.
- Juang, C.H. and Jiang, T. (2000). Assessing probabilistic methods for liquefaction potential evaluation. **Soil Dynamics and Liquefaction 2000**, GSP No. 107, ASCE Conference, Denver, 148-162.
- Juang, C.H., Chen, C.J and Jiang, T (2001). Probabilistic framework for liquefaction potential by shear wave velocity. **Journal of Geotechnical & Geoenvironmental Engineering**, ASCE, Vol. 127 (8): 670-678.
- Liao, T., and Mayne, P.W. (2002). Stratigraphy Delineation by Three-channel cluster analysis of CPT data. Internal Rept., Geosystems Engineering, School of Civil & Env. Engineering, Georgia Tech.
- Robertson, P.K. (1990). Soil classification using the cone penetration test. **Canadian Geotechnical Journal**, 27(1), 151-158.
- **Robertson, P.K. (1991).** Soil classification using the cone penetration test: Reply**. Canadian Geotechnical Journal, 28(1), 176-178.**
- Robertson, P.K. and Wride, C.E. (1998), "Evaluating cyclic liquefaction potential using the cone penetration test", **Canadian Geotechnical Journal**, Vol. 35, pg. 442-459.
- Robertson, P.K., Campanella, R.G., Gillispie, D.G. and Rice, A.(1986). Seismic CPT to measure in-situ shear wave velocity, **Journal of Geotechnical Engineering Division**, ASCE, Vol. 112, No. 8, pp. 791-803
- Seed, H.B and Idriss, I.M (1971). Simplified procedure for evaluating soil liquefaction potential. **Journal of the Soil Mechanics and Foundations Division**, ASCE, Vol. 97 (9): 1249-1273.
- Tuttle, M.P. (1999). Late Holocene earthquakes and their implications for earthquake potential of the New Madrid seismic zone, Central United States. **PhD Dissertation**, University of Maryland, College Park, 250 p.
- Vaughn, J.D. (1994), Paleoseismological Studies in the Western Lowlands of Southeastern Missouri, Final Report to the U.S. Geological Survey for grant number 14-09-0001-G1931, 27 p.
- Youd, T.L., Idriss, I.M., et al. (2001). Liquefaction resistance of soils: Summary report from the NCEER/NSF Workshops. **Journal of Geotechnical & Geoenvironmental Engineering** 127 (10), 817-833.