Georgia Tech Sponsored Research

Project	E-20-675	
Project director	Mayne	Paul
Research unit	CEE	
Title	Evaluating Ground Liquefaction Potential by Piezoviercone	
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Principal Investigator: Mayne, Paul W.

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Organization: GA Tech Res Corp - GIT

Evaluating Ground Liquefaction Potential by Piezovibrocone

Project Participants

Senior Personnel

Name: Mayne, Paul
Worked for more than 160 Hours: No
Contribution to Project:
Coordinating the joint research program between Georgia Tech & Virginia Tech on the development of the vibrocone unit.

Name: Rix, Glenn
Worked for more than 160 Hours: No
Contribution to Project:
Senior Associate for advisement of iMEMs used for acceleration records within the vibro-unit.

Post-doc

Graduate Student

Name: Quinn, Mark
Worked for more than 160 Hours: Yes
Contribution to Project:
Mark is a PhD candidate and developing penetrometer equipment for field use.

Name: Hendren, Tracy
Worked for more than 160 Hours: Yes
Contribution to Project:
Tracy built the second pneumatic vibro-unit for the project (Mark II), after the prototype unit was accidentally buried in the New Madrid Seismic Zone at a depth of 11 m. The second unit included a pneumatic solenoid & moving mass for the dynamic force generation enclosed in a steel cylindrical module. A MEMS was installed to serve as an accelerometer to measure the dynamic force magnitudes & waveform record of vibration. Uphole, a special control box with timer relay and pressure gage was provided.

Name: Casey, Tom
Worked for more than 160 Hours: Yes
Contribution to Project:
Tom has assisted in the field work with our new GeoStar cone rig and is currently designing our next generation of electrical vibro-unit. He worked with the pneumatic Mark II unit and then did research to find the piezo-actuator for dynamic loading.

Name: Schneider, James
Worked for more than 160 Hours: Yes
Contribution to Project:
James has worked with the original pneumatic vibro-unit with Craig Wise during design & development, including test trials at the NGES in Opelika/AL with Fugro; a test site in Atlanta with Law Engineering; and with Gregg In-Situ Inc. pushing the actual VCPTs in Charleston SC at paleoliquefaction sites. James was running GeoStar cone rig and penetrometer system in Blytheville AR when we lost the prototype in medium dense sands. He assisted in design of the Mark II unit, including our visits & discussions with Jim Mitchell, Tom Brandon, Jim Coffey, and John Bonita at Virginia Tech regarding the lab chamber testing. James also worked with Craig Wise and analyzed the field data from two successful VCPT series at Charleston.

Name: McGillivray, Alec
Worked for more than 160 Hours: Yes
Contribution to Project:
Alec worked with the design of the Mark II unit with Tom Casey, and later on the proposed design for an electrovibrocone unit. He also

'trained with James Schneider and now is the lead operator of the GT GeoStar Truck that operates our CPTs.

Name: Camp, Billy
Worked for more than 160 Hours: Yes
Contribution to Project:
Billy helped in design the next generation of vibrocone that will be entirely electronic. We have purchased a special electric dual-element penetrometer from A.P. van den Berg of Netherlands for this, using the premium check from insurance loss on the Mark I unit plus some NSF funds that were set aside from this project. We still need to purchase the piezo-electric actuator from Polytech PI or equivalent and encapsulate this within a downhole trailing module.

Undergraduate Student

Organizational Partners

U.S. Geological Survey, Reston, VA
USGS NEHRP was an original funding source for initial year and portion of second year.

Fugro Geosciences, Houston, Texas
Fugro has supplied a triple-element penetrometer for use in the calibration chamber tests at Virginia Tech. Fugro has also assisted in providing a cone truck for field trials of the vibro-units.

Gregg In-Situ, Aiken, SC
Gregg In-Situ has provided cone truck services for trial tests at historic paleoliquefaction test sites in Charleston, SC using the vibrocone.

Law Engineering and Environmental Services, Inc.
Law provided a drill rig and test site during very initial shakedown tests with the field vibrocone Mark I.

Applied Research Associates
ARA provided an above ground vibrator (pneumatic) for use on the chamber test series of CPT at VT during the vibrocone calibration and testing.

Virginia Polytechnic State Univ.
The research on the vibrocone was a joint Georgia Tech-Virginia Tech collaboration, initially funded by USGS and NSF.

Other Collaborators or Contacts

James Mitchell, Virginia Tech
Tom Brandon, Virginia Tech
John Bonita, Virginia Tech

Activities and Findings

Project Activities and Findings:
Summary of Progress: The collaborative research has been undertaken by Dr. Paul W. Mayne of Georgia Tech and Dr. James K. Mitchell of Virginia Tech, with assistance of Dr. Tom Brandon. Graduate research assistants who have contributed to the project have included Craig Wise, Tom Casey, Mark Quinn, James Schneider, Billy Camp, & Alec McGillivray at Georgia Tech and John Bonita, Jim Bob, and Mr. Jim Coffey of Virginia Tech. The project has several key tasks, primarily the development of a vibro-unit for dynamic excitation of a piezocone penetrometer to induce localized liquefaction in the vicinity of the probe. The intention is that the device will serve as an in-situ exploration tool to define zones or layers of high liquefaction potential within the subsurface medium. In addition, the residual measurements of tip stress (qt), friction (fs), and porewater pressures (ut and/or ub) may be useful in assessing the post-cyclic residual strength of these materials.

For the project, three vibrocone units were design & built, each using a controlled pneumatic solenoid to produce impulse loading and electric piezocone penetrometer. The first unit was constructed with a type 1 'Davey' piezocone (midface porewater pressure filter) and field trials were made at two historic paleoliquefaction test sites in the Charleston, SC seismic region (Wise, et al. 1999; Schneider, et al. 1998). Baseline tests with conventional CPTs and seismic piezocone tests (SCPTu) were made for comparison. A second unit was constructed and paired with a special triple-element 'Fugro' penetrometer (three simultaneous pore pressure elements) that was obtained on loan from Fugro Geosciences of Houston Texas & The Netherlands. This second unit was used during paired sets of static & dynamic series of cone penetration tests (CPT) in controlled calibration chamber tests (CCT) of Light Castle sand at Virginia Tech. These sands are also been subjected to index, triaxial static, and dynamic resonant column testing for characterization. Later, a type 2 'Davey' piezocone with an uphole (large pneumatic) vibratory device loaned by ARA was used in the chamber testing program.

The first vibro-unit was lost during downhole field trials by Georgia Tech in Blytheville, AR when attempting to map liquefiable sands in the New Madrid Seismic Zone (NMSZ) in December of 1998. A new GeoStar rig was obtained in 1998 and used to push these soundings. We have been successful in achieving seismic cone tests to depths of over 30 m in the NMSZ. The second downhole pneumatic unit was completed with a larger solenoid within the module housing and given to Virginia Tech for use in chamber tests. An integrated micro-electro-mechanical (iMEM) sensor had been installed to monitor dynamic forces, however, the forces apparently clipped during loading and the seal on the chamber mitigated force transmission to the penetrometer during dynamic soundings. The entry seal was modified later and a large vibrator with higher force capabilities was utilized in the chamber tests.

Project Training and Development:
The chamber tests required essentially a complete revamp of the original equipment because of the need to saturate the sands and provide backpressurization. Special sealing and membrane were required. The first year of study required that Craig Wise of GT stayed at VT all summer to help with John Bonita in reconstruction.

The CPTs in the chamber showed that dynamic forces could lower the overall qc resistance compared with static. Porewater pressures were difficult to measure in clean sands, perhaps because of the interface boundary with high shearing that masks the true porewater behavior in the immediate vicinity of the cone influence. Some special tests with a stationary piezometer in the sand deposit showed fairly high porewater pressures generated during VCPTs. However, at the cone face (u1) or shoulder (u2) filter elements on the penetrometer, little changes in porewater pressure were recorded. The PI believes this is reflecting an interface measurement difficulty (Burns & Mayne, Canadian Geotechnical Journal, Nov. 1998).

A resonant effect was observed at 40 Hz in the chamber test series, whereby much lower qc (dynamic) were obtained relative to qc (static). Yet this could be part due to the sand used, impulsed wave form, and/or chamber boundary effects. However, it does seem appropriate in guiding the selection of an operating frequency range for future vibrocone devices.

From the field trials with the vibrocone prototype, measured porewater pressures on the cone face (u1 element) showed significant increases in values during vibrocone testing (VCPT) when compared with baseline values from static piezocone testing (PCPT). Changes in measured tip stress (qc) were not quantifiable, yet it is possible to create different forms of liquefaction (see, e.g., Robertson & Wride, Canadian Geot. J. 1998), including: flow liquefaction, cyclic mobility, cyclic liquefaction, and quasi-liquefaction. These different modes may in fact create combinations of qc and/or ub in their responses. Fiedl tests were performed at two historic liquefaction sites in Charleston, SC. The pneumatic device can be improved in its performance, however, with a pure sinusoidal loading, uniformity of force generation, and variable excitation of frequencies. A new electrovibrocone has been designed and partially funded (new dual-element penetrometer), yet needs a downhole piezoactuator for the dynamic force generation.

Research Training:
Training has included the use of penetrometers, pneumatics, data acquisition, porewater filters, saturation techniques, seismic wave velocity measurements, dynamic force generation, and presentation of records in the field & lab training by James Schneider, Tom Casey, Mark Quinn, Ken Thomas, Billy Camp, Alec McGillivray, and Tracy Hendren. These efforts with the vibrocone have been presented to several undergraduate classes (different terms of CEE 4410) and graduate classes (CEE 6423) at Georgia Tech, as well at seminars and meetings of the Mid-America Earthquake Center (MAEC) and U.S. Geological Survey, as well as at conferences held by the ASCE Geo-Institute and workshop by the NSF (Baltimore).

Outreach Activities:
Presentations on the vibrocone have been made at:
1. ASCE Speciality Conference on Soil Dynamics & Earthquake Engineering, Session 1, Univ. of Washington, Seattle, August 1998.
2. NSF Workshop on Mechanics & Physics of Liquefaction (Johns Hopkins, Sept. 1998).
3. In-Situ Testing & Site Characterization, CEE 6423, Fall 1999.
4 MAE Geotechnical Seminar on Liquefaction in Mid-America, St. Louis/Collinsville/IL, Dec. 2000.
5. Geosystems Engineering Design (CEE 4410), Fall, 2000.
6. In-Situ Testing (CEE 6423), Fall 2000.
7. Conn DOT Seminar on CPT, June 2000.
8. USGS Hazard Mapping of Memphis, Jan. 2000.
9. MAE Annual Meeting, Hazards Evaluation Group, Atlanta, May 2000.

10. ASCE GeoDenver, Session 5 on Innovations in In-Situ Testing, August 8, 2000.

Journal Publications

Schneider, J.A., Mayne, P.W., and Rix, G.J., "Geotechnical Site Characterization in the Greater Memphis Area
Using Cone Penetration Tests
", *Engineering Geology, in press, 2001 (special issue to Mid-America earthquakes)*, p. , vol. , ().) Accepted

Books or Other One-time Publications

Schneider, J.A., Mayne, P.W., Hendren, T.L., and Wise, C.M., "Initial development of an impulse piezovibrocone for liquefaction evaluation", (1999). *paper*, workshop paper within book
Editor(s): P.V. Lade and J. Yamamuro
Collection: Physics and Mechanics of Soil Liquefaction
Bibliography: A.A. Balkema Publishers, Rotterdam, pp. 341-354.

Wise, C.M., Mayne, P.W., and Schneider, J.A., "Prototype piezovibrocone for evaluating soil liquefaction susceptability", (1999). *proceedings paper*, Published
Editor(s): Prof. Pedro SÛco e Pinto
Collection: Proceedings, 2nd International Conference on Earthquake Geotechnical Engineering
Bibliography: A.A. Balkema Publishers, Rotterdam

Schneider, J.A., Hoyos, L., Mayne, P.W., Macari, E.J. and Rix, G.J., "Field & Laboratory Measurements of Dynamic Shear Modulus of Piedmont Residual Soils", (1999). *proceedings*, Published
Collection: Behavior of Residual Soils
(Geotech Special Publication 92)
Bibliography: ASCE, Reston, VA

Schneider, J.A. and Mayne, P.W., "Liquefaction Response of Soils in Mid-America Evaluated by Seismic Cone Tests", (2000). *proceedings*, Published
Editor(s): Mayne, P.W. and Hryciw, R.D.
Collection: Innovations & Applications in Geotechnical Site Characterization (GSP 97)
Bibliography: ASCE, Reston, VA

McGillivray, Al, Casey, T., Mayne, P.W., and Schneider, J.A., "An Electrovibrocone for Site-Specific Evaluation of Soil Liquefaction Potential", (2000). *proceedings*, Published
Collection: Innovations & Applications in Geotechnical Site Characterization (GSP 97)
Bibliography: ASCE, Reston, VA

Schneider, J.A., Mayne, P.W., and Rix, G.J., "Ground Improvement Assessment Using SCPTu and Crosshole Data", (2000). *Proceedings*, Published
Editor(s): Mayne, P.W. and Hryciw, R.D.
Collection: Geotech Special Publication 97 (Innovations & Applications in Geotechnical Site Characterization)
Bibliography: ASCE GeoDenver Conference

Wise, C.M., "Development of a prototype piezovibrocone penetrometer for in-situ evaluation of soil liquefaction susceptibility", (1998). *Thesis*, Published
Collection: MS Thesis, School of Civil & Environmental Engineering
Bibliography: Georgia Institute of Technology, Atlanta, GA, 176 p.

Schneider, James A., "Liquefaction response of soils in Mid-America evaluated by seismic cone tests", (1999). *Thesis*, Published
Collection: MS Thesis, School of Civil & Environmental Engineering
Bibliography: Georgia Institute of Technology, Atlanta, GA, 273 p.

Casey, Thomas J., "Shear wave data collection in Mid-America using an automated surface source during seismic cone testing", (1999). *Thesis*,

Published
Collection: MS Thesis, School of Civil & Environmental Engineering
Bibliography: Georgia Institute of Technology, Atlanta, GA, 212 p.

Web/Internet Sites

URL(s):
http://www.ce.gatech.edu/~geosys
http://scholar.lib.vt.edu/theses/available/etd-11012000-08130056/
http://www.ce.gatech.edu/~geosys/Faculty/Mayne/Research/vibro2000/abstract.htm
Description:
1. Results from field work of the prototype vibrocone (Mark I) with downhole module at two liquefaction sites within the Charleston/SC seismic region.

2. Results from the chamber test calibration series with the Mark II and Mark III units.

3. Site with proposed new design of an electro-VCPT

Other Specific Products

Product Type: Other inventions
Product Description:
This is a new vertically-moving vibrocone penetrometer intended for evaluating soil liquefaction potential and post-cyclic residual strength. Previous attempts for a vibrocone used (1) horizontal oscillatory motion (that is at odds with the axial measurements taken by a cone penetrometer); or applied forces uphole (thus energy losses at the penetrometer with increasing depth).

Sharing Information:
The vibrocone may prove useful to investigate the effects of ground modification techniques, such as vibroflotation, stone columns, and subsurface blasting.

Product Type: Other inventions
Product Description:
AutoSeis: electronically activated solenoid to produce automated left and right generated impulses for downhole shear wave measurements. Details at: http://www.ce.gatech.edu/~geosys/Faculty/Mayne/Research/vibro2000/abstract.htm

Sharing Information:
Can use with conventional downhole geophysical surveys in cased boreholes or with seismic cone penetrometer. Additional use would include the newly-revisited seismic refraction technique.

Product Type: Software (or netware)
Product Description:
Software for field data collection of CPT data, specifically using a Labview setup. Intent will be to allow measurements of CPT and its derivatives (VCPT, CPTu, SCPTu, RCPTu, Dielectric cone soundings) of all types and manufacturers by the same data acquisition. Currently, each cone must be read by data acquisition of same manufacturer/supplier.

Sharing Information:
After developed, we will share via CD or downloadable form from internet.

Product Type: Software (or netware)
Product Description:
Crosscorrelation of downhole shear waves. Wave trains are analyzed for entire (or partial) wave forms to match successive events during pseudo-interval method to produce profile of shear wave velocities in a MATLAB format.

Sharing Information:
Data from analysis & field measurements downloadable from www.ce.gatech.edu/~geosys. Eventually, we hope to have software available as downloadable from this site too.

Contributions

Contributions within Discipline:
The vibrocone is intended to provide a rational and definitive means of assessing site-specific liquefaction problems in seismic regions. Current methods are empirical from databases and require many correction factors with high uncertainty. The VCPT can be analyzed using numerical simulation & analytics if additional funding is provided. The vibrocone may also be useful in assessing the post-cyclic undrained residual' strength of sands and silty sands that is required for lateral flow problems involving embankments, reservoirs, & dams. Finally, it may be useful for evaluating the applicability of soil improvement technologies such as vibroflotation, dynamic compaction, and underground blasting.

It is hoped that the vibrocone project will afford the opportunities to teach undergraduate & graduate students the logical fundamentals of soil liquefaction behavior, rather than have subject them to the current empiricism of today's practice.

Contributions to Other Disciplines:
Already, presentations to the ASCE Conference on Earthquake Engineering & Soil Dynamics (Seattle, Aug. 1998), the Mid-America Earthquake Center (MAEC) in Dec. 1998, Center for Earthquake Research & Information (CERI) in Sept. 1998, the CUSEC geologists at the Mid-America meeting at St. Louis, Univ. (Jan. 1999), and the U.S. Geological Survey Hazard Mapping project in Memphis/Shelby County (Nov. 1998) have been made on vibrocone project. The audience has included geologists, geophysicists, seismologists, insurance reps, structural engineers, and emergency management teams.

Contributions to Human Resource Development:
This summer, we added an NSF REU from Ohio-Wesleyan (Anna-Britt Mahler) to work with our 'coneheads' group in collecting CPT data in Mid-America.

Contributions to Science and Technology Infrastructure:
We have given short courses, seminars, and field demonstrations on CPT and its derivatives (CPTu, VCPT, SCPTu) to the ASCE Pittsburgh Geotech Society, Midwest DOTs at Mich DOT (included DOT representatives from MI, IL, IN, MO, MN, WI, and OH, and FHWA), ASCE Geotech Section in Minnesota, Conn DOT, Nebraska ASCE Geotech Section, Atlanta ASCE Geotech Section, and SC ASCE Section, as well as undergrad and graduate classes. My undergrad students all leave GT with some background in CPT, DMT, Vs, as well as conventional methods of exploration.

Beyond Science and Engineering:
We will hope that the vibrocone project can receive continued funding for its final stages of design, development, calibration, and analysis. It will provide a more robust & rational means of assessing ground susceptibility to liquefaction and post-cyclic undrained strength characteristics on national & international concerns. This will be useful for hazard mapping evaluations in CA, SC, TN, AR, MO, OR, WA, AL, PR, as well as international sites in Turkey, China, Taiwan, and elsewhere. Porewater generation is the cause behind liquefaction of soils, thus it must be measured by a dynamically-excited state during geotechnical site exploration.

VIBROCONE PENETRATION TEST

The recent major earthquakes in Kocaeli, Turkey (M = 7.8), Chichi, Taiwan (M = 7.6), and Duzce, Turkey (M = 7.1) in 1999 reflect the need for improved methods of geotechnical site characterization and the evaluation of seismic ground hazards, particularly as world population growth now exceeds 6 billion. Massive liquefaction-induced ground failures were clearly evident in the Turkish regions affected by these events and as a result, there has been a renewed international focus aimed at understanding these phenomenon. Better methods are needed in assessing liquefaction-prone soils. Improvements in measuring the post-cyclic residual (undrained) strength of sands and silty sands is of additional interest in analyzing embankments, reservoirs, empoundments, and earthen dams that may fail during seismic events. It is the intent of the electric-vibrocone to provide a site-specific tool for these purposes.

The basic concept of a vibrocone consists of an instrumented penetrometer with a trailing vibrator unit, as shown in Figure 1. Rather than rely on an indirect measurement of the soil liquefaction potential, a vibrocone will cyclically excite the soil thereby initiating localized liquefaction within a small zone around the probe. The tip stress, sleeve resistance, and pore pressures will be affected by the degree of liquefaction and the vibrational characteristics of the probe will enable the energy to be quantified. Prior versions of a vibrocone device have been developed in Japan, Italy, Canada, and the U.S.A. The original Japanese version applied a downhole horizontal centrifugal force of 32 kgf at a frequency of 200 Hz (Sasaki & Koga, 1982). Each test required two sister soundings [one static and one dynamic] with results obtained by superposition of the q_c records. This was followed by later designs with dynamic forces of 80 and 160 kgf at 200 Hz (Teparaksa, 1987). A similar model was developed in Italy (Piccoli, 1993).

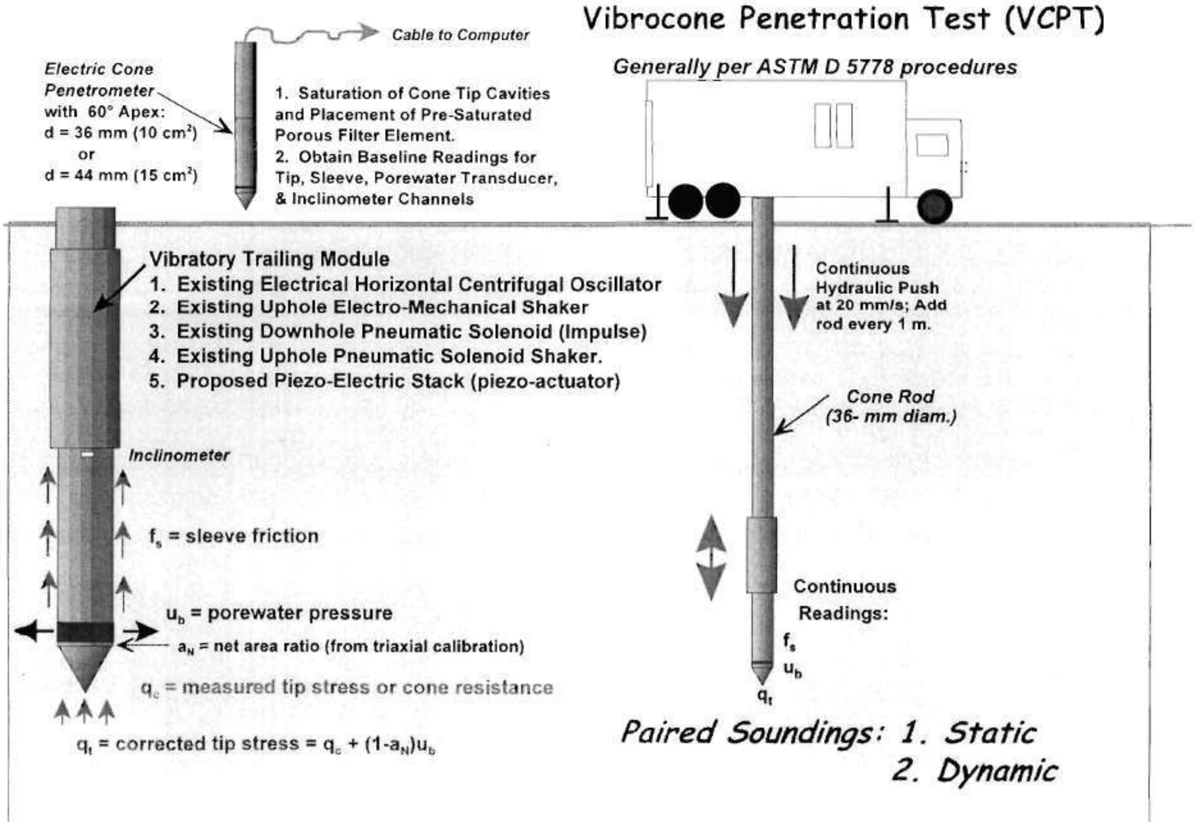

Figure 1. Concept of the Vibratory Piezocone

Side-by-side comparisons of static tip resistance (q_{cs}) with the dynamic tip resistance (q_{cd}) with the latter showing relative decreases in liquefiable zones. Calibration chamber tests showed some porewater changes yet the focus on these measurements was limited. A major shortcoming of the Japanese vibrocones is the use of horizontal centrifugal motion to liquefy the soil. This works well in causing localized liquefaction, as in the concrete vibrators used in forming and placing of wet concrete. However, the primary measurements of the CPT are based on purely axial forces and therefore the integrity and accuracy of the raw q_c, f_s, and u_b readings are compromised by the horizontal oscillations of the vibrator. Similar difficulties exist with the Italian ISMES version. A Canadian version of the vibrocone (Moore, 1987) was constructed using an electro-mechanical vertical vibrator applied at the top of the rods, however, there were energy losses with increasing depth. A sonically-vibrated CPT has been developed by Applied Research Associates of Royalton, Vermont that also applies vertical excitation at the top of the rods, however, the intent here is to facilitate the penetrometer through very dense sands and/or gravelly zone.

Table 1. Contributions to the Development of the Vibrocone

Country	Author(s)	Details	Results
Japan	Sasaki & Koga, 1982 Sasaki et al., 1984 (PWRI)	• Down-hole vibration at 200 Hz • 32 kgf horizontal centrifugal force	Reduction in q_c reflected possible liquefiable zones
Japan	Teparaksa, 1987 (PWRI)	• Down-hole vibration at 200 Hz • 80 kgf horizontal centrifugal force	Compared sister sets of static and dynamic soundings
Canada	Moore, 1987 (UBC)	• Vibration applied at top of rods • Vertical force at 75 Hz frequency	Shoulder porewater pressures did not identify liquefiable layers
Italy	Mitchell, 1988 Piccoli, 1993 (ISMES)	• Down-hole horizontal vibration • 200 Hz operational frequency	Qualitative interpretation of tip resistances
USA	Wise, et al. (1999) Schneider, et al. (1999) McGillivray et al. (2000)	• Downhole vertical-impulses by pneumatic solenids (5 Hz) • Midface porewater pressures (type 1 penetrometer)	Increased porewater pressures in liquefiable layers in field tests at historic Charleston/SC. Lost unit in New Madrid attempts.
USA	Hendren (1999)	• Type 2 piezocone with pneumatic downhole solenids with iMEMS for acceleration force measurements	Used in CPT chamber tests; Damaged accidently by overvoltage supply in laboratory trials.
USA	Bonita, et al. (2000) Bonita (2000).	• Chamber tests using pneumatic vibrators and type 2 piezocone and triple-element cone	Controlled series with Lightcastle sand in pressurized chambers. Vibrations applied to top of rods.

Under funding from the United States Geological Survey (USGS) and the National Science Foundation (NSF), the design and construction of three separate versions of vibrocone were completed in a joint research program at Georgia Tech and Virginia Tech (Wise, et al. 1999; Schneider, et al. 1999; Bonita et al. 2000, McGillivray, et al. 2000). These vibrocones offered the following features:

a. In field units, the dyynamic motion was applied downhole to prevent energy losses associated with uphole vibrators, as used on the prior UBC version and ARA sonic CPT device.
b. Motion was directed vertically to prevent gapping at the soil-cone interface, since the horizontal centrifugal oscillations of the prior PWRI and ISMES vibrocone penetration tests compromised the quality and integrity of the axial CPT measurements.

c. Calibration chamber tests were conducted in controlled deposits of pluviated sands that were saturated and K_0-consolidated prior to the cone penetration testing (Bonita, et al., 2000).
d. Both midface (u_1) and shoulder (u_2) porewater pressures were measured in chamber testing. Similar data were obtained separately in field tests.

Frequencies of operation were applied over the range of 5 to 125 hertz in laboratory chamber tests with an apparent resonance effect for tip stress measurements observed near 40 hertz. Field test trials were conducted in the 5 to 30 Hz range and indicated increased porewater effects.

For the initial design, several pneumatic systems were built to offer simplicity in operation and economy in construction. Impulse-type loading was used for the initial program and two units were needed: one for field trial use by Georgia Tech and one for CPT calibration chamber testing at Virginia Tech. The chamber tests were completed using Lightcastle Sand at two different relative densities at the Prices Fork Research Lab at Virginia Tech (Bonita, et al., 2000). The final set of results are now just available (Bonita, October 2000). For the chamber calibration tests, a special 15-cm^2 triple-element piezocone was loaned to our project by Fugro Geosciences of Houston/TX.. The triple element cone allows for the simultaneous measurement of cumulative cyclic pore pressures at three locations: midface (u_1), behind the tip (u_2 or u_b), and behind the sleeve (u_3).

For field trials, a type 1 piezocone with downhole actuator were used. The fabricated prototype "Mark I" was attached to a standard penetrometer, as illustrated in Figure 2. The initial unit employed a type 1 Davey penetrometer with midface element. The trailing module and control panel were designed and built by Wise (1998). Data acquisition was provided by an ADC-1 analog-digital converter and notebook computer system. A photo of the downhole pneumatic impulse unit and midface element piezocone is shown in Figure 4. Key resistance parameters are measured, including tip resistance (q_c), sleeve friction (f_s), porewater pressures (u_1), and frequency content of excitation. An HP oscilloscope was used in this initial version to monitor the dynamic force records.

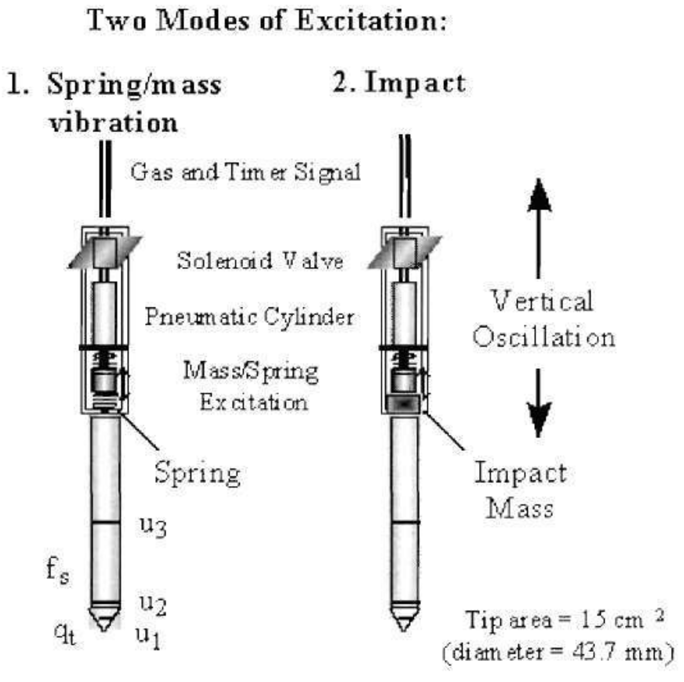

Figure 2. Downhole Pneumatic Impulse Generator and Piezocone Penetrometer (Wise, 1998).

Figure 3. Pneumatic Impulse Vibrocone with 36-mm diameter Type 1 Piezocone, Switch Box, HP Oscilloscope, and Nitrogen Supply Used in Initial Field Tests.

The 10-cm^2 Davey-type piezocone with a single midface (u_1) porous element was used at the NGES in Opelika, AL using a large Fugro cone truck and at a test site in Atlanta, GA using a standard drill rig, prior to deployment at liquefaction sites in South Carolina. The vibratory module consisted of a solenoid valve, air cylinder, an impact mass, velocity geophone, a housing assembly, and nitrogen gas. An electronic timer provides electrical pulses to a solenoid valve, which opens and closes at the rate dictated by the timer setting. The solenoid pressurizes the air piston, which in turn drives the excitation. Two modes of excitation are available to increase the versatility of the unit and range of applicability of the results. One mode is driven by a spring-mass oscillation and another uses impulse with an impacting mass. To measure the applied force and frequency, a small OYO Model 14-L9 geophone is installed in the unit.

Without reconfiguring the vibrator, the dynamic force can be adjusted at the control panel by increasing or decreasing the pressure from the tank or compressor. The air cylinder in the prototype has a bore size of 2.7 cm corresponding to a force of 100 kgf at 1.7 MPa pressure. The frequency of excitation can be varied by simply changing the timer setting which is capable of duty cycles from 0.001 seconds to 9999 hours and varied by increments of 0.001 seconds. The solenoid is rated to perform adequately at duty cycles down to 60 per second.

Successful series of tests were completed with the Davey vibrocone in the Charleston, SC region at pre-mapped sites with known liquefaction evidence (Wise, 1998). Gregg In-Situ Inc. provided a large cone truck for purposes of these tests. Later, tests using the device were attempted in the Blyeville, AR region at historic paleoliquefaction sites associated with the New Madrid earthquakes and unfortunately, the device was lost at a depth of 11 meters when a rod (or the module) buckled under the compressive forces. It was not possible to retrieve the unit. An insurance claim was filed for the financial value of the piezocone penetrometer and we received reimbursement towards the purchase of a new probe.

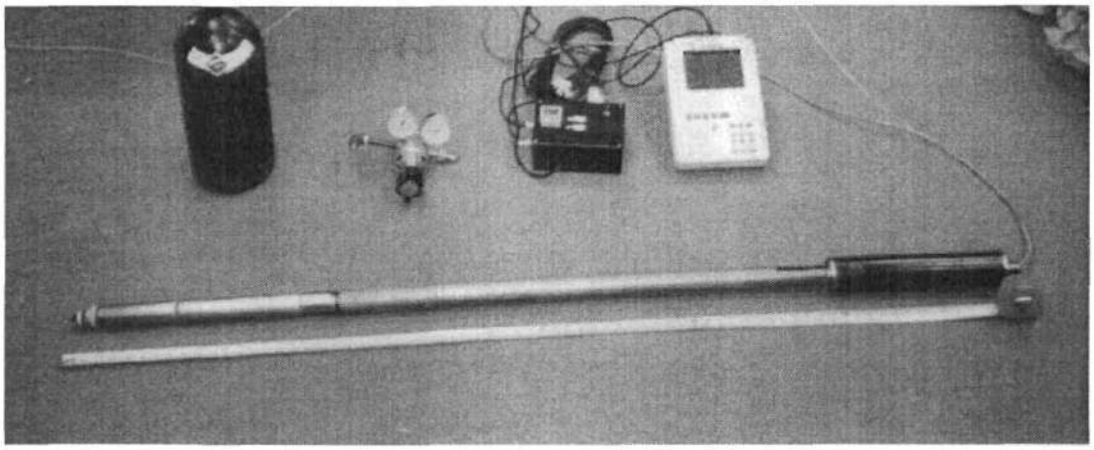

Figure 4. Version II Pneumatic Vibrocone Unit with 44-mm diameter Fugro Penetrometer

Calibration Chamber Testing

The chamber at VT required significant overhauling prior to its use since it had remained inactive for about one decade. Therefore, Craig Wise of GT spent the first summer funded in Blacksburg helping John Bonita of VT in replacing and repairing the shell, base, fittings, membranes, covers, and seals of the CPT chamber. Since saturation of the sand was extremely important, special details in sealing and pressurizing sand deposits needed additional attention (Bonita, 2000).

An improved vibro-unit was designed for the project, as shown in Figure 4, for use in calibration chamber tests at VT. Here, the triple-element piezocone was used at the front end and an HP spectrum analyzer provided for the dynamic load monitoring. The penetrometer was a special type that was on loan from Fugro Geosciences of Houston, Texas. The midface and shoulder pore pressure transducers were replaced at their factory in the Netherlands to allow better resolution of readings in the chamber settings at lower porewater pressures, as well as use of temperature-compensated sensors because of frictional heat during the penetration. This second version of the device was also intended to allow dynamic force measurements during advancement using an integrated micro-mechanical sensor (iMEMs) to serve as an accelerometer (Hendren, 1999). Unfortunately, a power surge at VT resulted in irreputable damage to this unit.

The final series of chamber tests were completed using two larger (non-downhole size) pneumatic vibrators and a type 2 piezocone (Davey penetrometer). The penetrometer was provided by Georgia Tech for this use. One pneumatic unit was loaned by ARA and another built by VT. An air compressor provided the necessary pressures to run the pneumatic vibrator. Paired static and dynamic tests were conducted in identical deposits of Lightcastle sand (Bonita, 2000). A view of the chamber embedded into the floor after setup is shown on the left along with the Mark II penetrometer.

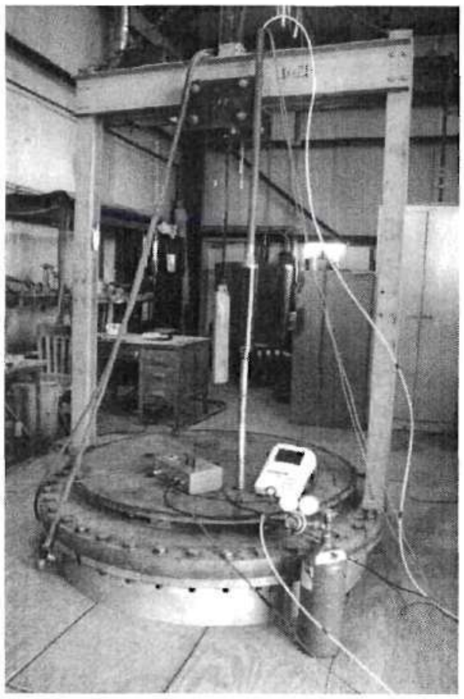

Figure 5. Calibration Chamber at VT Prices Fork Research Facility, Blacksburg, VA.

Results from the laboratory series showed that reductions in cone tip stress could be incurred with the use of vibrated penetrometers. Tests were made on saturated sands at anisotropic states of stress with normally consolidated deposits prepared at loose ($D_R \approx 25\%$) and medium dense ($D_R \approx 65\%$) and various confining stress levels. The full details are given in Bonita (2000), including results from loose sands at low stress levels using the 10-cm^2 penetrometer system presented in Figure 6.

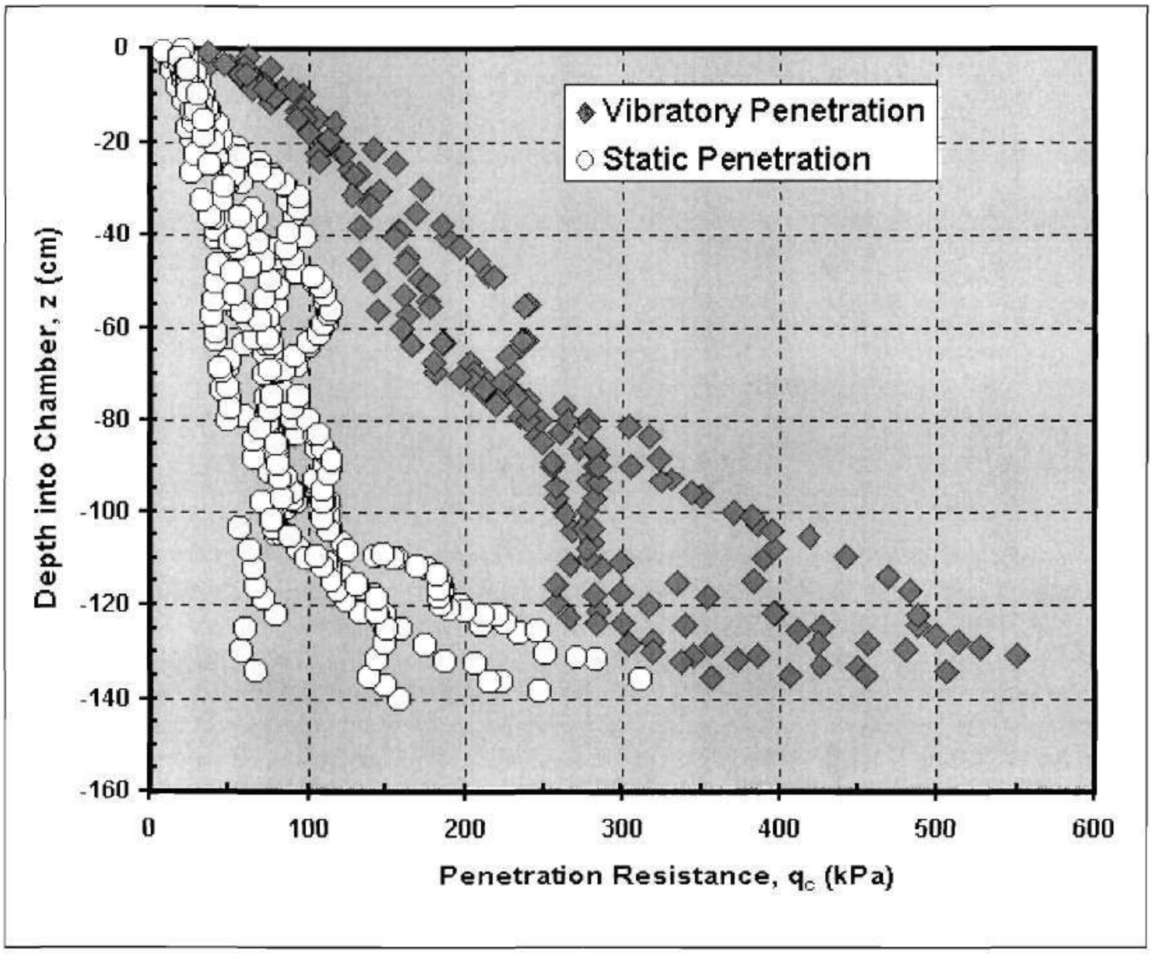

Figure 6. VCPT Results from Calibration Chamber Tests on LightCastle Sand (loose samples at low effective confining stress levels using the rotary turbine unit and type 2 Davey penetrometer).

Series of tests were conducted over a range of varying frequencies and showed an apparent resonance whereby the vibratory tip resistance (measured at sample center) decreased at approximately 40 hertz for both loose and medium dense specimens. Figure 7 illustrates the series using a counter rotating mass vibrator and shows the corresponding lowest measured tip stress (q_c) for one set of effective confining stress conditions: $\sigma_{vo}' = 55$ kPa and $\sigma_{ho}' = 27$ kPa. Note that the results from the chamber tests have not been corrected for boundary effect sizes (i.e., chamber diameter to cone diameter ratio).

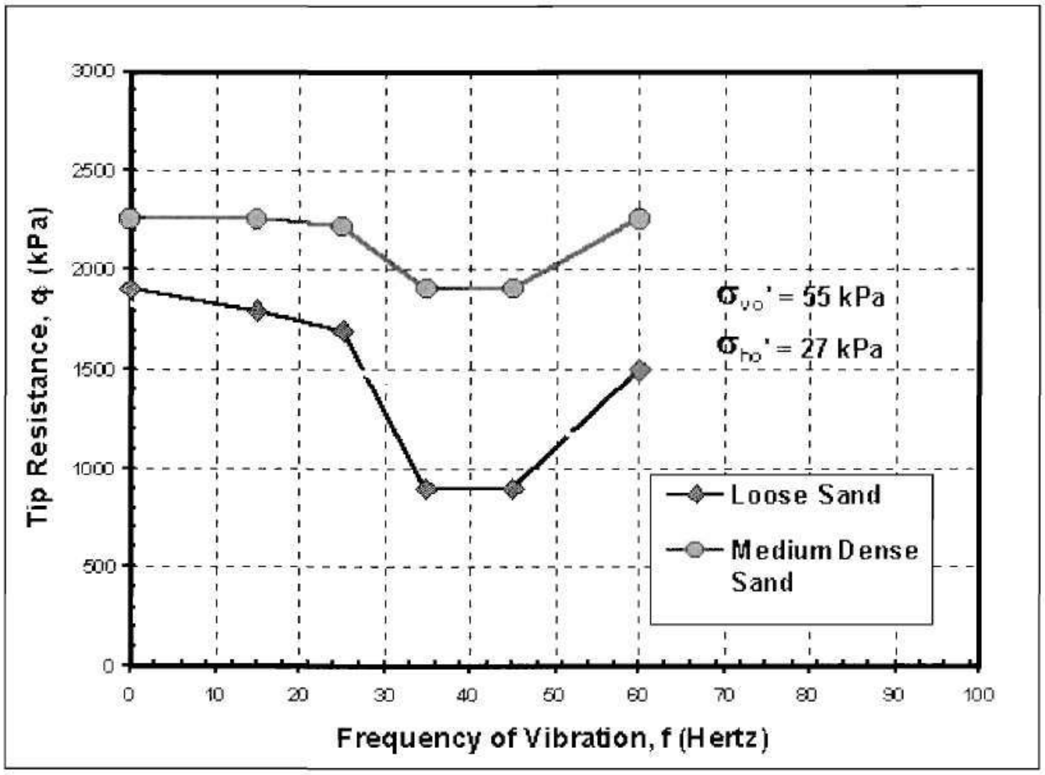

Figure 7. Operational Frequency Effects on CPT Chamber Test Results

Field Performance

The downhole impulse vibrocone system was trial-tested to evaluate its ability in generating localized excess porewater pressures in liquefaction-prone deposits. The device was advanced into historically- liquefied quartz sands in a series of soundings near Charleston, South Carolina. This seismic region was selected for trial soundings with the piezovibrocone due to the noted abundance of prior-mapped paleoliquefaction features (sand boils, dikes, sills, and subsidence regions) resulting from the Charleston Earthquake of 1886 with Moment Magnitude (M) = 7.5 to 7.7 (Martin & Clough, 1994). Two test sites have been investigated with the impulse VCPT in the Charleston area (Schneider, et al., 1999).

One selected site was the Thompson Industrial Services (TIS), which is very close to the Ten Mile Hill paleoliquefaction site. The water table was located about 1.5 m deep. Static reference soundings were performed with both an electronic ConeTec (type 2) seismic piezocone and the electric Davey (type 1) vibrocone model, with data shown in Figure 8. The latter served as the measurement package upfront for both the VCPT sounding during dynamic advancement as well as for static midface type piezocone reference soundings. The electronic type 2 cone provided signal conditioning and amplification of recordings downhole, while the electric type 1 penetrometer required filtering and amplification of the signals uphole with the data acquisition system. The tip stresses and sleeve resistances indicated very favorable comparisons between the two soundings, as shown by Figure 8. The midface u_1 readings mirrored the shoulder u_2 measurements, yet the midface pressures were generally above hydrostatic while shoulder pressures were slightly below hydrostatic conditions. This observation is consistent with static piezocone results reported in clean sands (Robertson, et al. 1986).

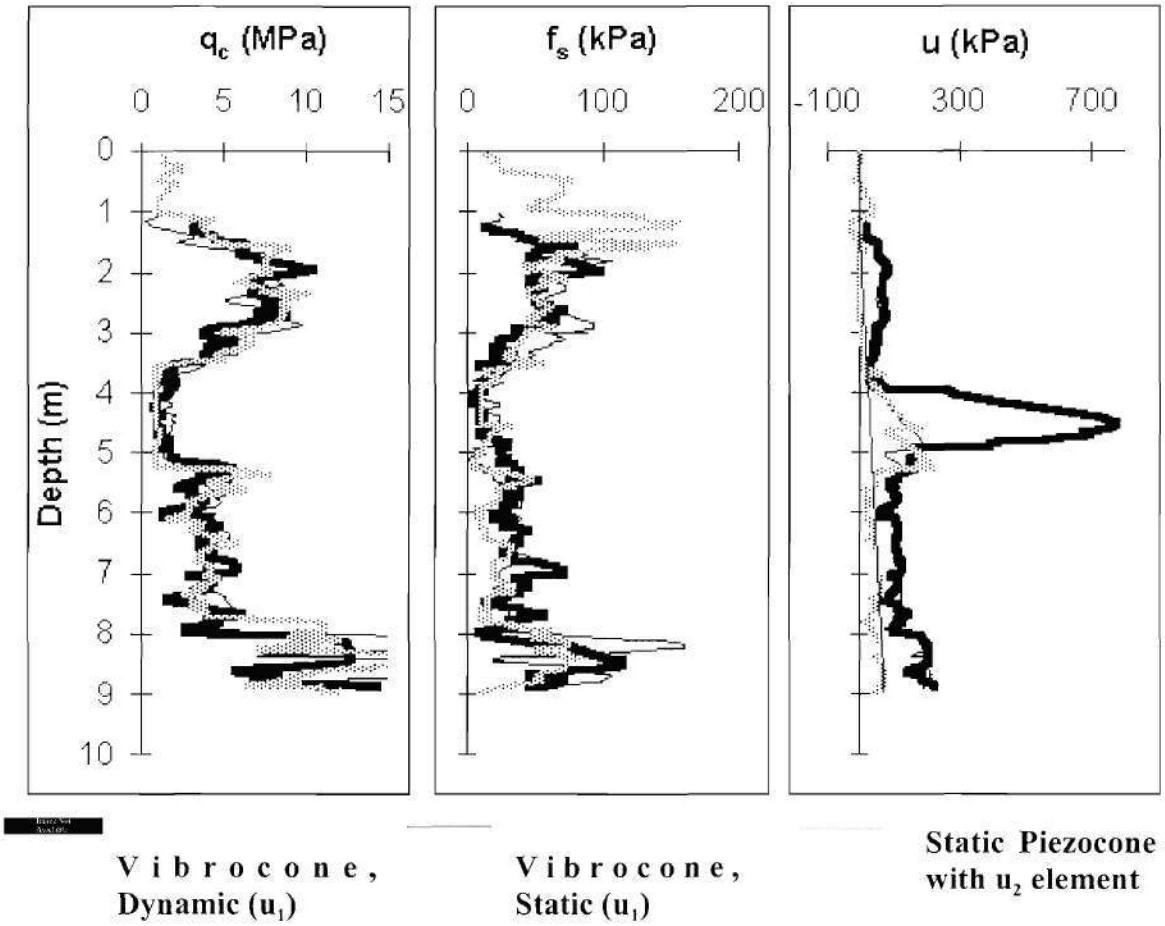

Figure 8. Impulse-Vibrocone Results at the Thompson Industrial Site in Charleston, SC. Readings compared with Both Type 1 and Type 2 Static Piezocone Soundings.

Based on published first-hand accounts and field reconnaissance, the extent of liquefaction due to the Charleston 1886 Earthquake had been characterized as "extensive" at the Ten Mile Hill and as moderate levels at the Eleven Mile Post site (Martin & Clough, 1994). The specific test site locations were based upon the prior documentation of accessible sites where prior SPT, CPT, and grain size information was reported (Martin & Clough, 1990).

For the static and vibratory soundings, Gregg In-Situ, Inc. of Aiken, South Carolina provided a 25-tonne cone truck (Figure 9) and an electronic 10-cm^2 seismic piezocone with a porous element at the u_2 (shoulder) position. These data provided a baseline reference for comparison with both static and dynamic soundings for the vibrocone field trials and are presented by Schneider, et al. (1999). Georgia Tech supplied the type 1 penetrometer, the downhole impulse unit, and data acquisition system. Static benchmark soundings were made with both the electronic type 2 and electric type 1 penetrometers with similar results.

Figure 9. Enclosed 25-tonne Cone Truck at Historic Liquefaction Site in Charleston, SC conducting VCPTs Using the Type 1 Penetrometer & Downhole Impulse Unit.

Adjacent to the two static tests, a dynamic sounding was also performed using the vibrocone probe operating at 5 Hz, thus completing a VCPT. At depths of between 3.5 to 5.1 meters, Figure 8 shows a significant spike in the porewater pressure response of the dynamic sounding. This response is interpreted to indicate the zone of liquefiable soil. Based on prior work by Japanese researchers and results from the VT chamber tests, it was expected that a decrease in tip stress (q_c) would be observed. However, the recorded tip resistances for all three soundings were all relatively low in this region and the dynamic tip resistance (VCPT) did not noticeably fall below either of the tip resistances from the two static soundings. In the future evaluations, it will be sought that a rational interpretation for the VCPT will consist of effective stress analyses to separate out the mechanisms of static liquefaction, steady-state response, quasi-liquefaction, cyclic mobility, and dilatant behavior of soils (Schneider, et al., 1999). The measured tip stresses q_c and penetration porewater pressure readings (u) may, in fact, reflect totally different portions of the induced effective stress paths.
Results were also obtained from VCPTs performed at the Hollywood Ditch site that was pre-mapped by Martin & Clough (1990). Baseline reference soundings were again obtained using an electronic type 2 cone and electric type 1 penetrometer. The latter unit provided the dynamic resistances during the VCPT mode. Figure 10 shows elevated penetration porewater pressures over much of the sounding depths, particularly in the liquefiable soils from 1.5 to 3 m range. Additional details from this test program can be found in Wise, et al. (1999) and Schneider, et al. (1999).

While the pneumatic vibrocone eliminated some of the problems evident in the original designs, it is not without its own disadvantages. The gas supply line, which must be threaded through the rods together with the electric penetrometer cable, causes tangling and difficulties in field use. The heavy nitrogen tank is awkward to transport and has to be refilled often. The increased diameter of the trailing vibro-unit required extra pushing force for the cone rig, and created a large diameter hole, which did not provide adequate support for the rods. Buckling in the rods can reduce the amount of force delivered to the tip of the penetrometer, and increases the chances of rods breaking in the hole. In fact, the loss of support behind the vibratory module resulted in a rod break that left the device buried in at a historic liquefaction site in Blyeville/AR in the New Madrid seismic region in December 1998.

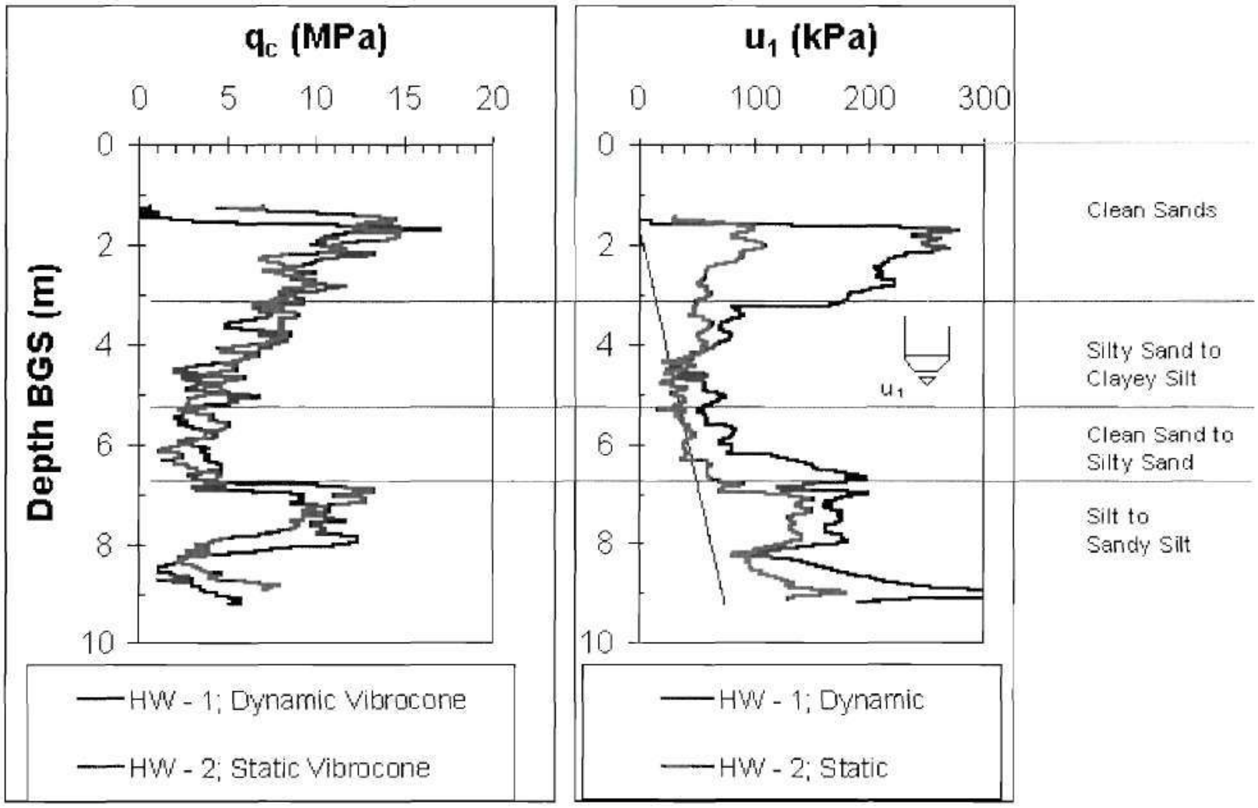

Figure 10. Results from Impulse Vibrocone at the Hollywood Ditch Site, Charleston, SC

The second version of the device was constructed so that dynamic forces could be measured during advancement with an integrated micro-mechanical sensor (iMEMs) that served as an accelerometer (Hendren, 1999). A piezoelectric stack (termed a piezo-actuator), appears to be a superior alternative to the pneumaticsolenoid-type vibrocone. The totally electronic system offers full control over the forces and/or displacements, frequencies, and waveform, as well as a simpler utilization in the field with a single electrical cable threaded through the cone rods.

NEW ELECTROVIBROCONE DESIGN

A new electrovibrocone has been designed with a stainless steel dual-element penetrometer and piezo-stack vibrator. This "Mark IV" version offers a completely electronic capability to facilitate use on conventional drill rigs and cone trucks. Improvements will consist of true sinusoidal (vertical) vibratory motion with accurate control of the applied dynamic forces and operational frequencies, as well as multiple porewater measurements at both midface and shoulder locations. Field testing at historic liquefaction sites near Charleston/SC, New Madrid Seismic Region (AR, TN, MO), and the Treasure Island test site (CA) are proposed for calibration and verification of the device operation. Numerical simulation and/or analytical modeling will be performed within the context of state parameter and critical state soil mechanics.

A new penetrometer offers four simultaneous channels (q_t, f_s, u_1, and u_2), where the face filter element is ceramic and the shoulder filter element is sintered stainless steel. The device utilizes a 16-wire cable terminated with a 16-pin Lemo connector. The stainless steel penetrometer requires only 12 wires for operation, leaving 4 available wires. The piezo-actuator unit requires only 2 wires, so the other two could be used to monitor a geophone for performing downhole seismic tests or for an accelerometer (or iMEMs) which could be used to measure the amount of dynamic force the cone is imparting into the soil. The midface reading should provide the magnitudes of pore pressures that cause localized liquefaction, while the shoulder readings provide the necessary values for correcting tip stresses (ASTM D 5778). This equipment, with a sample piezo-actuator, is shown in Figure 11, and will be used for field trial tests and calibration of the device.

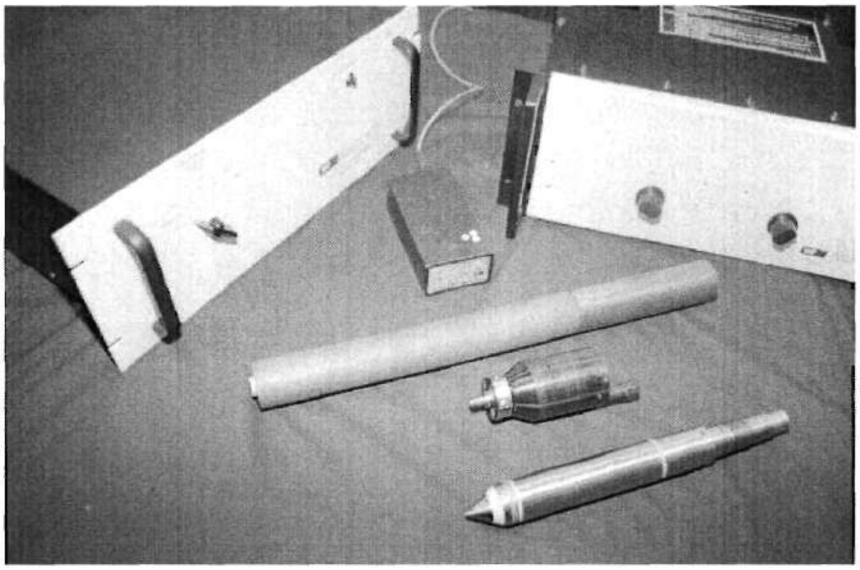

Figure 11. The Proposed Components of the Electro-Vibrocone Model with Dual-Element Piezocone, Downhole Piezoelectric Shaker, Signal Generator, and Amplifier.

We are currently developing our own LabView-based data acquisition system that runs on a notebook computer. In 1998, we acquired a new GeoStar cone rig that consists of a 20-tonne hydraulic pushing system mounted on a Ford 350 flatbed This system uses twin earth anchors at the back end for reaction and has successfully completed numerous soundings in Alabama, Arkansas, Georgia, Missouri, North Carolina, South Carolina, Tennessee, and Virginia. Results exemplifying our work are found at:

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

In addition to site-specific liquefaction evaluations, it is anticipated that the device will aid in the assessment of post-cyclic residual undrained strengths of silts and sands. The post-cyclic strength is important in stability analyses involving earth dams, reservoirs, embankments, and levees. The VCPT may also serve as a tool for evaluating the outcomes and effectiveness of ground modification techniques, such as vibro-compaction, underground blasting, and dynamic compaction.

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