Development of a Retrievable Subsurface Accelerometer

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ABSTRACT: This paper describes the development of a Retrievable Subsurface Accelerometer (RSA) for the NSF George E. Brown, Jr., Network for Earthquake Engineering Simulation (NEES) project at UCLA. The RSA was developed to obtain subsurface vibration data during forced-vibration experiments and aftershock events. The RSA can be rapidly installed using a CPT truck and subsequently retrieved using structural cables and a winch. This eliminates the need for conventional borehole drilling and grouting that is often more expensive than a downhole accelerometer. Lastly, the successfully completion of a recent pilot study is described.

1 INTRODUCTION

Accelerometer arrays have been used extensively since the early 1930's by seismologists and earthquake engineers to capture the nature of strong earthquake ground motions and their influence on structural systems. During this time, technological improvements have increased progressively. This has enabled digital recordings and nearly tripled the dynamic range of the instruments (50 dB to 145 dB), ultimately providing more robust, accurate and sensitive measurements. However, the spatial resolution of recordings has not kept pace with the technological improvements, increasing very slowly during the past 20 years (Trifunac and Todorovska, 2001). The slow growth of newly instrumented stations is principally due to the cost associated with deploying and maintaining these stations. In particular, downhole accelerometer arrays are typically an order of magnitude more expensive than instruments deployed within a building due to their laborious installation process and need to be hermetically sealed from groundwater. A downhole accelerometer installation requires an experienced contractor to drill and install PVC casing and grout, which often exceeds the cost of the subsurface accelerometer.

Clearly, subsurface acceleration data is needed for source mechanism, wave propagation and local site effect studies as well as defining free-field inputs for structural response studies. In an effort to meet this need in a cost-effective manner, the University of California, Los Angeles has developed the Retrievable Subsurface Accelerometer (RSA) that can be installed and subsequently retrieved using a standard cone penetration testing (CPT) truck. The objective of this paper is to describe the design and initial testing of the RSA. The development of the RSA is part of a broader effort by the UCLA George E. Brown, Jr., Network for Earthquake Engineering Simulation (NEES) project to develop a mobile field laboratory for forced vibration testing of full-scale structural systems (Stewart et al., 2002). The role of the RSAs in the UCLA NEES project is to monitor subsurface vibrations induced during forced-vibration testing experiments or earthquake aftershock events.

2 DESIGN CONSIDERATIONS

The principal advantages of the RSA over a traditional downhole accelerometer are the significant reduction in cost and time required for installation and the ability to easily and reliably retrieve the unit such that it can be reused many times. The CPT installation method eliminates the need to drill, case and grout, thereby enabling rapid deployment of the RSA to depths up to 30 m. In addition, environmental considerations such as drill tailings and excess water disposal, typical of rotary wash drilling, are circumvented. The ability for quick retrieval of the unit is also a tremendous cost savings in that a fleet of RSAs can be used indefinitely. In the following sections, the electrical and packaging design of the RSA which enables the new CPT-installation/retrieval method is described.

2.1 *Electrical*

The RSA contains a low cost, commercially available MEMS triaxial accelerometer hermetically sealed in a 15.5 cm^2 cylindrical cone. Miniature accelerometers made by Silicon Designs (model 1221J) were chosen for the RSA due to their combination of small form factor, low electrical noise and wide frequency range (0 to 200 Hz). The 1221J is a capacitive accelerometer which contains a nominal dynamic range (= 20 log[A_{max}/A_{min}], where A_{max} and A_{min} are the largest and smallest amplitudes that can be recorded) of 105 dB. Figure 1 shows a comparison of dynamic ranges of selected strong motion instruments that are commercially available, as well as a Fourier amplitude spectrum of various earthquake intensities. The 1221J accelerometer, which is comparable in bandwidth to the Kinemetrics, Inc. Etna instrument, is able to capture all strong motion data, and comfortably measure vibrations induced during typical aftershocks and forced-vibration experiments. However, the RSA is not currently suitable for recording weak motion data

Figure 2 shows a block diagram of the RSA circuit board designed by Hogentogler & Co., Inc. The RSA circuit was specially designed to incorporate downhole signal conditioning (signal amplification and low-pass filtering) to minimize the potential for noise contamination. A micro-controller was also integrated onto the RSA circuit board to provide built-in sensor intelligence, monitoring the inclination in all three orthogonal axes using the DC portion of the analog signal from the accelerometers. A RS232 serial port connection is used to interface the micro-controller with a terminal box, which computes the inclination angles using a software algorithm. In addition, the terminal box can download inclination calibration parameters onto the micro-controller using <u>E</u>lectrically <u>E</u>rasable <u>P</u>rogrammable <u>R</u>ead <u>O</u>nly <u>M</u>emory (EEPROM) to zero the DC gain offset after the RSA is installed in the subsurface.

The AC component of the analog signal, which measures the dynamic accelerations of the RSA, connects directly to a Kinemetrics, Inc., model Quanterra Q330 data logger positioned at the ground surface. The Q330 data logger digitizes the signal using a true 24-bit analog-to-digital (A/D) conversion and a dynamic range of ~145 dB. The data is then time-stamped by a GPS sensor for time synchronization (< 1 ms accuracy) across multiple RSA sensors, and transmitted using wireless telemetry to a central workstation (Stewart et al., 2002). The wireless telemetry enables convenient networking of high-spatial resolution measurements during field experiments.

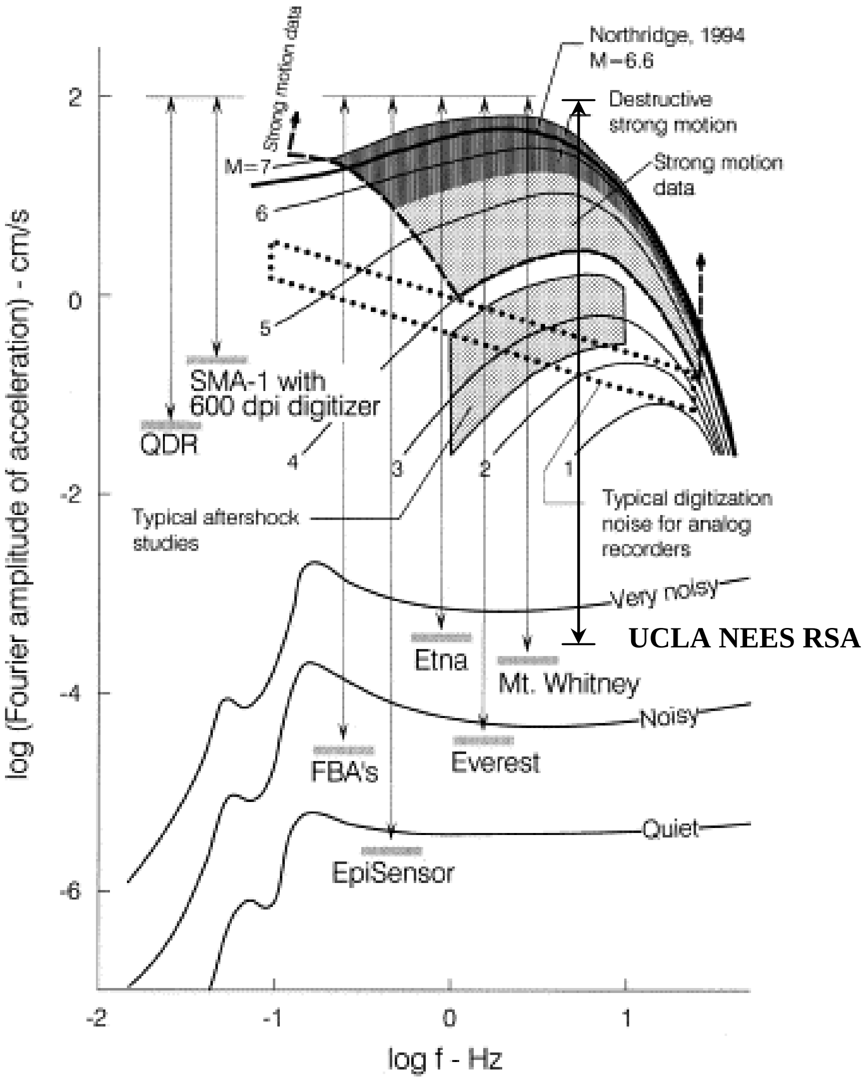

Figure 1. Comparison of Fourier spectrum amplitudes of selected accelerometers
(after Trifunac and Todorovska, 2001)

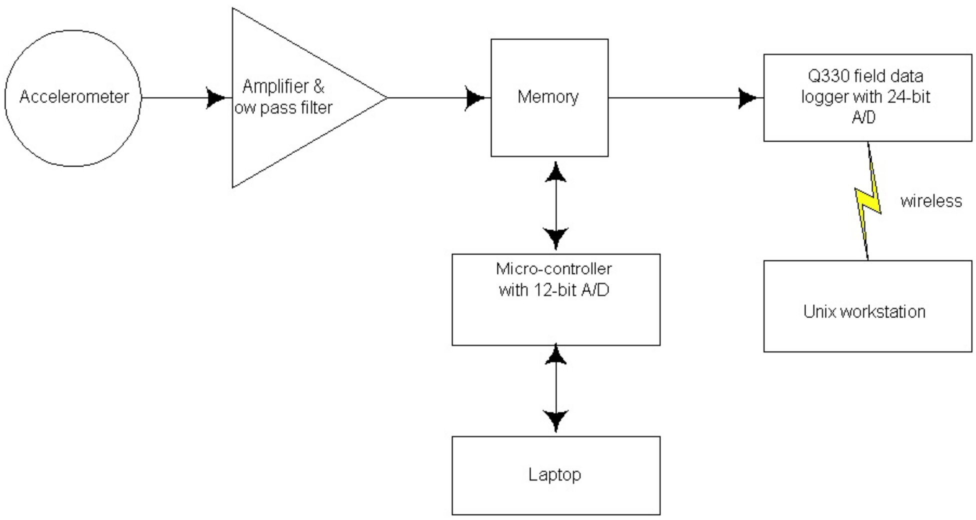

Figure 2. Block diagram of RSA circuit

2.2 *Packaging*

Figure 3 shows a schematic diagram of the RSA probe, constructed from stainless steel. The outer casing closely resembles a standard CPT cone with a 60° cone tip but it has a projected area of 15.5 cm^2 as compared to a standard 10 cm^2 projected area. The length of the RSA from the cone tip to the pulling adapter is 1.2 m, approximately double the length of a standard 10 cm^2 cone. The triaxial accelerometer and RSA circuit board are located approximately 10 and 35 cm behind the base of the cone, respectively, and are protected by a continuous hollow stainless steel cylinder. The pulling adapter attaches to the end of the cylinder, both of which are hermetically sealed with O-rings to protect the electronics from groundwater. One signal and two structural cables are permanently attached to the probe and extend up to the ground surface through the push rods. The pulling adapter attaches to the driving shoe adapter via a non-tension connection, such that it can drive the RSA into the subsurface, dislodge, and leave the RSA in position. Once the drive shoe and push rods are withdrawn, the cables to carry the signal to the surface Q330 unit and allow for retrieval of the probe.

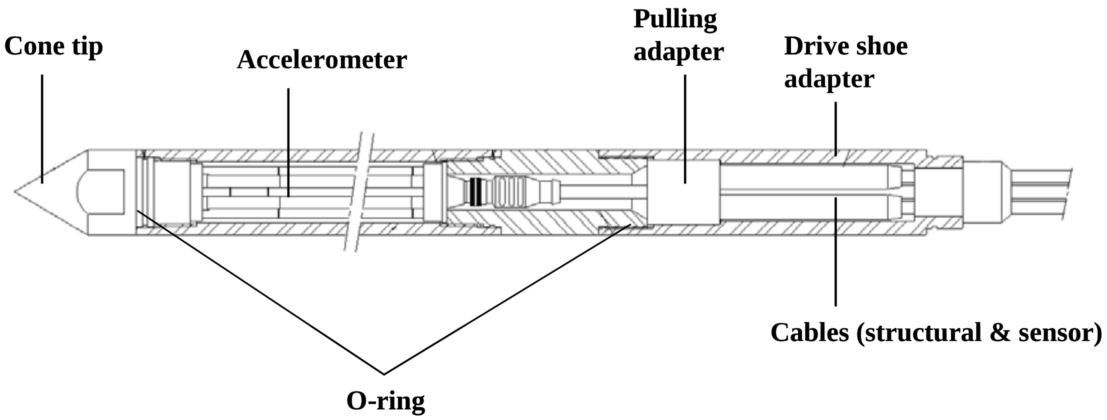

Figure 3. Schematic of the UCLA NEES Retrievable Subsurface Accelerometer

3 INSTALLATION PROCEDURE AND PILOT TESTING

3.1 *Installation Procedure*

The RSA mounts to a standard CPT hydraulic ram much like a standard cone penetrometer. Once attached to the push rods, the RSA is carefully lowered to just above the ground surface and aligned to the desired orientation using a hand compass before being guided into the ground. The RSA is pushed into the ground using standard CPT equipment and a drive shoe adapter. It is assumed that the RSA undergoes zero rotation about the vertical axis during pushing. The depth of the RSA is calculated by the number of rods, as is done in non-computerized drill rigs (we can’t use the regular depth counter on the CPT?). Once the RSA reaches the desired depth, the drive shoe adapter and rods are withdrawn leaving the RSA and cables in place. The RSA micro-controller then communicates with a terminal box to determine the inclination in three orthogonal axes using the DC gains from the accelerometer. The DC offset can then be re-zeroed using the micro-controller and flash memory. This installation can be repeated to install multiple RSAs using the same drive shoe adapter and push rods. The RSA is retrieved by pulling on the structural cables using a portable winch at the ground surface. Although this can be done from within the CPT truck, the retrieval process is simplified if the winch is an independent unit. Another attractive possibility is to mount the winch on the front of the CPT truck.

3.2 *Pilot Testing*

A preliminary field test was performed using a standard Hogentogler CPT truck in a marsh meadow along the shoreline of Rariton Bay in South Amboy, NJ. Figure 4 shows subsurface soil profile obtained from a CPT sounding approximately 100 ft away from the RSA hole. The RSA was pushed 10 m into the ground where several soundings were performed using a standard CPT hammer, then subsequently retrieved. The electrical and mechanical performance of the RSA was satisfactory, although the sensor cable experienced minor damage during retrievable. Additional field testing with sinusoidal loading from a forced-vibration experiment of known amplitude and frequency is planned in the near future.

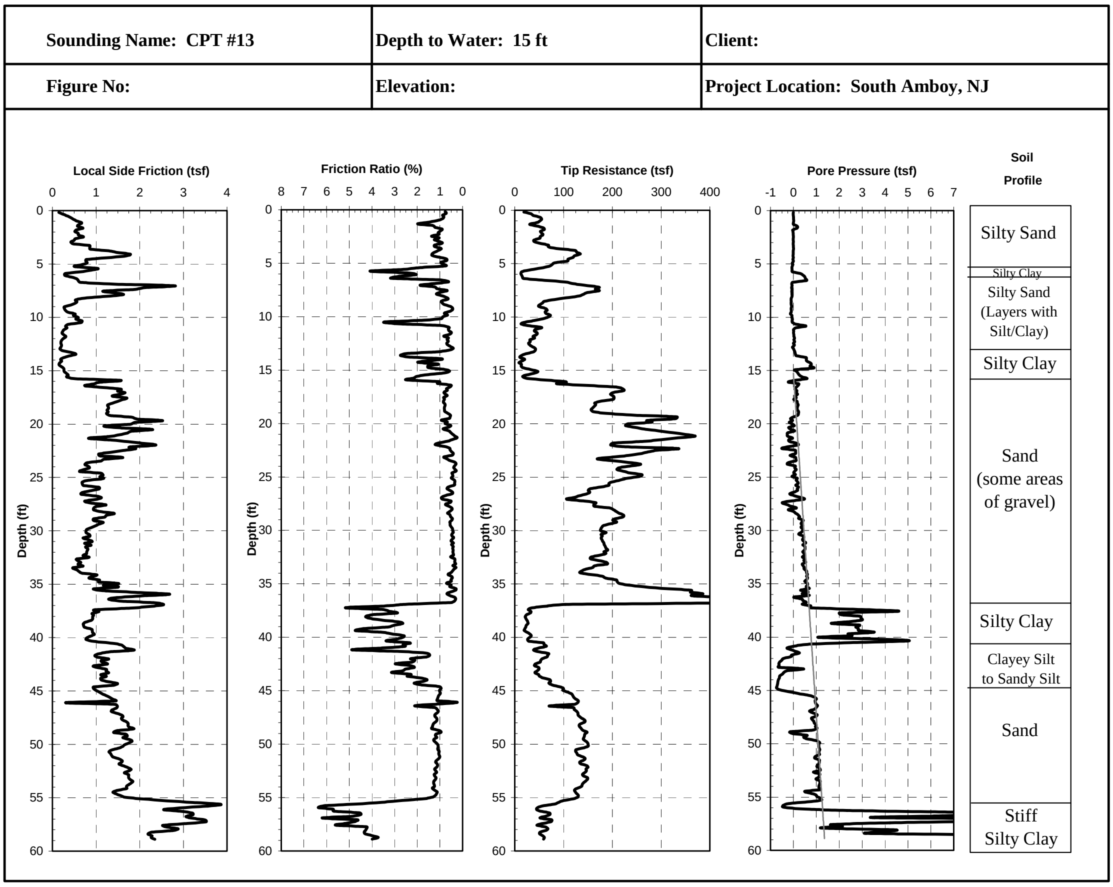

Figure 4. CPT sounding from Rariton Bay

4 SUMMARY AND CONCLUSIONS

This paper describes the development of a Retrievable Subsurface Accelerometer (RSA) for the NSF George E. Brown, Jr., Network for Earthquake Engineering Simulation (NEES) project at UCLA. The RSA was developed to obtain subsurface vibration data during forced-vibration experiments, in which instrumentation arrays are non-permanent deployments. The RSA can also serve as a cost-effective solution for permanent instrumentation stations at shallow depths (< ~40 m). The RSA is rapidly installed using a CPT truck and quickly retrieved using structural cables and a winch. This eliminates the need for conventional borehole drilling and grouting that is often more expensive than a downhole accelerometer. The RSA was successfully demonstrated in a recent pilot study.

ACKNOWLEDGEMENTS

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REFERENCES

Stewart, J.P., Whang, D.; Fox, P.J.; Wallace, J. W. 2002. "Application of the UCLA NEES Equipment for Testing of Soil-Foundation-Structure Interaction," *Proceedings, Earthquake Engineering Research Institute, 7th U.S. National Conference on Earthquake Engineering*, Boston, MA

Trifunac, M.D. & Todorovska, M.I. 2001. "Evolution of accelerographs, data processing, strong motion arrays and amplitude and spatial resolution in recording strong earthquake motion," *Soil Dynamics and Earthquake Engineering*, (21) 537-555