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Deep Installation Method for Three-Component Seismic Sensors

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Deep Installation Method for Three-component Seismic Sensors

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Abstract

Vector-dependent seismic sensors provide advantages in discriminating and localizing source signals of interest. To achieve this, optimal sensor installation must ensure proper and known orientation and coupling with the surrounding medium, as these will directly affect recorded signals used in signal processing routines. Certain applications require installation of a three-component seismic sensor at several meters' depth, achieved by installing sensors within a borehole; however, there are no standardized procedures for installation. A previous experiment created an installation procedure for a three-component seismic sensor in a hard rock environment. Applying the process from the prior three-component sensor experiment, four three-component seismic sensors were successfully installed at a 10-m depth in a soil environment. The sensor tests conducted afterwards confirmed that the sensors were operable, and the installation procedure was considered successful. This report describes the installation process, lessons learned, and recommendations for improvements in the process and applications to other installation environments. This information will ultimately be used as a basis for installations of deep three-component seismic or geophysical sensors and for creation of an installation procedure for a three-component seismic sensor that a non-expert can execute successfully with minimal training.

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Contents

Abstract	ii
Figures and Tables.....	iv
Preface	v
1 Background.....	1
2 Installation	3
2.1 Purpose.....	3
2.2 Test site.....	3
2.3 Geologic setting.....	4
2.4 Installation execution	7
2.4.1 <i>Installation steps</i>	7
2.4.2 <i>Installation execution for remaining locations</i>	21
3 Lessons Learned and Recommendations.....	24
4 Conclusion.....	29
References	30
Appendix A: Sensor Information	31
Report Documentation Page	

Figures and Tables

Figures

Figure 1. Test site.	4
Figure 2. Near-surface stratigraphy of immediate installation area.	5
Figure 3. Lithostratigraphic column for test site.	6
Table 1. List of equipment and materials used during installation.	8
Figures 4. Installation hardware components are the magnetic cap (4A) and segmented rods (4B). Figure 4A shows a close-up view of the tight fit of the magnetic cap attached to the sensor plate with one peg visible to aid in controlled release of the cap.	9
Figure 5. Three-component sensor hardware from prior experiment (bottom) and this experiment (top). The X or north direction for the sensor is shown by the notch in the orange part of the exterior casing.	11
Figure 6. Installing sensor hardware plates and rods on three-component sensor.	11
Figure 7. Plate of the previous sensor (right) and the sensor used in this experiment (left) for hardware verification.	12
Figure 8. Installation magnetic cap with paracord.	13
Figure 9. Demonstration of tight fit between the magnetic installation cap and the sensor plate.	13
Figure 10. Sensor with orienting notch (orange part), magnetic installation cap, and install tool with orientation stripe.	14
Figure 11. Adding segments to the installation tool.	15
Figure 12. Levelling sensor using install tool and 3-way bubble level.	16
Figure 13. Orienting the sensor to north using a compass and alignment/orientation stripe on the install tool.	17
Figure 14. Borehole camera front and bottom view.	18
Figure 15. Using PVC pail with trapdoor to lower Drylok powder down to the sensor.	19
Figure 16. Pouring water into top of install tool for cementing sensor coupling.	20
Figure 17. Screen shot from downhole camera to confirm sensor installation process.	21
Table 2. Installed sensor coordinates.	23
Figure A1. Sensor specification sheet from the manufacturer.	31
Figure A2. Manufacturer certification.	32
Figure A3. Geospace sensor diagram.	33
Figure A4. Sensor specification values.	33

Tables

Table 1. List of equipment and materials used during installation.	8
Table 2. Installed sensor coordinates.	23

Preface

The work was performed by the Geotechnical Engineering and Geosciences Branch (GSG) and the Structural Engineering Branch (GSS) of the Geosciences and Structures Division (GS), U.S. Army Engineer Research and Development Center, Geotechnical and Structures Laboratory (ERDC-GSL), and the Signature Physics Branch (SPB) of the Research and Engineering Division (RR), ERDC, Cold Regions Research and Engineering Laboratory (ERDC-CRREL).

At the time of publication, Mr. Christopher G. Price was Chief, CEERD-GSG; Mr. Charles W. Ertle was Chief, CEERD-GSS; Dr. M. Andrew Niccolai was Chief, CEERD-RRD; Mr. James L. Davis was Chief, CEERD-GS; Dr. Jimmy D. Horne Jr. was Chief, CEERD-RR; and Ms. Pamela G. Kinnebrew, CEERD-GZT, was the Technical Director for Military Engineering. The Deputy Director of ERDC-GSL was Dr. William P. Grogan, and the Director was Mr. Bartley P. Durst. The Acting Deputy Director of ERDC-CRREL was Dr. David B. Ringelberg, and the Director was Dr. Joseph L. Corriveau.

COL Ivan P. Beckman was the Commander of ERDC, and Dr. David W. Pittman was the Director.

1 Background

Successful sensor installation is important, as it directly affects how the sensor will perform. If conducted incorrectly, it could seriously degrade the data received and collective system performance. This is especially pertinent for three-component (3C) seismic sensors that have the additional parameters of orientation and leveling in addition to the need to be well-coupled to the surrounding media. Installations at several meters' depth within a borehole are more challenging, since achieving coupling and orientation underground cannot be easily confirmed. Protecting the sensor cable and connection on the surface while working at several meter separation from the sensor in a borehole is an added challenge. Three-component seismic sensors are of interest, as they have additional advantages over their one-component counterparts because they sense motion in XYZ directions commonly used as vertical, east-west, and north-south directions; whereas one-component geophones sense only a single component, typically vertical motion.

Sensor installations need to be adapted to their specific geologic or environmental setting to ensure proper installation and optimal sensor performance. Installation procedures should be tested and evaluated for that specific environment prior to sensor deployment, especially when those sensors have a potential for long-term, several-year usage.

There is no commercially available installation tool for the specific 3C seismic sensor used in this test. An installation process and hardware were developed by Raytheon BBN Technologies for a previous government experiment to ensure that the sensor was oriented correctly and coupled to the surrounding rock at several meters' depth (Krumhansl et al. 2013). This report will document the process used to install the sensors in a cohesive soil environment.

Our target scenario for these sensors is that the source and receivers are in the near-surface (e.g. 100m or less) and the signals of interest are high frequency (e.g. 10-500Hz). Near-surface maximum depth extent is not an absolute value definition that applies to any or all near-surface applications and the bottom depth of near-surface will vary depending on the focus of the target (Butler 2005). The sensors are buried in the near-

surface with the purpose of being closer to near-surface sources as well as minimizing surface noise; both aspects improving the overall signal-to-noise ratio. High frequency signals attenuate quickly with distance; therefore, sensor placement needs to be close to the target source in order to capture relevant signals. As the propagation path is in the near-surface, this installation method has an objective to not change or have minimum impact on the native conditions of the subsurface. This extends to, for soil settings, the sensor installation using native materials for coupling and backfilling and typically not using a permanent cased borehole or drill mud for installation. This style of installation has a tradeoff as once the sensor is buried (installed) there is a minimal surface footprint; however, it is not possible to recalibrate, easily recover, or repair a buried sensor.

The seismological community are the most common users of borehole installations for their instrumentation; it is for different reasons, however. For example, their objective sensor condition is a stable thermal and pressure environment that their sensors need for optimal operation and to escape surface noise. They utilize boreholes tens to hundreds of meters deep in bedrock to provide these conditions. In addition, the sources they are trying to locate (e.g. earthquakes) are at kilometers to global distances where they use low frequency signals (0.008 to 50Hz) with their sensor responses focused on low frequencies. See Hutt et al. (2002) for more information. As their end goals are different, their guidance is not used in this installation method as it is not immediately applicable to the objective sensor use and near-surface target scenario discussed in this report.

2 Installation

2.1 Purpose

A test scenario for sensor evaluation created a need for four three-component sensors to be installed at 10-m depth within boreholes at the U.S. Army Engineer Research and Development Center (ERDC) Vicksburg station test bed. This installation applied the same process created by Raytheon BBN for rock application (Krumhansl 2013); however, this installation would be in a cohesive soil environment, which previously had not been attempted. The sensor installation was performed by experienced personnel, and the goal of this report is to document the process in detail, lessons learned, suggestions for adaptations to other installation environments, and recommendations for other installation methods or approaches.

2.2 Test site

Sensor installation was conducted at a site referred to as the Test Track located at the ERDC, Vicksburg, shown in Figure 1. The site was selected due to existing infrastructure and testbedding used for other seismic sensor applications. The portion of the Test Track used is a relatively flat, open grassy area and is topographically elevated. There are no overhead utilities in the immediate area of the boreholes, and there are no known underground utilities. The site is surrounded by a wooded area, and the topography slopes away from the site except to the west. Sensors were installed at locations labeled as 3C1 to 3C4 on the Figure 1 inset.

Figure 1. Test site.



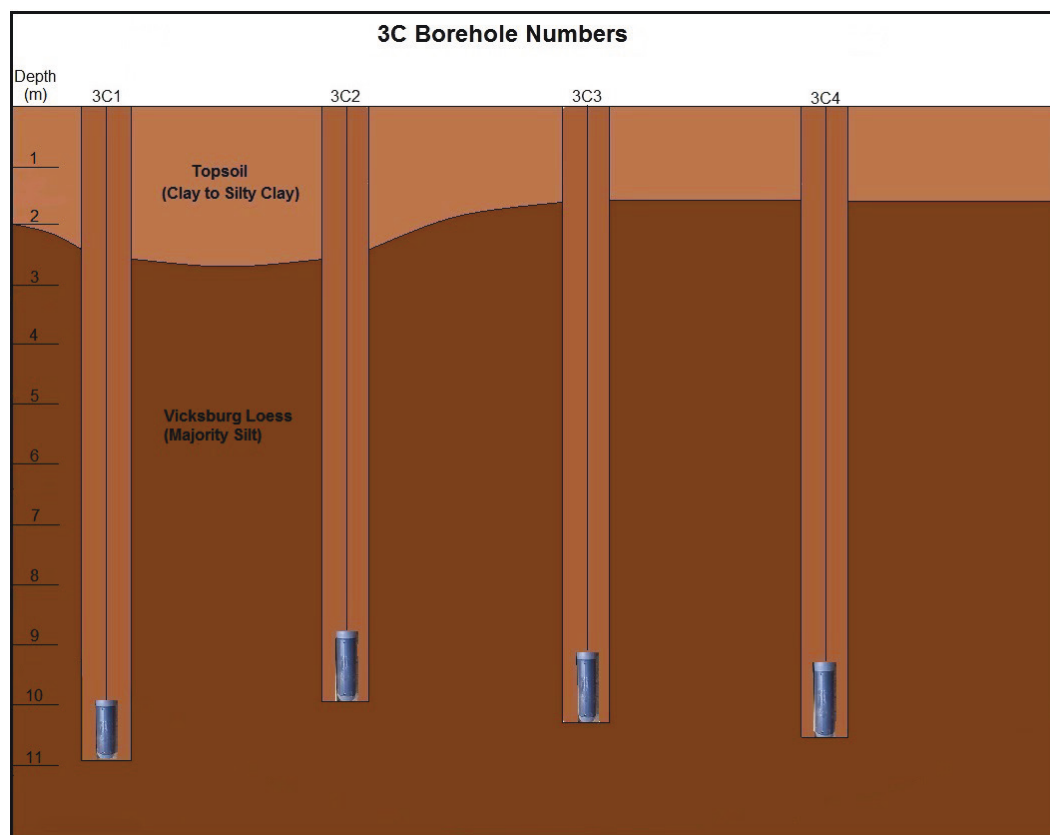
2.3 Geologic setting

This report focuses on the geology down to 10 m in depth, since this describes the subsurface material at the installation depth as well as a basis for the installation conditions at this location. Descriptions will assist in planning future installation applications where varying site conditions and geologies exist.

Figure 2. shows the geology at the Test Track. The topsoil varies slightly in the upper layer from approximately 1.5 to 2.5 m (5-8 ft), followed by a majority silt layer known as the Vicksburg Loess extending to depths of about 12 m. Groundwater was not encountered during drilling. General drill logs (geologic logs) noting the change in layers were recorded while drilling the boreholes. The test area geology is well-known by personnel, and it was expected that the boreholes would encounter similar geological

units or would show little variation from known conditions. If the installation area geology had been unfamiliar, boring logs would have been required as an additional step. Boring logs should include changes in geologic strata, water table, and any other features encountered (e.g. void, change in strata). Any soils should be classified using a standard logging system such as the United Soil Classification System (USCS). In-situ measurements such as hammer blow counts are valuable to tie engineering values to the logs as well.

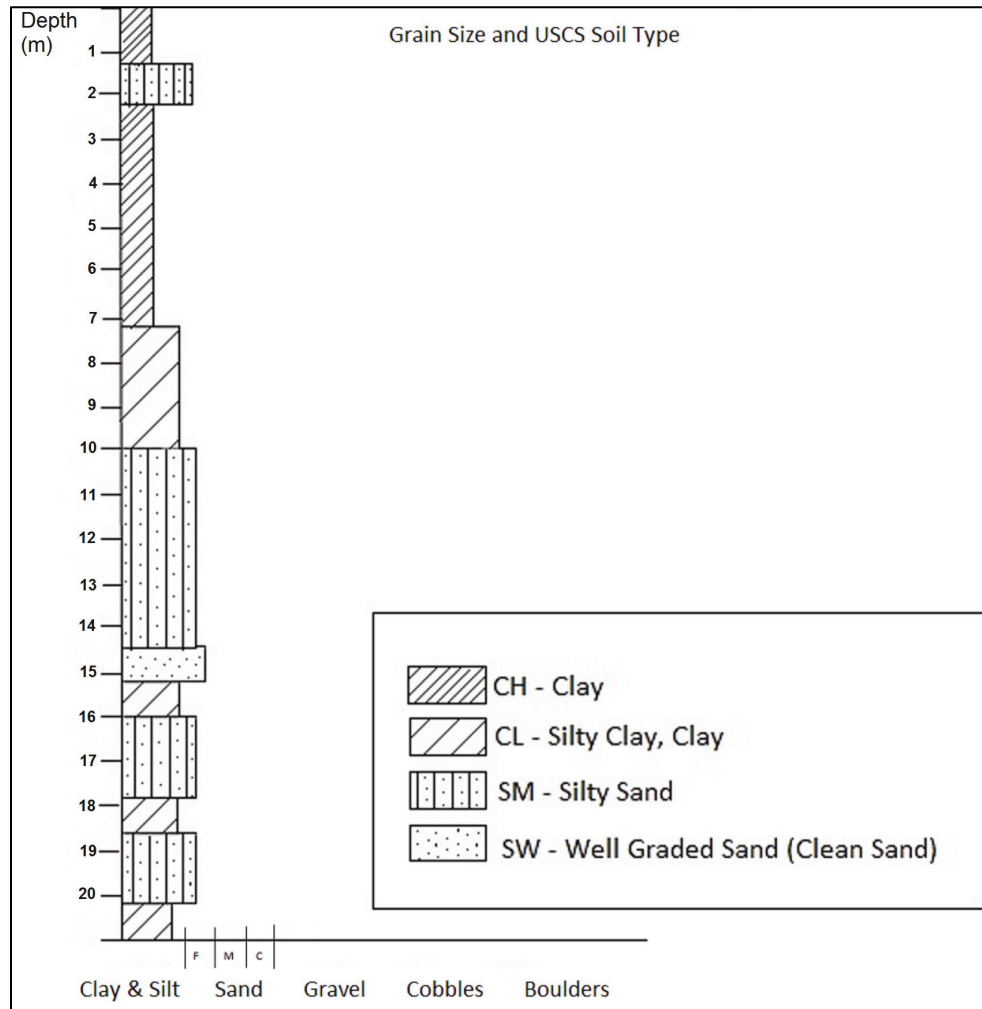
Figure 2. Near-surface stratigraphy of immediate installation area.



The sensors were installed in the Vicksburg loess layer. The Vicksburg loess is a fine-grained sediment that was carried downstream via post-glacial melt and then deposited as wind-blown clay, silt, and sand on the hills proximal to the Mississippi River alluvial valley (Murphy and Albertson 1996). The loess is not a uniform unit and does have some very thin layers of sand and clay. Figure 3 shows a stratigraphic column created off of observations during drilling at the test site. It is leached and calcareous at the surface but becomes less calcareous and more weathered with depth (Murphy and Albertson 1996). According to Krinitzsky and Turnbull (1967), internal drainage of the loess happens so quickly that the

loess does not become saturated unless there is a water table below, and the loess can remain somewhat dry a few feet below the surface. Prior tests conducted by Lutton (1969) and Krinitzsky and Turnbull (1967) show that the loess in this area ranges from 10% to 99% fines with liquid limits that range from 28-43%, plastic limits from 24-29%, a plasticity index ranging from 2-16%, natural water content ranging from 18%-33%, and density ranging from 79.4-96.2 lb per cubic foot (Murphy and Albertson 1996). Testing performed by Lutton (1969) showed porosities ranging from 45-53% and void ratios of 0.820-1.131. Quantitative information is provided here for characterization of this specific geology to aid in comparison to other geology settings for installation.

Figure 3. Lithostratigraphic column for test site.



The regional depth of loess in the Vicksburg area is variable and can be approximately 4.5 m (15 ft) thick or more. Below the loess are several formations of sedimentary deltaic deposits that can have local depositional variations. For more information on the strata below the loess, see Snowden and Priddy (1968).

2.4 Installation execution

2.4.1 Installation steps

2.4.1.1 STEP 1: Setup and materials

Prior to the installation, preparation activities included creating a sensor layout plan, obtaining geophones, procuring the installation tool, and determining how to install the sensors. Sensor hardware was custom-machined based on the pattern of the existing sensor hardware from a prior tested 3C geophone (Krumhansl et al. 2013), shown in Figures 4 and 5. In addition, other supplies were gathered such as Drylok cement powder and funnels. A complete list of equipment and materials is shown in Table 1.

Some items, specifically the PVC powder pail, rods and plate on the sensor, and installation tool with magnetic cap were all made from the previous installation of this type (Krumhansl et al. 2013).

The Drylok cement powder was selected as the coupling medium of choice as it had a medium value density similar to fill/sand or other commonly found material.* The Drylok would not create a weighing/heavy mass around the sensor yet would successfully bond quickly to the surrounding material. An undesired scenario could be having a coupling medium that would be orders of magnitude different in density from the native installation medium as it would create a different boundary condition that will translate into different attenuation, energy transfer function, and frequency response of incoming signals to the sensor.

* Rigaud, A. 2015. Personal communication.

Table 1. List of equipment and materials used during installation.

Four Geospace GS-Ones Three-component seismic sensors
Custom-machined rods and plates for attaching sensor to install tool
Subsea Video System Downhole Camera
Generator (power for downhole camera)
Extension cords for generator and downhole camera
PVC tube powder pail with trapdoor (for Drylok fast plug powder)
Drylok Fast Plug Hydraulic Cement Powder (1-2 buckets per sensor, 4 lb per bucket) – Primary Choice
Quikrete Hydraulic Water-Stop Cement Powder (20 lb per bucket) – Alternative if Drylok cannot be obtained
Engineering Compass
Three-bubble level (magnetic)
Custom-machined installation tool (with black stripe for easy alignment of segments and special seals for water flow)
Magnetic installation cap (one prong for easier detachment)
Paracord, 120-lb capacity (for lowering/tying things off)
Small ¼-in.-diam. funnel for water
Large 1.5-in.-diam. funnel for pouring Drylok powder
Small pitcher 16-oz (1-pint) capacity (spout and handle) for pouring water
Downhole tape measure
Tool bag with screwdrivers, pliers, wrenches, ratchet, electrical and duct tape, etc.
Sharpies (mark off depth or length as needed)
Tripod (to stabilize installation tool)
Flags or cones to mark borehole location
An anchor or weight (bucket with water worked well)

The installation tool had two main parts: a magnetic attachment cap and segmented rods with black striping down the side for orientation and alignment of the rods, referred to in this report as the installation hardware. The rods also had internal sealed connections to allow for the piping of water down to the sensor connection through holes on the magnetic tool cap (see Figure 4). There were seven rods, each approximately 1.8 m (6 ft) long, that could connect consecutively and a single rod with a flat top used for the top of the installation in a previous study. The attachment cap was a single-peg magnetic cap that allowed for easy detachment from the sensor's metal plate once the sensor was in place. Figures 9 through 15 show the tool in use.

Figures 4. Installation hardware components are the magnetic cap (4A) and segmented rods (4B). Figure 4A shows a close-up view of the tight fit of the magnetic cap attached to the sensor plate with one peg visible to aid in controlled release of the cap.



The sensor installation took place over three days in Vicksburg at the ERDC. The boreholes were all 6-in. auger drilled, and all but one had no permanent casing. Two to three days prior to the installation, there was approximately 8 in. (0.203 m) of rain, and the soil in the test area was saturated. Rain continued for the first day and then intermittently during installation. Light winds were present on the first day only and were not an issue on the second and third days. The weather and site conditions slowed down the installation and made it more difficult for the drill rig and personnel to move on site and conduct the installation. Information regarding the borehole and drilling are included as part of the installation process, as it affects the amount of time to complete and impacts sensor coupling and orientation.

The installed seismic sensors were three-component Geospace GS-Ones 15Hz, 1800 Ohm, in a PVC canister with a marsh nail case and 25 m of cable length made to fit in a borehole. The Geospace specification sheet listed the sensors as a SNG 3C GS-One Borehole CPVC, stated here solely for clarity. Prior experience with Geospace sensors with the marsh case show that they can be used in a wet environment and should be able to function for many years. The average sensitivity of the sensors installed over all three-component channels is 1.7867 V/i/s (69.2 V/m/s), as supplied by the Geospace sensor specification sheet. The sensors for this installation and the previous experiment are shown in Figure 1 Figure 5. The sensors are different in both exterior casing and interior components. However, both sensors are three-component seismic sensors and the orientation notch on one side at the top of the sensor, shown in

Figure 5, indicates the direction of the X or north channel. The GS-One sensors have an optional bottom spike to aid with sensor coupling; however, it was not applied for this installation because concrete was used for sensor coupling. When arriving from the manufacturer, the sensors do not come with the top plate and rods that are shown in

Figure 5. Small screws on the four corners are removed, and the plates and rods are added afterwards as shown in Figure 6.. The hardware for a single sensor is shown in Figure 7 and consists of one top plate with notches for the installation hardware magnetic pegs and sensor cable, four acorn nuts, four threaded rods, and four aluminum tubes that fit as sleeves over the top of each of the rods. The sensor hardware remained attached to the

sensor in the borehole. The plate and rods were machined using the prior experiment sensor as a template (Figure 7).

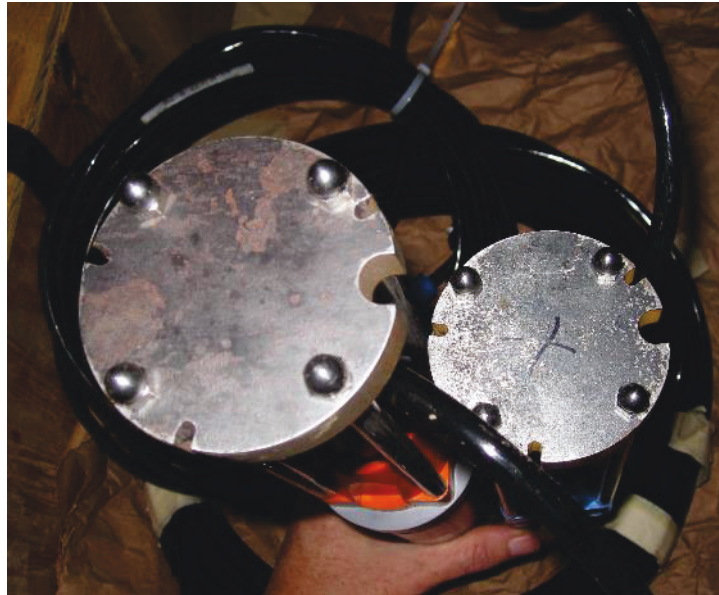
Figure 5. Three-component sensor hardware from prior experiment (bottom) and this experiment (top). The X or north direction for the sensor is shown by the notch in the orange part of the exterior casing.



Figure 6. Installing sensor hardware plates and rods on three-component sensor.



Figure 7. Plate of the previous sensor (right) and the sensor used in this experiment (left) for hardware verification.



The boreholes were drilled just before each sensor installation, i.e., on the same day or as soon as possible prior to the installation. The coordination of drilling and installation was executed specifically to minimize borehole collapse that could impact the sensor installation depth. For evaluation or estimation of complete installation time, the borehole drilling is important and is included in the report for consideration.

Sensor information as provided by the manufacturer is as available in Appendix A.

2.4.1.2 STEP 2: Borehole and install tool verification

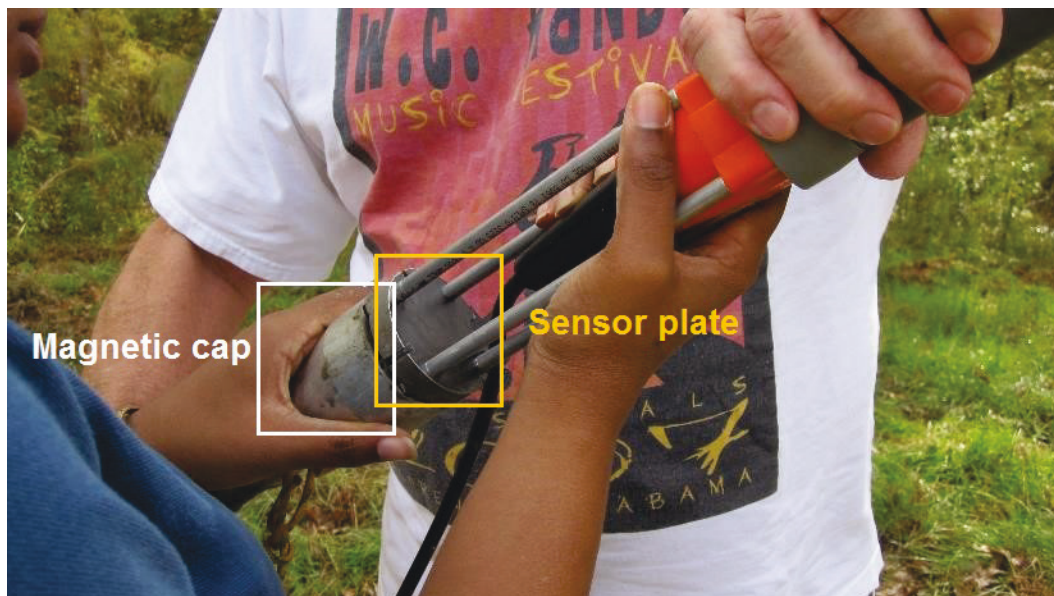
Trying to manipulate or operate equipment while in the borehole is challenging as the tools could be dropped and items can slip or shift position. Therefore, all installation procedures need to be practiced on the surface prior to being executed in the borehole. While the drillers completed the first sensor borehole (shown as 3C1 in Figure 1), the sensors and installation hardware were assembled and tested to confirm that they could connect and disconnect from the installation tool. The fit of the sensor plate and the magnetic installation cap was also checked to ensure a tight fit (Figure 9). Releasing the magnetic installation cap was practiced a few times to get a sense of how strong the magnet was, as the sensor orientation could be altered when trying to separate the cap during

installation. A length of paracord was then tied in the loops at the top of the magnetic installation cap (see Figure 8) so it could be raised back up in case something slipped or fell in the borehole. Figure 9 shows the tight fitting of the magnetic installation cap and the sensor plate.

Figure 8. Installation magnetic cap with paracord.



Figure 9. Demonstration of tight fit between the magnetic installation cap and the sensor plate.



For alignment of the sensors, a notch feature on the sensor corresponds to the direction of X, which was aligned to magnetic north direction. The notch on the sensor is aligned with the tool-head notch that is also aligned to the stripes on the installation tool segments. That alignment ensures the X/north direction is always known while installing in the borehole (see Figure 10).

Figure 10. Sensor with orienting notch (orange part), magnetic installation cap, and install tool with orientation stripe.



2.4.1.3 STEP 3: Lowering sensor with install tool

With the magnetic installation cap and the first segment of the installation tool attached, the sensor was lowered into the borehole. Care was taken

while lowering the sensor and tool assembly in order to not drop anything in the borehole and to have a rope tied off to particular parts for retrieval. Installation tool segments were added in 6-ft (1.828 m) increments until the sensor was at the bottom of the borehole (Figure 11). The installation is a 3-person operation as one holds the sensor and tool assembly, another attaches the next tool segment, and a third monitors the sensor cabling and other tie-off ropes as the sensor is lowered into the borehole. An anchor was used as needed to ensure items would stay in place.

Figure 11. Adding segments to the installation tool.



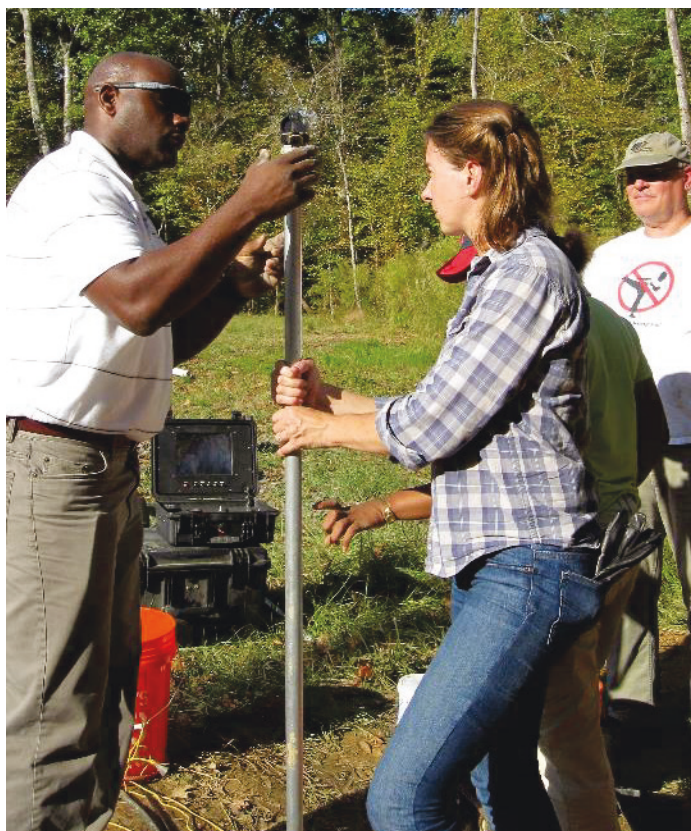
2.4.1.4 STEP 4: Orienting sensor

Once the sensor was at the bottom of the borehole, the alignment stripe on the installation tool segments was aligned to magnetic north using a compass placed on top of the installation tool; then the tool was leveled using the 3-way bubble level (in all directions) as best as possible. Prior to this step, magnetic north had been determined and a local landmark was established for noting orientation in case something, i.e. the drill rig, had been in the vicinity to alter the local magnetic field (see Figure 12 and 13).

Figure 12. Levelling sensor using install tool and 3-way bubble level.



Figure 13. Orienting the sensor to north using a compass and alignment/orientation stripe on the install tool.



2.4.1.5 STEP 5: Coupling the sensor to medium

One small bucket of Drylok powder (labeled as Fast Plug Hydraulic Cement) was poured or scooped into the powder pail. This particular step is a slow process, as care should be taken not to waste the powder as well as to prevent the powder from becoming airborne in order to maintain safe conditions for the personnel pouring the powder and holding the installation tool. This step is a 2-person task, as one is required to hold the powder pail as the other pours in the powder. Personal protective equipment is recommended as the powder can be a skin, eye, and respiratory irritant. The borehole camera was used at this point to verify the location of where to place the powder pail inside the borehole (Figure 14). The powder pail (Figure 15) was then lowered down the borehole while holding the installation tool steady and the lever released, placing the Drylok powder between the sensor and the medium and taking care to keep the Drylok powder below the level of the magnetic installation cap so that the cap does not become cemented in place with the sensor. Releasing the material at the bottom of the borehole rather than at the top ensures that

the Drylok powder is placed around the sensor as opposed to the top of the installation tool or lost to the borehole wall. An additional 2 lb of Drylok powder was lowered using the powder pail for a total of 6 lb of Drylok powder, using the borehole camera to ensure even placement of the powder. The additional 2 lb of powder is used to ensure coupling with the ground. The borehole camera was lifted slightly higher so that it would not be damaged when the water was added in the borehole. Then, with a small funnel fitted into the top of the installation tool, as shown in Figure 16, about a gal of water was poured. The water flowed down the tool and out the holes just above the sensor (in magnetic installation cap in Figure 10) to saturate the Drylok and cement the sensor in place. The Drylok specifications list a density of 24 lb /U.S. gal or 2.875 g/cc.

Figure 14. Borehole camera front and bottom view.



Figure 15. Using PVC pail with trapdoor to lower Drylok powder down to the sensor.



Figure 16. Pouring water into top of install tool for cementing sensor coupling.



The installation tool needs to be held in place (leveled and oriented) for at least 10 min for the Drylok to cure; this task can be performed with a tripod or by a person. Figure 16 shows a traffic cone being used to hold the install tool steady for the 10-min interval. The downhole camera confirmed that powder was around the jacket or bulk of the sensor. The orange part of the sensor was still visible with the water around it (Figure 17).

Figure 17. Screen shot from downhole camera to confirm sensor installation process.



It is likely that there was soil from the side of the borehole that fell in and mixed with the concrete as items were lowered into the borehole. For this installation, this was not a problem; the sensor coupled well, allowing for the installation tool to release.

2.4.1.6 STEP 6: Install tool removal, cleanup, and securing of cables

After the 10-min interval, the installation tool was then angled a bit to break the magnetic tie with the sensor plate, and the installation tool was disassembled and removed segment by segment. Again, this portion was best executed with two people. The tool segments and magnetic cap were cleaned if needed to remove soil or cement powder and inspected to confirm they were not damaged. The remaining sensor cable and connection plug at the surface was secured by wrapping it around a large stick (about 4-cm diameter and 1 m or longer) and then placing it over the hole until it was ready for connecting to a trunk cable. The sensor cable was secured so that it was easier to keep track of and to minimize the chance of faunal destruction.

2.4.2 Installation execution for remaining locations

Two sensors, 3C2 and 3C3, were installed on the second day. The weather conditions were sunny with calm winds and no rain during installation.

The second borehole (3C2) had cave-ins that decreased the depth by 2 ft. It was originally 35 ft (10.668 m), then 33 ft (10.058 m) after augers were removed. Due to the cave-ins, PVC was emplaced for the entire length to hold the borehole open. When the PVC was pulled up, it had made a further indentation downward (about 6 in. or 0.152 m), causing Drylok too near the top of the installation tool and making the sensor placement too deep. In order to make the bottom of the borehole level and raise its elevation, an entire bucket of Drylok powder was poured in the hole using powder pail. The sensor was then lowered and emplaced following the process above. The only difference was that the depth for this sensor was approximately 32.5 ft (9.905 m), i.e., unfortunately slightly higher than the desired depth.

The third borehole (3C3) did not have cave-in issues and was drilled to the 35-ft (10.668 m) depth. Sensor installation was executed as stated above.

On the third day, the fourth borehole, 3C4, was drilled. The weather was sunny and clear. Borehole 3C4 did not have cave-in issues, and the driller pushed a plug to make one long cylinder hole (as opposed to using the auger). This made the borehole a different shape relative to the other boreholes and was flat at its bottom. There was only one bucket (4 lb) of the Drylok compound left (it was not available at a local store), so hydraulic Quikrete compound (labeled as Hydraulic Water-Stop Cement) was used. A full powder pail (about 4 lb) of the Drylok was used first and then the entire Quikrete pail for this borehole, as the Quikrete may not have been quite as dense as the Drylok.

After all sensors were installed, all four of the boreholes were measured using the downhole camera to obtain the depths to the top of the plates. The downhole camera cable was marked, in 1-ft increments, with electrical tape between the 20- to 35-ft length to help measure the depth to the top of the plate on the sensor. Table 2 gives a summary of the depths for all the boreholes. If there are variances in sensor installation, such as the installation depths, they can be taken into account during post-processing of the data.

Table 2. Installed sensor coordinates.

Borehole	Northing (m)	Easting (m)	Depth to sensor plate in feet (meters)	Depth to sensor tip in feet (meters)
3C1	3576096.3	702523.6	32.9 (10.027)	34.31 (10.457)
3C2	3576085.3	702513.7	30 (9.144)	31.41 (9.573)
3C3	3576073.2	702518.2	31 (9.448m)	32.41 (9.878)
3C4	3576064.8	702506.3	31.5 (9.601)	32.91 (10.30)

The boreholes were backfilled using the native silt/clay left on the surface from the drilling activities to allow for settling and compaction. This is to allow for optimal wave propagation that will act like the native material where the sensors are installed and also to not cause unsafe surface conditions for personnel. The sensor locations were then marked at the surface with an orange cone.

The sensors were tested about a month later and were operating and responsive to surface activity (e.g. hammer hits).

3 Lessons Learned and Recommendations

The following suggestions are made to expand on the current installation procedures that could occur in different subsurface situations, surface environments, or areas for specific improvement.

- This procedure in total or some portion could be used for installation for other three-component deep borehole sensors, especially those that require orientation.
- A quantitative and qualitative evaluation of the performance impact on the sensor being misaligned in orientation or tilted or combination of both needs to be evaluated. It is known that it has direct impact on the sensor performance; however, at this time, there is no definitive statement as to impact. Most sensors have an optimal tilt tolerance defined in the manufacturer specification and the performance impact will be dependent on what specific sensor is being installed.
- In unfamiliar environments, it is strongly suggested that the boreholes are logged to confirm geologic strata and that the geologic setting is well-understood by research or ground truth.
- In general, it took at least three people to execute the sensor installation portion; however, other support people were present and usually were assisting with supplies/tools and documentation. The drilling crew was separate from the sensor installation personnel and had at least two people. The speed of installation varied from one to two boreholes a day and was very dependent on conditions such as weather, progression of borehole drilling, adjustments needed for specific borehole depths, and supplies on hand. The installation emphasis was to execute the sensor installation well and was not an attempt to maximize time efficiency. The manpower needed and speed in other installation environments would vary, and the values stated here are solely approximate value for future planning.
- A lesson learned is that each sensor serial number, provided in the specification sheet from the manufacturer, should be documented as to its specific installation location. This is important when looking at the sensor manufacturer specification page for that specific sensor as the sensitivity can vary between sensors or channels. Also, this information is valuable in verifying that the sensor is performing within expected levels and should be examined in case differences are observed between sensors or channels. The specific sensors' locations were not

documented in this process, and the average instrument sensitivity was used for sensor evaluation.

- It would be helpful to make a bubble level and compass sleeve that fits over the top of any segment of the installation tool. This adjustment varies from the current installation tool that only has the compass on one segment of the tool, which may be much longer and not visible when standing on the surface. In addition, this adaptation would allow for variability of depth for installation. The current install tool also had a bubble level and compass that were not permanently attached and, when shipped to ERDC, one or both of them had detached.
- During installation, it would be good to have a retrieval device in case something is lost or dropped down the borehole. This procedure describes ways to prevent losing equipment; however, it is difficult to prevent entirely.
- A line-of-sight tool (target tool) for orientation might be more beneficial in place of a compass in case the work area is tight and the drill rig cannot move. The drill rig in close proximity will interfere with a compass.
- After installation, the question of how the sensor orientation varied in alignment with north (orientation) was asked and there was an approximate ± 5 degrees of variability for this installation based on the degree of visual accuracy of using the compass and installation tool. A suggestion is to directly measure the orientation and error for each of the three-component sensors. This is crucial information that is used in the sensor analysis itself and, if this parameter is quantitatively known, it could improve data post-processing. Some parameters such as orientation angle or tilt can be corrected during data analysis if they are known or measured. This information could be included in the sensor layout information (latitude, longitude, depth).
- It is possible that sensors can shift (tilt or settle) after installation or during long-term use due to a number of reasons. This was a question or topic raised while conducting the installation activities. At this time, there is no recommendation to aid with this problem and it is an area that should be considered for further development.
- A suggested area for development would be for a rapid installation method that could reduce steps or installation time. Installation of one borehole sensor including drilling the borehole took approximately half a day for this setting. One suggestion is to use one of the Drylok buckets with the blunt nose of the geophone attached, perhaps by epoxy, and have the Drylok powder around it. Lower the entire package

- down the hole, assuming a 6-in. hole at least and wide enough to fit. Then orient it and add water.
- Installation during challenging weather conditions such as high winds or heavy rain could be problematic due to the use of the powdered Drylok, as well as keeping the sensor oriented or leveled. A recommendation of either waiting for weather conditions to resolve or allowing for more time for overall installation would be required for the specific weather condition. However, safety of personnel is paramount in all activities.
 - The installation described in this report is mainly in silt and, for the most part, the borehole walls remained stable. The procedures used here would have to be adapted depending on the soils. For example, if the borehole walls did not hold (i.e., had a cave-in), then PVC pipe would have to be used. The kind of PVC pipe recommended is at least a 6-in. diameter and thin walled. The PVC pipe would remain in place through pouring the Drylok powder and then pulled out before adding the water. The recommended PVC pipe size should be as close to the diameter of the hole as possible (some augured holes are 4 in. while others are 6 in. or more). The rationale is that the sensor can be placed within the PVC once the pipe is pulled up some to avoid bonding with the Drylok. This also avoids the formation of a secondary narrower hole within the drilled diameter should collapse occur. A secondary hole makes placement of the geophone difficult since the implant tool risks being buried. Removing the PVC can be problematic depending on its length and installation environment.
 - During installation, some of the borehole material will likely cave and mix in with the concrete that will couple to the surrounding material. This specific installation environment had successful conditions as the magnetic installation tool head could be released as the sensor coupled with the media strongly. However, if there is too much cave-in material in the borehole due to a different geology or moisture environment, then the installation tool could have trouble releasing. If this happens, adjustments would have to be made in the field to correct or accommodate for conditions; however, not damaging the installation tool or the sensor would be prudent.
 - Other future adaptations should include solutions for installation in wet conditions. The application discussed in this report worked well because water was not infiltrating the hole. If it were, placing the Drylok powder into the borehole would not be possible as it would get wet in the pail and would set before reaching the bottom.

- An area for future research is the use of different density coupling mediums that may be necessary for different installation environments. The Drylok compound was used so that it would not be a weighing or heavy mass around the sensor yet bond to the surrounding material quickly. Prior testing using normal concrete, light-weight concrete, foams, and other products were found to have some impact on wave propagation of the sensor signals.* The coupling medium should not be orders of magnitude different from the densities of the installation environment as their presence would be discernible on sensor readings. The Drylok mixture is about 110 lb/ft³ (1.762 g/cc), which is the typical density for fill/sand and commonly found material, and a good general choice. Lighter sand would be 100 lb/ft³ (1.602 g/cc) and below. Clay would go towards 130-140 lb/ft³ (2.082 to 2.242 g/cc). In denser material like a clay (not necessarily stiffer), there may be some issues as coupling will not be adequate and clay has dampening properties that could cause signal loss when transitioning towards the sensor.
- Applications in other soil conditions (sand, non-cohesive/non-rock material, etc.) need to be explored, especially where the differences between the anchoring agent and the surrounding geology could dramatically cause wave propagation distortion. The density difference in the materials (anchoring agent vs. surrounding geology) may not be an issue; however, the stiffness/strength parameters differences may be.

One suggestion for development is for a validation check to test the sensors in-situ right after installation is complete to validate and characterize sensor response and to confirm orientation immediately after installation. For the sensor and hardware used in this report, the sensor component and channel mapping is dependent on which connection of the cable is connected to the data acquisition and needs to be field-verified. Part of this development would be establishing the acceptable operable value range for the specific sensor and the quantitative range could be from the manufacturer's response curves or from prior field test results. Specific tasks should include confirming connectivity (no dead channels) and operation (responding to various activity and not clipping); however, what kind of information is needed and at what level would likely be objective driven (what information is needed for the specific algorithms

* Rigaud, A. 2015. Personal communication.

and accuracy level needed). The sensor response would have to be evaluated at the frequency range of whatever source is used and a repeatable known source over the relevant frequency range of interest (for the sensor) would be desirable for this purpose. Sensor response levels are dependent on the source amplitude and frequency as well as propagation scenario (distance, azimuth) and subsurface conditions (e.g. dry or wet, type of soil or rock). The guideline would be useful to compare to different sensor responses in-situ (of the same type or different sensors entirely) as well as give comparison basis for different geologies for the same sensor or different sensors.

A post-installation performance test is suggested to help characterize sensor response over time and how it is changing. The sensors may be used for an unspecified amount of time, which could extend into years. If so, every effort should be made to make the sensors as robust and as matching to their environmental conditions as possible. It is unknown how these sensors will respond over time and it is assumed that they will degrade mechanically as well as be affected by the environmental elements (e.g. water). Suggested test ideas would be to install several sensors and check periodically (e.g. weekly, monthly) to see what the response is to the same known source; keep all variables the same like test scenario and track the response over time. This would give a baseline response for that test environment; however, each installation environment will have its own variables that could have different impacts. There may not be a single value of good or bad; perhaps more of a general evaluation indicating needed replacement vs. a specific sensor's new baseline level.

4 Conclusion

Optimal sensor installation is key to any sensor performance. Installation procedures should be tailored to fit the specific scenario for the installation environment or conditions as well as the designed use of the specific sensor.

A sensor evaluation test created a need for installing three-component seismic sensors at several meters' depth in a soil environment. The challenge is how to couple the sensor, orient and level it for three-component operation, and preserve all of the cabling while the sensor is at several meters' depth using a surface man-operated tool. Using a previous installation process for three-component seismic sensors in a hard-rock setting at several meters' depth and applying it to a soil environment, four three-component seismic sensors were successfully installed. The sensors were used in testing afterwards and were operational; therefore, the installation process was successful.

The goal of this report is to document the procedures used and lessons learned and provide suggestions of adaptations to different environments and ideas for continued improvement. At the current development stage, the procedure presented in this report is recommended for experts or those with prior sensor deployment experience. This information will ultimately be used as a basis for installations of deep three-component seismic sensors and for creation of an installation procedure for a three-component seismic sensor that a non-expert can execute successfully with minimal training.

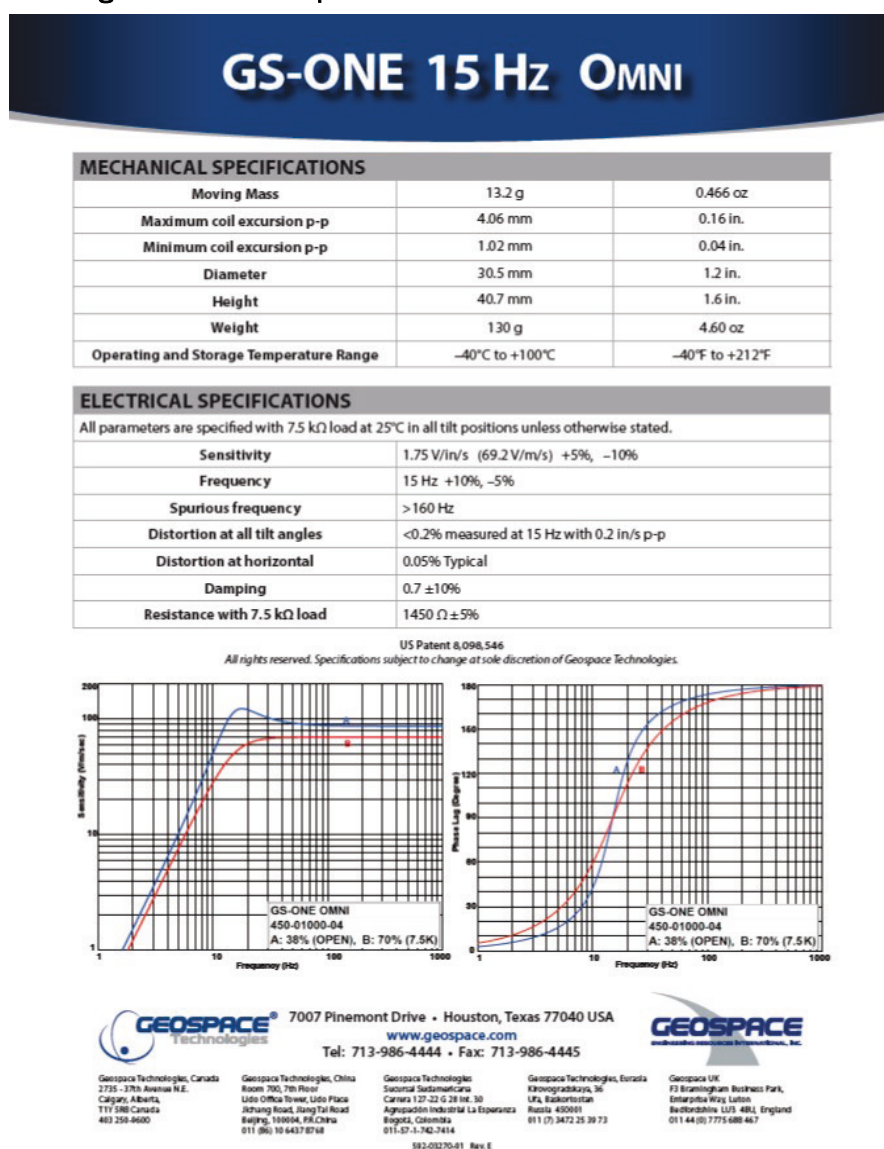
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Appendix A: Sensor Information

Figure A1 shows the sensor specification information and response curve from the manufacturer.* Figures A2 through A4 show the sensor specification information supplied by the manufacturer. Figure A4 under the column heading “Sens” shows the sensitivity of each sensor component. An average value, 1.79 V/i/sec, using all of the components values is used for data conversion.

Figure A1. Sensor specification sheet from the manufacturer.



* Allmendinger, T. 2018. Personal communication.

Figure A2. Manufacturer certification.



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Geospace Technologies Certification of Conformance

Geospace Technologies certifies that the finished product detailed below has been manufactured in accordance with the manufacturers specifications referenced therein and all work performed according to manufacturers specifications. Materials used and inspections performed are in accordance with Geospace Technologies drawing specifications.

Sales Order	Work Order	Part Number	Date	Total
86365	231345	GEO93406-01	10/20/15	4
Part Description				
SNG 3C GS-ONE Borehole CPVC,				
Customer	US ARMY ENGINEER R & D CENTER			

Thai Vuong

Quality Representative

592-04830-01 REV.A

Figure A3. Geospace sensor diagram.

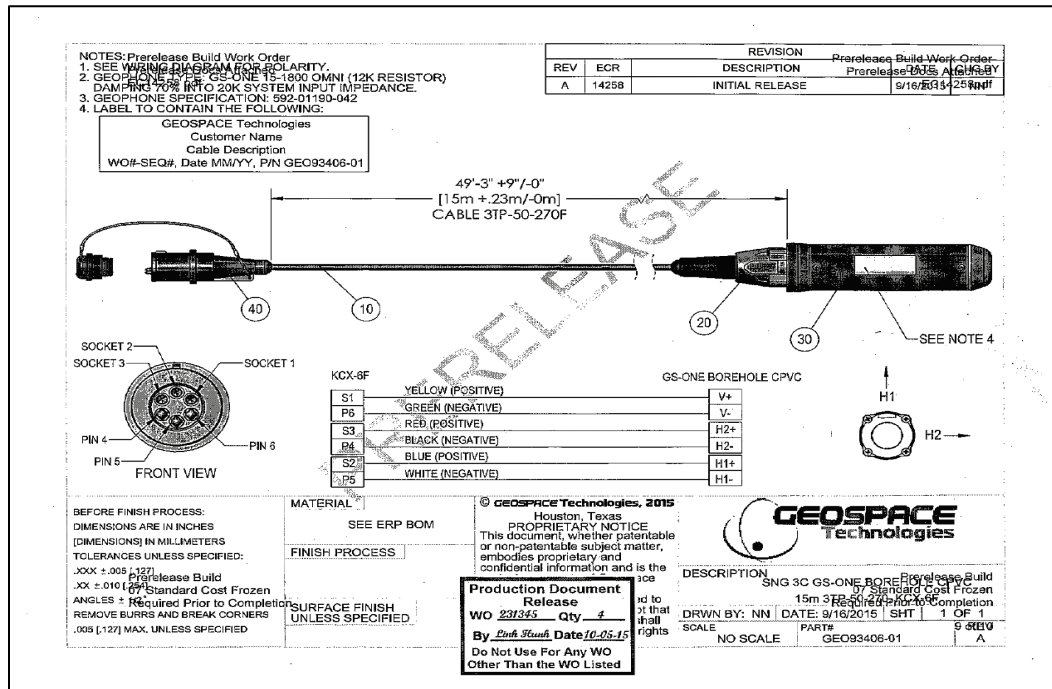


Figure A4. Sensor specification values.

10/19/2015	14:16:13	Geospace Geophone/Hydrophone Tester									
Spec	Ser	Par	Shunt	Mass	Fdist	VelDist	Excur	Temp			
ONE-OMNI	1	1	7500	13.2	15	0.2	6.6	25.0C			
->	Pol	Res	Freq	Damp	Sens	Dist					
Min	-1	1393.5	14.32	0.754	1.6						
Norm		1451.6	15	0.828	1.758						
Max	1	1509.7	16.35	0.903	1.837	0.18					
Ser#	Pol	Res (Ohm)	Freq (Hz)	Damp	Sens (v/i/s)	Dist (%)	Imped	Reject	Temp	Date	Time
231345-001V	1	1432.4	15.578	0.6514	1.7479	0.1109	4167.6	Test Ok	21.38 C	10-19-2015	09:20:58
231345-001H1	1	1445.3	15.473	0.6881	1.8009	0.0702	4236.9	Test Ok	21.38 C	10-19-2015	09:22:45
231345-001H2	1	1431.9	15.232	0.698	1.807	0.0742	4240.4	Test Ok	21.38 C	10-19-2015	09:23:33
231345-002V	1	1430.1	15.338	0.6619	1.7397	0.1131	4142.6	Test Ok	21.38 C	10-19-2015	09:26:12
231345-002H1	1	1438.8	15.272	0.6788	1.7932	0.0859	4281.9	Test Ok	21.38 C	10-19-2015	09:26:46
231345-002H2	1	1441.1	15.405	0.6989	1.8175	0.0778	4249.5	Test Ok	21.38 C	10-19-2015	09:27:30
231345-003V	1	1438.7	15.436	0.6747	1.7619	0.099	4155.2	Test Ok	21.38 C	10-19-2015	09:43:43
231345-003H1	1	1428.3	15.345	0.6915	1.8132	0.0586	4270.9	Test Ok	21.38 C	10-19-2015	09:44:35
231345-003H2	1	1435.8	15.232	0.6832	1.7991	0.0605	4280.9	Test Ok	21.38 C	10-19-2015	09:45:10
231345-004V	1	1429.2	15.564	0.6598	1.7606	0.0975	4160.9	Test Ok	21.44 C	10-19-2015	09:49:30
231345-004H1	1	1433.7	15.45	0.6821	1.8049	0.0489	4262.4	Test Ok	21.44 C	10-19-2015	09:50:13
231345-004H2	1	1422.8	14.985	0.6973	1.7954	0.0496	4247.1	Test Ok	21.44 C	10-19-2015	09:51:08

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14. ABSTRACT Vector-dependent seismic sensors provide advantages in discriminating and localizing source signals of interest. To achieve this, optimal sensor installation must ensure proper and known orientation and coupling with the surrounding medium, as these will directly affect recorded signals used in signal processing routines. Certain applications require installation of a three-component seismic sensor at several meters' depth, achieved by installing sensors within a borehole; however, there are no standardized procedures for installation. A previous experiment created an installation procedure for a three-component seismic sensor in a hard rock environment. Applying the process from the prior three-component sensor experiment, four three-component seismic sensors were successfully installed at a 10-m depth in a soil environment. The sensor tests conducted afterwards confirmed that the sensors were operable, and the installation procedure was considered successful. This report describes the installation process, lessons learned, and recommendations for improvements in the process and applications to other installation environments. This information will ultimately be used as a basis for installations of deep three-component seismic or geophysical sensors and for creation of an installation procedure for a three-component seismic sensor that a non-expert can execute successfully with minimal training.					
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