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Cone Penetrometer Off-Surface Sensor

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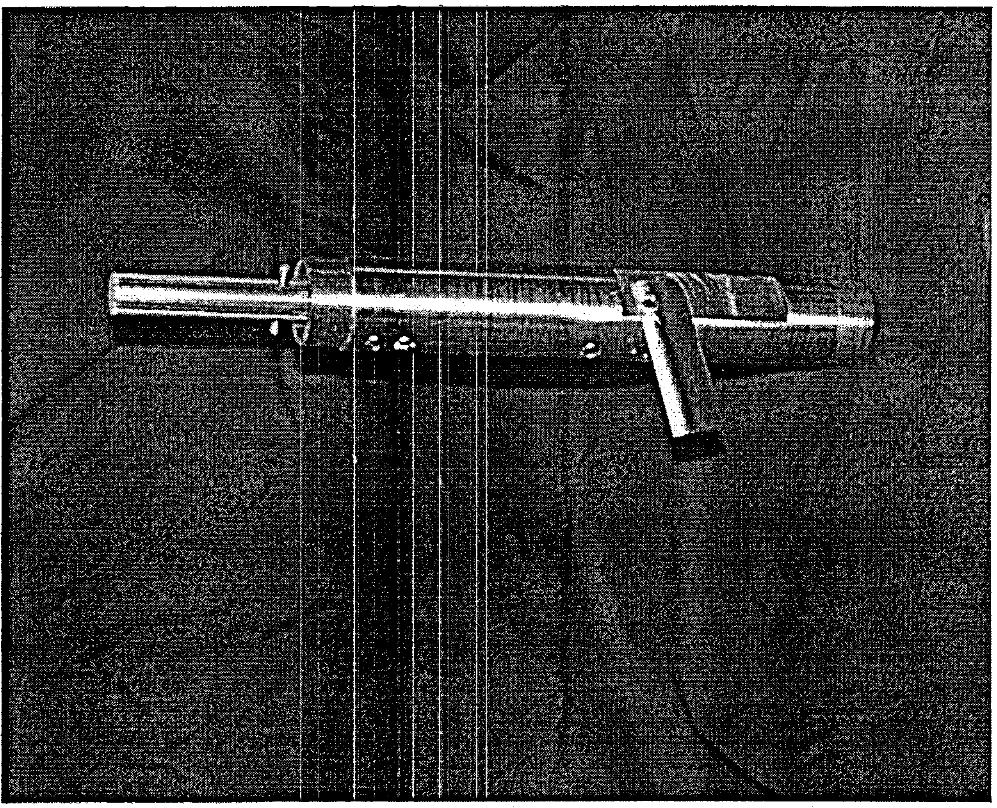
Revision 0

SUMMARY REPORT

CONE PENETROMETER OFF SURFACE SENSOR



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LIST OF REVISIONS

Rev. 0	9/24/99	Initial Issue

LIST OF ACRONYMS

ARA	Advanced Research Associates
CPOSS	Cone Penetrometer Off Surface Sensor
CPT	Cone Penetrometer Truck
EES	Engineered Equipment and Systems Department
ERD	Environmental Restoration Division
SRS	Savannah River Site
SRTC	Savannah River Technology Center
WSRC	Westinghouse Savannah River Company

EXECUTIVE SUMMARY

Cone penetrometer technology accounts for approximately 50% of the subsurface drilling performed at the Savannah River Site (SRS). This technology provides a means of collecting data for use in the characterization of the subsurface. The cone penetrometer consists of a steel cone attached to a pipe column that is hydraulically inserted into the ground. Sensors mounted on the tip and side continually take measurements as the cone pentrometer is being inserted. Specialized trucks were developed to deploy the cone penetrometer with the use of a 20-40 ton hydraulic ram. The Army Corp of Engineers-Waterways Experiment Station and Advanced Research Associates (ARA) are two of the companies that have developed sensor packages for deployment with the cone penetrometer.

However, to this point, only measurements at the surface of the cone penetrometer have been achievable. While providing researchers with a better understanding of the subsurface, these sensors are not able to overcome an inherent problem with existing cone penetrometers that is related to the act of inserting the cone penetrometer into the ground. Specifically, as the cone penetrometer is inserted, the soil compacts in a region around the inserted probe. This is known as the "skin effect." It is believed the "skin effect" is responsible for inaccurate sensor readings directly attributed to soil compaction and the soil compaction pressing contaminants away from the sensors.

To allow researchers to accurately measure subsurface properties, without the inherent problem of existing cone penetrometer equipment, the Engineered Equipment and Systems Department (EES) of the Savannah River Technology Center (SRTC) has developed the Cone Penetrometer Off Surface Sensor (CPOSS). The CPOSS is a tool that was developed for deploying sensors 1" to 3" off the surface of the cone penetrometer. The design consists of a knife blade mechanism mounted along the surface of a module capable of being attached to existing cone penetrometer equipment and being deployed at depths of up to 200 feet. During deployment, the knife blade with an embedded sensor is rotated, thus extending the tip of blade away from the cone pentrometer surface.

In the 4th quarter of FY98, the Environmental Restoration Division (ERD) provided EES with $50K of funding. The initial step of the design was to determine soil-loading effects on a knife blade. Due to the lack of available data, it was determined the best way of obtaining this the data was to build a manually deployable prototype and measure loading values on the knife during subsurface deployment. In FY99, the project was funded through the Savannah River Strategic R&D Program for $100K. Scope of work for this funding included the design, fabrication and testing of a manually deployable prototype and two remotely deployable prototypes. Additional funds were requested and received totaling $136.4K to finish the remotely deployable prototypes and the field testing.

Based on the mechanical design of the prototype and knife blade loading data, it was determined that a motor with sufficient torque was unavailable to meet the size restriction of the design (capable of fitting inside a 1.5" id pipe). A brainstorming session was held with subject matter experts in an attempt to devise alternate deployment strategies.

The two remotely deployable prototypes were designed and fabricated during the third and fourth quarters of FY99. After lab testing, the two prototypes were tested using the SRTC Cone Penetrometer Truck (CPT). Of the two systems tested, the linkage driven design proved to be the more robust design as it successfully deployed at a depth of approximately 13' next to 704-D. The rack drive system experienced a recurrent component failure during field-testing and is not recommended for future CPOSS deployments.

Based on the success of the linkage drive system during field-testing, the CPOSS shows a very high probability of successfully meeting the original design goals with additional design enhancements. Incorporating field data and lessons learned during the FY99 design effort, a redesigned linkage drive system has a very high probability for success. SRTC Strategic R&D money will be solicited in FY00 for this design effort. Once this design effort is complete, previously secured EM-50 money will be used to incorporate sensors into the deployment mechanism.

1. BACKGROUND

Cone penetrometer technology accounts for approximately 50% of the subsurface drilling performed at the Savannah River Site (SRS). This technology provides a means of collecting data for use in the characterization of the subsurface. The cone penetrometer consists of a steel cone attached to a pipe column that is hydraulically inserted into the ground. Sensors mounted on the tip and side continually take measurements as the cone pentrometer is being inserted. Specialized trucks were developed to deploy the cone penetrometer with the use of a 20-40 ton hydraulic ram. (Figure 1: Cone Penetrometer Truck) The Army Corp of Engineers-Waterways Experiment Station and Advanced Research Associates (ARA) are two of the companies that have developed sensor packages for deployment with the cone penetrometer.

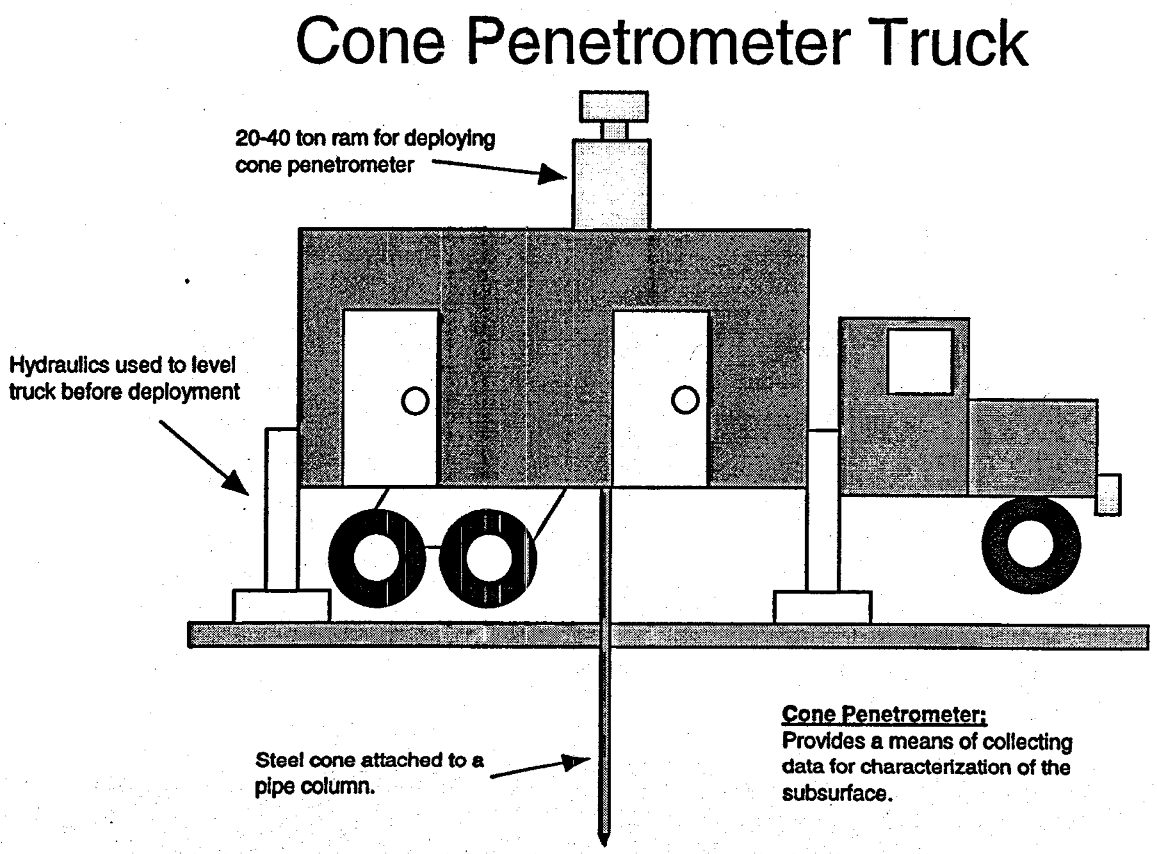

Figure 1: Cone Penetrometer Truck

However, to this point, only measurements at the surface of the cone penetrometer have been achievable. While providing researchers with a better understanding of the subsurface, these sensors are not able to overcome an inherent problem with existing cone penetrometers that is related to the act of inserting the cone penetrometer in the ground. Specifically, as the cone penetrometer is inserted, the soil compacts in a region around the inserted probe. This is known as the "skin effect." It is believed the "skin effect" is responsible for inaccurate sensor readings directly attributed to soil compaction and the soil compaction pressing contaminants away from the sensors.

To allow researchers to accurately measure subsurface properties, without the inherent problem of existing cone penetrometer equipment, the Engineered Equipment and Systems Department (EES) of the Savannah River Technology Center (SRTC) developed the Cone Penetrometer Off Surface Sensor (CPOSS). The CPOSS is a tool that was developed for deploying sensors 1" to 3" from the surface of the cone penetrometer. The design consists of a knife blade mechanism, with sensors embedded in the tip, mounted along the surface of a module capable of attaching to existing cone penetrometer equipment. During deployment, the knife blade is rotated, thus extending the sensor away from the cone pentrometer surface.

During February of 1998, Environmental Restoration Division (ERD) personnel met with EES engineers to brainstorm ideas for using instrumentation to locate and characterize solvent contamination. The results of this meeting was a list of seventeen (17) ideas that were presented to the ERD and the Environmental Restoration Technology group of SRTC for viability. The list of ideas was narrowed down to the three most promising and given to the ERD so funding could be sought. In the 4th quarter of FY98, the ERD provided EES with $50K of funding to begin initial design of the most promising idea, the CPOSS. In FY99, the project was funded through the Savannah River Strategic R&D Program for $100K.

2. FY99 ACCOMPLISHMENTS

2.1 Design

2.1.1 Manually Deployed Prototype

The first prototype CPOSS module was designed primarily to establish load design criteria needed to develop a drive mechanism. The prototype design consisted of a stock rack & pinion drive, configured to transmit a rotary motion to the off-surface sensor blade (Figure 2). A removable head was attached to the top of the module so that an impact load could be applied to drive the unit into the ground. An alternate head was used to apply the load for sensor blade deployment. The deployment load was a downward force applied directly to the rack component, which rotated the spur gear and deployed the blade.

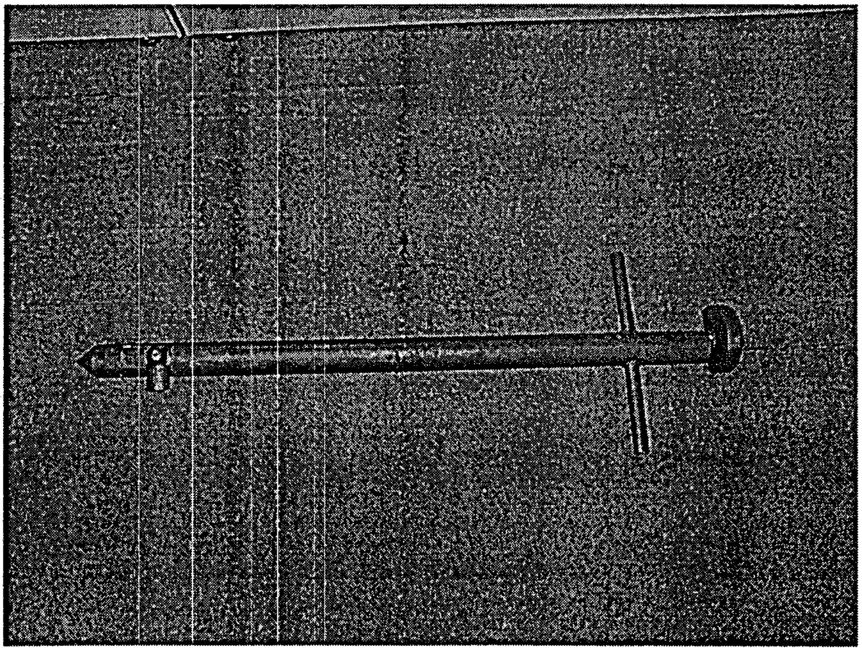

Figure 2: Manually Deployed Prototype

A load cell was used on the deployment head in order to measure the force required to cause the blade to rotate (Figure 3). The load cell was positioned between the module and a clamping device consisting of a 1" bolt and bracket.

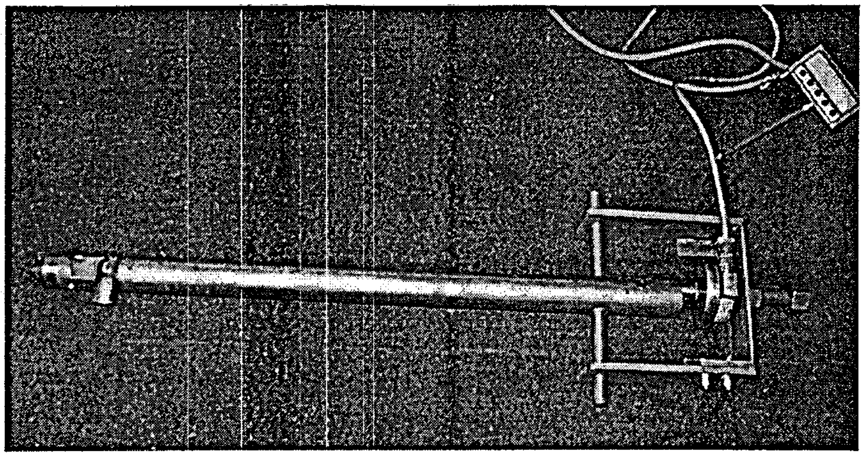

Figure 3: Manually Deployed Prototype with Load Cell

This early design served to define the design criteria for blade loading and established a basis for a remotely deployable prototype.

2.1.2 Brainstorming Session

Key to development of a remotely deployable prototype module was a drive system capable of generating sufficient loads to deploy the sensor blade, while meeting the size requirements to fit the limited space available in a cone penetrometer. The drive bolt used in the manually deployed prototype, although capable of supplying a tremendous force, was much too large.

The initial concept was to use a direct drive motor designed to turn a bevel gear set. This concept had the potential to minimize the quantity, size, and weight of moving components, keeping the system simple and maximizing the chance of successful deployment. It was discovered, however, that no bevel gear set that would fit in the cone penetrometer space, could accommodate the loads that would be generated. Several gear-manufacturing firms were contacted regarding this drive system problem and the response from all was that straight gearing would not sustain the required loads.

A brainstorming session was held with engineers in the EES in order to generate ideas for an appropriate drive mechanism. Among the ideas discussed were use of hydraulic cylinders, incendiary devices, horizontal blade rotation, a linkage drive system, and a modified version of the rack & pinion drive concept.

The use of hydraulics was eliminated because of the effort involved in threading hydraulic hose through the penetrometer system. In addition, these hoses would occupy space within the module that was needed for electrical cables and instrumentation. Incendiaries are single use devices and were, therefore, unacceptable if multiple deployments were required on a single penetrometer push. Accommodating a horizontal blade rotation would weaken the penetrometer probe and therefore jeopardize the compressive strength of the system.

The linkage drive concept and the modified rack & pinion drive system tested seemed to offer the highest potential for success. These two concepts were then developed and fabricated on a parallel path.

2.1.3 Rack and Linkage Driven Prototypes and Control System

Linkage Driven

The linkage drive concept utilizes a motor driven acme screw, rotating within a fixed nut (Figure 4). As the screw rotates, it also translates vertically downward. The screw is coupled to a block through which a horizontal pin is secured. A linkage connects this pin to the sensor blade shaft. As the block is driven downward, linkage movement causes rotation of the sensor blade. The sensor blade conforms to the contour of the cone penetrometer outer surface. The blade shaft is welded to the blade and pinned to the linkage inside. Electron beam welding was chosen as the method of joining these two components to reduce the risk of warping. The materials of construction for these components (Blade/shaft: ASTM A514, Internal components: SAE 4140, Casing: Carbon Steel) had to be compatible for welding and have sufficient strength to withstand the excessive loads to which they would be exposed. Clearances at the interface between the blade and penetrometer were minimal to prevent compacting of soil during deployment of the CPOSS. Any entrapped soil could cause binding of the blade and potentially damage components. This would inhibit retraction of the blade and prevent additional deployments on a given penetrometer push.

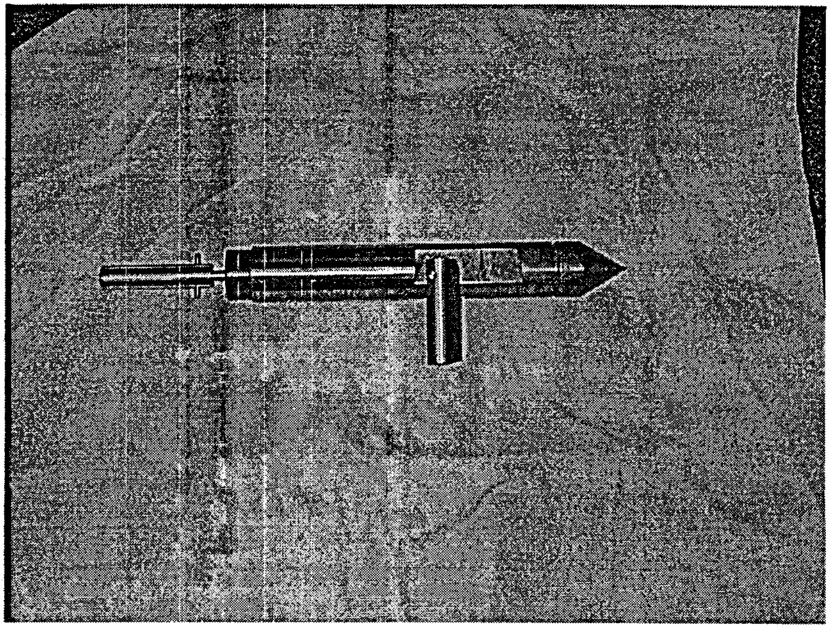

Figure 4: Linkage Driven Prototype

Rack Driven

The rack driven concept was similar in design to the manually deployed prototype. A motorized acme screw, similar to one used in the linkage drive system, was rotated in a translating nut. This nut was coupled to a vertically mounted gear rack. As the rack moved downward, it drove a spur gear, which in turn rotated the sensor blade. Welding materials and techniques similar to the linkage driven version were employed.

Control System

The control system prototype consisted of the following elements: motor control for blade extension and retraction, blade position monitoring and recording, motor torque monitoring and recording, sensor monitoring and recording, and remote access to data. The electrical components utilized to meet the design requirements were to be as cost effective as reasonably achievable, facilitate future design modifications, and produce an overall package that was easily transportable.

The need to perform motion control (motor operation) and data acquisition (sensor, torque, and position monitoring) eliminated a laptop computer as a viable candidate due to the type and number of special computer cards required. It was also not desirable to use a standard PC due to size and cost restrictions. The inexpensive cost and flexibility of an eight-bit microcontroller proved to be the most flexible and compact design option that could easily incorporate the desired features. In addition to the main controller, a single axis servo motor controller peripheral card, 12-bit analog to digital converter card, and 16 Megabyte PCMCIA memory storage card were used. The serial port available on the embedded controller was used to interface to the serial port on a standard laptop computer for data transfer and permanent storage. User interface was performed through two 20 character by 4 line LCD displays and a 20 character keypad that interfaced directly to the embedded controller. The entire embedded controller package resided in a package that was 11" x 8" x 7", excluding power supplies.

As part of the electrical design, it was desirable to know when the CPOSS blade had been deployed or fully retracted. Due to space restrictions, it was deemed undesirable to use electromechanical switches to monitor the CPOSS blade position. Instead, the number of motor shaft rotations was counted by an incremental encoder mounted on the rear motor shaft. Provided no mechanical linkage failure, it could be determined from the number of motor shaft rotations the position of the CPOSS blade. Since it was not known the exact amount of torque that would be required to deploy the CPOSS blade in different soil compositions, a shunt resistor was placed in line with the DC common wire to the motor power. This signal was amplified by an OP07 operational amplifier and fed to the 12-bit analog to digital converter card. By monitoring the current draw through the motor, the corresponding torque could be calculated. Excess current conditions could also be monitored to prevent motor damage. Furthermore, mechanical failure could be detected by monitoring the current draw by the motor. A significant and unexpected decrease in current draw by the motor was indicative of a sudden decrease in motor load and thus a strong indicator of a mechanical failure in the deployment mechanism.

The position and motor current values were constantly monitored during deployment and retraction with the values being written to the embedded controller memory storage card. The data saved on the memory storage card was retrieved by a laptop computer through the embedded controller serial port and easily converted to an Excel based file once the download was complete. Analysis of the downloaded data was useful for tracking required torque versus blade position and for determining torque requirements for different soil compositions, and for determining mechanical limits of the CPOSS system. The same memory storage routines and analog to digital card will be used in the future to capture sensor data as well.

Due to the distance between the motor encoder and embedded computer equipment , up to 100 feet, it was necessary to install a high current differential driver / receiver pair to successfully transmit the encoder information to the embedded controller unit. It was also determined that there was sufficient electrical noise from the motor power wiring to interfere with the encoder signals. Integration of the transmitter / receiver pair and separate cabling for the motor and encoder provided sufficient electrical isolation to allow the encoder signals to be read through 100 feet of cable.

Operator interface was primarily performed through the embedded controller's keypad and LCD displays. Operation of the controller consisted of selecting the type of deployment arm attached (rack drive or linkage drive) and selecting either the automatic deployment / retraction options, where the controller automatically stopped operation when the motor reached the desired position, or jog deployment. All data during either remote or jog deployment / retraction was captured on the embedded controller's 16 megabyte memory card. The controller had a built-in stall limit that ceased operation of the motor when the motor current exceeded a preset limit. The operator had the ability through the keypad to enable or disable these features. The maximum current drawn by the motor, instantaneous current being drawn by the motor, and present position of the CPOSS arm were displayed during retraction and deployment operations. If the unit was in automatic mode, the display alerted the operator when the requested operation was complete. If the stall limit was active and the stall current exceeded during operation, the display indicated a stall condition had occurred and ceased operation of the motor.

2.2 Testing

2.2.1 Manually Deployed Prototype

The manually deployed prototype was inserted in the ground approximately eight inches. The removable head was replaced with the deployment head and the load cell and bolt clamp mechanism attached. The system load was applied by slowly turning the drive bolt on the clamping device. The torque at the blade shaft was calculated based on the measured load applied. (See chart below) Initially the blade shaft twisted before deployment was achieved. A new shaft was fabricated with a 25 percent increase in diameter. The larger diameter shaft enabled CPOSS to successfully deploy. Deployment was confirmed by digging down to the blade location to verify extension of the sensor blade. These results were repeatable, however the gear teeth sustained some damage.

Test Number	Load Cell Reading (lbs)	Torque (inch-pounds)
1	800	400
2	530	265
3	770	385
4	560	280

In summary, the blade shaft torque required to deploy the CPOSS was calculated to be approximately 500 inch-pounds. This value was used as part of the design basis in selecting remotely deployable prototype components.

2.2.2 Rack and Linkage Driven Prototypes

Linkage Driven

The linkage driven prototype was initially tested by manually deploying the blade against a load cell. The test was designed to confirm that the prototype could produce the torque required to deploy underground without damage. The input torque was measured to confirm adequacy of the selected drive motor. The rack driven prototype was not tested in this manner due to time constraints.

Initially, the measured input torque to the drive mechanism exceeded the output of the selected gear head before achieving the desired deployment torque. All moving components were then coated with a lubricant and testing was repeated. After lubrication, the input torque was within the operating range of the selected motor and gear head set. At one point, as the blade loading increased, the torque began to decrease and it became evident that some failure had occurred. Upon disassembly of the CPOSS it was discovered that the taper pin which locked the linkage to the blade shaft had started to tear through the shaft taper pin hole. The taper pin was redesigned, reducing its average diameter while maintaining the same taper. Because of time constraints the modified linkage driven prototype module was coupled to the electric motor drive unit and delivered to the CPT for field deployment without retesting in the laboratory.

The linkage driven prototype was attached to the cone penetrometer system and lowered beneath the truck. The blade was actuated to confirm operation prior to inserting the penetrometer into the ground. The module was inserted to a depth of approximately 13 feet. The deployment mechanism was activated and the pattern of measured current values was as expected. The encoder count indicated that the blade had fully deployed. The mechanism was then retracted. The encoder count indicated complete retraction. The CPT then removed the unit from the ground. Some superficial damage was indicated on the leading edge of the blade, however the unit remained functional. Soil samples were taken and torque measurements were recorded for further analysis.

Rack Driven

The rack driven prototype was tested by manual insertion into the ground to a blade depth of approximately six inches. Due to time constraints previously mentioned, the spur gear from the manually deployed prototype was reused in this unit. Upon attempt to deploy, it became evident that some failure had occurred due to a reduction in input torque required. Disassembly of the unit revealed that two of the spur gear teeth had been sheared off. It was postulated that this may have been due to a defective gear as a result of earlier use where the gear was subjected to repeated testing under severe load.

The spur gear, shaft, and blade were replaced and the rack driven prototype was tested on the CPT. During underground deployment, however the motor current readings indicated a failure had again occurred. Upon removal and disassembly of this prototype it was observed that two gear teeth had been sheared off of the spur gear as observed in the previous tests. At this point, development of the rack driven prototype was discontinued.

Control System

Lab and field-testing proved the viability of the electrical portion of the CPOSS system. The encoder counts proved to be a good indicator of blade position. The motor current value proved to be a good indicator of the torque output of the system and was also a good indicator of when mechanical failure either was impending or had occurred. It was determined during field testing that the stall limit selected for the system was significantly lower than needed and resulted in numerous aborted deployments due to the stall current being exceeded. As a result the stall limit was disabled for most of the field-testing.

The major electrical problems encountered during field-testing were broken wires and damage that occurred when the CPOSS probe was assembled onto other cone penetrometer piping. It was determined that better protection of the electrical components would be needed in future design work.

Data was stored on the embedded controller and was downloaded on demand to the laptop computer. The embedded controller reinitialized the data card whenever power was lost and reapplied to the unit or when the system reset button was depressed. In one instance, this resulted in the loss of data. It was later determined that sufficient space was available on the memory card to store all information without an automatic reset feature.

This feature will be replaced by a memory reset on demand feature in future design revisions.

3. TECHNICAL RESULTS

One of the primary engineering challenges in this CPOSS development activity has been that of successfully configuring an efficient, reliable, and compact drive system compatible with the cone penetrometer application. The limited development and testing results to date suggest that a successful drive system can be developed.

Test results to date have been positive with regard to deployment of the sensor blade beneath the ground surface. Testing has been limited due to funding and scheduling challenges. The linkage drive system concept in its current form is usable, but not optimal. That is, physical deployment may be achieved, however attaining repeatable deployments will require further development. The forces required to create the desired mechanical movement in this environment are extreme. The dimensional constraints provided add a formidable challenge to generation of these forces. The linkage drive system has shown that the deployment motion is achievable. With some design modification and additional testing, the cone penetrometer off surface sensor will provide a reasonable method for characterization of the penetrometer "skin effect". It will also allow for subsurface characterization without the errors introduced by such effects.

4. STRATEGIC R&D PROGRAM STATUS

Throughout the year, problems arose with managing the spend plan and schedule associated with the Strategic R&D Program. As seen from the chart below, where predicted spend plan is compared against actual spend, the project was severely under funded.

Month	Predicted Spend Out ($K)	Actual Spend Out ($K)
October	0	0
November	0	0
December	0	0
January	1	1.9
February	5	6.6
March	14	2.7
April	22	18.1
May	11	16.6
June	22	7.8
July	12	48.2
August	8	2.1
September	5	32.4
Totals	100	136.4

The funding issues and subsequent stop work order placed on the project led to the schedule deviations. Funding problems became evident in July. Machine shop work on both prototypes was ongoing at the site machine shop, 717-A and the SRTC machine shop, 749-A. A stop work order was received when the spend out reached 90% of the total funded amount. Upon investigation of how the money was being spent, it was determined that the time to complete the prototype was underestimated.

Due to the stop work, all work was put on hold until additional money could be obtained to complete the prototypes. Scheduling conflicts arose and the field-testing was delayed three weeks until September. Additional funding was received, near the end of August, through the Strategic R&D Program and ERD. Machine shops restarted work on the prototypes, but were required to work overtime to meet the schedule.

Fabrication of the prototypes was completed over Labor Day weekend, two days before field-testing. Additional machine shop work was also needed to support the field-testing.

The Principal Investigators on the CPOSS were also faced with other site work taking priority over Strategic R&D. Though this problem is not a new one, additional awareness must be raised that research and development is vital to the success of SRTC and an important compliment to our site customer work.

5. Future Work

During the field tests, EES was able to work with Environmental Restoration Technology and ARA personnel to develop a list of design modifications that would make the CPOSS system more robust. These modifications include:

- Make the unit a single module.
- Provide mounting brackets for the motor drive and encoder cables.
- Provide an area for the CPT ram to grasp.
- Select stronger materials for the blade shaft and pin.
- Make the control system more user friendly.

EES has also received $125K, each of the next two fiscal years (FY00 and FY01) from the EM-50, Subsurface Contaminants Focus Area, for incorporation of subsurface characterization sensors into the CPOSS. Success of this EM-50 project will depend directly on EES receiving Strategic R&D funding in FY00 to incorporate the modifications listed above into the design.

6. Attachments

None