Final Scientific/Technical Report

Project Title:

Automated High Power Permanent Borehole Seismic Source Systems for Long-Term Monitoring of Subsurface CO2 Containment and Storage

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Disclaimer

Acknowledgement

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1.0 Executive Summary

The geologic storage of CO2 emitted from fixed sources, such as coal or gas power plants, is currently considered one of the prime technologies for short term (~50 year) mitigation of greenhouse gas emissions. The subsurface storage of CO2 for greenhouse gas mitigation will require monitoring to verify that CO2 remains effectively trapped underground, thus permanent seismic sources are needed to provide 24/7 monitoring. GPUSA Inc. has developed and successfully demonstrated numerous prototype vibratory seismic sources with power and performance far beyond any available on the market. The primary objective of this project was to validate in an operational field environment GPUSA's powerful, low cost, automated borehole seismic source systems for the CO2 storage monitoring application. GPUSA originally proposed the building and testing of two types of permanent sources but ended up building and delivering three types of permanent seismic sources. These sources were delivered to the field test site (Carbon Management Canada's Containment and Monitoring site near Calgary), however, only two of the systems were able to be tested before the contract ended (despite two contract extensions). The reasons for the delay were primarily weather related both at the US preliminary field test site and Carbon Management Canada site. But in the end, based upon the preliminary field testing in the US and the limited testing that was completed at the Carbon Management Canada site, the results were very impressive, and in some cases far exceeding expectations.

2.0 Introduction

2.1 Statement of the Problem

The geologic storage of CO2 emitted from fixed sources, such as coal or gas power plants, is currently considered one of the prime technologies for short term (~50 year) mitigation of greenhouse gas emissions. Brine aquifers provide the largest potential storage capacity for geologic sequestration of CO2, however, subsurface storage of CO2 for greenhouse gas mitigation is expected to require monitoring to verify that CO2 remains effectively trapped underground. Field testing has shown that continuous active-source seismic monitoring (CASSM) championed by Lawrence Berkeley National Lab (LBNL) is a very effective technique for monitoring the size and location of the injected CO2 plume on an almost real-time basis. Unfortunately, continuous monitoring using existing seismic source technology is not practical or cost effective, and also limits the resolution needed for CO2 monitoring. Clearly a new seismic source technology is needed for successful and effective cost-effective implementation of CASSM.

For example, to undertake a conventional 3D surface seismic or vertical seismic profile (VSP) survey, one must have an available borehole within the survey area, obtain numerous land access permits, deploy an extensive temporary monitoring network, shoot multiple source locations using either vibroseis trucks or dynamite, and subsequently process and interpret the acquired data. These surveys are exceptionally costly due to the significant deployment of manpower & equipment, landowner payments, and weather-related delays. In January 2015, the Illinois Basin-Decatur Project (IBDP) and Illinois Industrial Carbon Capture and Storage Project (ICCS) projects spent over $3.5 million to conduct a 3D survey covering 3,000 acres. In addition to cost, these surveys require significant pre and post survey activities that include land access permitting, data processing, and data interpretation, thus a single survey can take over six months. Obviously, for a time critical monitoring of subsurface storage of CO2, obtaining an update once every six months is not adequate.

Monitoring, Verification and Accounting (MVA) technologies is a technology area of the Advanced Storage R&D technology component of DOE's Carbon Storage program. The primary objective of the MVA technology area is to develop tools and protocols that provide assurance of storage permanence for geologic CO_2 storage. The Carbon Storage program seeks to continue the development of advanced monitoring technologies, as well as supporting protocols, in order to decrease the cost and uncertainty in measurements needed to satisfy regulations for tracking the fate of subsurface CO_2 plume as part of reservoir management. **This includes development of technologies that are capable of continuous (real-time) monitoring, long-term durability, improved resolution, and covering a large area with improved accuracy.**

Thus, for seismic technology to be effectively applied to meet the goals of the US Department of Energy's (DOE) Carbon Storage Program's MVA requirements, one needs permanently-installed seismic sources and sensors that can be continuously queried, providing results almost instantaneously. Fortunately, over the past several decades oilfield seismic sensors and sensor processing technology has advanced tremendously, i.e., the move from analog to digital to MEMs sensors, the rapid advances in computing processing power and speed, and the advent of Distributed Acoustic Sensing (DAS) employing Rayleigh backscatter that transforms standard optical fiber into an acoustic sensor.

Comparatively through this same time period, however, seismic source technology has changed very little. For decades, the primary non-impulsive land seismic sources have been seismic vibrators (vibroseis) for surface, and piezoelectric vibrators for downhole. The primary impulsive land seismic sources include downhole sparkers and dynamite. Impulse-type sources such as sparkers, airguns, dynamite, etc., concentrate most of their energy over a very small time interval and as a result, are typically non-linear, not reproducible and therefore not well-suited for SNR enhancement via stacking. And, decades of US Navy sonar research and operation have proven that traditional piezoelectric sources are ineffective at producing the displacements necessary for powerful, low frequency (<500 Hz) sonar projectors. CGG's Seismovie concept using permanent piezoelectric sources never achieved commercial success due to the high cost and low power of its sources. Adapting or "scaling" any of these traditional seismic source technologies to meet the requirements for long-term monitoring of subsurface CO2 is not a reasonable approach.

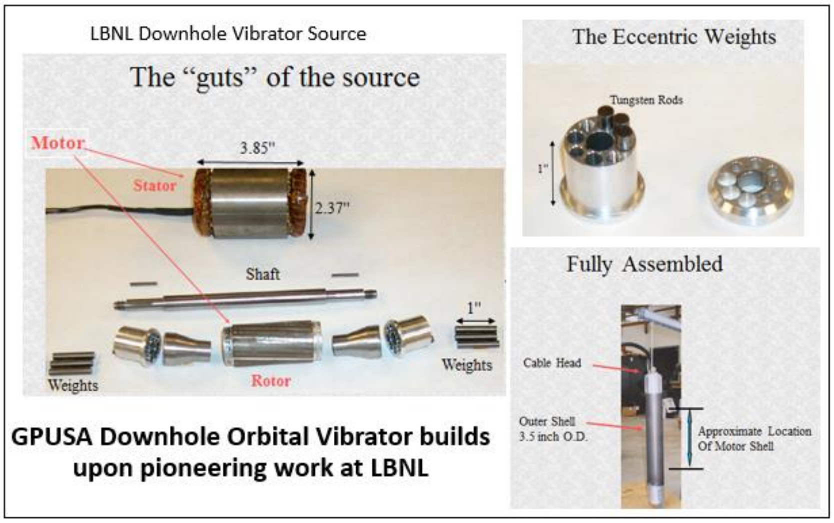
2.2 GPUSA's Proposed Solution

GPUSA Inc. has developed and successfully demonstrated numerous prototype orbital vibratory seismic sources with power and performance far beyond any available on the market today. The primary objective of this project is to design, build, and then validate in an operational field environment GPUSA's powerful, low cost, automated seismic source systems, designed for permanent 24/7 operation. Once commercialized, these systems will enable continuous near real-time tracking and monitoring of injected CO2's plume, trajectory, and containment via crosswell and vertical seismic profile (VSP) techniques thereby meeting the Carbon Storage Program Goal to "*Develop and validate technologies to ensure 99 percent storage permanence.*" This project will demonstrate various models of GPUSA's orbital vibrator seismic source technology, providing sources with sufficient power, the correct bandwidth, high reliability, and low cost needed to facilitate widespread adoption of the CASSM technology. Successfully demonstrating the ability to permanently deploy and operate such powerful sources downhole, bypassing the attenuation and filtering of the unconsolidated near surface layers will represent a breakthrough in seismic source technology.

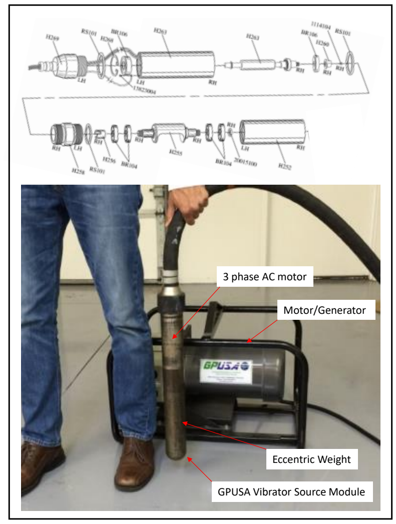
3.0 Technology, Approach, and Accomplishments

3.1 GPUSA's Orbital Vibrator Technology

The orbital vibrator source was originally developed by Conoco, Inc. in the 1980's but was never commercialized. In the early 2000's OYO Geospace licensed the technology from Conoco but had limited success at commercialization due to mechanical/reliability issues. LBNL successfully developed a downhole orbital vibrator prototype in 2003 (see left photo below) that generated over 1600 pounds of force at 900 Hz. LBNL did not commercialize its orbital vibrator. In November of 2014, GPUSA tested its first prototype downhole orbital vibrator (see photo at right below) at the LBNL Geoscience Measurement Facility (GMF). GPUSA's vibrator was placed into a shallow well



GPUSA Downhole Orbital Vibrator builds upon pioneering work at LBNL



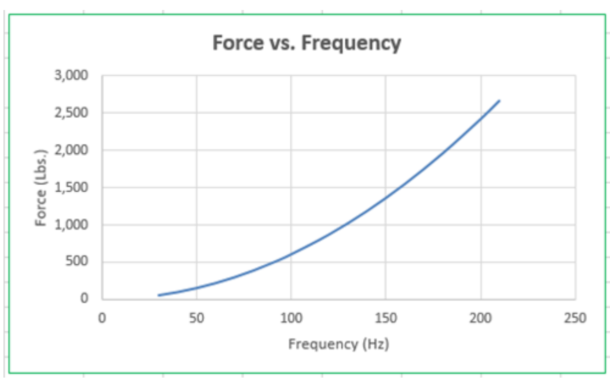
and produced 2400 pounds of force at 200 Hz from the 2.5-inch diameter source. This successful test encouraged the GPUSA team to pursue further development of the source. GPUSA's patent-pending, compact, rugged, downhole seismic sources are based upon orbital vibrator technology originally developed and proven by 40 years of commercial use in the construction industry. GPUSA has partnered with one of the industry leaders in the commercial industrial vibrator industry (Denver Concrete Vibrator) to build its orbital vibrators to ensure they a built to the highest commercial standards. GPUSA's vibrators are capable of generating forces 10 to 50 times greater than traditional downhole piezo sources.

Downhole Orbital Vibrator (DHOV) Description - The downhole orbital vibrator source consists of an eccentric mass spinning around the source axis, driven by an electric motor, encased in a pressure-tight cylindrical housing that is suspended in the borehole fluid. The centrifugal force induced by the rotation of the mass moves the whole source in the radial directions of the borehole, introducing the compression of the fluid on one side and tension on the other side of the source. This rotating compressional motion is converted into seismic waves at the borehole wall. The resulting waves have the same primary frequency as the spin frequency of the source. This effect has been modeled and described at length in numerous technical articles by Leary and Walter (2005) and Nakagawa and Daley (2004) but due to space limitations, cannot be included here.

The force generated by an orbital vibrator can be described by the equation,

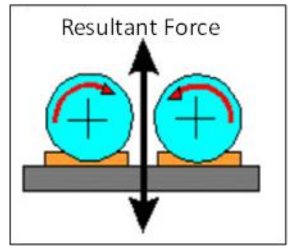
$$F = MR\omega^2$$

where M represents the mass of the eccentric weight, R represents the distance between the center of rotation of the mass to the center of the mass (i.e., eccentricity), and ω represents the angular velocity. The chart at right shows the calculated output force of the GPUSA DSS™ DHOV Crosswell source,



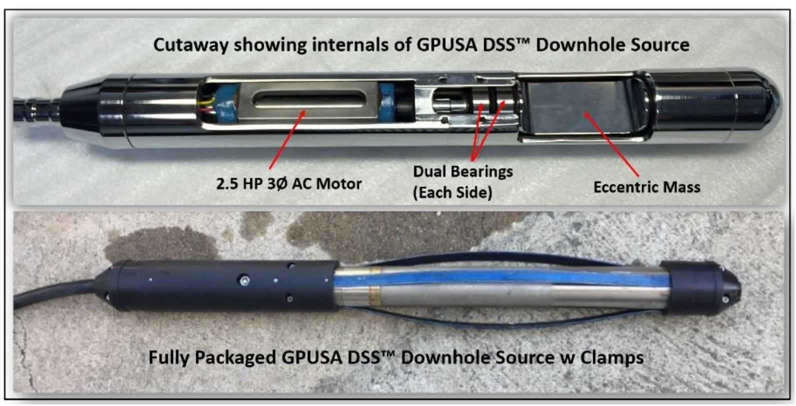
generating just over 50 pounds of force at 30 Hz increasing to just over 2400 pounds of force at 200 Hz.

Downhole Linear Vibrator Description - The MicroVib™ represents GPUSA's latest seismic source development. It is well understood within the commercial vibrator and shaker industry that if two identical orbital vibrators are placed side-by-side with the two synchronized and rotating in opposite directions, the resultant vibration will be in the linear direction only (see picture at right), as all other forces cancel out. GPUSA's MicroVib™ takes advantage of this feature, packaging two contra-rotating eccentric masses and electric motor in a small (approximately 9.0-inch O.D) package that is designed to be permanently installed (cemented) in shallow boreholes. The MicroVib™ generates over 4500 pounds of force at 200 Hz.



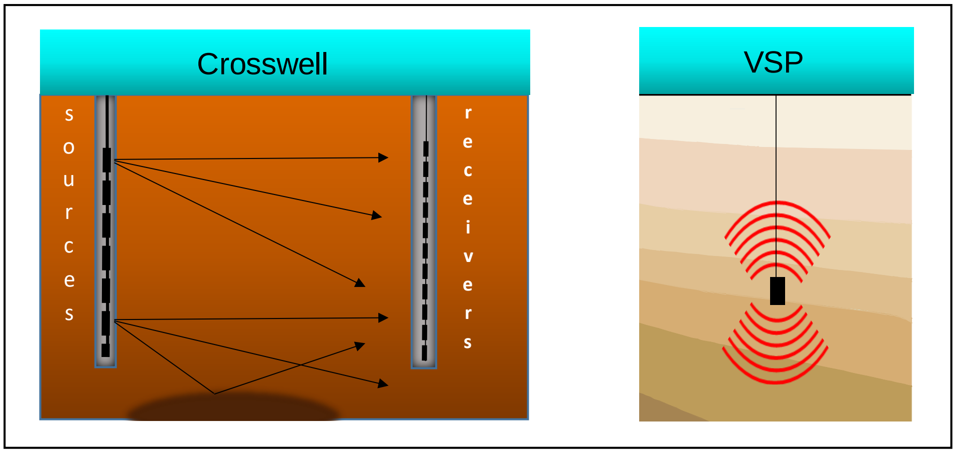
Digital Monitoring Accelerometer - Both downhole sources include a built-in digital monitoring accelerometer. The rugged, high performance digital accelerometer provides data for real-time QC monitoring and for correlation processing (deconvolution). The digital monitoring accelerometer (see photo at right) is manufactured by Measurement Specialties Inc., a Division of Tyco Electronics. It has an operating range of ±250g, and each module is tested to withstand ±5000g. The accelerometers are designed to be daisy-chained (multi-drop communications) via RS-485 with noise-free transmission to 4000 feet without a booster/repeater

The two types of vibratory sources originally proposed for the project are shown below:



MicroVib™ MV4K-200S Linear Vibrator Seismic Source

GPUSA originally proposed to design, build and validate two types of orbital vibrator downhole sources for this project, a multi-level DHOV Crosswell system (shown below left) that generates a radial pattern orthogonal to or outward from the well bore and a single-level MicroVib™ VSP system generating linear vibrations in the direction of the well bore (shown below left).



3.2 Planned Technical Approach

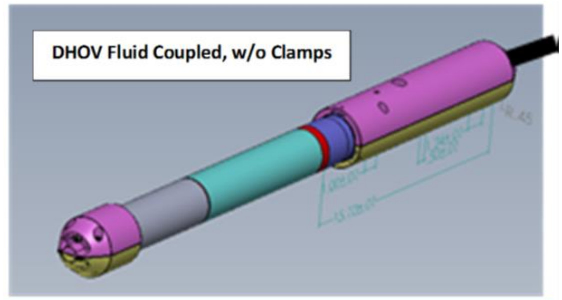
The proposed technical approach for the project is outlined below:

- A thorough requirements review was performed with the entire cross functional team. The results of the review were then to be used to modify/update GPUSA's existing orbital vibrator designs (DHOV for Crosswell, and MicroVib™ Linear Vibrator for VSP) as needed to meet the MVA requirements.
- Updated prototype units of each type were then to be built incorporating the design modifications above, followed by field testing verify their relevant operating parameters at the LBNL Geoscience Measurement Facility (GMF) and Richmond Field Station.
- Based upon the prototype testing at LBNL, the designs of both units were to be finalized and released for manufacturing following a Critical Design Review.
- A complete 6-level DOV Crosswell system and two MicroVib™ VSP systems were to be built for system testing at the CaMI Research Field Station in Alberta, Canada
- Both systems were to be installed at the CaMI site and used in conjunction with the existing permanently installed fiber optic DAS systems and LBNL's conventional multi-level downhole receiver array to track/monitor injected CO2. The six-level Crosswell system is to be installed in a vertical monitoring well. Two separate shallow (approximately 50 feet deep) wells are to be drilled for the MicroVib™ VSP systems for permanent (cemented) installation of the VSP sources, located to provide desired offsets for VSP surveys. The results will be compared with results using piezo sources and conventional vibroseis sources.

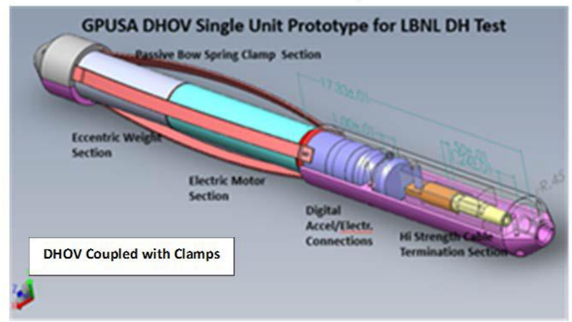
3.3 Summary of Accomplishments (by Quarter)

Jan-Mar 2017 Accomplishments - Based upon the detailed technical requirement reviews completed in December 2016, the prototype designs were modified and updated. These design updates included improved sealing methods, removeable bow spring clamps, and an automatic-self release mechanism for the bow spring clamps that relies on one-time, initial vibratory motion to engage the clamps to the well bore. Based upon internal preliminary design reviews with the team, an updated version of the prototype DHOV (with and without downhole clamps) was built.

In-House Testing. The updated prototype unit incorporating these design features has successfully completed an end-to-end functional test in our lab, including an operational test in our well simulator. We tested with and without clamps. The new patent-pending, self-releasing downhole clamp performed flawlessly. The three bow spring clamps automatically released in about 10-15 seconds upon energizing the DHOV and also centralized the DHOV in the borehole. We completed over 100 cycles of 30 second sweeps to the maximum operating frequency with no apparent degradation or change in performance.



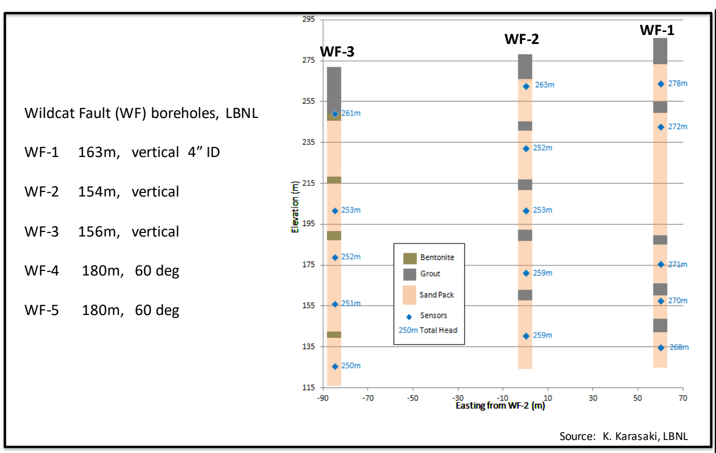
Description	Frequency Range	Output Force (Lbs.)	Proposed Well Depth	Outside Diameter
DHOV w/o Downhole Clamp	200 Hz	2200	60 Feet	3.25 inches

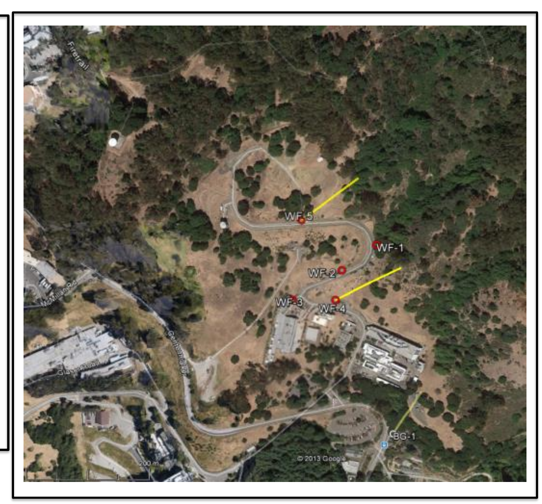


Description	Frequency Range	Output Force (Lbs.)	Proposed Well Depth	Outside Diameter
DHOV w/ Downhole Clamp	200 Hz	2200	60 Feet	3.25 inches

LBNL Field Testing. The updated prototype unit incorporating these design features was field tested downhole at LBNL, both with and without clamps. The purpose was to validate the performance seen in-house, and to determine the crosswell distances achievable, both with and without clamps. Since LBNL does not have a test site with well separations beyond a few hundred meters, we had to extrapolate actual to determine the actual distances achievable. We did an initial successful system checkout in the 65 foot deep wells at the LBNL GMF. With a 12 foot spacing between these wells, strong signals were received, but actual power measurement could not be made due to excessive signal clipping. Again, the new patent-pending, self-releasing downhole clamp performed very reliably in the field, releasing the three bow spring clamps automatically in about 10-15 seconds upon energizing the DOV and centralizing the DHOV in the borehole.

Of the many potential LBNL test sites for the DHOV initial prototypes, we next tested the DHOV at the LBNL Wildcat Fault Wells installed by Dr. Kenzi Karasakai for hydrologic testing of the Wildcat fault. The wells are about 1.5 km east of the Hayward Fault, on LBNL property, at about 275 m elevation. The wells are already instrumented and relatively deep.





At the LBNL Wildcat Fault (WF) test site, we placed the GPUSA prototype source in WF-1, which is about 500 feet deep. We deployed to a depth of about 100 feet, as the downhole lead cable was only about 150 feet long. The LBNL downhole sensors were placed in WF-2, which was about 200 feet away. We did make several sweeps using our DHOV, however, we were unable to detect any signals on the LBNL downhole sensor array. There were many delays in getting the downhole sensors operational, making it late afternoon before we could actually start testing, therefore due to time limitations at the site, we were unable complete the DHOV test plan. We decided at the time that we would have reschedule to test again at the site in mid to late May.

The GPUSA DOV (shown) was placed in well WF-1 to about 100 feet of depth, LBNL's sensors were placed in WF-2 about 200 feet away.

April-June 2017 Accomplishments:

No additional testing took place at LBNL during this reporting period due to the unavailability of the preferred LBNL Richmond Field Station (RFS) site. It has many wells already installed at the size, depth and distances that are ideal for DHOV testing, which made testing easier than the WF-1 site. Initially RFS was unavailable due to the heavy rains that made it impossible to bring vehicles on the site. Their environmental group would not allow any vehicles on the site as they would would get stuck in the mud and then tear up the natural ground cover and grass. We finally received clearance on 23 May.

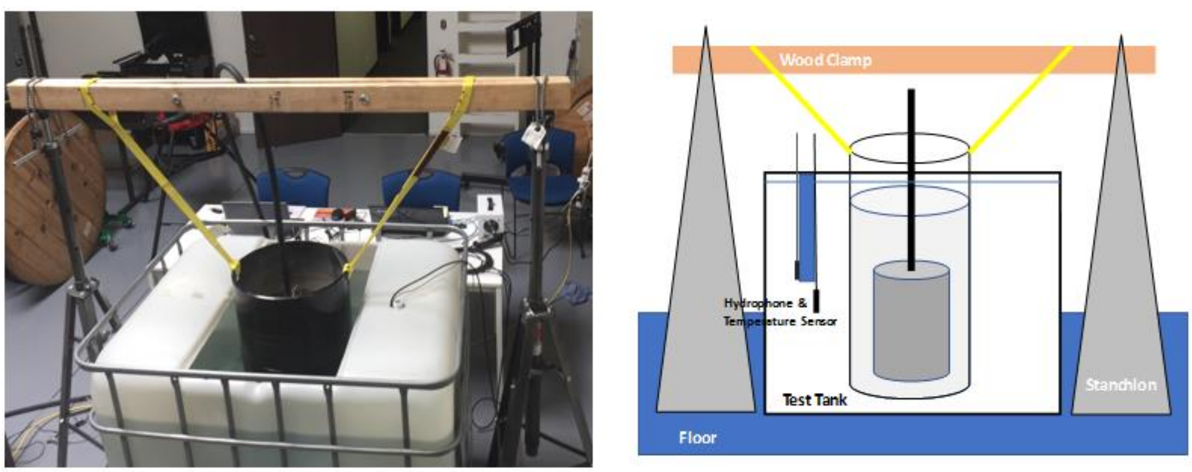
The original MicroVib™ designed and built by GPUSA included two individual motors and two eccentric rotating masses. Based upon this design, the resultant prototype, shown in the photo at right was approximately 11.5 inches in diameter. The


GPUSA's new single motor MicroVib™ (MV24P-200s) is now 9.0 inches in outside diameter vs the initial 10.5 inches, and produces the same amount of force.

main target performance specifications were a frequency range of 180 Hz, (200 Hz was the goal), with a force in excess of 4000 pounds. The initial MicroVib™ was designed to be cemented in a shallow well. Following discussions with the team and oilfield clients, it was determined that the diameter was too large for cementing even in a shallow well, as the well drilling costs would be too high. The consensus was that the outside diameter had to be 10 inches or less. Our initial MicroVib™ was tested in house and did achieve the 200 Hz frequency range. We then made a decision to replace the two 2 horsepower motors with a single custom 4 horsepower motor, and in doing so, reduced the outside diameter to approximately 9 inches. The field test delays caused by the weather allowed us to do some additional in-house field testing of our units. Based upon the prototype testing, we finalized the product designs of the DHOV, and the system for CMC was released for manufacturing following a Critical Design Review. It was scheduled for completion in early August 2017. We also completed the manufacturing drawings for the Single-Motor MicroVib™. A photograph of the completed Single-Motor MicroVib™ is shown above.

July-September 2017 Accomplishments:

The new Single Motor MicroVib™ was built and the system was assembled and put through extended life-testing in house. Due to time constraints it could not be field tested at LBNL, thus the extended life testing described below was deemed a sufficient relevant operational environment. Thus, we took advantage of the delay caused by the unavailability of a test site for the MicroVib™, and used that time to perform additional testing of the single motor MicroVib™, including the testing of it in our acoustic test tank cemented inside a steel cylinder (to simulate a well bore), as well as direct burial testing in a large plastic container (with approximately 12 inches of earth below and 12 inches above). See pictures below:

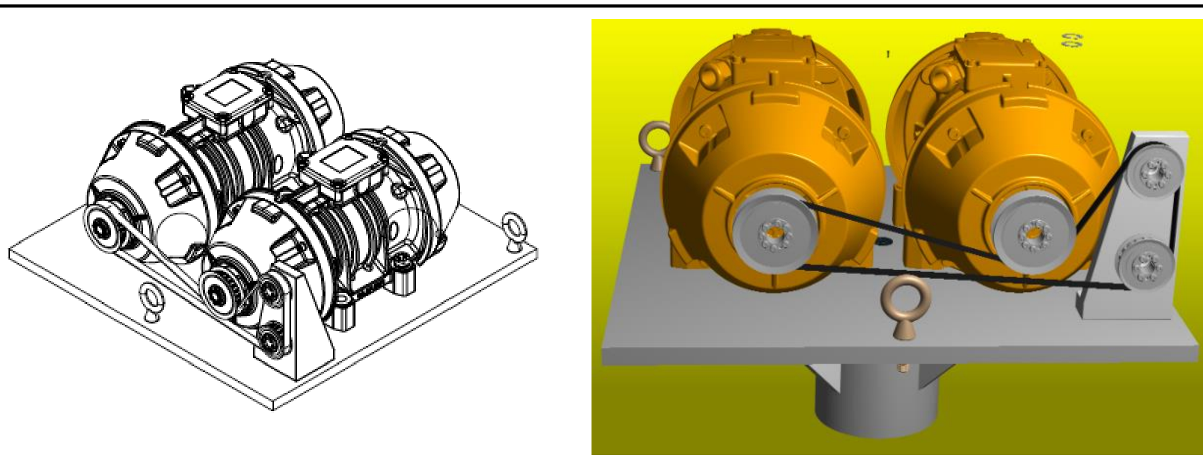


Test Setup with MicroVib™ in in Acoustic Test Tank Cemented in Simulated Well Bore

Test Setup with MicroVib™ Buried in Sand

The unit was repeatedly cycled through a 30 second sweep over 120 times in the sand and over 2600 times over a 30 day period cemented in the simulated well bore. The unit performed flawlessly throughout the test period.

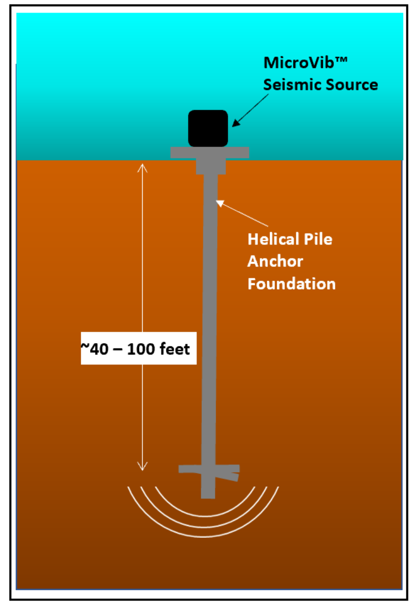
During this time we had also been developing a higher power version of of the MicroVib™ as an internal R&D project. It consisted of two completely standard rotary vibrators, modified by GPUSA via pulleys and belts to synchronize the motors to counter-rotate. (See drawings below). They perform the exact same function as the single motor MicroVib™ described above, yet they are designed to produce linear vibrations to 11,000 pounds of force at 100 Hz, allowing them to see deeper into the earth (target depth 5000+ feet). At the same time we began working with manufactureres of helical pile foundation anchors to develop a lightweight anchoring method for the new higher power MicroVib™ units since they were



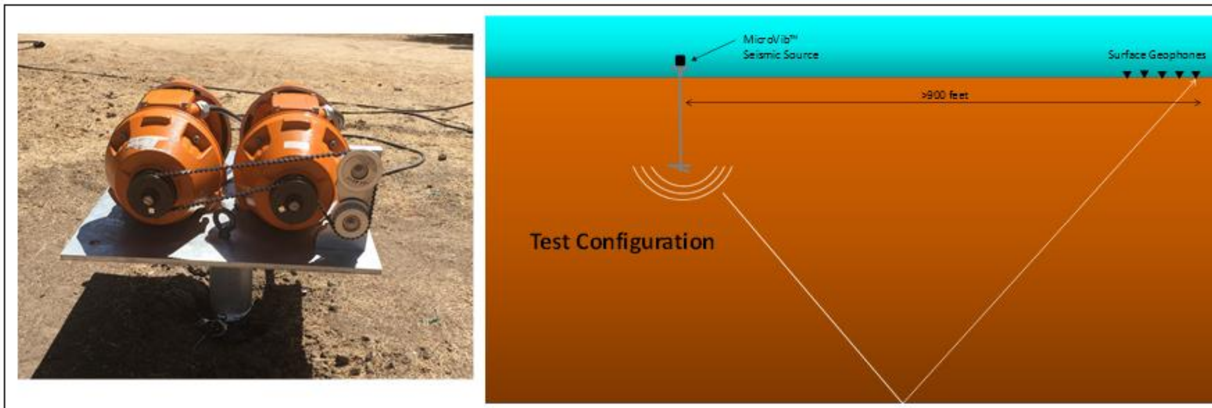
The GPUSA Dual-Motor MicroVib™ uses two high power standard orbital vibrators, linked to counter rotate to produce more powerful linear vibrations too big to be buried/cemented. Based upon sucessful testing in our lab, (and following discussions with the NETL Program Manager) we decided to include them as a third option on this project at no additional cost.

The advantages of the dual motor MicroVib™ include:

- All components are off-the-shelf making it less expensive
- They are no restrictive size limitations (does not have to be buried) which allows larger motors/larger forces
- Standard motors are rated for continuous operation in air, i.e., 100 per cent duty cycle w/o overheating.
- Since they are not buried, they are always accessible for maintenance
- They are designed to be mounted atop helical pile foundation anchors which provide over 100,000 pounds of anchoring force.
- Helical anchors bypass much of the near surface layers, effectively performing like a buried/cemented source.



We then conducted some preliminary field testing of the dual motor MicroVib™ with LBNL at a 100 acre ranch site (Santa Margarita) near San Luis Obisbo, CA. With the unit mounted atop a helical pile drilled down to about 35 feet, we were able to achieve reflected signals to about 900 feet with LBNL's surface mounted geophones. We performed 30 second sweeps and LBNL recorded the data with a 60 second record length. Test layout pictures are shown below.



Dual Motor MicroVib™ Field Test Configuration

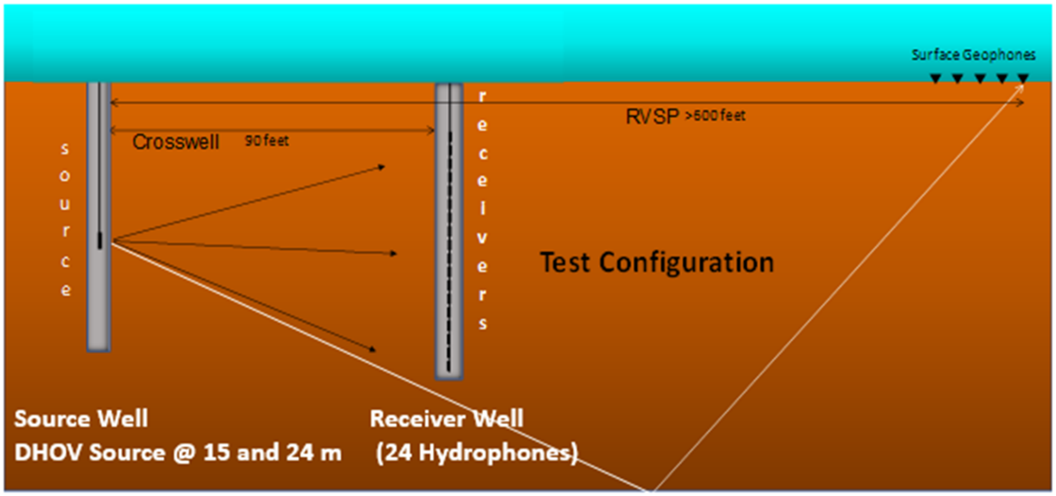
LBNL processed some of the from the dual motor MicroVib™testing near San Luis Obisbo, CA. The testing showed that at over 900 feet (284 meters) distance the surface geophones detected very strong signals. Some representative data results are shown below.

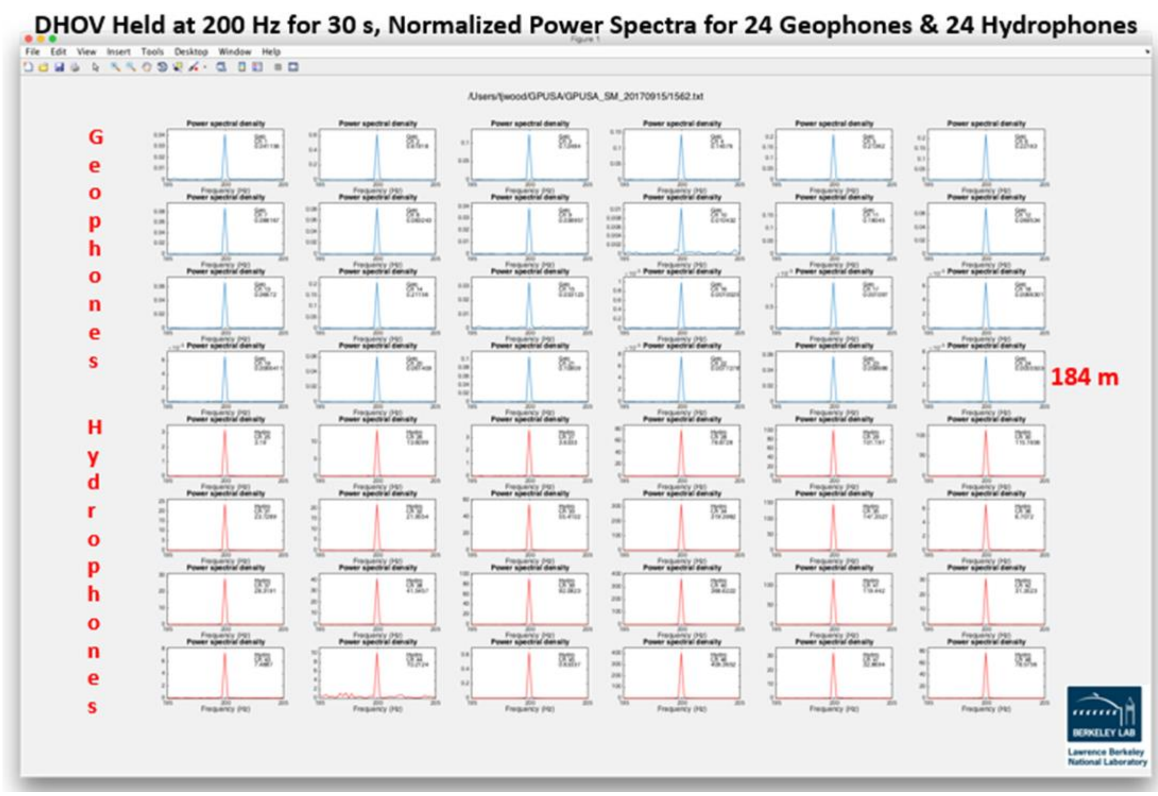
Surface Source signal recorded on Geophone string at Santa Margarita Site

Geophone #1 was 192 m from source (4 m spacing), #24 was at 284 m
Source was held at 100 Hz for 30 s

We field tested the DHOV at LBNL's Richmond Field Site (RFS). The DHOV performance was even better than we had planned/expected. During Crosswell testing the received signal was so strong that we had to significantly reduce the gain of the receiver hydrophones to prevent clipping. Since the 90 foot distance between the two wells was the maximum available at the site, we decided to test the DHOV in the Reverse Vertical Seismic Profile (RVSP) configuration using surface geophones as the receivers. Even in this configuration we received very strong signals to the maximum extent of the field (605 feet). Of note, the testing revealed that our stiffest downhole clamps provided the best performance, which caused us to drop the fluid-coupled version (without any downhole clamps). We also noted that just lowering the source (i.e., deeper) from 15 meters to 24 meters (maximum depth of test well) greatly improved the results. Some pictures of the test configuration and some sample data are shown below:

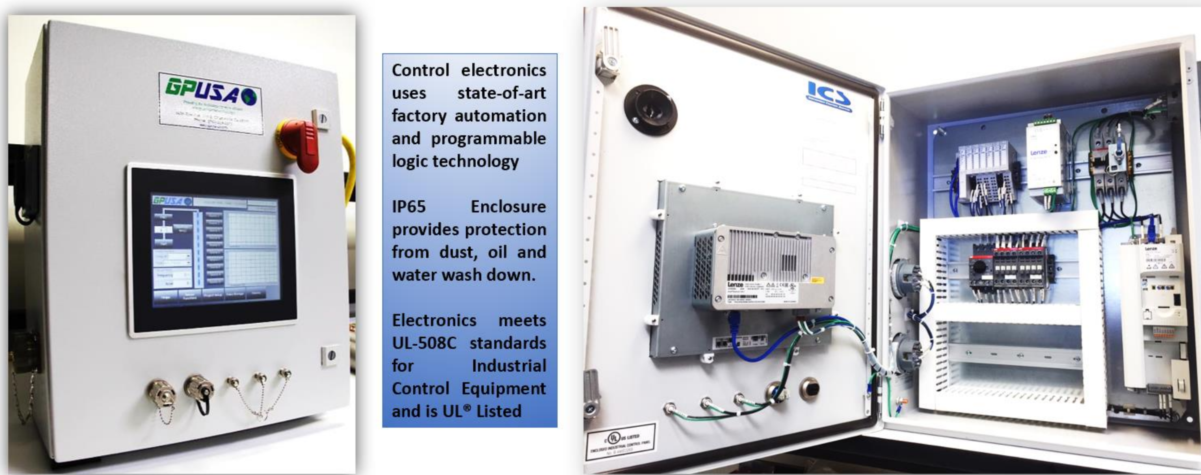
DHOV Field Test Results





October-December 2017 Accomplishments:

The Six Level DHOV source array, and all MicroVib™ units were all completely assembled. The two Electronic Control Units (ECUs) that are part of the shipment to the CMC site had also been built by our contract manufacturer and following a successful source inspection, were received at the GPUSA facility on November 10. Both units received UL® Listing/Certification. Photographs of one of the completed units prior to shipment is shown below.



Control Electronics uses state-of-the-art factory automation/programmable logic technology and is UL® Listed

Once received, the latest control software was loaded onto each of the ECU's on-board processors and the systems successfully passed an end-to-end test connected to their respective seismic source modules.

Since the larger dual-motor MicroVib™ operated at 480V three phase vs. 240V three phase for the DHOV and the two smaller MicroVib units, a prototype electronic control unit (ECU) was provided (not shown) for it. Unfortunately, it did not contain all of the features, of the production ECU's due to cost limitations, i.e., the variable frequency drive was manually controlled rather than computer controlled.

We also updated our test plans with regard to testing at the CMC site . At the CMC site, we planned to install one of the smaller MicroVib™ units via cementing in a well bore and the other on a helical pile foundation. The components for the one helical pile were drop shipped directly to the CMC site. Our helical pile supplier in the US contacted one of their affiliates in Canada to install the helical pile at the CMC site. CMC coordinated with that company to install the helical pile prior to the first day or so of our arrival at the site. The larger dual-motor MicroVib™ will also be tested atop the helical pile at the CMC site

All equipment for the CMC Containment and Monitoring Institute (CAMI) site testing had been built, checked out and has been ready to ship as of 12/14/2017. We decided to hold off shipping during the holiday season as the delivery dates were getting pushed into early 2018 anyway. Don Lawton, Director of the CAMI site informed us that the ground was now be too frozen to drill the well for the cemented MicroVib™ and suggested that we might need to wait until late March or early April to drill the new well.

Jan-Mar 2018 Accomplishments:

We received word in February and in March from the CAMI site that the ground was still frozen and covered by many feet of snow. While installation is still possible under such conditions, it would be difficult and unpleasant for all involved, thus we mutually decided to hold of the installation until conditions improved. Personnel at the CAMI site felt conditions would markedly improve by mid-April so that has become the new target date for installation.

April-June 2018 Accomplishments:
During the week of 24 June the CAMI site site preparations for testing were completed, i.e., the well was drilled for the cemented MV4K-200 Linear MicroVib™, the helical pile that is to be used for the other MicroVib™ units was installed, and the operability of the site power was checked out.

The well for the cemented MicroVib™ was drilled, cased, and cemented. The well depth was about 50 feet, and we pumped in about 3 feet of cement above and below the vibrator. Prior to the cementing we built a rebar cage for the unit to reinforce the concrete around the vibrator. At right are some photos of the well drilling and MicroVib™ installation.


Rebar cage around MicroVib™ unit

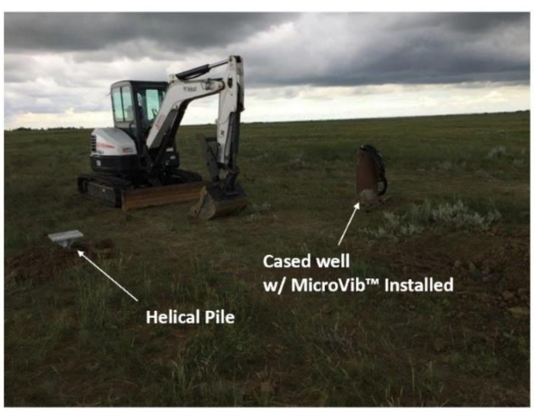

Installing in cased well


Cementing…


Casing lifted ~3 ft. during cementing

A rotary hydraulic motor powered by a Bobcat® Skid Steer Loader was used to install the helical piles. The helical pile anchor system was installed to a depth of about 50 feet, then the custom mounting plate that is compatible with both GPUSA MicroVib™ Linear Vibrators was installed on the top.

The picture below shows the well with the cemented unit and the installed helical pile side-by-side.



All done…, ready to start testing

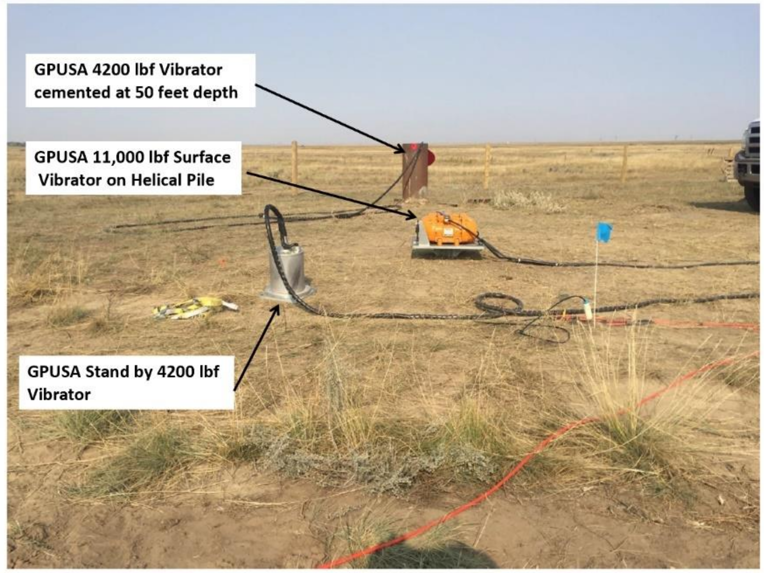

Connecting Skid Steer to first pile


Driving first pile


Final extension going in

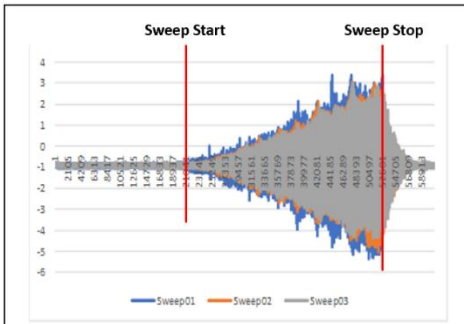

Custom mounting plate being added

July-September 2018 Accomplishments:



We had planned to start testing at the CaMI site the week of August 6th but unfortunately, we had some shipping /import problems getting the final equipment into Canada. Instead of taking 5-7 days to ship equipment and clear customs, it took over 3 weeks. The equipment eventually arrived at the CaMI site in early August. Because of all these delays, we were unable to coordinate with all of the team members and schedule testing until last week of August.

The photo at right shows field layout of three of the GPUSA sources at the CaMI site. At the top in the photo shows the location for the smaller MV4K-200S source cemented to 50 feet. The higher power MV11K-100S (orange) is shown mounted atop the installed helical pile anchor. The additional MV4K-100S shown in the photo has a bottom mounting plate installed to make it compatible for mounting to the helical pile also for later comparison to the identical cemented version.



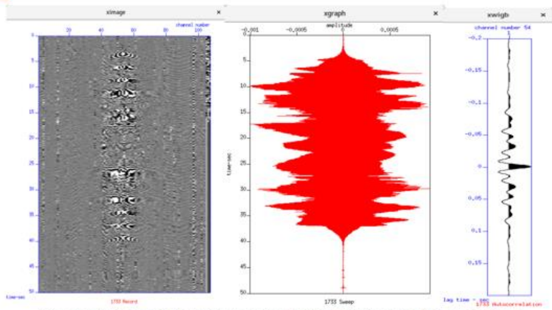
Typical Sweep Pattern for GPUSA MicroVib™

We decide to test the MV11K-100S vibrator mounted on the helical pile first. The initial test results were somewhat disappointing as the frequency sweeps produced highly irregular patterns that seemed to include many resonant subharmonics. The chart at right shows actual sweep data obtained in the GPUSA lab, which is what we were expecting to see at the CaMI site. (The only expected difference being that the sweeps at CaMI included a controlled up sweep and down sweep whereas the lab testing consisted of a controlled up sweep only.) After much investigation (both electrical and mechanical) it was determined that the culprit was the loose connections between the interconnected helical pile sections. The loose connections allowed approximately ¼ inch of movement at each of the six connection points between the helical pile sections. This set up many uncontrolled sub-harmonic resonances within the pile resulting in a highly distorted signal at the reference sensor.

A discussion of the MicroVib™ testing atop the existing helical pile is provided below:
The MV11K-100S source was installed and wired on Friday morning, Sep 7 at CaMI. The source location was near the center of a 104-channel wired 1-C geophone line, at channel 54 (station 154). Coordinates and geophone details are in the SEG-Y headers. Line length is a nominal 1 km, with 10 m receiver spacing. The channel 54 geophone was offset 4.5 m from the source and gained differently than surrounding phones by the addition of resistors to serve as a pilot trace for the sweep. The onboard accelerometer was not recorded during the test. Separate sweeps were run later to record accelerometer signals. Records were recorded uncorrelated on an Aries system in SEG-Y format. File numbers are 1733, 1735, 1737, 1739, 1741, & 1743 recorded from 12:10 pm to 12:44 pm. Triggering was not working. Both the source electronics and the recording system were activated on a radio countdown. An arbitrary time lag at time-zero may exist from shot to shot. Sweeping did not use a computer-controlled variable frequency drive due to the fact that it was not provided in the control box for this particular vibrator. On start, the

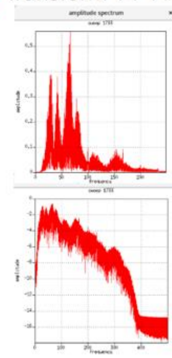
vibrator was energized, and it powered up from 0 at its own speed to 100 Hz. After 24 sec on a manual timer the power was switched off, and the vibrator cycled down to zero. Recording stopped after 50 seconds for a nominal 24 sec up and 24 sec down, with a 2 second listen for the first 5 records. Shot 1743 was a 60 second record. Indications are the vibrator was idle well before tmax for 1741 and 1743 as the vibrator was shutting down immediately on reaching 100 Hz due to an over-current error.

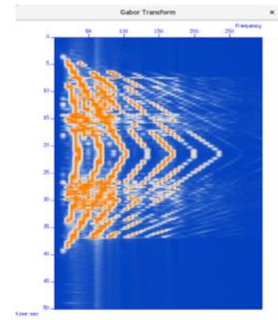
Shot 1733: 50 sec, Sweep, Autocorrelation



The sweep is notchy and asymmetric. Reverberations are indicated on the autocorrelation.

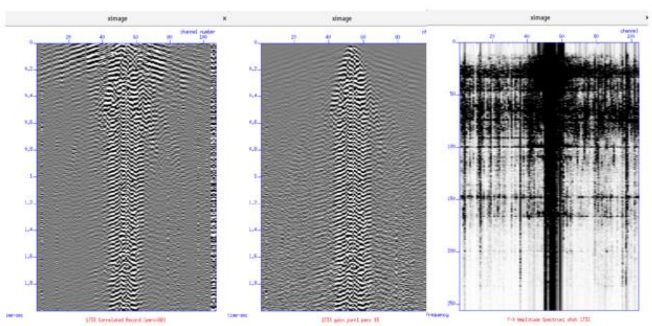
1733: Sweep Pilot Trace Spectra & Gabor Transform T-F Plot



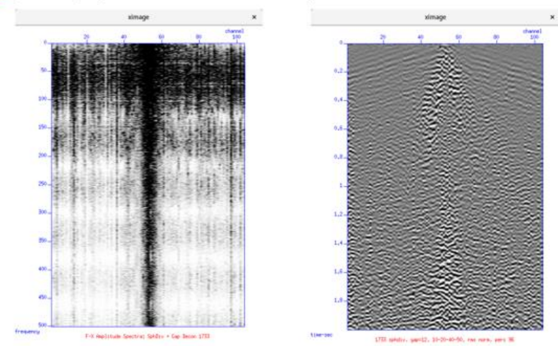


Frequency scales are different on each plot.
Multiple harmonics and subharmonics are indicated.

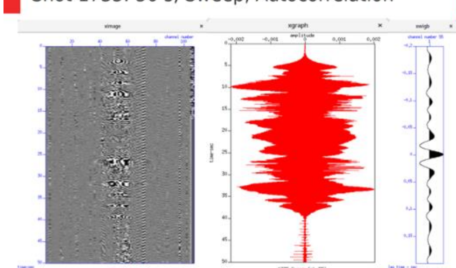
1733: Correlated records; 1) display gain only; 2) with t^2 gain; 3) FX spectra to 250 Hz



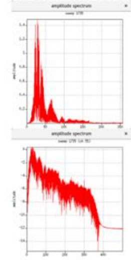
1733: FX spectra after 12 ms gap decon; record with t^2 gain, gap decon, 15-45 Hz bp filter, RMS normalization

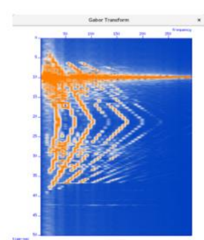


Shot 1735: 50 s, Sweep, Autocorrelation



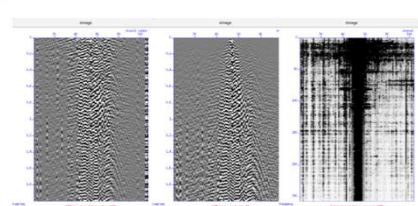
1735: Sweep Pilot Trace Spectra & Gabor Transform T-F Plot



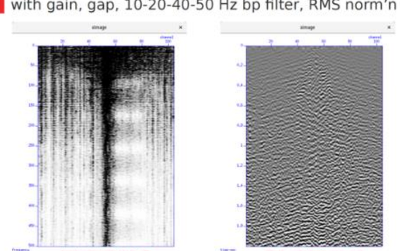


Motion on the line is indicated at 10 sec. Xcor was done with trace 55 instead of 54 for this shot.

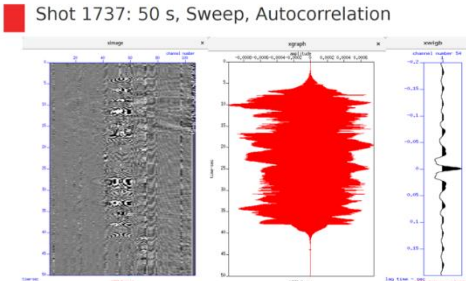
1735: Correlated records - display gain only; with t^2 gain; FX spectra to 250 Hz



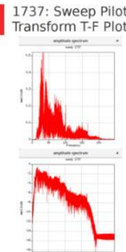
1735: FX spectra after gain & 12 ms gap decon; record with gain, gap, 10-20-40-50 Hz bp filter, RMS norm'n

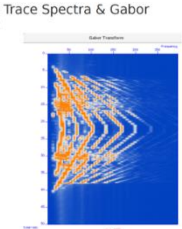


Shot 1737: 50 s, Sweep, Autocorrelation



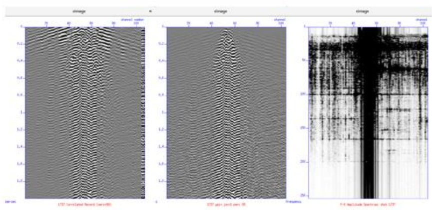
1737: Sweep Pilot Trace Spectra & Gabor Transform T-F Plot



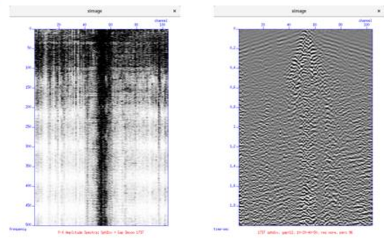


Sweep completed at ~43 seconds.

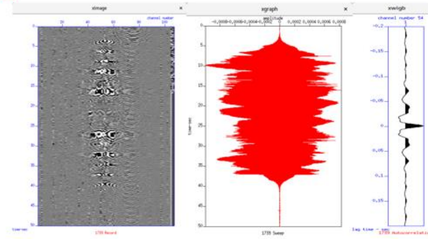
1737: Correlated records - display gain only; with t^2 gain; FX spectra to 250 Hz



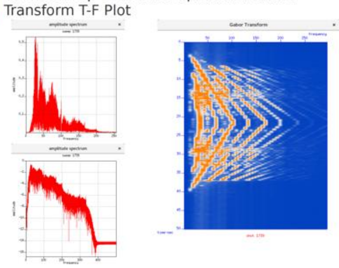
1737: FX spectra after gain & 12 ms gap decon; record with gain, gap, 10-20-40-50 Hz bp filter, RMS norm'n



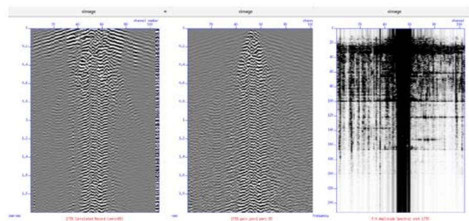
Shot 1739: 50 s, Sweep, Autocorrelation



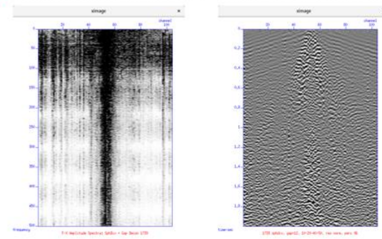
1739: Sweep Pilot Trace Spectra & Gabor Transform T-F Plot



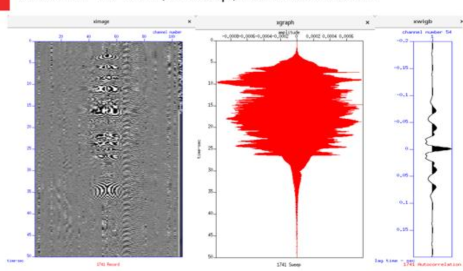
1739: Correlated records - display gain only; with t^2 gain; FX spectra to 250 Hz



1739: FX spectra after gain & 12 ms gap decon; record with gain, gap, 10-20-40-50 Hz bp filter, RMS norm'n

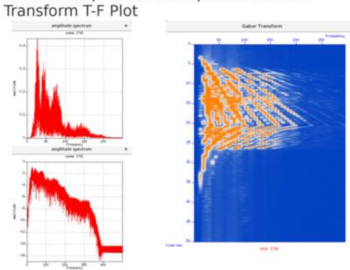


Shot 1741: 50 s, Sweep, Autocorrelation

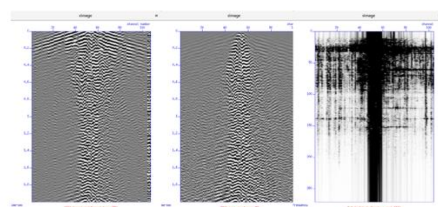


Sweep truncated early due to over-current condition (?)

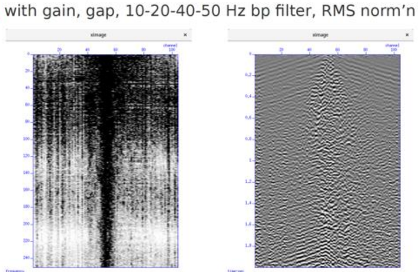
1741: Sweep Pilot Trace Spectra & Gabor Transform T-F Plot



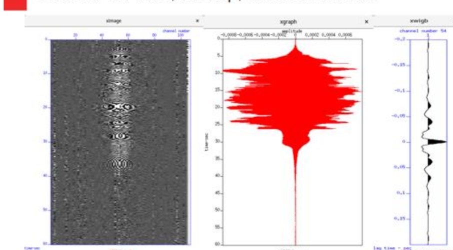
1741: Correlated records - display gain only; with t^2 gain; FX spectra to 250 Hz



1741: FX spectra after gain & 12 ms gap decon; record with gain, gap, 10-20-40-50 Hz bp filter, RMS norm'n

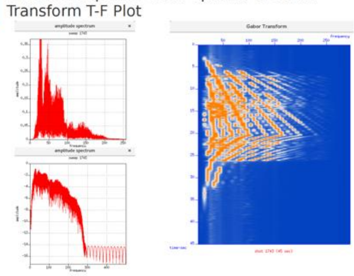


Shot 1743: 50 s, Sweep, Autocorrelation

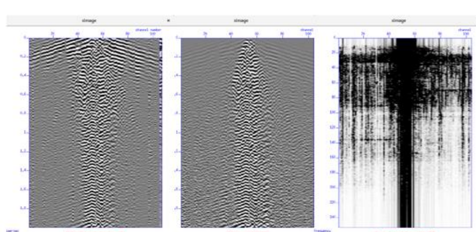


Recording was set for 60 sec, but the sweep ceased early.

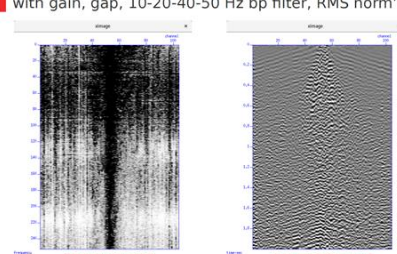
1743: Sweep Pilot Trace Spectra & Gabor Transform T-F Plot



1743: Correlated records - display gain only; with t^2 gain; FX spectra to 250 Hz



1743: FX spectra after gain & 12 ms gap decon; record with gain, gap, 10-20-40-50 Hz bp filter, RMS norm'n



The asymmetry of the sweep traces from the MV11K suggest a complex source signature. Significant vibration modes on the plate can be inferred from the video of the sweeps and close inspection of the sweep wiggle trace. The cause of the problem was determined to be the loose connections between the helical pile sections which allowed approximately ¼-inch of play at each joint. Further testing on the helical pile was suspended until a resolution could be found.

Testing was then conducted on the buried/cemented MV4K-100S MicroVib™. The purpose of the testing was to investigate initial data acquired by a buried, permanent seismic source for rapid time-lapse seismic surveys and compare it to a more traditional Vibroseis (INNOVA UniVibe) truck. Installation and initial testing of the buried permanent source at the Field Research Station was performed in September 2018. The differences between the buried permanent source installed at the FRS and a traditional surface vibratory source were evaluated. Acquisition parameters used in the initial tests are evaluated in terms of up-sweep and down-sweep time duration and frequency range.

After applying Gabor deconvolution to the correlated data, the down-going and up-going wavefields are more easily identifiable, ***and image is comparable, if not superior to, those from a more conventional Vibroseis source at the ground surface, as shown in Figure 1*****.**

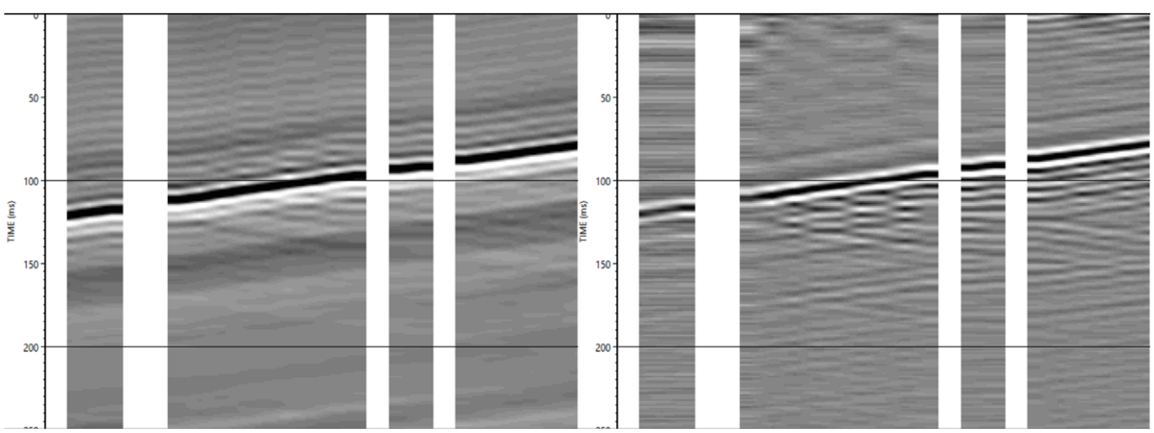
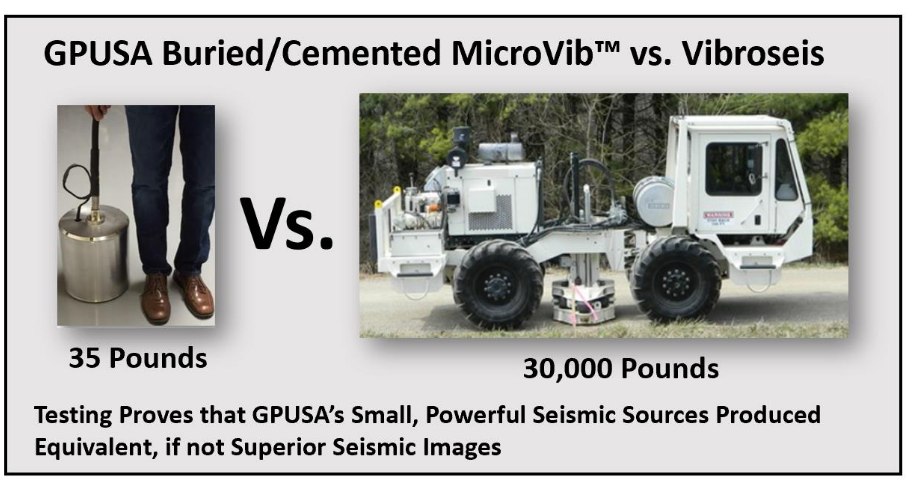


FIG. 1: VSP data acquired with Vibroseis source (left) and a GPUSA buried permanent seismic source (right). Gabor deconvolution has been applied to both records. White stripes are noisy geophones that were nulled for this display. (CREWES Research Report — Volume 30 (2018))



October 2018 – January 2019 Accomplishments:

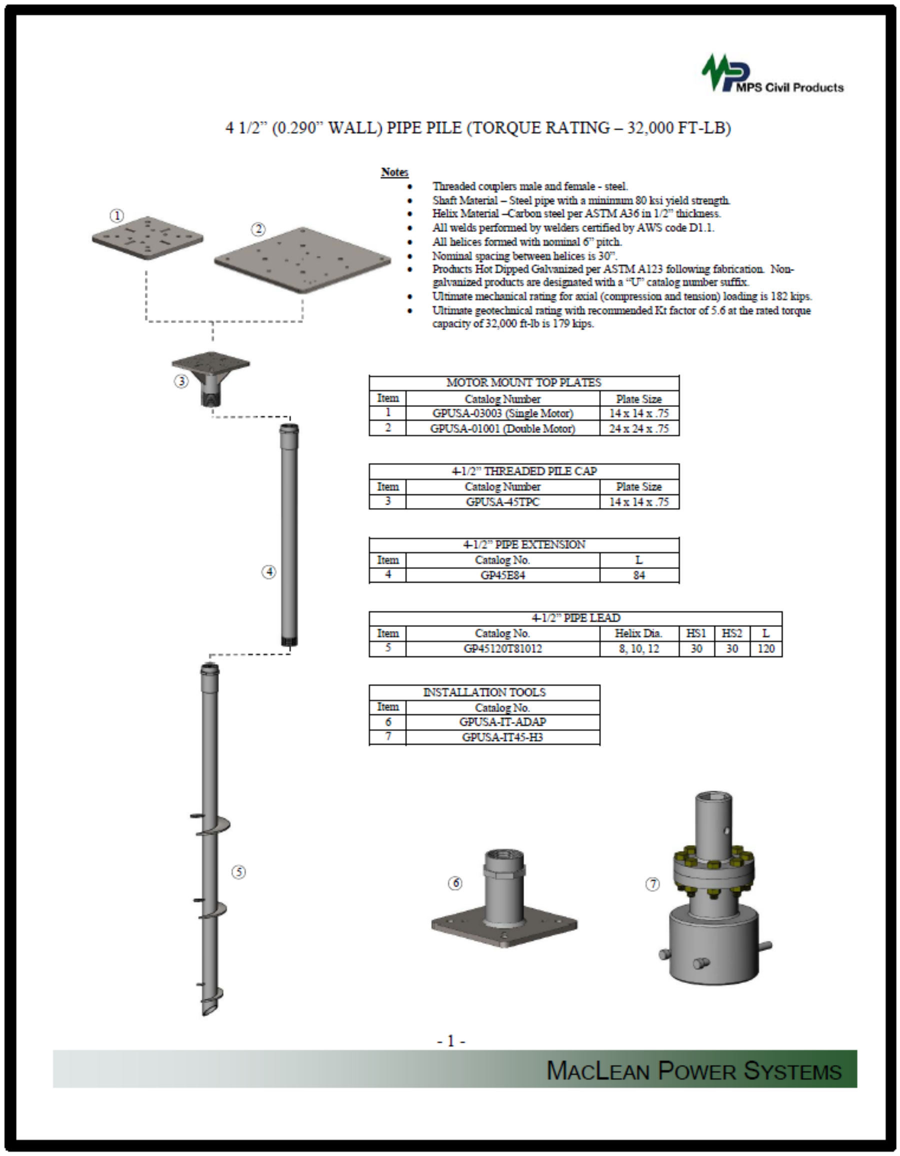
Original Box and Pin Screw Pile Anchors

New "Drill Pipe" type Couplings for Helical Anchor Joints

After analyzing the results from the helical pile testing it was determined that the original box and pin joints between the extension piles did not provide a tight enough fit between the sections allowing up and down movement of approximately ¼ inch at each joint. This excessive "play" between sections led to multiple subharmonic resonances along the shaft which created complex waveforms that were very attenuative to the linear vibration signal. Multiple fixes were considered to try to improve the tightness of the box and pin joints, but in the end it was determined that the joint had to be redesigned. The solution required a means to tightly couple each helical pile section together to allow no relative motion under load (linear vibration). GPUSA got together with the helical pile manufacturer (MacLean Power Systems) and together they redesigned the helical pile section to incorporate threaded ends with threaded pipe couplings to fasten them together (similar to a drill pile coupling) see picture at right. It was also decided to increase the diameter and thickness of the helical pile sections to 4.5 inches OD vs. the 3.5-inch OD of the original pile sections. This more than doubled the load carrying capability of the helical pile anchoring systems from 50,000 pounds to well over 100,000 pounds. The torque rating of the much stronger helical pile sections was now 32,000 lb-ft as compared to approximately 20,000 lb-ft of the original versions.

The redesigned anchors were delivered to the CAMI Research site in mid-January 2019. This included (see picture at right):

- One (1) 4-1/2" OD helical lead-in pile, 84” (7 ft) long with threaded coupling
- Eight (12) 4-1/2" extension piles, 84” (7 ft) long with threaded couplings
- One (1) GUPSA 4.5-inch threaded pile cap with attaching plate
- One (1) GUPSA adaptor installation tool/plate
- One (1) GUPSA drive tool



MPS Civil Products

4 1/2” (0.290” WALL) PIPE PILE (TORQUE RATING – 32,000 FT-LB)

Notes

- Threaded couplers male and female - steel.
- Shaft Material – Steel pipe with a minimum 80 ksi yield strength.
- Helix Material –Carbon steel per ASTM A36 in 1/2” thickness.
- All welds performed by welders certified by AWS code D1.1.
- All helices formed with nominal 6” pitch.
- Nominal spacing between helices is 30”.
- Products Hot Dipped Galvanized per ASTM A123 following fabrication. Non-galvanized products are designated with a “U” catalog number suffix.
- Ultimate mechanical rating for axial (compression and tension) loading is 182 kips.
- Ultimate geotechnical rating with recommended Kt factor of 5.6 at the rated torque capacity of 32,000 ft-lb is 179 kips.

MOTOR MOUNT TOP PLATES		
Item	Catalog Number	Plate Size
1	GPUSA-03003 (Single Motor)	14 x 14 x .75
2	GPUSA-01001 (Double Motor)	24 x 24 x .75

4-1/2” THREADED PILE CAP		
Item	Catalog Number	Plate Size
3	GPUSA-45TPC	14 x 14 x .75

4-1/2” PIPE EXTENSION		
Item	Catalog No.	L
4	GP45E84	84

4-1/2” PIPE LEAD					
Item	Catalog No.	Helix Dia.	HS1	HS2	L
5	GP45120T81012	8, 10, 12	30	30	120

INSTALLATION TOOLS	
Item	Catalog No.
6	GPUSA-IT-ADAP
7	GPUSA-IT45-H3

- 1 -

MACLEAN POWER SYSTEMS

The original screw piles were installed to a depth of 51 feet (15.5 m). The installation had been contracted to TerraCana of Richmond, B.C. Installation was slow and difficult as their hydraulics could only produce about 9,000 lb-ft or torque.

This second installation was contracted to Inland Screw Pile of Coaldale, Alberta. Inland Screw Pile mobilized to the CAMI site on Wednesday January 30. 2019. The equipment they used was capable of producing 30,000 lb-ft of installation torque. The pile installation proceeded very smoothly and the pile depth was measured to be 78 feet (23.8 m). The actual maximum torque achieved was 19.000 lb-ft. The pile could have been set deeper but there was a chance that a coal seam would be encountered that could result in a loss of rotational resistance. With the addition of the final adaptor plate the total depth 81 was feet (24.7 m) below the ground surface.

Installation photos of the installation of the new helical pile foundation anchors at the CAMI site on January 30, 2019 shown below:

Test Screw Pile

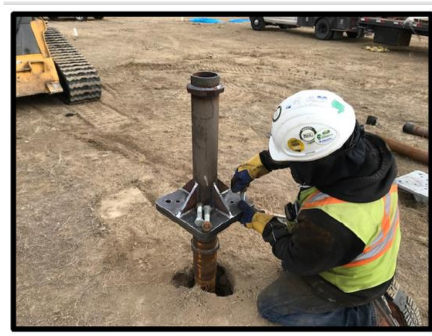
Lead Screw Anchor

Drive Head & Lead Anchor

First Extension

First Extension Leveling

Extension #6



Installing Mounting Plate Drive Tool

Driving Mounting Plate

Mounting Plate Set

MicroVib™ Seismic Source atop Mounting Plate

The plan was to begin testing the MicroVib™ atop the new helical pile mounting plates in early February, however, the weather (extreme cold, heavy snow on the ground) made further testing impractical until the weather improved, which is not expected until late March/early April.

4.0 Results and Discussion

The following required deliverable equipment was built, checked out at the factory, successfully field tested stateside, then delivered to the CAMI site for testing:

- Two identical Single Motor MicroVib™ Linear Vibrator units (MV4K-200S) systems including their Electronics Control Unit and all associated cabling
- One DHOV system including the Electronics Control Unit and all associated cabling.

In addition, a prototype version of the Dual-Motor Microvib™ Linear Vibrator unit (MV11K-100S) including its Electronic Control Unit, all associated cabling, a 240-480 transformer, and helical pile foundation anchors were delivered to the site for testing.

Unfortunately, due primarily to weather delays at the stateside field test sites and the CAMI site in Alberta, not all of the equipment could be adequately tested at the CAMI site, despite two no-cost contract extensions totaling about 10 months. The table below summarizes the actual testing performed and results achieved.

Product	Field Testing in US incl. Results Achieved	Field Testing performed at CAMI site	CAMI Field Test Results Achieved
MV4K-200S Linear Vibrator Systems	30-day life testing cemented in a simulated wellbore. 2600 30-second sweeps w/ no failures. Also tested 120 cycles buried in sand pit w/ no failures.	Cemented to 45-foot depth. Comparison tested against 30K Vibroseis truck.	Achieved comparable, if not superior images to Vibroseis truck. Remains to be tested atop new helical pile.
MV11K-100S Linear Vibrator Prototype System	Field tested w/LBNL at Santa Magarita test site atop helical pile deployed to 35 feet. Achieved strong, clean 100 Hz reflection signals on surface geophones at over 930 feet, which was the maximum extent of field	Field tested atop helical pile deployed to 50 feet.	Initial testing on helical pile showed unsatisfactory results due to loose joints between helical pile sections. Helical pile was redesigned with stiff joints between helical pile sections. Redesigned helical pile was deployed to 80 feet but remains to be tested.
DHOV Rotary Vibrator System	Field tested at LBNL Wildcat site, GMF, and Richmond Field Station. Achieved strong, clean 200 Hz signals during crosswell (downhole hydrophones) and reverse VSP (surface geophones) to the maximum extent of the field.	Not yet field tested.	Remains to be field tested.

5.0 Conclusions

The primary conclusions reached are that the GPUSA Downhole Orbital Vibrator and MicroVib™ Linear Vibrators are capable of producing powerful seismic signals well beyond traditional piezo type vibrators, and if buried and well coupled can even rival the performance of traditional vibroseis trucks. The MicroVib™ Linear Vibrator seismic sources have also demonstrated the capability to provide reliable, long-term, 24/7 permanent monitoring. For the smaller MV4K-200S this was proven via 30-days of life testing (automatic programmed running of 10 consecutive 30 seconds sweeps every hour for 12 hours per day) cemented in a simulated wellbore pipe section. The unit performed flawlessly with no failures/issues. For the larger MV11K-100S, the vibrator motors were selected on their proven record of continuous operation (100% duty cycle) for 3000 hours without maintenance (primarily lubrication).

The initial US field test results regarding the mounting of the larger MV11K-100S MicroVib™ Linear Vibrators atop helical pile foundation anchors demonstrated very promising results, however, the initial testing at the CAMI site did not produce data comparable to the results in the US. The difference has been attributed to loose connections between the individual helical pile sections that allowed approximately ¼ inches of movement/play. During the US field testing many GPUSA engineers were present and they took special measures to ensure each joint connection was connected tightly. At CAMI, the installation of the helical piles was performed by a contractor prior to GPUSA engineers arriving on site. To eliminate this as a potential problem in the future, the helical pile sections were completely redesigned to incorporate threaded pipe sections and threaded couplings similar to drill pipe. Unfortunately, the redesigned helical piles did not arrive at the CAMI site until mid-January 2019. The were installed in late January, however, severe weather in February prevented the MicroVib™ system from being tested atop the new helical pile.

The Downhole Orbital Vibrators (DHOV) were successfully field tested in the US only. Test results led to the following conclusions. The clamped DHOV seismic sources performed so much better than the unclamped (fluid-coupled) versions that we eliminated the unclamped version as an option. The stiffest clamps provided the best performance, so they were the ones used for the all of the test results depicted in this report. The self-releasing clamp ring also performed flawlessly. It held the clamp in the closed position for easy installation downhole without the need for any additional weight bars. Once in position, energizing the vibrator for 10-15 seconds releases the ring, fully clamping and centralizing the DHOV in the well bore. The high strength lead-in cable provided more than sufficient strength for repositioning the DHOV to a higher level or for system removal from the wellbore.

6.0 Recommendations

GPUSA recommends completion of the testing at the CAMI site once the weather improves and plans on doing so.

7.0 References

1. P. C. Leary and L. A. Walter (2005), Physical model for the downhole orbital vibrator (DOV) – I. Acoustic and borehole seismic radiation, *Geophysical Journal International*, Volume 163**,** 2 August 2005, Pages 647–662

2. S. Nakagawa and T. M. Daley (2004) Analytical Modeling of Wave Generation by the Borehole Orbital Vibrator Source, Geophysics, Volume 71, January 2004