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Embedment of the Sediment Layer Electrode Deployer (SLED): Results from 2006 Tests at Stennis Space Center

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14. ABSTRACT In 2006, five field tests were made at Stennis Space Center of a Sediment Layer Electrode Deployer (SLED). The objective was to submerge an array of vertical-plate electrodes, with a total surface area of 18,580 cm ² into anoxic sediment layers by a method that may be accomplished from research vessels. The embedded electrodes would allow power generation from the Benthic Unattended Generator (BUG) technique. Towed-deployment and vibration-deployment techniques were investigated. The best results were incomplete embedment depths ranging from 17.8 cm to 30.5 cm. Problems for towed tests included an imbalance of forces between the front and rear sections of the SLED, and a catastrophic material failure during embedment with anchor flukes. Uneven embedment during vibration-deployment may have resulted from obstacles in the sediment, a sloping bottom effect, or greater resistance to vibration as the SLED embeds. Further research and development is necessary to find an effective embedment technique.					
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1. Introduction

Initial results are presented for NRL-7332 research and testing with Sediment Layer Electrode Deployer (SLED). The goal of the SLED device is to completely imbed an array of electrode plates into the anoxic zone of the sublittoral, benthic-sediments. The electrode array will be utilized by the Benthic Unattended Generator (BUG) Equipped SEPTR (BES) to provide power for charging of device batteries (2006, Tender et al.). Throughout the year of 2006, the SLED was modified and tested several times. The testing performed in 2006 investigated towed-deployment and vibration-deployment techniques. The outcome of these tests showed that more research and development is required to allow for an ocean functional SLED design and deployment technique.

2. Background

Robert Tyce at the University of Rhode Island (URI) created the original SLED design with consultation by Jeffrey Book (NRL 7332) in 2005. This original design had trapezoidal shaped electrode plates, made from single pieces of 3/8" (0.95 cm) fiberglass sheet. The SLED was tested at the URI Narragansett Bay campus on the beach by pulling with a small electric winch. The design showed problems with the aft end embedment, and an outward flexing of the embedment plates. After this trial the SLED was shipped to NRL code 7332 for research and development, while the URI team focused efforts on an alternative caisson embedment technique (see Section 8).

3. Methods

Work at Stennis Space Center (SSC) primarily focused on physical modification of the SLED and testing of the physical design. The details of the SLED structure and the modifications to it are described in Section 3.1. However, some preparation work was also done for future electrical power generation tests which required attachment of electrode material to the SLED fins (Section 3.2), monitoring of power generation (Section 3.3), and localized environmental monitoring (Section 3.4).

3.1. SLED Structure and Modification

The basic SLED design used a Mooring Systems Inc., bottom-mounted, trawl-resistant enclosure (MSI enclosure) for attachment of the embedment plates. The fiberglass embedment plates were made out of 3/8" (0.95 cm) fiberglass sheet, and were held in place between two 90° angle sections of fiberglass. The electrode plates were redesigned 2 times during the year, based on test results described in Section 5.

The first redesign included tapering the front side of the plate, to reduce drag while embedding into the sediment. Also, the plates were attached in a staggered arrangement to allow for sediment transport through the rows of plates, which reduces the compressing of the sediment and reduce the flexing of the plates (Figure 1). A total of ten plates were attached, each with a surface area estimate of 288 in² (1858 cm²) per plate. All ten plates have a total usable surface area estimate of 2880 in² (18580 cm²) for the graphite electrode. The base of the enclosure was reinforced with a layer of 3/8" (0.95 cm) fiberglass sheet to keep the platform rigid. Stainless steel hardware was used to connect all parts together.

A second modification to the sled was the addition of anchoring flukes to the rear of the SLED, and addition of a "tow-lever". The flukes, much like the ones found on a

danforth anchor, are 4" wide (10.2 cm), and made out of the 90° fiberglass angle. Their vertical height from the base is greater than other plates and thus they will be the first plates to contact the sediment. The fiberglass flukes were tapered on both front and rear edges to lower the friction as they penetrate and when they are removed from the sediment. These flukes were also given a downward angle of 7° to create downward movement while towed (Figure 2). Two of the rear electrode plates had anchor flukes attached. A C-channel aluminum beam (3" x ¼") was attached to the front-center of the sled, to act as a "tow-lever" to assist in the balancing of the downward force. The bridle-wire was attached to the rear of the SLED, and then run through shackles, which fed the wire towards the front of the lever. It was then attached to the front-end of the lever by running it through 3" aluminum pipe and then u-bolting the pipe to the beam.

A third modification was to remove the anchor flukes, and use a 12V DC concrete vibrator (made by Vibco, model DC-60) along with 109 lbs. (49 kg) of weight. The vibrator had 27 kg of shaking force, and a speed of 3600 rpm. The vibrator was encapsulated using a 2-part urethane encapsulant (Kindt-Collins Co., Dynacast). The encapsulated vibrator was then clamped to the topside of the SLED, with the vibration force acting perpendicular to the electrode plates (Figure 3). The vibrator was powered with a 12V DC power supply, and the duty cycle was set to ~50% (~30 second period) using a 555-timer and 12V relay.

3.2. Electrode Material

A graphite sheet was attached to the fiberglass electrode plates (Figure 4). The graphite sheet is approximately 1/10" (2.4 mm) thick and comes in 4ft x 4ft (1.2m x 1.2m) sheets. The graphite sheet was cut to the shape of the electrode plate, leaving a small border between the graphite and the edge of the electrode plate. The edge of the graphite sheet was cut at an angle, so that the epoxy will overlap the graphite by a nominal 0.25" (6.4mm). The graphite and fiberglass surfaces were scored with a non-metallic scrubbing pad, to provide a good surface for bonding. An underwater epoxy (Denapox Aquagel, by DeNeef) was used along with a process known as "vacuum bagging" to produce a secure bond between the two materials. The vacuum bag process creates a large, even pressure over the bonding surfaces, and results with a secure bond. The vacuum bag process allowed the epoxy to be tapered to the fiberglass, which will reduce drag. The electrical connection was made by connecting a 16 AWG gauge copper wire to a small titanium bolt and nut that compresses the wires into the graphite sheet. The connection was sealed using silicon, and protected with a piece of fiberglass to prevent damage.

3.3. Power Monitoring

Monitoring the current and voltage produced by the electrode array is carried out by the use of a programmable load cell, manufactured by Scribner Associates, Inc. Model 870 is used for the laboratory testing and two 871 models, enclosed in a waterproof housing, will be used to monitor current and voltage while in the field. These devices can monitor up to 500ma of current, and have a resolution of 100 μamps.

3.4. Water Parameter Monitoring

A Sea-bird model-25 ctd was set up to record conductivity, temperature, pressure, and dissolved oxygen (SBE 43 sensor). Also, 2 Oxyguard, type III galvanic-cell, dissolved oxygen sensors (Point Four Systems, Inc., British Columbia, Canada) were connected to the analog channels of the ctd. A three point calibration method was used to calibrate the Oxyguard sensors to an anoxic water (nitrogen purged), room temperature water (against the SBE 43 oxygen sensor), and to water saturated air at 1atm and 21° C. The ctd arrangement will be used to monitor tank testing of electrodes and environmental parameters of deployment sites.

4. Test Sites

Three test sites were used during the trial period. The first site was sandy-shell area along the Pear River inside the SSC. Large veins of clay, tree roots, and miscellaneous debris were features in the substrate at this site. This site was used to test the towed-embedment of the SLED device.

A second test site was chosen along the Bay St. Louis shoreline. This area was a homogeneous sandy shore, with sporadic areas of soft-silt deposits, found just below the sediment surface. This site was also used to test the towed-embedment of the SLED device.

The third test site was located on the SSC dock, near the 7332 warehouse building. The depth of the sediments at the SSC dock was examined using a jet-probe. The jet-probe was created by attaching a 20 piece of ¾" (0.29 cm) PVC pipe to a pressure washer. The probe pushes the sediments out of the way using the water pressure, and will stop penetrating when the bedrock or other large obstacles are encountered. Relative sediment depth was measured by marking the PVC pipe every 6" (15.2 cm), and finding the difference of the distance traveled from the surface of the sediment to the base rock, relative to the water level. Jet-probing revealed that this site had approximately 2' (0.6 m) of fine sediment, and had little debris visible on the surface. This site was used when testing the vibration-embedment of the SLED device. An underwater camera was used to observe the embedment depth of the SLED for tests at the SSC dock. The camera was mounted to a 20' (6 m) pole, with the video being recorded by handheld video camera on land. Underwater lights were also used on days when sunlight was clouded.

5. Results

The first of 5 field trials occurred in January 2006. The sled was slowly towed by a truck in 1-2' (0.3 – 0.6 m) of water, along a 200ft of sandy-shell shoreline of the Pearl River at SSC. One highly visible problem was that the back end of the BES was not embedding as fast as the front, causing an end-over-end flip. Adding approximately 400 lbs (181 kg) of weight to the back-end of the SLED helped to stabilize the balance, and maximum embedment was approximately 7" (17.8 cm) deep. However, the remaining imbalance of force between the front and rear of the SLED was a fundamental problem and it was determined that significant modification was needed to address this design challenge.

The second trial was also at the Pearl River shoreline at SSC. The addition of the anchor flukes to three of the electrode plates was tested, and showed a small increase of effectiveness. On the first attempt, imbalanced forces between the front and rear plates

still existed, and therefore 400 lbs. (181 kg) were added to the rear of the device. A second attempt was made with 3 forward plates removed (1 with anchor fluke, 2 without) and the 400 lbs (181 kg) of weight on rear section, resulting in another small increase in effectiveness, but the imbalance of downward force was still present. A third attempt was with the tow-rope elevated, but this did not have a significant change on the performance. In this configuration, the sled was embedded to a depth of 10" (25.4 cm) (Figure 5).

The third trial was at the Bay St. Louis shoreline in May 2006. The SLED was configured with anchor flukes on two of the back embedment plates, and a tow-lever was attached. While positioning the SLED for the initial tow, it was noticed that the forward section was embedding into the sand, by its own weight. The aft section was not sinking, even with 159 lbs. (72 kg) of weight added, due to the larger surface area ("footprint") of the anchoring flukes. The tow path of the truck caused the SLED to veer slightly to the right, which created a pivot-point on the front electrode plate. The turning of the tow path caused two of the right-side plates to break in half, and ended the day of testing. The embedment of the SLED was unable to be recorded due to the catastrophic failure of the plates (Figure 6).

The fourth and fifth trials were to test the SLED device using vibration and weight as the embedment method at the SSC dock. The test plan was to set the SLED onto the sediment, examine the depth of embedment, run the vibrator for 24 hours, and then periodically reexamine the depth of embedment. During the fourth tests, the power supply of the vibration unit overheated and destroyed the vibrator unit motor. On the 6th hour of the test, however, the SLED was examined and no change had occurred. On the fifth test, the 50% duty cycle timer was installed, and a new encapsulated vibrator motor was used. The observed depth of embedment after deploying the SLED showed that the left side of the SLED embedded to approximately 12" (30.5 cm), but the right side did not embed more than 6" (15.2) (Figures 7 & 8). No change in embedment was observed after running the vibration motor for a 24-hour period.

6. Discussion

The SLED device was tested 5 times, which examined 3 redesigns. Each of the redesigns showed improvement, but none showed an effective design. However, trials did reveal valuable information.

The first and second trials showed how the forces were imbalanced between the front and rear of the SLED, which resulted in an end-over-end flip while being towed. To avoid having to add massive amounts of weight, the anchor flukes were added to provide grip to the back end and thus better balance downward torque on the front end. Furthermore, the flukes were designed with the downward angle to keep the SLED device digging into the sediments while being towed. The second trial used the anchor fluke design, but still had unbalanced torque. With the addition of approximately 400lbs. (181 kg), the removal of 3 of the forward plates, and elevating the towrope, the SLED was able to embed 10" (25.4 cm). The SLED device may have been sliding across a hard layer in the heterogeneous substrate at this site, allowing it to only reach the 10" (25.4 cm) depth. Relocating to the Bay St. Louis, MS shoreline provided a more homogenous sandy sediment substrate for testing.

The third trial at the Bay St. Louis, MS shore, showed improvement in the embedment depth and the balancing of force with the flukes, but it also showed another problem with the SLED design. This time, due to a slight veering to the right by the tow vehicle, two of the plates were snapped in half. This exhibits the fact that the SLED would need to be designed using much more robust materials, or delicately-towed in a straight line, which is impossible in an oceanic setting, due to winds, currents, and the capabilities of any research vessel. During this trial, it was noticed that the sand substrate allowed the front of the SLED to embed a few inches by its weight alone. In contrast, the rear of the SLED did not embed without towing due to the anchoring flukes, and did not embed fully during towing despite the anchoring flukes. The natural sinking of the front end of the SLED suggested testing non-towed embedment techniques.

The depths of the vibration embedment were slightly greater than those from the towed tests, but some new problems did come to light. It appears that with the desired sediment bed of organic rich mud, the sled is capable of embedding with a slight vibration and the force of gravity. However, embedment was incomplete for all fins and the uneven depths of embedment across the SLED is as severe of a problem as the lack of embedment of the back end during tows. Possible causes for this poor performance include unseen obstacles or a hard substrate layer below the sediment surface, or issues arising from small scale variations of the sediment surface. It appears that the SLED was deployed across a small depression in the sediment, resulting in the plates located on the sides of the SLED to embed deeper than the plates in the middle. Another theory is as the plates penetrate into the sediment, sediment to vertical plate coupling provides greater and greater resistance to the vibrational force of the top plate. If the plates are not completely embedded, a short circuit will occur, and no power will be produced. Minor sediment depression problems could possibly be solved with a development of an insulating skirt, but only if the skirt could be seated to the sediment firmly enough to allow the water in the created pocket to become anoxic.

7. Conclusions

Testing of SLED at SSC in 2006 revealed fundamental challenges for towed deployment techniques. Without anchor fins, the SLED slid across the bottom and had unbalanced torque leading to poor embedment of rear fins. With anchor fins, the SLED can dig in better but then the entire force of the tow is felt by the fins and small imbalances cause large structural stress. With a requirement for complete embedment, towed techniques are thereby impractical for ship deployment of SLED.

Vibrational deployment has so far not achieved much better results than towed tests. However, further testing of this deployment technique is needed to determine if the 2006 test findings are truly representative or only from anomalous local problems.

8. Future Research

In order to solve SLED deployment problems, further research and design is necessary. On the forefront of the research is the investigation of the most effective electrode material. Motivation for the vertical plate array design is the massive need for electrode surface area, but these vertical arrays have not performed well in embedment tests. However, Robert Tyce and Darren Flynn (URI), during their research on a caisson-suction embedment technique, have shown promising results for increased power

generation from foam-type graphite compared to that of the sheet-graphite. If foam-graphite is an effective enough material, it will change basic design restrictions of SLED. Higher power generation per area would reduce the amount of surface area required to be in direct contact with sediment and thus permit a wider diversity of electrode plate configurations. For example it might be possible that a foam-graphite arrangement could meet power generation requirements when only placed on the sediment interface and therefore not require the downward embedment force of vertical plates. If the electrode material is only to be placed on the sediment interface, than a modification that needs to be tested is the addition of an insulating skirt to inhibit the sediment electrodes from being shorted and stopping the power generation.

As for the vertical plate arrangement, a future work includes testing a water-jet embedment method. Water-jets will be outfitted on the tips of the electrode plates, and the flowing water will fluidize the sediment, allowing gravity to embed the electrode plates. Also further vibration tests may be conducted at new test sites.

The URI team has been conducting tests using suction caisson embedment techniques. This technique is best suited for horizontal plate deployment but might also work for vertical plate deployment. Research on this technique will continue in collaboration with URI.

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References

2006 Leonard M. Tender¹, Sam A. Gray, Ethan Grooveman², Daniel A. Lowy, Peter Kauffman and Julio Melhado **First Practical Application of a Microbial Fuel Cell**



Figure 1.

Image of redesigned electrode plate attached to the bottom of the MSI enclosure's base. The plates are in a staggered arrangement, allowing sediment transport through the rows of plates, reducing the compression of the sediment. A 12 " ruler was placed at the bottom of the front plate for scale.



Figure 2.

View looking aft, of modified electrode plate with anchor fluke attachment, showing the tapered edges and the 7 degree angle. One fluke is attached on the front-center plate, and the other two are attached to the rear plates. The tow-lever is not shown.



Figure 3

Image of the third modification using an encapsulated vibrator (blue cube) and 109 lbs. (49 kg) of weight, with anchoring flukes removed.



Figure 4.

Image of full electrode plate with 16" x 24" square for comparison.



Figure 5.

Left: Results of the first attempt of the second trial, with no weight added. Right: Result with 3 forward plates removed, an elevated tow rope, and 400lbs of ballast on rear of instrument. The embedded depth was to a depth of 10" (25.4 cm).



Figure 6.

- A: Starting position of the SLED, showing the sinking of the front-end.*
- B: Approximately the deepest-embedment depth, before the bending of the mooring.*
- C: Bending of mooring base, and beginning of end-over-end flip.*
- D: Breaking of embedment plates.*



Figure 7.
Image of the forward, right-side plate, during the vibration embedment test. The estimated depth of this plate was 12" (30.5 cm).



Figure 8.
Image of the aft embedment plates, showing that the depth of embedment was not uniform for all plates.