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Steerable/Distance Enhanced Penetrometer Delivery System

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4.4 Steerable/Distance Enhanced Penetrometer Delivery System

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Introduction

The first steps toward contaminant plume containment and remediation are detection and mapping of the plume. Penetrometers can be used to map the plume efficiently and also provide the means for in-situ sampling and remediation. In traditional penetrometer applications, the instrumentation package located at the tip measures soil resistance. However, for environmental monitoring purposes, an array of environmental sensors is packed inside the penetrometer rods for in-situ sampling and analysis, or for collection of laboratory samples.

At present, penetrometer applications are limited primarily to vertical pushes and because of their heavy weight, the use of penetrometer trucks over shallow buried storage tanks is restricted. To close the technology gap in the use of penetrometers for environmental purposes, UTD took the initiative by developing a new position location device referred to as POLO (short for Position Locator), which provides real-time position location without blocking downhole access for environmental sensors. The next step taken was the initiation of work to make penetrometers steerable and capable of greater penetration capabilities. The product of this work will be a relatively lightweight vibratory steerable penetrometer that can provide greater penetration capability than traditional penetrometers of the same weight, permitting applications over shallow buried storage tanks.

The initial development of POLO was carried out through internal funds at UTD. Recognizing the benefits of this new technology, DOE Morgantown Energy Technology Center (METC) funded the development of a prototype system under a PRDA contract. At the completion of the PRDA contract in September, 1994, for the first time the penetrometer operator had the capability of knowing the position of his sampling locations. Encouraged by this capability, DOE awarded UTD a new contract to develop a steerable distance enhanced penetrometer delivery system. In addition, in order to bring POLO into the commercial market in a timely fashion, the new contract was modified (in-scope modification) and new tasks were added to integrate a commercial POLO into a Site Characterization and Analysis Penetrometer System (SCAPS) truck. The new contract including its in-scope modification was awarded under a Research Opportunity Announcement (ROA) program and

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is comprised of a base program (Phase 1) and two optional phases (Phase 2 and Phase 3).

**Objectives and Approach**

An objective of this research effort is to complete the development of steering and vibratory thrusting capabilities for penetrometer delivery systems. Steering permits controlled directional use of the penetrometer, and vibratory thrusting can provide greater depth penetration and improve the ability to penetrate harder materials. Another objective of the research effort is to integrate a commercial POLO into a SCAPS truck.

The project consists of three phases. Phase 1 included analysis, design, and laboratory experiments covering the individual sub-systems required to perform vibratory thrusting and steering of penetrometers. In addition, the work in Phase 1 included the design, assembly and integration of a commercial POLO system into a SCAPS truck.

Phase 2 work includes the integration of all steerable, navigational, and vibratory thrusting components and Phase 3 work includes field testing and demonstration of the full-scale integrated steerable/vibratory system.

**Project Description and Results**

In order to accomplish the project objectives, a commercial POLO system was manufactured and tested for compatibility with a SCAPS truck. In addition, several sub-systems of a steerable vibratory penetrometer system were analyzed, designed and manufactured. Later, the performance of the various sub-systems was verified through laboratory and field tests. The main sub-systems of a steerable vibratory penetrometer system described in this paper include the steerable tip, and penetrometer rod joints.

**Commercial POLO System**

Capabilities of the prototype POLO system were demonstrated under a DOE sponsored PRDA contract in July, 1994[1]. The optimum way to make commercial POLO systems available to DOE contractors was to develop a commercial system integrated into a SCAPS truck. This effort involved the design and manufacturing of a commercial POLO module, its initializer, and the integration of a user friendly data acquisition package as shown in Figure 1.

The POLO rod module, the main component of the system, measures bending strains imposed on it as it is pushed into the ground. The strain signals are processed by UTD's down-hole data acquisition package and sent to the surface computer through a two-wire umbilical. The POLO initializer is used to measure the initial orientation of the penetrometer rod as it begins to penetrate the soil surface.

The POLO surface computer is a portable "lunch box" computer connected to an up-hole processor box which receives the strain signals. The computer is also connected to two clinometers of the initializer. The POLO tracking program installed on the surface computer utilizes the strain signals and initializer readouts to compute the path of the penetrometer tip. The tracking data are updated at the end of 1 meter shoves. Figure 2 shows a sample of the tracking data. The data shows the X and Y coordinates of the tip on a reference circle and the Z coordinate along a depth bar. The origin of the reference coordinate system is at the point of insertion of penetrometer rods into the ground. X and Y are orthogonal axes on a horizontal
Figure 1. POLO system components.

Figure 2. Sample tracking program output.
plane and the Z axis is a vertical axis passing through the point of insertion.

Field tests were performed in order to test POLO within the confines of a SCAPS truck and to familiarize the SCAPS operator with the use of POLO. Figure 3 shows the POLO computer inside the operator compartment of the SCAPS truck and Figure 4 shows POLO initialization in progress.

Figure 3. POLO computer inside SCAPS truck.

The results of SCAPS field tests indicated that POLO fits within the confines of the penetrometer truck and does not hinder the normal operations of the truck. At present, commercial POLO systems are available for sale to DOE contractors and commercial penetrometer truck manufacturers and operators.

Steering Tip Analysis and Prototype Manufacture

Analysis and Laboratory Test Currently, penetrometer rods are passive devices used to deliver a set of sensors to a desired underground destination but with no ability of on-line trajectory alteration to correct for course alteration due to unforeseen obstacles. Upon successful completion of this contract, future penetrometer systems will include a steering mechanism, permitting maneuvering of the penetrometer tip. Prior to the development of such a system for commercial applications, a laboratory study was performed to identify system parameters, tool configuration, and operational procedures. The primary purpose of the study was to show that tip maneuver is possible, and to determine procedural guidelines and operational boundaries. In the following paragraphs, a description of the steering methodology is provided. The description includes penetrometer rod and tip modeling, simulation of the penetration process in terms of tip trajectory, and sizing of the force-couple system associated with the penetration process. Laboratory test results validate the theoretical model, test data are compared to simulation results and the prototype steering tip capabilities are demonstrated.

Steerability of a penetrometer may be defined as the ability to change the curvature of the rod and the orientation of its bending plane in real-time in order to achieve a prescribed penetration path. Steering can be achieved by the application of a transverse force to the front end of the rod. Generation of such a force may be
accomplished by a directional actuator in the form of a wedge or an oblique conical tip. The intensity of the force depends on the system parameters associated with the penetration process. Some of these parameters are related to the soil properties such as density, angle of internal friction, angle of friction between the soil and steel (skin friction), and point bearing capacity of the soil. Other system parameters are related to the rod material and diameters, the tip geometrical configuration, and penetration process dynamics. An analytical model was employed for a preliminary study and simulation of the rod steering mechanism. For simplicity enhancement, the mathematical model used in this simulation represented a two-dimensional domain and was based on incremental insertion of a planar penetrometer rod equipped with a planar directional wedged tip.

The lateral deflection of each element was modeled as a beam in accordance with the “simple beam theory”. The simulation generated the penetrometer rod trajectory and also computed the related force-couple history at the insertion point. A cantilever beam, shown in Figure 5, was selected as the fundamental element of the trajectory calculations and the deflection and rotation of its free end were calculated as a function of soil properties, rigidity of penetrometer rods and the tilt angle of the penetrometer tip.

In Figure 5, α is the wedge slope angle at the tip, δ is the friction angle between the soil and the beam material, \(Q_p\) is the tip point force, and \(q_p\) and \(q_o\) are the passive and at-rest distributed skin forces per unit length, respectively [2]. The modeled trajectory is an evolution of sequential additions of one beam to another in a tail-to-head fashion as depicted in Figure 5.

Applying soil mechanics principles, the distributed normal and skin friction forces were
calculated along the penetrometer rod as well as the point force at the rod tip [2], [3]. The following parameters were selected for simulation:

**Soil Parameters:**
- soil density: 120 lb/ft³
- angle of soil internal friction: 35°
- angle of soil-steel surface friction: 23°

**Penetrometer rod parameters:**
- outer diameter: 1.75 in
- inner diameter: 1.00 in
- modulus of elasticity: 28*10⁶ psi

The two-dimensional trajectory was generated by the deflected tip force. In this study, the selected tip angle $\alpha$ was fixed in magnitude for a particular trajectory but its polarity could be changed from $+\alpha$ to $-\alpha$ due to a tip command. In addition to trajectory generation, the simulation also computed the force-couple system at the insertion point, (the system origin). Components of the force-couple are the reaction shear force perpendicular to the rod axis, the normal "push" force along the rod axis of symmetry, and the reaction couple. The force-couple calculation for the entire insertion process provides the instantaneous reaction components as a function of the penetration depth that must be supported by the penetrometer insertion equipment.

A set of laboratory experiments was performed to test steerability capabilities of directional tips and also to validate the simulation model. Such validation will enhance confidence in the model and methods used, permitting the...
extrapolation of test and simulation results to real-time field work. Two phases of experiments were conducted. In the first, the test bed was constructed as a two-dimensional space to fit a two-dimensional rod and tip configuration. This reduced complexity arrangement allows comparison of test data to simulation results, as well as a preliminary validation of the steerability concept and capabilities. In the second phase of the experiment, the test bed was constructed as a three-dimensional space where a test rod simulating a penetrometer rod was tested for steerability. In both cases, the stiffness of the rod specimen was reduced so as to permit development of observable lateral displacements in the limited space of the laboratory environment.

Figure 6 depicts test results, where a rod with a 5° wedge angle was pushed into wet sand under a constant tip command. Comparison between simulation results and test data, shown in Figure 6, reveals good agreement. The departure of the test data from the simulation output toward the tip of the rod, shown in Figure 6, is mainly due to the proximity of the tip to the sandbox boundaries.

![Figure 6](image.png)

**Figure 6.** 5° wedge angle with constant tip command: trajectory -- comparison between simulation results and test data.
In another case, shown in Figure 7, the rod with a 5° wedge angle was pushed into wet sand under a variable tip command. At about 18 inches deep, the rod was carefully pulled out all the way and then returned reversed, to reflect a change in tip command polarity from +5° to -5°. Also for this case, comparison between simulation results and test data, shown in Figure 7, reveals good agreement. Again, the departure of the test data from the simulation output toward the tip of the rod, shown in Figure 7, is mainly due to the proximity of the tip to the sandbox boundaries.

Upon completion of the 2D tests, the sandbox was extended and tests were carried out in three dimensions using a cylindrical specimen with a 5° oblique cone as shown in Figure 8. Experimentally observed deflections are compared with simulation results in Figure 9. In Figure 10 the normal forces measured during the experiment are compared with those predicted by the simulation model.

The simulation study and laboratory test results provide an insight into the directional penetrometer technique and a preliminary parameter evaluation methodology. Test data collected at the sandbox experimental facility were used to establish initial guidelines for directional penetration. The results of the laboratory steering tests led to two important conclusions. First, it was shown that it is possible to reverse the direction of travel of the penetrometer rod by changing the tilt angle of the tip. Second, the simulation model predicted deflections and force levels accurately. As a result, a very useful tool is now available for designing of the prototype and full-scale steering tips.

Prototype Steering Tip Manufacture
Steerability is defined as the ability to change the curvature of a penetrometer rod and the orientation of its bending plane in real-time. Two main factors affect the ability to steer a penetrometer rod toward a prescribed target. One is the ability to generate a transverse bending force of a desirable magnitude at the penetrometer tip; the other is the ability to change its orientation with respect to the rod body so as to achieve tip spatial maneuverability. To this end, several design options were considered, some of which were of the passive tip configuration while others were associated with active tip mechanisms. All options considered for transverse force generation involved tips formed as a simple wedge or an oblique cone.

Using the passive tip approach, a fixed tip configuration is installed. Pushing of the penetrometer rod with such a tip generates rod deflection constantly. In order to reach a specified target, on-line tip position detection coupled with continuous reorientation of its transverse bending force is essential. Obviously, these activities must be commanded from the ground surface. This requires the application of an increasing continuous axial torque to the entire penetrometer rod system. In long pushes, the constant reorientation of the tip from the surface can slow down the penetration process considerably.

The active tip approach involves a mechanical tip installed at the rod front end that can be actuated to turn or change its position through signals sent from the surface. A tip for this purpose will have many mechanical parts and will require an umbilical for the actuation signals. Because of the vibratory nature of the penetration process, a mechanical tip with many parts is susceptible to breakdown and fatigue failure of components and connections. In addition, the actuation signal umbilical occupies a fairly large volume inside the penetrometer.
Figure 7. 5° wedge angle with variable tip command: trajectory -- comparison between simulation results and test data.

Figure 8. Cylindrical specimen with 5° oblique cone.
Figure 9. 5° cone angle: trajectory comparison between simulation results and test data.

Figure 10. 5° cone angle: normal force comparison between simulation results and test data.
rods, leaving little or no space for the umbilicals of the environmental sensing instruments.

Realizing the limitations of the fully passive or fully active steering tips, it was decided to use a semi-passive tip developed and patented by Foster-Miller Incorporated for ground piercing applications. The semi-passive tip shown in Figure 11 can be pushed into the ground either in a symmetrical configuration, as shown, or in an asymmetrical fashion as shown in Figure 12. The change from symmetrical to asymmetrical configuration is achieved through rotation of the penetrometer rod by 180°. The stabilizer fins at the tip keep its position locked until another 180° rotation is performed from the surface. The advantages of the semi-passive tip lie in its mechanical simplicity and the limited need for re-orientation from the surface, making it easy to use and control in the field. If an unexpected barrier is encountered, the penetrometer tip can be drawn back and redirected to maneuver around the barrier.

The simulation model described earlier was used to determine the tip cone geometry and its angle of attack that would limit the rod bending below the failure margin. A prototype steerable tip was then manufactured and tested in the field. Two sets of tests were performed in two different soils. The tests were carried out at two sites, Ft. Belvoir (1), and Fredericksburg (2), Virginia, using a field POLO module and the META-DRILL vibratory penetrometer system purchased for this project. This equipment is shown in Figure 13. The soil at site 1 consisted of very stiff clay, whereas the soil at site 2 consisted of medium dense sand. The first objective of these tests was to verify that tip configuration changes from symmetric to asymmetric upon a 180° rotation of the rods from the surface. The second objective was to determine the radius of curvature of the bends generated by the steerable tip in different soils.

The tests were begun by setting up the META-DRILL rig at each site and connecting the POLO unit equipped with the steerable tip to the vibratory head. Initially the steerable tip was positioned in a symmetric position (for straight pushes). After about six inches of penetration the drilling operation was stopped and the POLO unit was turned 180° counterclockwise, activating the tip to its asymmetric configuration for a curved push. The POLO tracking program was then turned on and penetrometer operation resumed. The tests were completed after 74 inches of penetration in stiff clay and 173 inches in medium dense sand.

Table 1 shows the radius of curvature of penetrometer rods due to steering in each of the two sites. The radius of curvature for each test was obtained by using the POLO predicted coordinates of the tip. According to Table 1 the radius of curvature obtained in stiff clay was 114 ft, whereas that obtained in sand was 90 ft. It is worth noting that the initial inclination of POLO was vertical and all the tip displacements were due to bending of the rods by the steerable tip.

Penetrometer Rod Joints

Penetrometer joints commercially used today are designed for penetrometer rods inserted in straight trajectories. A typical penetrometer joint is shown in Figure 14. Under straight insertion conditions, the axially applied compression load is transmitted through the shoulders of the mating rod sections. If the joint is subjected to bending due to steering of the penetrometer tip or due to encounter with geologic anomalies, several weaknesses in the joint design may cause failure or permanent damage in the joint.
Figure 11. Semi-passive steering tip in a symmetrical configuration.

Figure 12. Semi-passive steering tip in an asymmetrical configuration.
One of the weaknesses of a typical joint in bending is the shoulder contact. As shown in Figure 14, thread stresses are intensified in one region of the bend. In addition, the shoulder bearing load is decreased in the tensile region of the bend, and at small axial compressive loads this part of the shoulder may actually separate, resulting in a reduced section modulus. On the other hand, the opposite part of the shoulder will be subjected to increased bearing stresses which can permanently damage the joint.

Another problem with the use of commercial penetrometer joints in a steerable system is loosening of the joints under counterclockwise steering torques. This can happen when the rods are turned from the surface to steer the tip and the steering torque is applied in the opposite direction to that for tightening the joint. To overcome the problems associated with standard joints, a locking joint concept developed earlier by UTD was adapted for the steerable vibratory penetrometer system.

Table 1. Steerable tip field test result.

<table>
<thead>
<tr>
<th>Site</th>
<th>Soil Formation</th>
<th>Radius of Curvature</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ft. Belvoir</td>
<td>Stiff Clay</td>
<td>114 ft</td>
</tr>
<tr>
<td>Fredericksburg</td>
<td>Medium Dense Sand</td>
<td>90 ft</td>
</tr>
</tbody>
</table>

Figure 13. Field testing with the META-DRILL.
To verify the performance of the joint for steerable penetrometers, a set of new joints was machined and tested in a test frame built especially for this purpose. The test frame shown in Figure 15 applies bending moment and axial load simultaneously to a 28 inch long simply supported rod. The joint loadings can be varied independently.

Figure 16 is a summary of test results performed on four different rods made of the same material. In order to establish a baseline, one of the rods tested was jointless. The other three specimens were jointed rods, one using a commercial penetrometer joint, another using the new steerable joint, and the third using the new steerable joint combined with its joint locking mechanism. According to Figure 11, the jointless rod started yielding at a deflection of 0.21" which corresponds to a radius of curvature of 29'.

The curve for the commercial joint had an initial dogleg at 0.07" deflection or 85' radius of curvature. In practice it is common to keep the radius of curvature of commercial rods above 100' to avoid damage to the joints. Another observation related to the shouldered joint is the general yielding of the metal which starts at 0.17" of deflection or 35' radius of curvature. The curve for the steerable joint is very similar to that of the jointless rod except that the joint starts yielding at 0.19" of deflection or 31.5' radius of curvature. In contrast with the commercial joint, the steerable joint does not go through a dogleg phase. Bending test results on the steerable joint equipped with a locking mechanism (Figure 16) indicated that for all practical purposes its performance approached that of the jointless rod.

In addition to bending tests, laboratory torque and field performance tests were performed on the locking joints. The design torque for the locking joint had been selected at 9,000 in-lbs. The torque test was performed at 9,130 in-lbs without any observable damage to the locking joint mechanism.

The field test carried out on the locking joint consisted of vibratory testing using the META-DRILL. The purpose of this test was to
Figure 15. Test frame for laboratory testing of joints.

Figure 16. Results of laboratory tests on four rods.
push the locking joint into the ground and to examine its performance under the harsh vibratory environment. After several minutes of vibrations into the ground the locking joint was brought to the surface and examined. The examination indicated that with the exception of a minor component that had come loose, the entire assembly had remained intact and had performed as expected.

Tests For Effects Of Vibrations On Resisting Forces

In normal penetrometer applications the resisting forces exerted by the soil on penetrometer rods depend on the geometry of the rods, and the type of soil. However, under vibratory loading the constant motion between penetrometer rods and the soil reduces the magnitude of the resisting forces because a dynamic rather than a static coefficient of friction applies, which in turn increases depth of penetration for comparable thrust levels. To test this hypothesis, two sets of field tests were carried out with the META-DRILL rig at the aforementioned sites 1 and 2, where site 1 consisted of very stiff clay and site 2 of medium dense sand.

In these tests, first the hydraulic thrusters of the META-DRILL rig alone were used to thrust penetrometer rods into the ground. The vibratory drive was off during this stage of the test. The length of rods pushed into the ground was 32.5" in clay and 24" in sand under a thrust of 1500 lbs. After the rods stopped under the 1500 lbs of thrust, the vibratory drive was turned on, which made it possible to push additional length of rod into the ground equal to 53" in clay and 276" in sand.

The frequency of vibrations in clay was approximately 100 Hz which translates to 1875 lbs of dynamic load. In sand the frequency of vibrations was about 140 Hz which translates to 3,675 lbs of dynamic load. A review of the test results indicated that when the vibrations were turned on, the total thrust force was increased by 125% in clay, but the length of rods pushed increased by 163%. This is an indication that the dynamic nature of the load affected the soil-rod interaction. In sand the effects of vibrations were more pronounced, because by increasing the total force from 1,500 lbs to 5,175 lbs (1,500 lbs static + 3,675 lbs dynamic), namely, an increase of 245%, the length of rods pushed into the ground was increased by 1,150%.

The effects of vibrations were quantified in more detail by applying principles of soil mechanics. In this approach, physical properties of the soils were back calculated from the lengths of rod pushed into the ground by hydraulic thrusting alone. Then the resisting forces for the entire penetration length in clay and sand were calculated and compared with the actual forces, static and dynamic, exerted in the field. The results are shown in Table 2. According to this table the resisting forces under vibratory loading were reduced by 15% in the very stiff clay soil and 48% in medium dense sand.

Application

A steerable, vibratory penetrometer system has many applications in the environmental clean up area. The system can be used in conjunction with POLO to characterize and remediate contaminant plumes at specific locations under buildings and buried storage tanks. It is insensitive to the presence of magnetic or gravitational influences. Because of its light weight the system can also be used over shallow buried storage tanks. These applications will reduce the cost of clean up because of more focused characterization and remediation. They
Table 2. Reduction of resisting forces due to vibrations.

<table>
<thead>
<tr>
<th>Soil Formation</th>
<th>Penetration Length (ft)</th>
<th>Required Thrust (Static Conditions)</th>
<th>Applied Thrust (Static + Dynamic)</th>
<th>% Reduction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Very stiff clay</td>
<td>7.2</td>
<td>3,942 lbs</td>
<td>3,375 lbs</td>
<td>15%</td>
</tr>
<tr>
<td>Med-Dense Sand</td>
<td>25.0</td>
<td>10,052 lbs</td>
<td>5,175 lbs</td>
<td>48%</td>
</tr>
</tbody>
</table>

also provide for in-situ remediation in locations that are not reachable with the current penetrometer technology.

Ongoing and Future Activities

At present, the Phase 2 work, which consists of integrated design of the full-scale steerable vibratory penetrometer system is underway. This work is expected to be completed in the winter of 1996. Upon completion of the Phase 2 work, and award of the Phase 3 option, the full-scale system will be manufactured and field tests will be performed to demonstrate the capabilities of the system. The field tests are expected to occur in the fall of 1996.

References


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