

FINAL REPORT

Limited Scope Development of a Sediment Fluidization and Target Handling Claw for UXO Burial at Underwater Munitions Test Ranges

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| 14. ABSTRACT This work developed a new method for the burial of surrogate UXO targets in marine sediments based on sediment fluidization. Laboratory tests showed that fine and medium grained sands can be fluidized by jetting water from above, and that broad-sided targets can easily be buried in the fluidized sediment. The combination of higher hydraulic conductivity and increased minimum fluidization velocity in larger grained sediments make fluidization of coarse-grained sands impractical. Field tests were conducted at three sites ranging from medium grained sand to mud. The system was successfully able to fluidize sediments and bury targets into the fluidized sediments up to 0.65 m deep. Sediment core data at field test sites showed no significant change to the bulk grain size distribution due to fluidization and burial. This burial method can be developed into a surface operated bottom lander with low technical risk. Such a bottom lander would have minimal operational limitations compared to dive teams, be able to bury targets quickly, and provide accurate target burial position, depth, and orientation to test site operators. | | | | | |
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List of acronyms

| | |
|--------|--|
| APL/UW | Applied Physics Laboratory, University of Washington |
| ESTCP | Environmental Security Technology Certification Program |
| LPM | Liters Per Minute |
| SERDP | Strategic Environmental Research and Development Program |
| UXO | Unexploded Ordnance |

Keywords

Sediment Fluidization, Surrogate UXO Burial

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We would like to thank SERDP and ESTCP for their support of this work. We would also like to thank Dr. Nina Stark from Virginia Tech for her conversations about the physical processes involved and her feedback on experimental techniques, and Dr. Kevin Williams from APL/UW for his feedback throughout the project. Lastly, we are indebted to the work of everyone who has preceded us.

Abstract

Objectives: The objective of this research is to develop and test a new method for the burial of surrogate UXO targets in marine sediments based on sediment fluidization. Fluidized sediments have no compressive or shear strength, and in this state targets can be lowered into the sediment with only buoyant and drag forces acting on them. Once the fluidization flow is stopped the sediment will regain its natural state and emplaced targets will remain buried in place. Once developed this technique can be used to build a ship operated bottom lander capable of burying targets to 0.5 m depth or more in marine sand and silt sediments quickly and with minimal operational limitations. With the integration of existing underwater navigation technology such a target burial system could provide accurate target burial position, depth, and orientation to test site operators.

Technical Approach: Testing will incrementally develop and validate methods to fluidize sediments from above, while descending through the fluidized area with a manipulator and target to be buried. Laboratory tests performed with commercially available sands will define operational parameters such as fluidization flow rates, burial rates, and jet sizes as a function of sediment grain size. Field tests will validate the method in real world sediments.

During the project a hydraulically operated manipulator capable of fluidizing seafloor sediment and handling surrogate UXO targets up to the size of 155 mm mortar shells will be designed and built. The manipulator will be integrated into a ship deployed bottom lander for field testing.

Results: Laboratory tests showed that fine and medium grained sands can be fluidized by jetting water from above, and that broad-sided targets can easily be buried in the fluidized sediment. The combination of higher hydraulic conductivity and increased minimum fluidization velocity in larger grained sediments make fluidization of coarse-grained sands (laboratory tests were conducted in sand with mean grain diameter of 1.18 mm) impractical without restricting the radially outwards flow of water through the sediment with a coffer dam.

Field tests were conducted at three sites ranging from medium grained sand to mud. The system was successfully able to fluidize sediments and bury targets into the fluidized sediments up to 0.65 m deep. When fluidization flow was stopped the targets remained buried. A dense shell layer at one test site could not be penetrated. Sediment core data at field test sites showed no significant change to the bulk grain size distribution due to fluidization and burial.

Benefits: This limited scope project developed a new method for surrogate UXO and clutter target burial at demonstration sites, or for establishing calibration lines at real world UXO survey sites. This burial method can be developed into a surface operated bottom lander with low technical risk. Such a bottom lander would have minimal operational limitations compared to dive teams, be able to bury targets quickly, and provide accurate target burial position, depth, and orientation to test site operators.

Executive summary

Introduction

Munitions Response projects that deal with the development of technologies for detection and classification of unexploded ordnances (UXO) in the marine environment require surrogate UXO targets to be buried in seafloor sediments to establish test and demonstration sites. As research programs transition from basic research to technical demonstrations and blind tests the georeferenced position accuracy, and knowledge of target burial depth and orientation becomes more important [1]. At the same time the number of targets buried at demonstration sites may grow to cover the wide range of munitions and test cases. Both of these needs require new solutions to target placement and burial. The overarching goal of project MR20-1220 is the development and proof-of-concept testing of a new surrogate UXO target burial method based on sediment fluidization for logistically simple, cost-effective target burial with minimal disturbance to the seafloor sediment. This goal is directly in line with the enabling developments and testbed requirements listed in sections 2.0 and 4.3 of the 2018 SERDP underwater munitions response workshop [1].

The proposed approach to this problem is to bury surrogate UXOs by fluidizing the seafloor sediment and inserting targets into the fluidized sediment with a manipulator capable of precisely controlling target burial depth. Once positioned the fluidization flow is stopped and the sediment returns to its normal, consolidated state with the target buried. One major advantage to this technique is that it does not require excavating the sediment in order to bury a target, reducing the disturbance to the sediment, and saving time and effort. The following research questions were identified to develop this new burial technique: 1. Can sediment fluidization work in an unconstrained environment (without a caisson or side walls) and how large would the fluidized area be? 2. What range of sediment grain sizes will this technique work over? 3. Once fluidized, can a broad-sided target be easily buried? 4. How do real world sediments and environments affect the technique?

Objectives

This project was organized in two phases, first a laboratory effort followed by field-testing. The project was structured to incrementally develop and test the methods for in-situ sediment fluidization and target burial. As such there were an incremental series of objectives.

Sediment fluidization is a well-developed engineering technique used in fluidized bed reactors and other chemical processing environments. Literature on the method makes it clear that in the controlled environment of a reactor chamber, where the grain size distribution is very narrow and the fluidization flow is retained by the side walls of the chamber there should be no issue burying broad-sided objects in the sediment while fluidized. The realities of working in-situ in the marine environment are quite different: the grain size distributions can be quite large, there are typically no solid walls to retain fluidization flow near the burial target, and it is impossible to pump the fluidization flow from below; anything reaching into the sediment must come from above. These differences clearly require a different experimental approach, and little was previously known about how these differences would affect the ability to fluidize the sediment and bury targets.

In the first phase of the project a controlled laboratory test environment was built for basic fluidization testing with commercially available sands that spanned marine sand grain sizes. The test equipment was kept as simple as possible in order to focus on if, and under what conditions, a volume of sand could be fluidized by water jetting from above within a larger continuum of sand. The objective was to establish the geometries and parameters in which sediment fluidization worked for this approach. The knowledge gained in this phase of the project informed the design of the field-testing equipment.

In the second phase of the project a ship deployed bottom lander with a target handling manipulator capable of jetting fluidization flow and handling surrogate UXO burial targets was designed and built. This system was field tested at multiple sites in Puget Sound and Lake Washington across a range of sand and mud sediments. The objective was to show that surrogate UXO targets could be buried to 0.6 m burial depth or greater in real world marine sediments by sediment fluidization.

Technical Approach

Sediment fluidization occurs when a fluid is pumped vertically upwards through a granular material and the drag imparted on each solid particle counteracts its weight: it becomes suspended, thereby reducing the effective stress between grains to zero. When this balance of forces occurs, the granular material behaves like a fluid for as long as the gas or liquid flowrate is maintained. Sediment fluidization is described by the Ergun equation [2,7] which defines the conditions required to balance all forces on the sediment particles, allowing them to lose cohesion and act as a fluid. This equation can be rearranged to calculate minimum fluidization velocity:

$$u_{mf} = \frac{(\phi_s d_p)^2}{150} \frac{\rho_s - \rho_w}{\mu} g \left(\frac{\epsilon_{mf}^3}{1 - \epsilon_{mf}} \right)$$

Where some parameters relate to the granular medium (d_p - grain diameter, ρ_s - sediment density, ϕ_s - sphericity, ϵ_{mf} - void fraction) and the rest to the fluid (ρ_w - fluid density, μ - dynamic viscosity). Because of the differences in experimental geometry between this work and a typical fluidized bed the Ergun equation and any other established design guidelines were useful starting points but could not ensure a successful system design, for this testing would be required.

The first phase of the project was laboratory testing to investigate how these differences in approach would affect fluidization. A simple conceptual layout of the laboratory testing is shown in figure E1. The goal was to jet fluid downward into the sediment directly below a burial target, where it would reverse direction and exit the sediment by rising vertically upwards around the target and manipulator, fluidizing the sediment below and around the manipulator and up to the sediment surface.

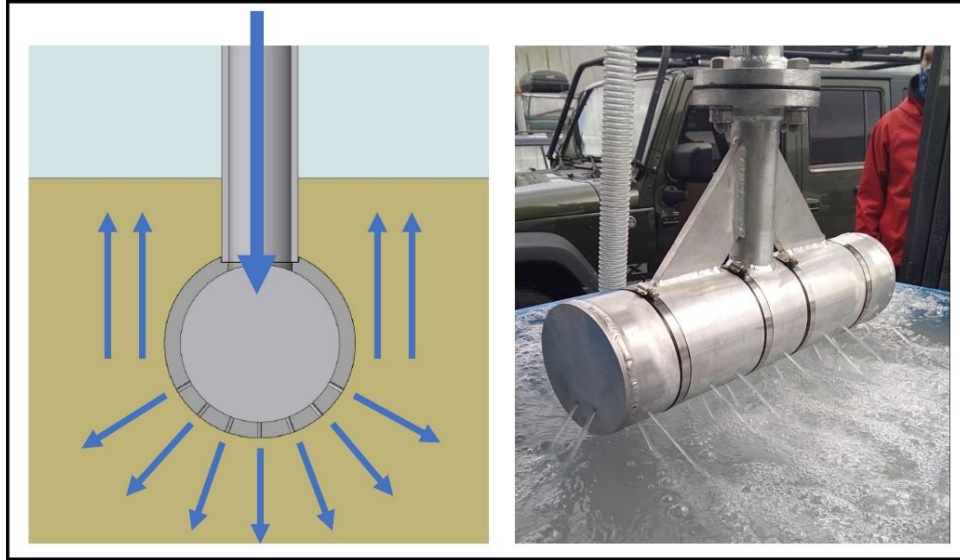


Figure E 1. Conceptual layout of laboratory testing method

The fluidization and burial target was a simple cylinder with jetting holes drilled radially around its lower half, and a vertical pipe welded to it used both for pumping fluidization flow down into the target, and for manipulating it while in the sediment. The target was sized to have approximately the same major dimensions as a 155 mm mortar shell, without the characteristic taper of a projectile. The work was carried out in a large tank filled with commercially available sand and city water. Three different sands, Granusil 2095, Granusil 4075, Granusil 7030, were used in laboratory testing, spanning typical marine sand grain size distributions. Their grain size distribution is shown in the lower panel of Figure E3. Tests were conducted varying the sand, the fluidization flowrate, the jetting hole diameter, and the number of jets, and established the parameter space in which fluidization and burial worked well as a function of sediment grain size.

The second phase of the project involved developing a manipulator capable of handling burial targets and fluidizing the sediment, integrated into a ship deployable bottom lander, and field testing the system. The manipulator was developed based on the results of laboratory testing and is shown in Figure E2. Fluidization flow is pumped into two connected manifolds, one on each side of the manipulator, which feed water to the manipulator fingers, and from there is jetted into the sediment. The two sides of the manipulator open and close hydraulically, and a second hydraulic circuit raises and lowers the manipulator into the sediment. This manipulator was integrated into an existing bottom lander along with diver operated hydraulic controls and fluidization flow control and monitoring (Figure E2, right pane).

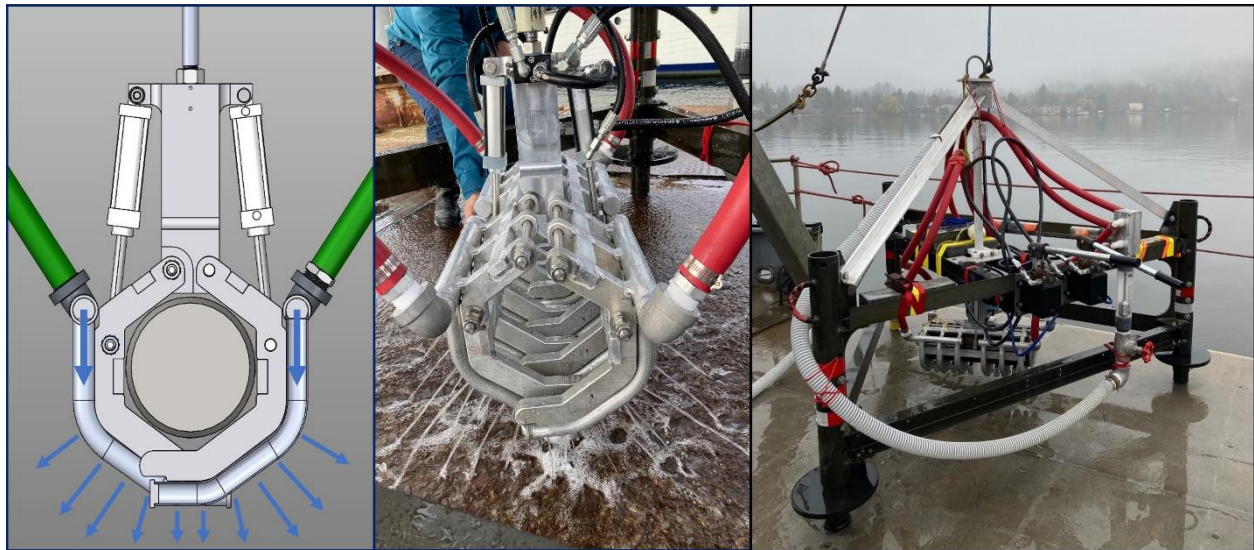


Figure E 2. Conceptual model of field-testing manipulator (left), manipulator jetting fluidization flow (center), field testing bottom lander (right)

Results and Discussion

Laboratory tests showed that the proposed fluidization and burial method worked, with some limitations. The system was able to fluidize sediment from above and bury targets to the full tank depth for the two finer grained test sands, Granusil 4075 and 7030, with mean grain diameters of .425 mm and .15 mm, respectively. The system was not able to fluidize the coarse-grained sand, Granusil 2095, with a mean grain diameter of 1.18 mm, in the large test tank. Further investigation showed that this was due to two effects driven by changes in grain size: first the hydraulic conductivity increases with grain size and allows a greater fraction of the pumped fluid to flow radially away from the fluidization target, reducing the local flowrates rising vertically around the target. Secondly the minimum fluidization velocity also increases with grain size, requiring more flow around the target. Both the hydraulic conductivity and the minimum fluidization velocity increase with the square of the grain diameter, and their combined effect makes fluidization impractical for large-grained sediments. This made fluidization in a non-constrained tank impossible for the coarse-grained sand. To confirm these conclusions a smaller tank was built, that constrained the fluid to stay near the fluidization target: when the flow could not spread radially it fluidized the coarse-grained sediment and the target could be buried to the bottom of the tank without issue.

Field testing showed that the methods developed in the laboratory work can be applied successfully to real world in-situ marine sediments. Field tests were carried out at two sites in Puget Sound and one site in Lake Washington during spring of 2022. The grain size distributions for each test site are shown in the upper panel of figure E3, the test sites were chosen to span from medium coarse sand to mud bottoms. In all sediments tested the system was able to fluidize the sediment, and bury and release test targets (six inch diameter, twenty three inch long cylinders). Photos of initial fluidization and burial are shown in Figure E4. At the Meadow Point and Lake Washington test sites the system buried targets to 0.65 m, the deepest the manipulator

could reach. At Blakely Harbor the manipulator hit a shell later at 0.40 m that it was unable to fluidize and the target was buried to this depth.

In all burial tests a shallow crater was observed after burial, approximately one meter in diameter and ten centimeters deep, with a ridge of sediment built up around it (Figures E4 and E5). Targets at Meadow Point and Blakely Harbor were left buried and recovered one week later, during recovery it was observed that the sediment craters had begun to fill in and flatten, shown in Figure E5.

One attempt was made at investigating changes in sediment grain size distribution due to fluidization. At the Blakely harbor test site a sample core was taken before fluidization and target burial, again immediately afterwards, and a third core was taken one hour later. The upper panel of Figure E6 shows the three grain size distributions, the lower panel shows the percent difference from the pre-burial conditions for the core taken immediately post burial, and the core taken one hour later. Although limited, the largest differences are on the order of 5 %, and suggest that fluidization does not change the bulk grain size distribution significantly in the marine sediments tested.

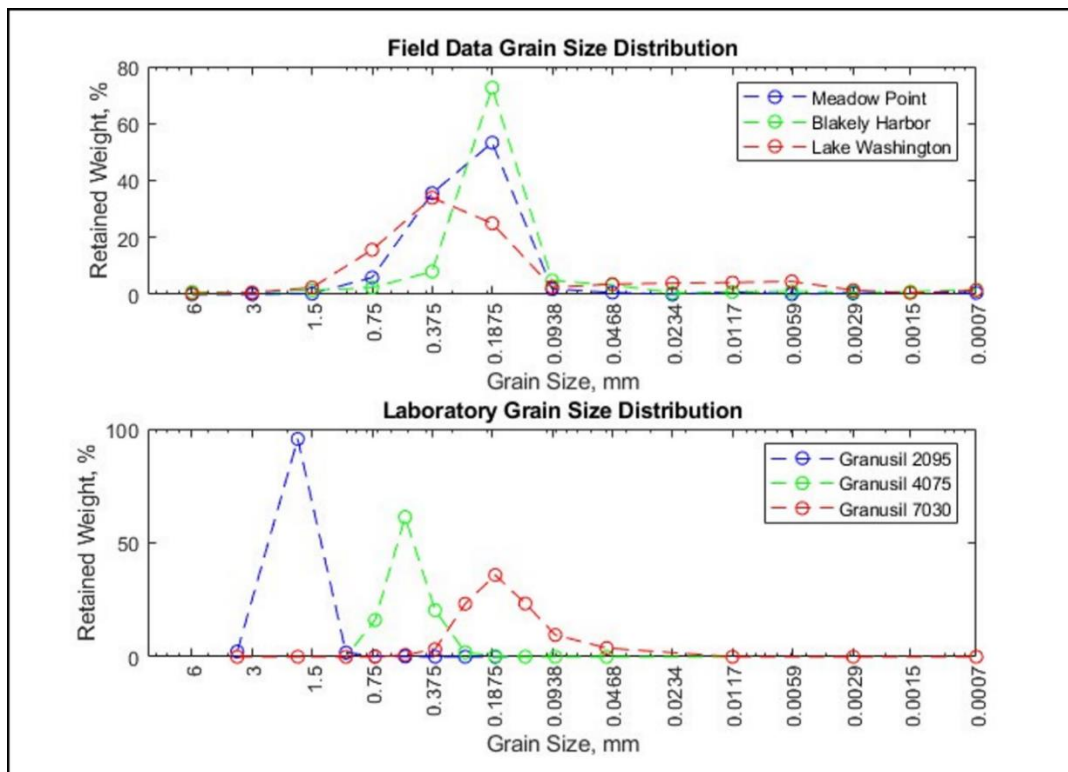


Figure E 3. Laboratory and field test grain size distributions

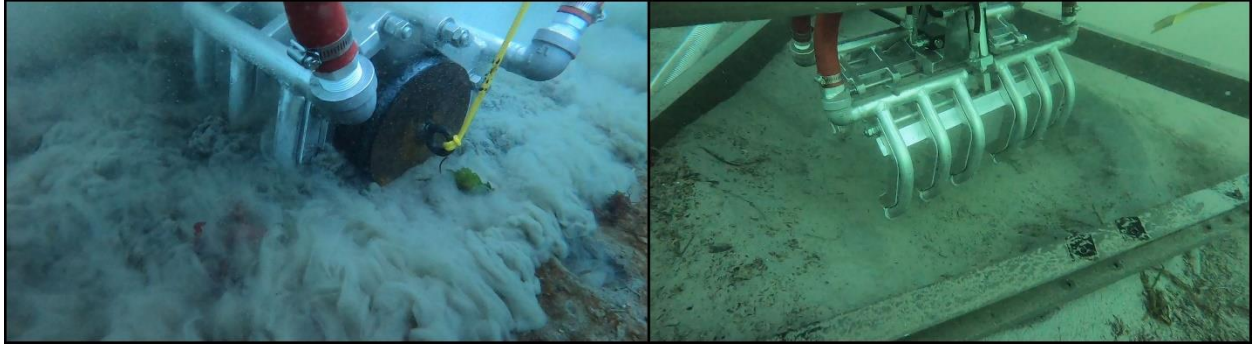


Figure E 4. Field test system at the start of fluidization (left) and after target burial (right)



Figure E 5. Target burial crater immediately after burial (left) and again one week later (right)

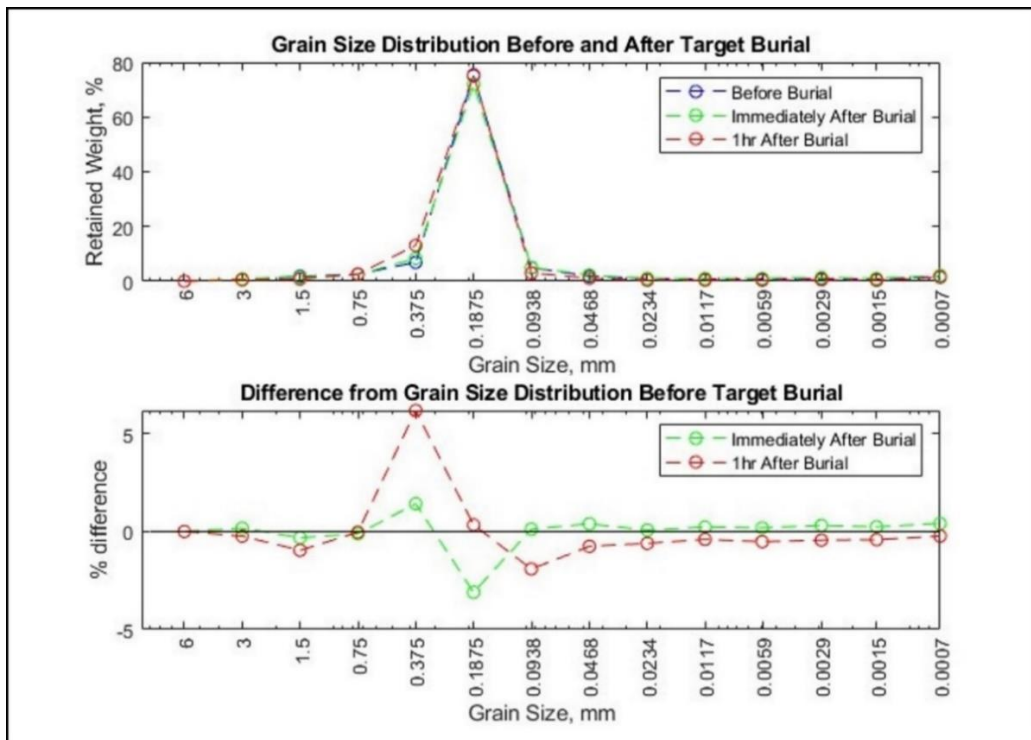


Figure E 6. Comparison of grain size analysis before and after fluidization and target burial

Implications for Future Research and Benefits

This work shows that surrogate UXO targets can be buried broad-sided in marine sand and mud sediments by sediment fluidization, eliminating the need to excavate sediment in order to bury targets. It furthermore suggests that this technique is not limited to shallow burial depths, if a sediment can be fluidized a target can be placed at any reasonable depth a manipulator can reach. The laboratory testing system was able to bury targets to the bottom of the tank at 0.75 m depth. The field system was able to bury targets to 0.65 m in under two minutes, where the burial depth was limited by the reach of the manipulator.

Some limitations of the fluidization technique were also identified in this work. Primarily it was shown in laboratory tests that as sediment grain sizes increases to approximately 1.2 mm diameter the increase in sediment hydraulic conductivity coupled with higher minimum fluidization velocities (both scaling with the square of grain diameter) requires fluidization flowrates to increase rapidly and quickly become impractical when the sediment volume was not constrained. This set an upper limit to the grain size distributions for which this technique could realistically be applied, however this limit is quite high compared to many marine sands. Secondly, in field testing it was shown that dense shell layers within the sediment structure were able to block the fluidization jets and stop the burial process from proceeding any deeper.

Field tests of the system consistently left a small shallow crater in the seafloor around the area that had been fluidized, and survey dives seven to ten days after burial showed that the ridges of these craters has significantly collapsed, and that the seafloor surface has started to even out.

A single effort at observing changes to the sediment grain structure before and after fluidization and target burial suggested that there is little change to the sediment grain size distribution due to fluidization and therefore in areas without distinct sedimentary layers it may be impossible for UXO detection technologies to observe the changes in the sediment due to fluidization and target burial. In areas with distinct sediment layers within the burial depth these layers would be mixed by the fluidization and burial. No effort was made to quantify changes in sediment porosity or pore water content or measure relaxation time of these parameters if any exists. Better characterization of changes in the grain size distribution, sediment porosity, and the ability of UXO detection methods to observe these changes warrant further investigation.

This proof-of-concept work has shown that sediment fluidization is a viable technique for surrogate UXO burial, and that there would be little risk associated with developing a surface operated bottom lander, or remotely operated vehicle, designed to bury targets for surrogate UXO target fields or calibration lines. The implementation of this burial method could be done using established subsea engineering techniques and produce an efficient, logistically simple means of burying targets. If subsea navigation equipment was integrated into the bottom lander accurate burial position, depth and orientation information could be provided to test site operators. This envisioned system could be used for deploying large numbers of targets at demonstration sites, or for deploying calibration lines at real-world UXO remediation sites.

Objective

Munitions Response projects that deal with the detection and classification of UXOs in the marine environment require surrogate UXO targets to be buried in seafloor sediments to establish test and demonstration sites. As research programs transition from basic research to technical demonstrations and blind tests the georeferenced position accuracy, and knowledge of target burial depth and orientation becomes more important [1]. At the same time the number of targets buried at demonstration sites may grow to cover the wide range of munitions and test cases. Both of these needs require new solutions to target placement and burial. This project was conceived to address challenges in burying surrogate UXO targets in the marine environment in a time and cost-effective manner.

The proposed approach to this problem is to bury surrogate UXOs by fluidizing the seafloor sediment and inserting the targets into the fluidized sediment with a manipulator capable of precisely controlling target burial depth. Once positioned the fluidization flow is stopped and the sediment returns to its normal, consolidated state with the target buried. One major advantage to this technique is that it does not require excavating the sediment in order to bury a target, reducing the disturbance to the sediment, and saving time and effort. Although sediment fluidization is a well-developed engineering technique [2], and earlier work at the Applied Physics Laboratory (APL/UW) has taken advantage of similar water jetting methods to insert acoustic receivers into marine sand sediments [3,4], the authors could find no published work showing that natural sediments could be fully fluidized in-situ, nor that if fluidization did work that the technique could be used to bury broad sided objects. This SEED funding was therefore aimed at validating the technique and reducing risk to any follow-on program to build a remotely operated bottom lander for surrogate UXO burial.

Background

Need for New Burial Methods

SERDP and ESTCP have been involved in UXO detection and classification research in the marine environment for many years, and have funded numerous large field experiments aimed at understanding the science behind the problem and developing the technology to solve it. One recurring experimental problem has been how to bury surrogate UXO targets in marine sediments with minimal disturbance to the sediment structure, and at known positions, orientations and burial depths. The most common method is for SCUBA divers to place targets. Table 1 lists some of the pros and cons of this method.

| Pros | Cons |
|---|--|
| <ol style="list-style-type: none"> 1. Can be done with existing technology 2. SERDP and ESTCP funded groups have experience doing this 3. Works for small to large objects | <ol style="list-style-type: none"> 1. Limited by time divers can be at depth 2. Limited by environmental conditions such as daylight, bad weather, visibility, etc 3. Requires significant surface side support 4. Positions are generally known relative to diver installed ground lines, multiple uncertainties stack up to final estimated position 5. Burial depth is difficult to measure, and heading is often assumed to nearest ~10 deg |

Table 1. Pros and Cons of target burial by SCUBA diver

The cons can be organized into two general categories: first are issues that relate to the limitations of dive teams and the support they require, and the second are issues that relate to knowing exactly where and how the targets are buried. The first category is fundamentally a cost issue. Any new technique that can speed this up, or remove the need for dive teams and their associated logistical limitations and expense could create a cost savings to the program. The second category was less important during the basic research on UXO detection, but as SERDP and ESTCP funded groups transition to technical demonstrations and in particular blind tests of system performance, knowing precisely where and how targets are buried becomes increasingly important.

A ship operated bottom lander capable of fluidizing the seafloor sediment and burying targets within the fluidized sediment has the potential to deploy targets quickly and with minimal operational limitations. Off the shelf technologies for underwater navigation and geolocation, and precise measurement and control of the burial depth, tilt and compass orientation could easily be integrated, giving high fidelity position and burial information to system operators. Such a system could greatly enhance the program’s ability to bury targets to establish demonstration sites or to deploy calibration targets at real world remediation sites.

Fluidization and its Application to Target Burial

Sediment fluidization is an engineering process with some similarities to sediment liquefaction. Liquefaction occurs in the natural world and plays a significant role in marine sediment behaviors including the burial of UXOs and mines on the seafloor due to environmental forcing [5,6]. Liquefaction occurs when static or oscillating loading of a saturated sediment causes compression of the sediment structure and an increase in the local pore pressure to the total stress, reducing the effective stress between grains of the sediment to zero. At this point the sediment loses all shear strength and behaves like a liquid. It will stay in this state until the pore pressure is reduced and the local stresses are again supported by intergranular forces.

Fluidization occurs when the effective intergranular stresses are also reduced to zero, but the process occurs when a fluid is pumped vertically upwards through granular material. As the fluid flowrates become high enough the drag imparted on each solid particle counteracts its weight, and it becomes suspended, thereby reducing the effective stress to zero. This process is common in the chemical processing industries [2] where fluidized bed reactors are used for processes such as hydrocarbon cracking and the production of many plastic polymers. When this balance of forces occurs, the granular material behaves like a fluid for as long as the gas or liquid flowrate is maintained, and the granular medium is said to be fluidized.

If seafloor sediments can be fluidized by jetting ambient water and in this process lose all cohesion, then surrogate UXO targets should be able to be buried in the sediment with only buoyant and drag forces acting on them. Once the targets are placed and the fluidization flow is stopped the sediment will return to its consolidated state and the targets will remain buried.

Sediment fluidization is described by the Ergun equation [2,7] which defines the conditions required to balance all forces on the sediment particles. This equation can be rearranged to calculate minimum fluidization velocity:

$$u_{mf} = \frac{(\phi_s d_p)^2}{150} \frac{\rho_s - \rho_w}{\mu} g \left(\frac{\epsilon_{mf}^3}{1 - \epsilon_{mf}} \right)$$

Where some parameters relate to the granular medium (d_p - grain diameter, ρ_s - sediment density, ϕ_s - sphericity, ϵ_{mf} - void fraction) and the rest to the fluid (ρ_w - fluid density, μ - dynamic viscosity). Fluidized bed reactor designs generally have flow rates on the order of five to seven times the minimum fluidization flow to ensure there are no unfluidized areas in case of uneven flow, boundary wall effects, etc.

The geometric considerations of fluidizing seafloor sediment are somewhat different than those of operating a fluidized bed reactor. At the seafloor the fluid cannot be pumped in from below, and there are no side walls to retain the flow. At the same time there is no requirement to fluidize a large area, simply the area surrounding and immediately below the manipulator and burial target. These differences clearly require a different experimental approach, and suggest that the Ergun equation, and any other established fluidized bed design guidelines, may be useful starting points but cannot ensure a successful system design.

Materials and Methods

This project was divided into two phases. In the first phase laboratory work was performed to test the fluidization technique in a controlled environment, and to understand the operational parameters. In the second phase a field testing system was designed, built, and tested in local waters. The goal of both phases was to incrementally develop the techniques necessary to fluidize seafloor sediments and bury surrogate UXO targets. This section of the report is split into two sections discussing the laboratory and field-testing phases of the work separately.

Materials and Methods: Laboratory Testing

A full-scale laboratory system was built at APL/UW’s warehouse in Seattle and tests were performed using commercially available sands that spanned grain sizes expected in the marine environment.

A 42” x 42” x 36” deep tank was purchased, shown in Figure 1. The tank was large enough that a fluidization and burial target with the approximate major dimensions as a 155 mm mortar shell could be tested in the center of the tank, with space around it for sediment to be fluidized with minimal effects due to the tank walls. Three different commercially available test sands (Granusil 2095, Granusil 4075, Granusil 7030) were selected based discussions with Dr. Nina Stark (Virginia Tech, Dept of Civil and Environmental Engineering) to cover the range of typical marine sand grain sizes. The sands used and their grain size distribution are shown in Table 2, and their spec sheet is included in Appendix A.

| Mesh Size | Granusil 2095 | Granusil 4075 | Granusil 7030 |
|-------------|---------------|---------------|---------------|
| 2.36 mm | 2.3 | --- | --- |
| 1.18 mm | 95.6 | --- | --- |
| 850 microns | 1.8 | --- | --- |
| 600 microns | 0.2 | 16.1 | --- |
| 425 microns | 0.1 | 61.3 | 0.8 |
| 300 microns | --- | 20.4 | 3.3 |
| 212 microns | --- | 1.9 | 23.3 |
| 150 microns | --- | 0.3 | 35.9 |
| 106 microns | --- | --- | 23.4 |
| 75 microns | --- | --- | 9.6 |
| PAN | --- | --- | 3.8 |

Table 2. Grain size distribution of sands used in laboratory testing, reported as % by weight



Figure 1. Laboratory Testing Tank, fluidization test target shown in right pane

For each different sand the tank was filled with thirty inches of dry sand, then filled to the top with city water. As this testing was very much proof-of-concept there was no effort made to degas the sediment, and there was no effort to pluviote the sediments when filling the tank.

In order to easily test different configurations of fluidization jets and flowrates, a simple fluidization burial target was built. It comprised a twenty-three inch long horizontal section of six inch diameter aluminum pipe, welded shut with flat plates at each end, and with a forty eight inch long, two inch diameter pipe welded vertically on its center. This vertical pipe allowed fluidization water to be pumped down into the horizontal pipe, and at the same time allowed the horizontal pipe to be handled, raised and lowered from above the tank. The horizontal pipe had small diameter holes, originally .047" (1.2 mm) diameter and later opened to .125" (3.18 mm) for jetting fluidization flow. These holes were drilled in eleven rows of seven holes. The fluidization and burial target is shown in Figures 2 and 3. The target is handled and lowered by forklift, allowing for controlled descent as it fluidized the sediment. The weight of the forklift carriage and fluidization burial target combined provided the maximum amount of force that the target could apply into the sand, which was on the order of 220 kg. As testing progressed the hole sizes and the number of holes used for the fluidization jets was varied to optimize performance.



Figure 2. Laboratory fluidization and burial target. Fluidization jet holes shown in the right pane

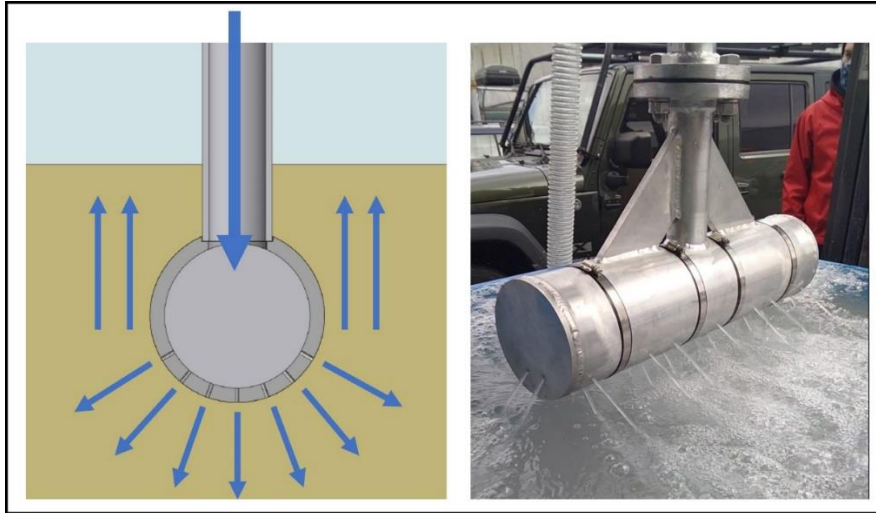


Figure 3. Representation of fluidization flow in laboratory test system

The fluidization burial target was supplied with water from a large source tank, six feet in diameter and five feet tall, filled with city water before a test would begin. Two inch diameter reinforced hoses supplied water from the tank to a four-horsepower gasoline powered centrifugal pump (AMT-3824-99) and 380 liters per minute (LPM) flowmeter. For some tests requiring a lower flowrate a three phase, two-horsepower electric pump (Dayton 5UXJ3) was used with a 150 LPM flowmeter. The throttle on the pump's gasoline engine was used to manually control the flowrate on the larger pump. A gate valve was used to control the flowrate on the electric pump. The gasoline powered pump and 380 LPM flowmeter are shown in Figure 4.

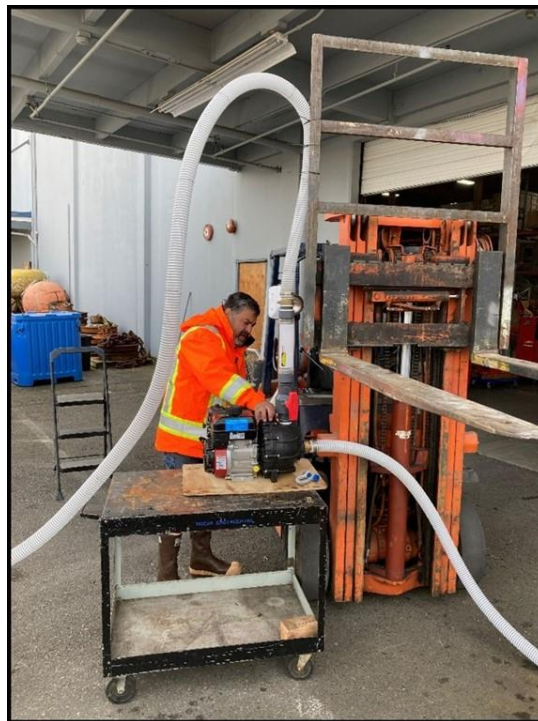


Figure 4. Fluidization pump and flowmeter

For each test run a set of conditions would be established, this would include sand type, jet hole sizing and spacing, and flowrate. The test would begin with the target above the tank water surface, the pump would be turned on, lines primed to remove any air, and flowrate adjusted to the desired test flowrate. The burial target would be slowly lowered by forklift into the water, and into the sediment. The descent rate was controlled manually, with a goal of one inch per second or less. The burial target would descend into the sediment until either it reached the bottom of the tank, or if the sediment was not fluidizing well, it would stop descending when the sediment would support the weight of the forklift carriage and burial target combined.

For each different sand tests were conducted to find the minimum fluidization flow required. Tests were then conducted to find the maximum flowrate that the system could fluidize at without lifting large quantities of sediment from the sediment surface. Once these parameters were known the number of holes were reduced by covering some of the rings of holes in the burial target with strips of rubber and hose clamps. The hose clamps would hold the rubber tight against the burial target and completely stop flow from exiting those holes. In this way tests were conducted with incrementally reduced number of fluidization jets until the limit was found as to how many were necessary to fluidize the sediment and bury the target effectively.

Materials and Methods: Field Testing

In order to perform local field tests an existing triangular instrument frame, 1.8 m in length per side, was repurposed to build a ship deployable bottom lander, shown in Figure 5. The lander provided the platform to mount and operate a newly designed manipulator. The manipulator served two purposes: first, using hydraulic cylinders it was able to both hold and release a surrogate UXO target in the manipulator, and lower the manipulator from within the bottom lander frame to 0.65 meters below the lander's foot pads. Secondly, the fingers of the target handling manipulator were hollow, plumbed to a common manifold, and had fluidization jet holes drilled along their outside surfaces: the manipulator itself distributed the fluidization flow and jetted it into the sediment immediately surrounding the manipulator and target. Figure 6 shows a cross section of the manipulator including the manifold, fingers and jets for fluidization flow, and shows an image of the manipulator jetting water. The manipulator design was driven by the lessons learned in the laboratory testing phase of the project and was at the heart of the field-testing system. Figure 7 shows the manipulator grasping and releasing one of the targets used in field testing.

The two hydraulic circuits, one to open and close the manipulator, and the other to raise and lower it, were diver operated. Each consisted of the necessary dual acting cylinders, hoses, and each had their own hand operated hydraulic pump with switching valve. Divers could choose which direction to run the hydraulic circuits with the flip of a lever, then use the hand operated pump to circulate the hydraulic fluid. Each hydraulic circuit was filled with Panolin Sprint 32, a biodegradable hydraulic fluid, and had a simple pressure balanced accumulator plumbed to its reservoir to allow it to work at depth without any further modifications or concern of water intrusion.



Figure 5. Bottom lander frame with manipulator, water hoses and hydraulic controls

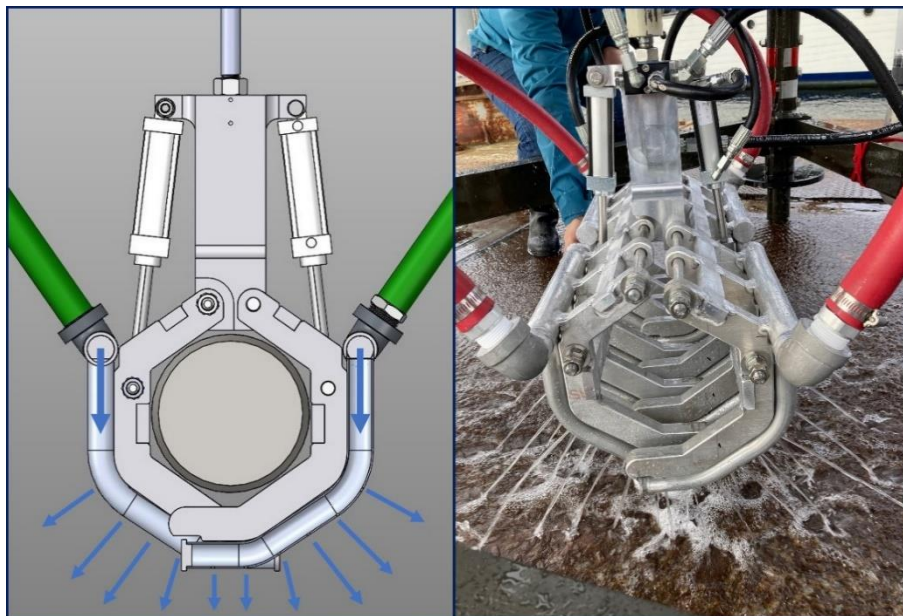


Figure 6. manipulator cross section with water flow directions shown, and photo with fluidization jets



Figure 7. Manipulator with burial target

The field-test burial targets were designed to be simple as possible and, like the laboratory burial target, were made to have similar major dimensions to a 155 mm mortar shell. They were cylinders six inches in diameter and twenty-three inches long. They were made of steel pipe with flat plates welded on the ends. Their density was 2170 kg/m^3 , denser than seawater or the bulk density of fully saturated sand, ensuring the targets would not rise in testing due to buoyant forcing. A pad eye was welded to the center of one end of each target to attach a recovery line. A 2 m long length of 1/8" diameter yellow Amsteel line was spliced to the pad eye, with a lifting eye and a small peanut float at the far end. The float kept the line rising vertically through the sediment and into the water column. Four of the targets were built. Figure 8 shows one burial target with line and float.



Figure 8. Field testing burial target with marking/lifting line and float

The fluidization flow was provided by the same gasoline powered pump that was used in the laboratory tests. It was run on the ship's deck with a short intake hose pulling seawater from alongside the vessel and a seventy foot long two inch diameter hose was used to pump water down to the bottom lander. The hose was married to the lowering line as the bottom lander was lowered, and twelve inch diameter hardball floats were attached to the hose at approximately half the water depth to keep the bottom section of the hose vertical in the water column. The pump was run at full throttle on the surface. The 380 LPM flowmeter that was used in the laboratory testing, along with a two inch diameter gate valve, were installed on the bottom lander frame where the flow could be controlled and monitored by divers. This system proved quite effective for testing, although it was noted that in some tests quite a bit of air was in the hoses at the start of the test and as this air jetted through the manipulator fingers it entrained the top layer of the sediment and reduced visibility significantly. In later tests the valve was slowly opened and air allowed to escape before the manipulator was lowered, avoiding this issue.

The bottom lander was designed to be lowered from a ships winch. Its total in-water weight was 350 kg. The frame weight was important as it provided the reaction force if there was any resistance by the sediment to burial, for example if there were obstructions below the sediment surface.

All field testing was conducted on board APL/UW's research vessel R/V Robertson. In all tests the sequence of events was the same. First the vessel went into a three-point moor at the test site, this allowed the vessel to hold station for as long as required and made it easy to shift the vessel over in small increments to perform multiple tests in one area. Once in the moor, a surrogate UXO burial target was loaded into the manipulator on deck, then the bottom lander was lowered from the ship's A-frame to the seafloor, with the fluidization flow supply hose being married to the lowering line as it descended. Once on the bottom the lowering line was overpaid to decouple the bottom lander from the ship. At this point divers would get in the water, and the supply pump was turned on. Divers would descent and take a sediment core immediately adjacent to where the fluidization and burial test would occur. Then one diver would film the test while the other would open the gate valve, set the flowrate to the desired starting flow, and slowly lower the manipulator and target into the sediment. The flowrate was adjusted as needed in order to get to the maximum burial depth, while keeping the flowrate as low as possible to reduce disturbance to the sediment and maintain visibility in the water column. Once the manipulator was at its full extension, or once the system was unable to bury any deeper, the diver operating the system would open the manipulator, releasing the target, and raise the manipulator back up into the bottom lander while shutting down the fluidization flow. At this point the target was buried and free from the bottom lander and manipulator, with its location marked by the recovery line with a small float. Divers then ascended, and once on board the lander was recovered. Post recovery another dive was done to film the burial site and document the condition of the sediment post burial. These tests were repeated twice at each test site.

It was planned to leave the targets buried, and to return after one week to document how the seafloor had changed from immediately after the burial, and to recover the targets. At two of the test sites this was done, but no targets were left behind at the Lake Washington test site. At that site diving visibility was so poor that divers had to do all testing by feel, were unable to take photos

of the bottom after burial, and would not have been able to find the marking lines again after leaving the site.

Core samples from each burial test were collected and at the end of the field-testing program were sent to ALS Global to have grain size analysis done per ASTM-D422M. ALS Global was selected as they had been used on previous SERDP funded APL/UW projects (personal communication, Dr. Todd Hefner). The core tubes were 6 cm in diameter, core samples ranged from 30 to 40 cm in length. There was no effort to observe sedimentary layers within the cores, and with the exception of repeat samples for quality control there was only one analysis performed per core.

The system as described was simple and allowed for easy operations during proof-of-concept testing. Divers were able to observe the operation and use their hands to feel what was happening while controlling the fluidization flowrate and operating the hydraulic circuits. In any system beyond a proof of concept all of this functionality would be controlled remotely from the surface and observed by subsea instrumentation, without the need for divers. The decision to build a diver operated system was simply to put the human operator as close to the action as possible for this first proof-of-concept testing.

Results and Discussion

This section is again divided into two subsections, the first will cover laboratory testing, and the second will cover field testing results.

Results and Discussion: Laboratory Testing

The goal of the laboratory testing was to establish if, and under what conditions, jetted water could fluidize surrogate marine sands and bury UXO sized objects up to 0.6 m deep into the sediment. A table of the complete laboratory testing records and results are presented in Appendix A. The key takeaway data organized by sand grain size is presented here in Table 3.

| | Granusil 2095 | Granusil 4075 | Granusil 7030 |
|---|-------------------|-------------------|-------------------|
| Mean grain size (mm) | 1.18 | 0.425 | 0.15 |
| Minimum fluidization flow (LPM) | --- | 150 | 75 |
| Maximum fluidization flow without ejecting sand (LPM) | --- | 265 | 190 |
| Burial target size | 6"Ø x 23" long | 6"Ø x 23" long | 6"Ø x 23" long |
| Jetting hole diameter (mm) | 3.18 | 3.18 | 3.18 |
| Jetting hole spacing | 11 rows, 77 holes | 11 rows, 77 holes | 11 rows, 77 holes |

Table 3. Condensed results of laboratory tank testing

The first tests were conducted with the coarsest sand, Granusil 2095. The initial results were poor: the system was unable to fluidize the sediment in the tank at 360 LPM, the highest flowrates the experimental system could deliver. Efforts to fluidize the sediment with the same flowrates but smaller burial targets were similarly unsuccessful: in all cases targets would bury to a depth of approximately one diameter, then stop as the sand would carry the weight of the target and forklift

carriage, a total of approximately 220 kg. Initial theoretical estimates of the minimum fluidization flowrates had been calculated using the Ergun equation to inform the sizing of the test equipment. In order to do this an estimate of the cross section of fluidized area around the target was chosen to be four inches around on all sides. A simple plot of this estimated minimum flow rate as a function of grain size, using fresh water as the fluidization flow, is shown in Figure 9. The minimum fluidization flowrate scales with the square of the grain size and increases quickly at the larger sand grain sizes. Granusil 2095, at approximately 1.18 mm mean diameter, is near the knee shown in the plot. Our initial interpretation was that the flowrates were insufficient for the volume that was being attempted to fluidize, and that the same flowrates would be able to fluidize a smaller volume, but efforts to fluidize smaller volumes and bury smaller targets were unsuccessful.

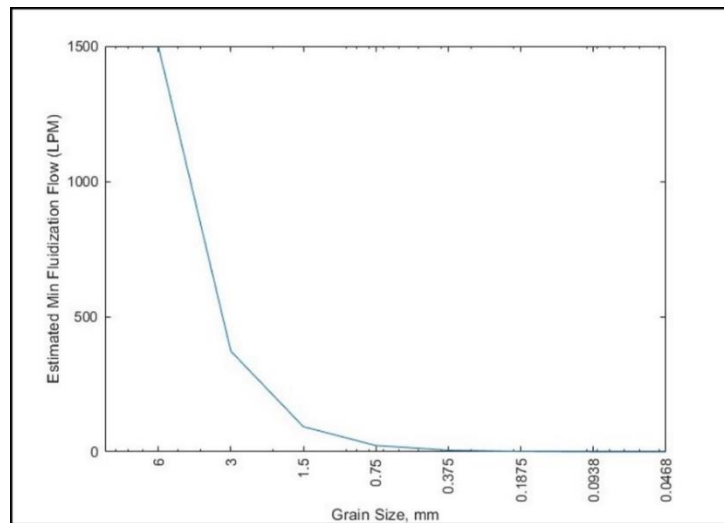


Figure 9. Calculated estimate of minimum fluidization flow as a function of grain size diameter

Experimental observations at this point showed that there appeared to be little fluid flow around the burial target despite flowrates of 360 LPM going into the sediment. Short lengths of yarn showed that flow was coming vertically out of the sediment across its entire top surface. The sediment had high enough hydraulic conductivity that the pumped fluid was dispersing in all directions from the burial target, and the local flowrates immediately around the burial target were therefore low. This was in opposition to our assumption that the flow would quickly change direction from jetting downwards to escaping out of the sediment vertically upwards alongside the burial target. Further investigation showed that hydraulic conductivity scales with the square of grain size diameter [8,9], and typically covers three orders of magnitude from fine to coarse grained sands [10]. It became immediately clear that if hydraulic conductivity increases with the square of the grain diameter, and that the minimum fluidization velocity also increases with the square of the grain size, working in coarse grained sediments would be the most difficult regime to fluidize. At some grain size the fluid flow necessary would quickly surpass any practical experimental or operational limits.

As it appeared that this was the case for Granusil 2095, we set up a quick test to confirm this new hypothesis. In fluidized bed reactors the sediment and the pumped fluid are retained by the walls of the reactor chamber. We decided to do the same and build a smaller tank, four inches wider and

four inches longer than our fluidization and burial target (ten inches by twenty-seven inches). The tank, with target above it, is shown in Figure 10. In this tank the fluidization flow could not disperse radially outwards beyond the area to be fluidized. These tests were successful: the system fluidized the sand without issue and was able to bury the target to the bottom of the tank. This test made it clear that fluidization as a burial technique is possible, but that larger grain sizes would create a practical limit, and that Granusil 2095 was on the impractical side of that limit.



Figure 10. Experimental setup for captured flow test with Granusil 2095

Following these tests, the original large test tank was drained of Granusil 2095 and filled with Granusil 4075 and city water. In this sediment the system was able to fluidize the sediment without issue: the pumped water stayed near the target, fluidized the sediment and the target buried to the bottom of the tank easily. Tests were conducted to identify the minimum practical flowrate for target burial, and the flowrate at which sediment started being ejected by the flow. The minimum fluidization flowrate was found to be 150 LPM, and at 265 LPM the water draining off the top of the tank began to carry sediment. It was clear that at this smaller grain size the hydraulic conductivity was much lower and the fluid being pumped into the sediment tended to stay near the target.

The tank was then emptied and refilled with Granusil 7030 and city water. Granusil 7030 is a very fine sand. The system had no issue fluidizing the sand and burying the target. The same tests were repeated to establish flowrate limits for burial and for sediment ejection. The minimum fluidization flowrate was 75 LPM and the sediment started being ejected at 190 LPM.

At this point follow on tests were conducted where up to half of the fluidization jets were plugged to investigate the relationship between number of jets and performance. In all cases the system operated identically, it appeared that the limitations on the system operation was the amount of pumped fluid, not how dispersed the jetting was. There was no reason to test below half of the original jetting holes as the conceptual design for the field testing manipulator already assumed one row of jets on each manipulator finger, and at least five fingers per side of the manipulator, which was approximately three quarters of the number of jetting holes in the original laboratory test target.

It was noted qualitatively that as the sediment grain size became smaller the boundary between fluidized and unfluidized sediment became more distinct, and the sides of the fluidized area became more vertical. This was observed by reaching into the fluidized area and feeling this boundary by hand during testing. This observation aligns with the understanding that as grain size decreases hydraulic conductivity also decreases and therefore the boundary layer between the area with high flow and no flow should become narrower and more distinct.

Results and Discussion: Field Testing

Testing was carried out at three different field sites local to APL/UW. The sites were chosen for their varied sediments, ranging from a medium coarse sand to mud. The locations are shown in Figure 11, and the average grain size distribution in sediment cores taken at each site is given in Table 4. Figure 12 shows the same grain size data with a comparison to the lab sediments; the upper plot presents the field-testing data and the lower plot presents the laboratory data. Grain size scaling on the x axis of both plots is identical, allowing for a direct comparison of the field and lab sediment size distributions. One day of testing was performed at each site, tests were performed on 2/25/22 at Meadow Point, 3/21/22 at Blakely Harbor and 3/22/22 at the north end of Lake Washington.

The complete testing records are presented in Appendix B, which includes the grain size analysis for each test, burial data, notes on performance, and photos of each test. A number of videos of the field tests are also available on YouTube, the links are listed in Appendix B.

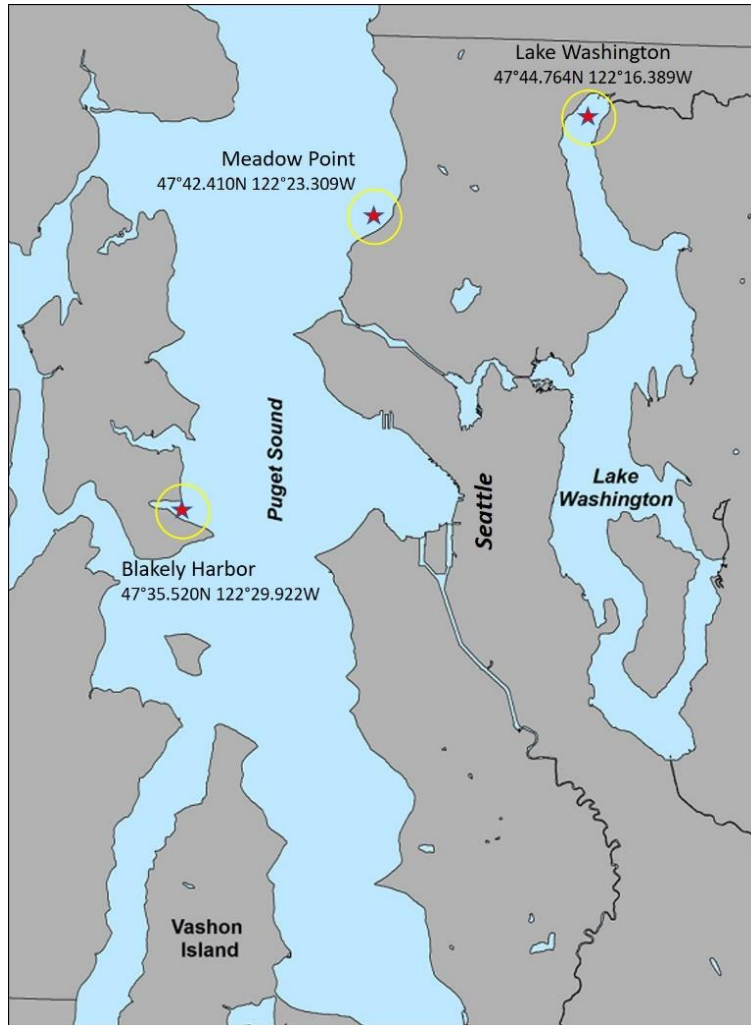


Figure 11. Map of field test sites

| Mesh Size (mm) | Meadow Point | Blakely Harbor | Lake Washington |
|----------------|--------------|----------------|-----------------|
| 4.00 | -- | 0.9 | 0.2 |
| 2.00 | -- | 0.7 | 0.6 |
| 1.00 | 0.3 | 1.4 | 2.4 |
| 0.500 | 5.9 | 2.4 | 15.7 |
| 0.250 | 35.5 | 8.0 | 34.0 |
| 0.125 | 53.3 | 72.6 | 24.9 |
| 0.0625 | 1.9 | 4.9 | 2.5 |
| 0.0313 | 0.6 | 3.3 | 3.6 |
| 0.0156 | --- | 0.5 | 4.0 |
| 0.0078 | 0.9 | 0.9 | 4.2 |
| 0.0039 | 0.1 | 1.0 | 4.6 |
| 0.0020 | 0.4 | 0.8 | 1.5 |
| 0.0010 | 0.6 | 0.9 | 0.5 |
| 0.0005 | 0.5 | 1.7 | 1.4 |

Table 4. Mean grain size distribution at field test sites, reported as % by weight

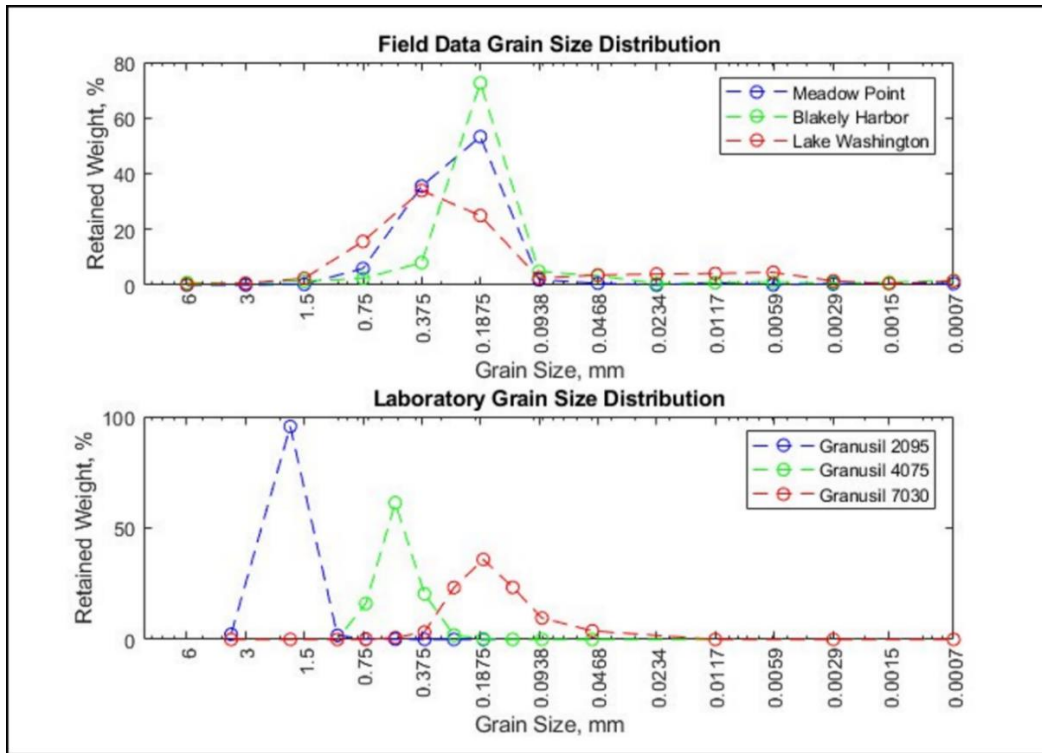


Figure 12. Laboratory and field grain size analyses, grain size scaling is identical in each plot

The first tests were performed near Meadow Point, just north of Seattle, in fourteen meters water depths with good visibility. As shown in Figure 12 the sediment at this site is a mix of medium and fine grained sands, spanning the grain sizes of Granusil 4075 and 7030 used in laboratory testing. The two tests conducted at this site were successful, both were able to bury the surrogate UXO target to the maximum 0.65 m burial depth of the manipulator, with 300 LPM flowrates and very little resistance from the sediment. During fluidization very little sediment was lifted from the seafloor, rather it spread laterally and had a characteristic boiling look. This can be seen in the videos linked in Appendix B, and in Figure 13.

A typical example of the disturbed sediment post target burial is shown in Figure 14. The fluidization and burial process left a shallow crater, approximately one meter in diameter with a ridge approximately 10 cm above the flat seafloor, and the center of the crater a flat area approximately 5 cm below the surrounding seafloor, 15 cm below the crater ridge.

Both targets were left buried, with ground lines marking the burial sites and connected to a single anchor with a line up to the surface and floats marking the location. At each target a sand screw was also left behind with a go-pro camera in time lapse mode, taking a photo once per hour. The goal of the time lapse cameras was to make simple visual observations of how the sediment disturbance by fluidization and burial changes over time. Divers returned one week later and filmed the condition of the site, recovered the time lapse cameras and the burial targets. The crater at each burial site had significantly reduced in height, filled in in its center, and become more

rounded. The tidal exchange during this week had daily exchanges of ten to twelve feet, and likely drove most of the change to the seafloor over the week. There was one day of strong southerly winds during the week, which may have created waves large enough to transfer energy to the seabed, but otherwise the meteorological conditions were calm. The Figure 14 shows one of the two target burial sites, the photo on the left was taken immediately after the burial, the photo on the right was during the recover dive one week later.

Unfortunately, after recovery it was discovered that go-pro cameras do not have a sleep mode between photos when taking long interval time lapse series, so the batteries only lasted long enough to take a few photos at the beginning of the deployment, and provided no meaningful data. The time lapse cameras were not deployed at the second and third test sites.

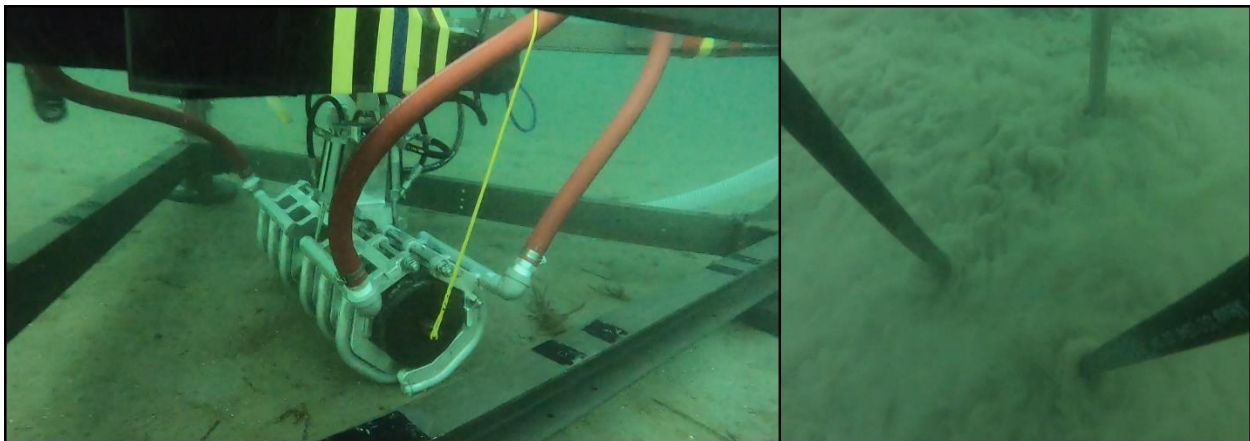


Figure 13. Bottom lander, manipulator and burial target immediately before burial (left), Fluidized sediment during target burial, hoses reaching into sediment are providing the fluidization flow (right)

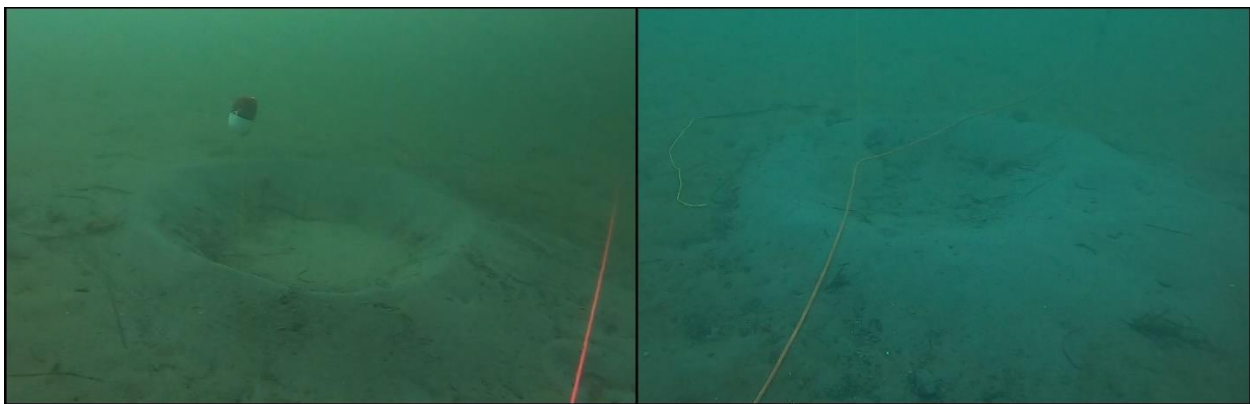


Figure 14. Sediment disturbance immediately after target burial (left), and one week later (right) at Meadow Point

The second day of testing took place in Blakely Harbor in twelve meters water depth, where the bottom has a finer grained sand with some silt; divers found the sediment to be more cohesive than

at Meadow Point. In Figure 12 the Blakely Harbor sediment shows a peak in grain size distribution that matches Granusil 7030, but note that Granusil 7030 has a much broader grain size distribution, while the Blakely harbor sediment was highly concentrated around the 0.188 mm diameter grain size. The system had no issue fluidizing the surface layer of sediment but in both tests the manipulator was obstructed by a shell later at 40 cm burial depth. Fluidization flow up to this point was 300-320 LPM, it was raised to 350 LPM, the maximum the system could deliver, but this made no difference. With the fluidization flow pumping into the sediment divers were able to reach into the fluidized sediment and pull large flat shells out from under the manipulator. It may be possible for the fluidized sediment to allow a single or a few shells or other obstructions to fall to the bottom of the fluidized area and allow the manipulator and target to continue to bury, but it was clear that dense layers of shells would simply block the fluidization flow. This is consistent with earlier experimental observations that used water jetting techniques to insert acoustic receivers into seafloor sediments: shell layers within the sediment would consistently stop instrument penetration regardless of flowrate [3].

Divers did note that the edges of the fluidized area were very close to the manipulator, steep, and felt much more solid than was the case in the coarser sand at Meadow Point. This agrees with the qualitative observations of the fluidized area in laboratory tests with Granusil 7030 and suggests that in fine grained sediments the area affected by fluidization is relatively small.

Post fluidization and burial a survey dive was done on both test sites in Blakely Harbor, but only one of the two burial targets was left behind. This decision was made in order to keep as many targets on board for the testing the following day in Lake Washington. One week later divers surveyed the site again and recovered the remaining target. Figure 15 show the burial site at Blakely Harbor immediately after burial and again one week later.

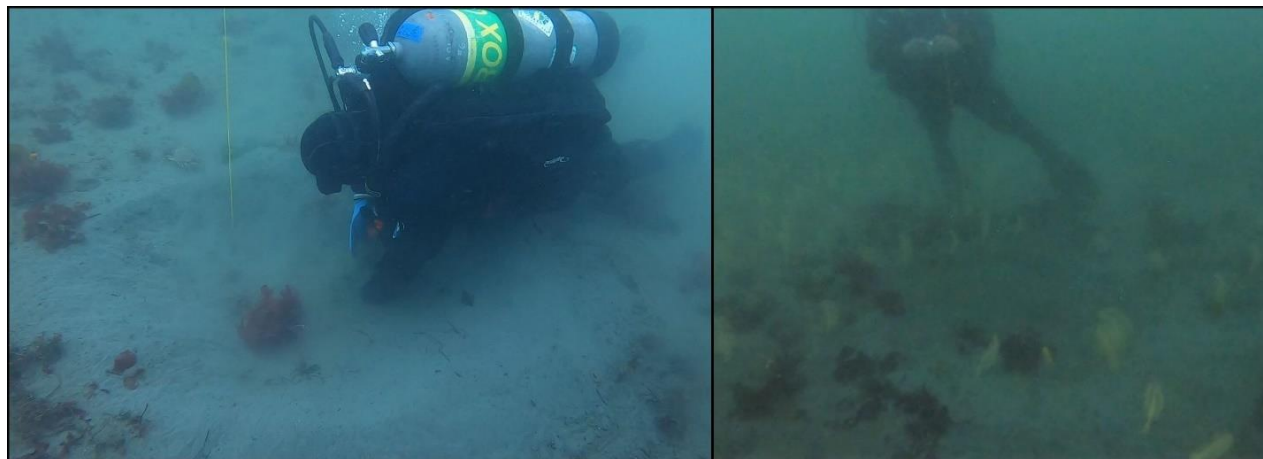


Figure 15. Sediment disturbance immediately after target burial (left), and one week later (right) at Blakely Harbor

The last day of field testing took place at the north end of Lake Washington at a site with mud bottom in nine meters water depth. The visibility underwater was very poor and the entire test had

to be done by feel. This system had no issues whatsoever fluidizing and burying targets to 0.65 m, and did so at 190 LPM flowrates, significantly lower than at the other two test sites. Two targets were buried and released by the manipulator, but immediately recovered as they would have been impossible to find in the poor visibility. Divers filmed both of these tests, but nothing could be seen in the video footage. The sediment cores recovered showed alternating layers of very soft silt and sand, with one thin layer of fine gravel.

The limitations of the time lapse cameras became clear after the first field test. In an effort to find a different method to characterize sediment response to fluidization sediment cores were taken at one Blakely Harbor test site immediately before, immediately after, and one hour after fluidization and target burial, in the center of the target burial area. The core tubes and sampling methodology were not robust enough for the retention of the pore water, so no effort was made to observe changes in porosity or pore water content, only a comparison of grain size was conducted. The results are shown in Figure 16. The top plot shows the grain size distribution before fluidization, immediately after, and again one hour later. The lower plot shows the difference from the pre-burial data for the sample taken immediately after fluidization and the sample taken one hour later.

The differences in grain size distribution are minor, and no clear conclusion can be drawn from this small series of observations. It is worth noting that the largest differences in sediment grain size distribution are on the order of five percent, possibly within the variation in core samples taken side by side, and small enough to be difficult if not impossible to observe by UXO detection technologies.

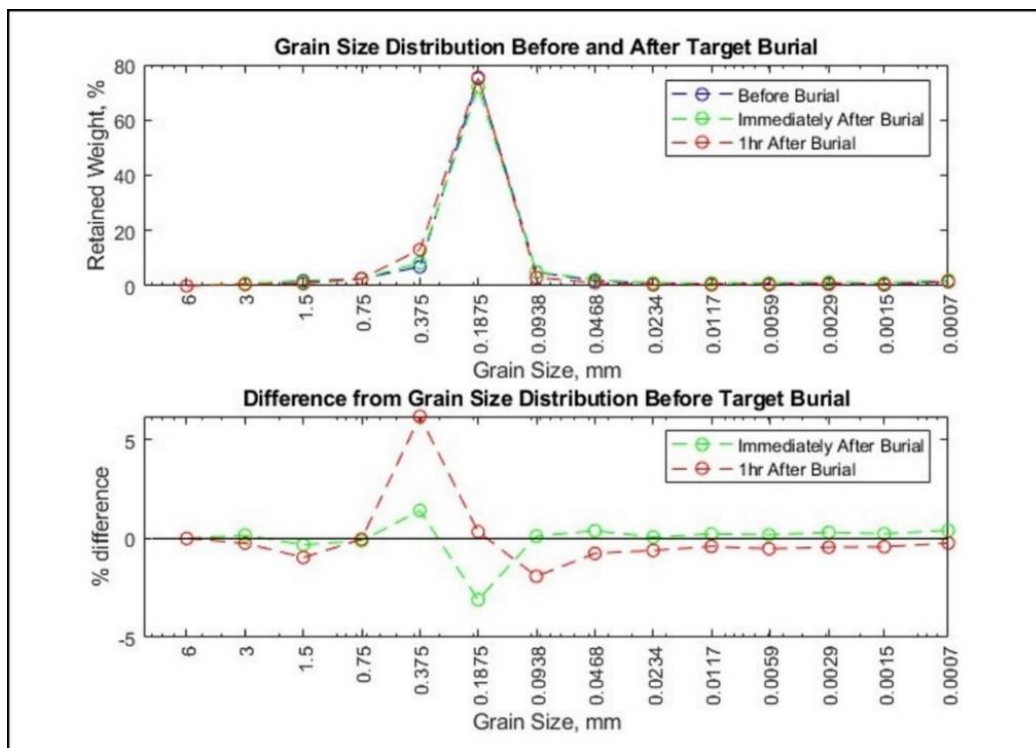


Figure 16. Comparison of grain size analysis before and after fluidization and target burial

Conclusions and Implications for Future Research

This work shows that surrogate UXO targets can be buried broad-sided in marine sand and mud sediments by sediment fluidization, eliminating the need to excavate sediment in order to bury targets. It furthermore suggests that this technique is not limited to shallow burial depths, if a sediment can be fluidized a target can be placed at any reasonable depth a manipulator can reach. The laboratory testing system was able to bury targets to the bottom of the tank at 0.75 m depth. The field system was able to bury targets to 0.65 m in under two minutes, where the burial depth was limited by the reach of the manipulator.

Some limitations of the fluidization technique were also identified in this work. Primarily it was shown in laboratory tests that as sediment grain sizes increases to approximately 1.2 mm diameter the increase in sediment hydraulic conductivity coupled with higher minimum fluidization velocities (both scaling with the square of grain diameter) requires fluidization flowrates to increase rapidly and quickly become impractical when the sediment volume was not constrained. This set an upper limit to the grain size distributions for which this technique could realistically be applied, however this limit is quite high compared to many marine sands. Secondly, in field testing it was shown that dense shell layers within the sediment structure were able to block the fluidization jets and stop the burial process from proceeding any deeper.

Field tests of the system consistently left a small shallow crater in the seafloor around the area that had been fluidized, and survey dives seven to ten days after burial showed that the ridges of these craters has significantly collapsed, and that the seafloor surface has started to even out.

A single effort at observing changes to the sediment grain structure before and after fluidization and target burial suggested that there is little change to the sediment grain size distribution due to fluidization and therefore in areas without distinct sedimentary layers it may be impossible for UXO detection technologies to observe the changes in the sediment due to fluidization and target burial. In areas with distinct sediment layers within the burial depth these layers would be mixed by the fluidization and burial. No effort was made to quantify changes in sediment porosity or pore water content or measure relaxation time of these parameters if any exists. Better characterization of changes in the grain size distribution, sediment porosity, and the ability of UXO detection methods to observe these changes warrant further investigation.

This proof-of-concept work has shown that sediment fluidization is a viable technique for surrogate UXO burial, and that there would be little technical risk associated with developing a surface operated bottom lander, or remotely operated vehicle, designed to bury targets for surrogate UXO target fields or calibration lines. The implementation of this burial method could be done using established subsea engineering techniques and produce an efficient, logistically simple means of burying targets. Future work to be done before building an operationally ready target burial system should include two components:

First, a design study should be conducted to characterize the increase in burial geolocation precision over existing diver deployment methods and well as the cost and time savings this system

could deliver. This would include identifying commercial off the shelf subsea navigation equipment suitable to the task and conducting an end-to-end uncertainty analysis of the burial position accuracy. This design study would also include a detailed budget estimate for non-recurring engineering, component procurement, and fabrication of the system. Lastly, it would include the requirements for an operational support vessel, a well-defined estimate of the number of targets that could be deployed per day, and a detailed estimate of operational costs as a function of the size of target field to be established. This design study would provide test site operators and program managers with reliable estimates of the costs they would incur to establish buried target fields at test sites, and the burial precision they can expect from the system.

Secondly, a study of the potential change in sediment impedance due to fluidization, and characterization of the time required for the sediment impedance to return to its original state, should be conducted. It is likely that both the magnitude of this disturbance and the time scale for its return to its natural state will vary with sediment conditions, and therefore this variability should be explored as well. These investigations could be conducted using the equipment developed in this effort and SERDP funded acoustic detection technologies. This understanding will inform how far ahead of planned UXO detection testing targets would need to be buried in order for the fluidized sediment to return to its original state before testing or demonstration work occurred.

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Appendices

Appendix A – Laboratory testing results

The complete list of laboratory tests and results is shown below:

| Date | Run # | Flowrate (GPM) | Hole Sizing | Burial Depth (in) | Test Sediment | Test Tank | Pump | Performance |
|------------|-------|----------------|-----------------------------|-------------------|---------------|-----------------|--------------|---|
| 11/15/2020 | 1 | 7.5 | .047" 11x7 grid | 6 | Granusil 2095 | large tank | city water | Tube fully buries then stops. Flowrate stays constant |
| 11/15/2020 | 2 | 13 | .047" 11x7 grid | 6 | Granusil 2095 | large tank | Dayton SUX15 | Tube fully buries then stops. Flowrate stays constant |
| 11/15/2020 | 3 | 24 | .062" 11x7 grid | 6 | Granusil 2095 | large tank | Dayton SUX15 | Tube fully buries then stops. Flowrate stays constant |
| 11/19/2020 | 4 | unknown | ICEX small meter ring | 3 | Granusil 2095 | large tank | Dayton SUX15 | Stops shortly below surface. Flowrate stays constant |
| 11/19/2020 | 5 | 5 | ICEX jetting pipe | 6 | Granusil 2095 | large tank | Dayton SUX15 | 6" burial depth. Flowrate stays constant |
| 11/19/2020 | 6 | 10 | ICEX jetting pipe | 9 | Granusil 2095 | large tank | Dayton SUX15 | 9" burial depth. Flowrate stays constant |
| 11/19/2020 | 7 | 15 | ICEX jetting pipe | 11 | Granusil 2095 | large tank | Dayton SUX15 | 11" burial depth. Flowrate stays constant |
| 11/19/2020 | 8 | 20 | ICEX jetting pipe | 15 | Granusil 2095 | large tank | Dayton SUX15 | 15" burial depth. Flowrate stays constant |
| 11/19/2020 | 9 | 22 | ICEX jetting pipe | 15 | Granusil 2095 | large tank | Dayton SUX15 | 15" burial depth. Flowrate stays constant |
| 1/10/2021 | 10 | 24 | .062" 11x7 grid | 6 | Granusil 2095 | coffer, 10"x27" | Dayton SUX15 | Tube fully buries then stops. Flowrate stays constant |
| 1/10/2021 | 11 | >25 | flange only | 30 | Granusil 2095 | coffer, 10"x27" | Dayton SUX15 | fluidizes well, buries to the bottom of the tank |
| 1/10/2021 | 12 | 18 | flange only | 30 | Granusil 2095 | coffer, 10"x27" | Dayton SUX15 | sediment fluidizes, rig buries to the bottom of the tank |
| 1/10/2021 | 13 | 10 | flange only | 4 | Granusil 2095 | coffer, 10"x27" | Dayton SUX15 | Buries a few inches then stops. Flowrate stays constant |
| 2/24/2021 | 14 | unknown | .125", 11x7 | 30 | Granusil 2095 | coffer, 10"x27" | AMT 3824-99 | fluidizes well, buries to the bottom of the tank |
| 2/24/2021 | 15 | unknown | .125", 11x7 | 6 | Granusil 2095 | large tank | AMT 3824-99 | Tube fully buries then stops. Flowrate stays constant |
| 3/2/2021 | 16 | 105 | .125", 11x7 | 30 | Granusil 2095 | coffer, 10"x27" | AMT 3824-99 | Fluidizes but blows out sand |
| 3/2/2021 | 17 | 82 | .125", 11x7 | 30 | Granusil 2095 | coffer, 10"x27" | AMT 3824-99 | Fluidizes well |
| 3/2/2021 | 18 | 69 | .125", 11x7 | 30 | Granusil 2095 | coffer, 10"x27" | AMT 3824-99 | Fluidizes well |
| 3/2/2021 | 19 | 60 | .125", 11x7 | 30 | Granusil 2095 | coffer, 10"x27" | AMT 3824-99 | Fluidizes well |
| 3/2/2021 | 20 | 50 | .125", 11x7 | 30 | Granusil 2095 | coffer, 10"x27" | AMT 3824-99 | Fluidizes well |
| 3/2/2021 | 21 | 50 | .125", 11x7 | 30 | Granusil 2095 | coffer, 10"x27" | AMT 3824-99 | Fluidizes well |
| 3/2/2021 | 22 | 45 | .125", 11x7 | 14 | Granusil 2095 | coffer, 10"x27" | AMT 3824-99 | Poor fluidization |
| 9/15/2021 | 23 | 40 | .125", 11x7 | 30 | Granusil 4075 | large tank | AMT 3824-99 | fluidizes well |
| 9/15/2021 | 24 | 50 | .125", 11x7 | 30 | Granusil 4075 | large tank | AMT 3824-99 | fluidizes well |
| 9/15/2021 | 25 | 60 | .125", 11x7 | 30 | Granusil 4075 | large tank | AMT 3824-99 | fluidizes well, minimal sand ejection |
| 9/15/2021 | 26 | 70 | .125", 11x7 | 30 | Granusil 4075 | large tank | AMT 3824-99 | fluidizes well, some sand ejected |
| 9/15/2021 | 27 | 80 | .125", 11x7 | 30 | Granusil 4075 | large tank | AMT 3824-99 | fluidizes well, some sand ejected |
| 9/15/2021 | 28 | 40 | .125", 7x7 - 4 rows covered | 30 | Granusil 4075 | large tank | AMT 3824-99 | fluidizes well, no noticeable difference from 11x7 |
| 11/2/2021 | 29 | 50 | .125", 7x7 - 4 rows covered | 30 | Granusil 7030 | large tank | AMT 3824-99 | fluidizes well, large area around target |
| 11/2/2021 | 30 | 40 | .125", 7x7 - 4 rows covered | 30 | Granusil 7030 | large tank | AMT 3824-99 | fluidizes well |
| 11/2/2021 | 31 | 35 | .125", 7x7 - 4 rows covered | 30 | Granusil 7030 | large tank | AMT 3824-99 | fluidizes well, small fluidized area around target |
| 11/2/2021 | 32 | 20 | .125", 7x7 - 4 rows covered | 30 | Granusil 7030 | large tank | Dayton SUX15 | fluidizes well, small fluidized area around target |
| 11/2/2021 | 33 | 18 | .125", 7x7 - 4 rows covered | 15 | Granusil 7030 | large tank | Dayton SUX15 | doesn't fluidize well, load is carried by sand during descent |
| 11/2/2021 | 34 | 16 | .125", 7x7 - 4 rows covered | 15 | Granusil 7030 | large tank | Dayton SUX15 | doesn't fluidize well, load is carried by sand during descent |

Grausil sands were used in the laboratory testing, their vendor spec sheet is shown below:



TECHNICAL DATA

FEATURES AND BENEFITS

EMMETT, ID

GRANUSIL® Mineral Fillers are produced from high purity industrial quartz sands for a wide variety of industrial and contractor mixed applications which need a reliable silica contribution or require a chemically inert structural filler. Consistently uniform grain shapes and particle size distributions offer excellent placement, compaction and mechanical properties. High silica content combined with low level soluble ions, alkalis and alkaline oxides provide non-reactive service in most corrosive and exposed environments.

These durable monocrystalline structures resist abrasion in high traffic-excessive wear applications and provide the stability formulators seek in high solids emulsions, elastomerics, cemented and modified cementitious systems. GRANUSIL® is the preferred structural component in systems ranging from polymerized floor overlays to artificial sports turf.

All GRANUSIL® grades are processed and sized under rigid SPC and UNIMIN QIPSM statistical and quality assurance programs. The result is chemical purity and consistently uniform particle size distributions for predictable performance in either manufactured or site-prepared products.

PARTICLE SIZE ANALYSIS AND PROPERTIES

Mean Values. These Do Not Represent A Specification.

| | Mesh Size | | 2095 | 2075 | 4095 | 4075 | 4010 | 7030 |
|-------------------|-----------|---------|------|------|------|------|------|------|
| | ASTM | Microns | | | | | | |
| | 8 | 2.36mm | 2.3 | --- | --- | --- | --- | --- |
| | 16 | 1.18mm | 95.6 | 59.6 | 1.8 | --- | --- | --- |
| | 20 | 850 | 1.8 | 31.2 | 27.8 | --- | --- | --- |
| Typical Mean % | 30 | 600 | 0.2 | 5.7 | 42.0 | 16.1 | --- | --- |
| Retained on | 40 | 425 | 0.1 | 2.7 | 23.6 | 61.3 | 11.5 | 0.8 |
| Individual Sieves | 50 | 300 | --- | 0.6 | 4.3 | 20.4 | 32.8 | 3.3 |
| | 70 | 212 | --- | 0.1 | 0.4 | 1.9 | 28.3 | 23.3 |
| | 100 | 150 | --- | --- | 0.1 | 0.3 | 19.1 | 35.9 |
| | 140 | 106 | --- | --- | --- | --- | 6.3 | 23.4 |
| | 200 | 75 | --- | --- | --- | --- | 1.6 | 9.6 |
| | PAN | PAN | --- | --- | --- | --- | 0.3 | 3.8 |

| | | |
|---|------------|-------------|
| Grain Shape | Subangular | Visual |
| Hardness (Mohs) | 7.0 | Moh's Scale |
| Moisture Content (%) | <0.1 | ASTM C-566 |
| Specific Gravity (g/cm ³) | 2.65 | ASTM C-128 |
| Bulk Density, loose (lb/ft ³) | 92-95 | ASTM C-29 |
| Bulk Density, compacted (lb/ft ³) | 98-100 | ASTM C-29 |



Appendix B – Field Test Results

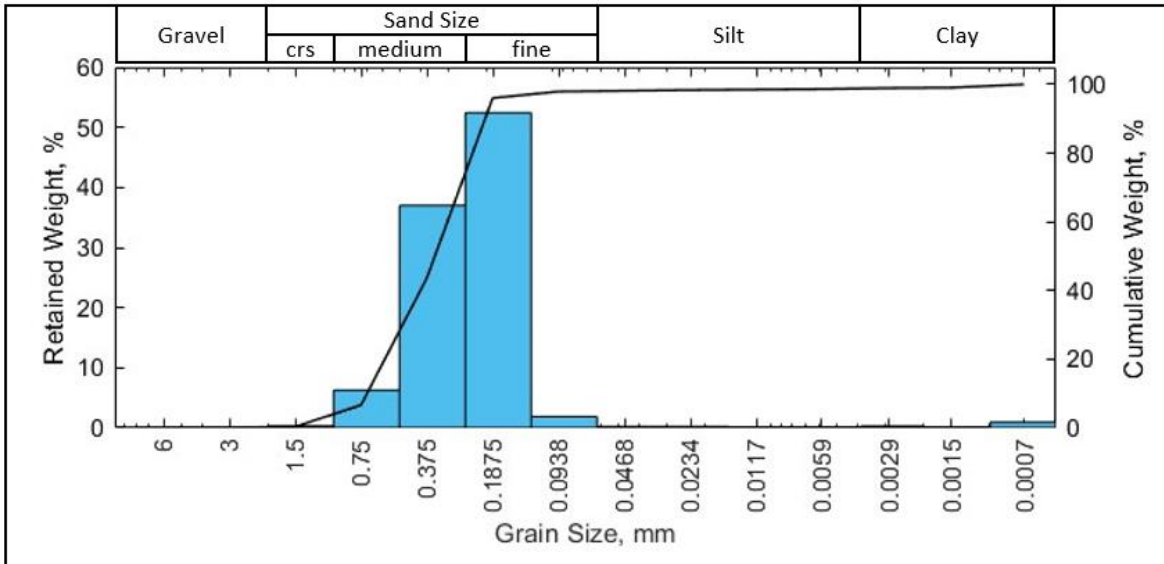
Videos of field tests can be seen at the following links:

<https://www.youtube.com/watch?v=ox1PZIEvDGQ>

<https://www.youtube.com/watch?v=o1qgXxZZMMM>

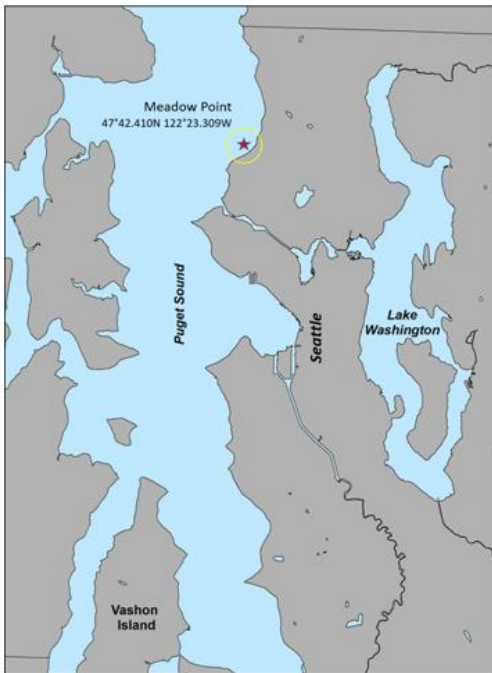
Field testing data is presented on the following pages. Each field test has a page showing grain size analysis, flowrates and burial depth, a map showing testing location, as well as notes about the test.

| | | |
|--------------------------|------------------|-----------|
| Test no. 1 of 6 | Meadow Point, WA | 2/25/2022 |
| 47°42.410 N 122°23.309 W | | |

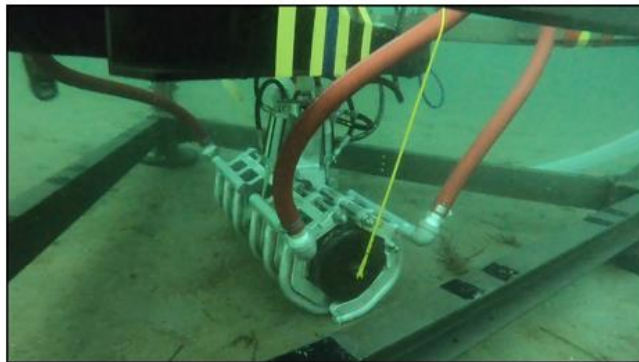


Test Notes

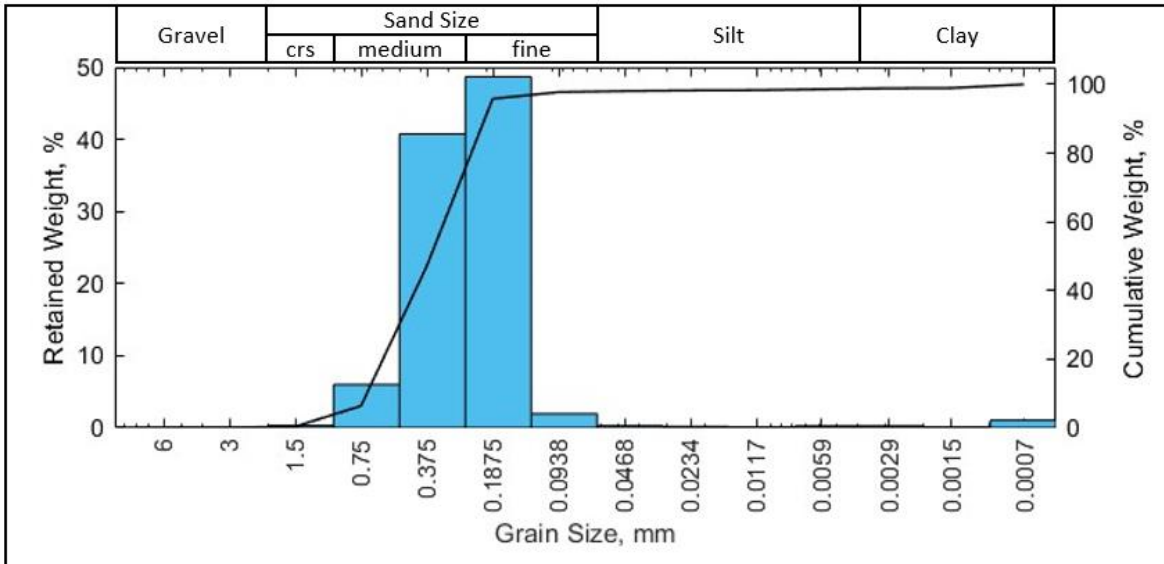
Fluidization flow started at 225 lpm, manipulator penetrated to 0.35 m without issue, then became difficult to continue. Flow raised to 300 lpm, manipulator was able to fluidize and reach the full 0.65 m burial depth. Target released and manipulator raised without issue. Sediment had characteristic boiling look, with very fine particles lifting into the water column and spreading across the seafloor. Once finished a shallow crater approx. 1 m in diameter and .15 m deep was present.



| Test Data | |
|-----------------------|----------------|
| Water Depth | 14 m |
| Burial Depth | 0.65 m |
| Fluidization Flowrate | 300 liters/min |

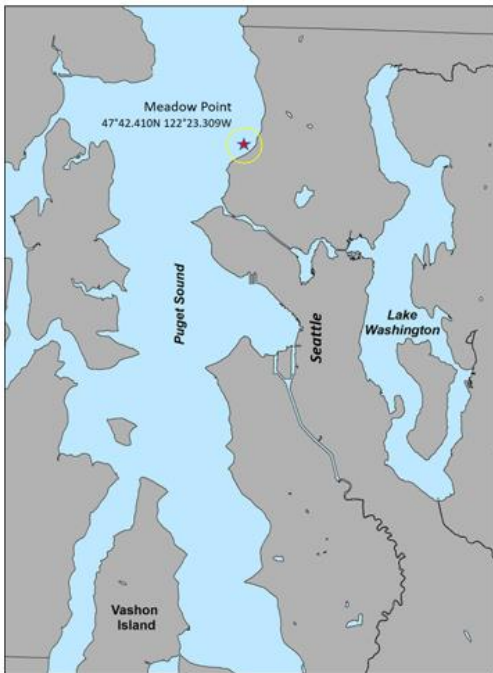


| | | |
|--------------------------|------------------|-----------|
| Test no. 2 of 6 | Meadow Point, WA | 2/25/2022 |
| 47°42.410 N 122°23.309 W | | |

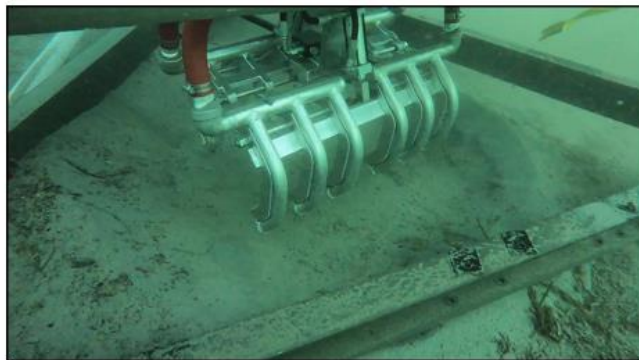


Test Notes

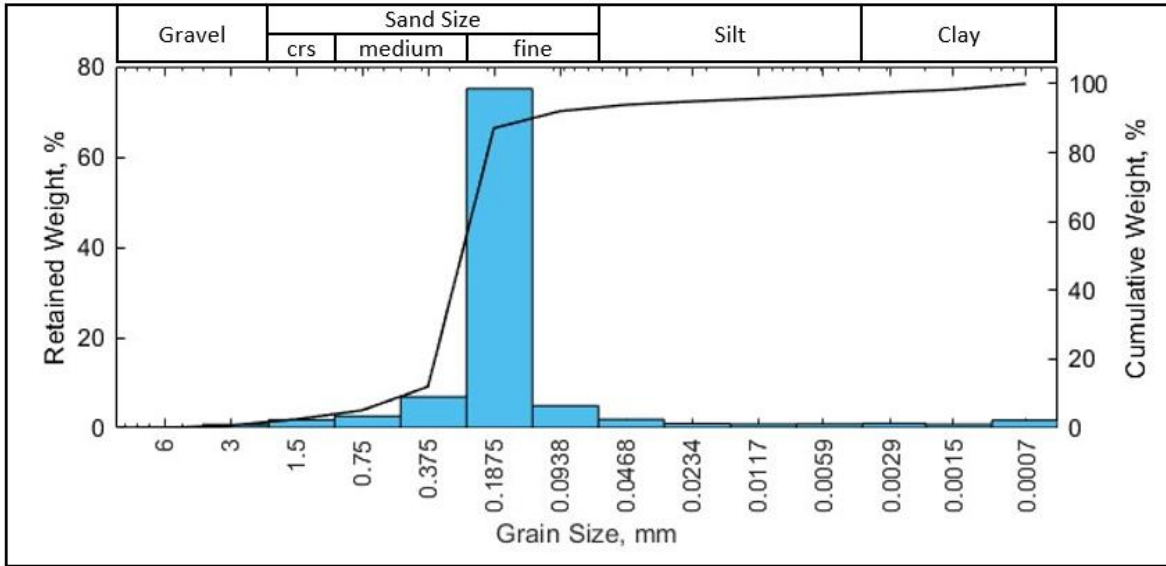
Fluidization flow started at 225 lpm, manipulator penetrated to 0.35 m without issue, then became difficult to continue. Flow raised to 320 lpm, manipulator was able to fluidize and reach the full 0.65 m burial depth. Target released and manipulator raised without issue. Crater was similar to the one from test no.1. Sediment seemed a bit more consolidated when taking core sample, harder to push core in.



| Test Data | |
|-----------------------|----------------|
| Water Depth | 14 m |
| Burial Depth | 0.65 m |
| Fluidization Flowrate | 320 liters/min |

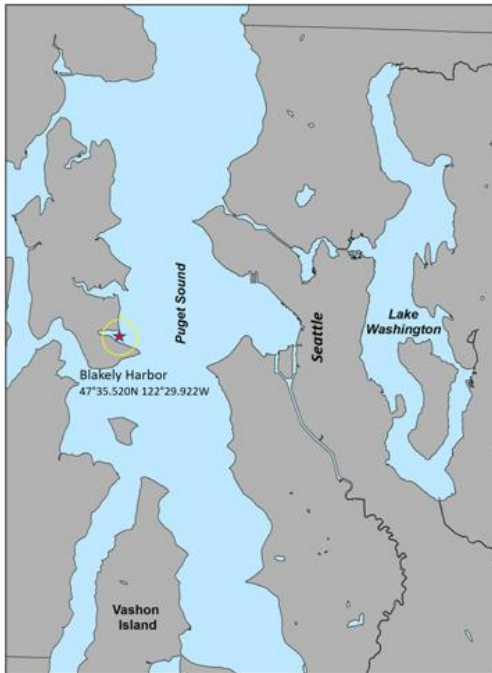


| | | |
|--------------------------|--------------------|-----------|
| Test no. 3 of 6 | Blakely Harbor, WA | 3/21/2022 |
| 47°35.520 N 122°29.922 W | | |

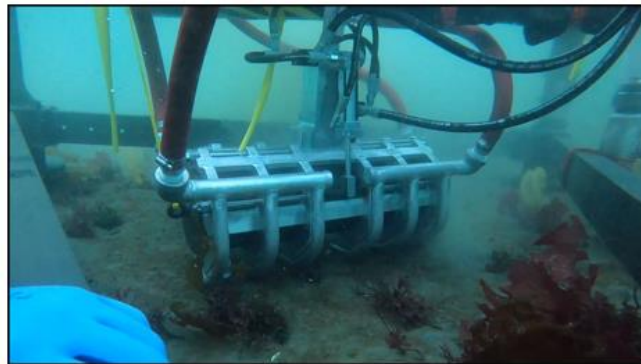


Test Notes

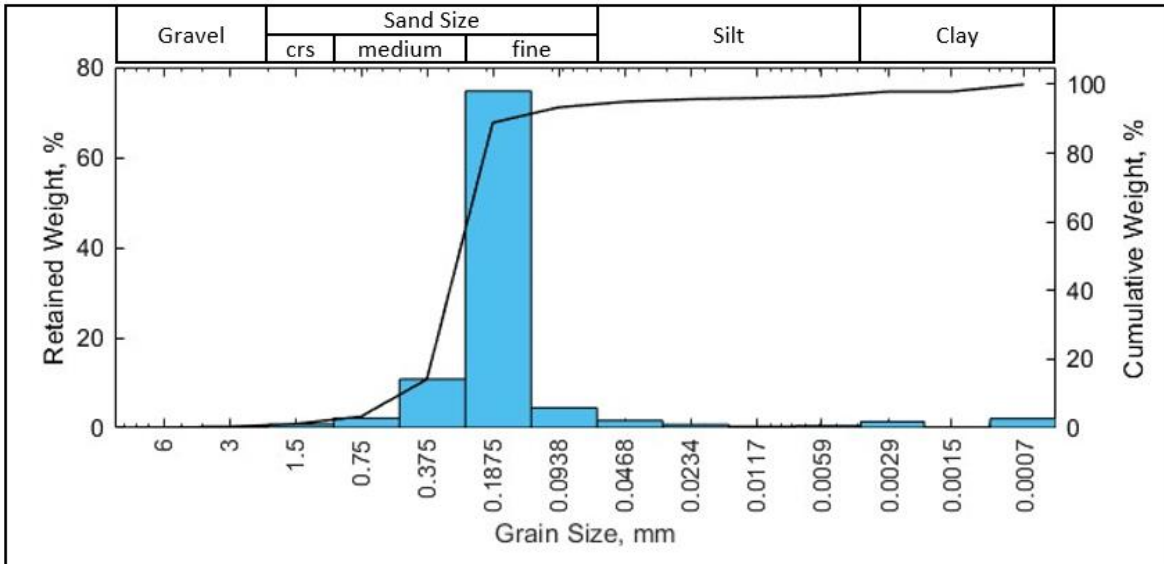
Fine grained sediment with some cohesion. 190 lpm flowrate at start. System fluidized and penetrated easily, with a narrow, steep sided fluidized area observed by diver reaching in. At .45 m burial depth system stopped descending, flowrate was increased to 320 lpm (system maximum) but did not penetrate deeper. Reaching into the fluidized area and under manipulator divers found a dense shell layer present.



| Test Data | |
|-----------------------|----------------|
| Water Depth | 12 m |
| Burial Depth | 0.45 m |
| Fluidization Flowrate | 320 liters/min |

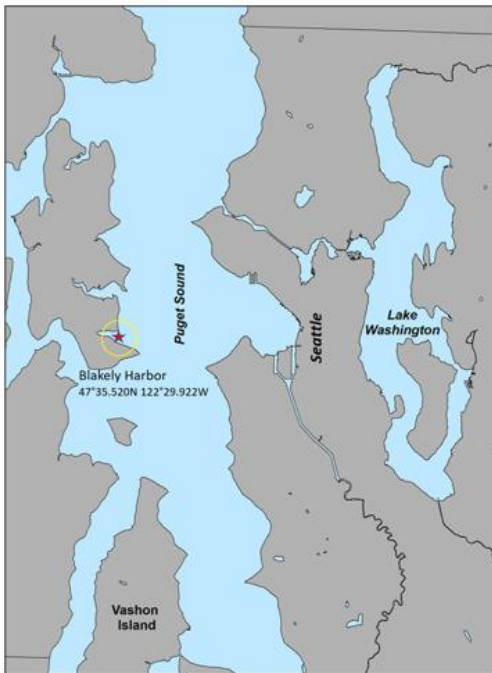


| | | |
|--------------------------|--------------------|-----------|
| Test no. 4 of 6 | Blakely Harbor, WA | 3/21/2022 |
| 47°35.520 N 122°29.922 W | | |



Test Notes

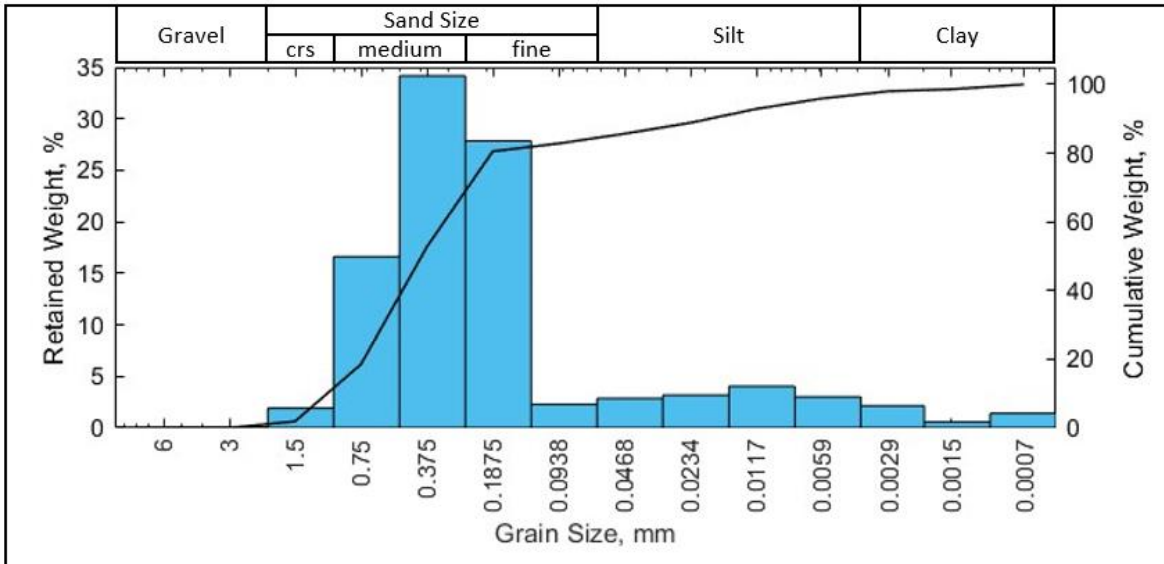
Same notes as for test no. 3. Fine grained sediment with some cohesion. 190 lpm flowrate at start. System fluidized and penetrated easily, with a narrow, steep sided fluidized area. At .45 m burial depth system stopped descending, flowrate was increased to 320 lpm (system maximum) but did not penetrate deeper. Reaching into the fluidized area and under manipulator divers found a dense shell layer present.



| Test Data | |
|-----------------------|----------------|
| Water Depth | 12 m |
| Burial Depth | 0.45 m |
| Fluidization Flowrate | 320 liters/min |

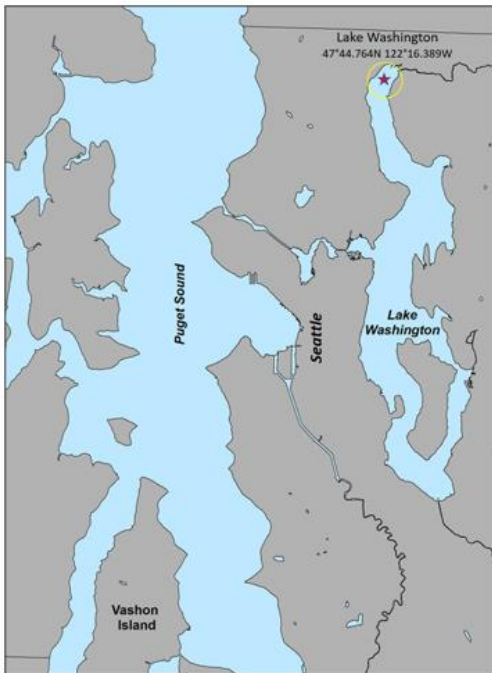


| | | |
|--------------------------|---------------------|-----------|
| Test no. 5 of 6 | Lake Washington, WA | 3/22/2022 |
| 47°44.764 N 122°16.389 W | | |



Test Notes

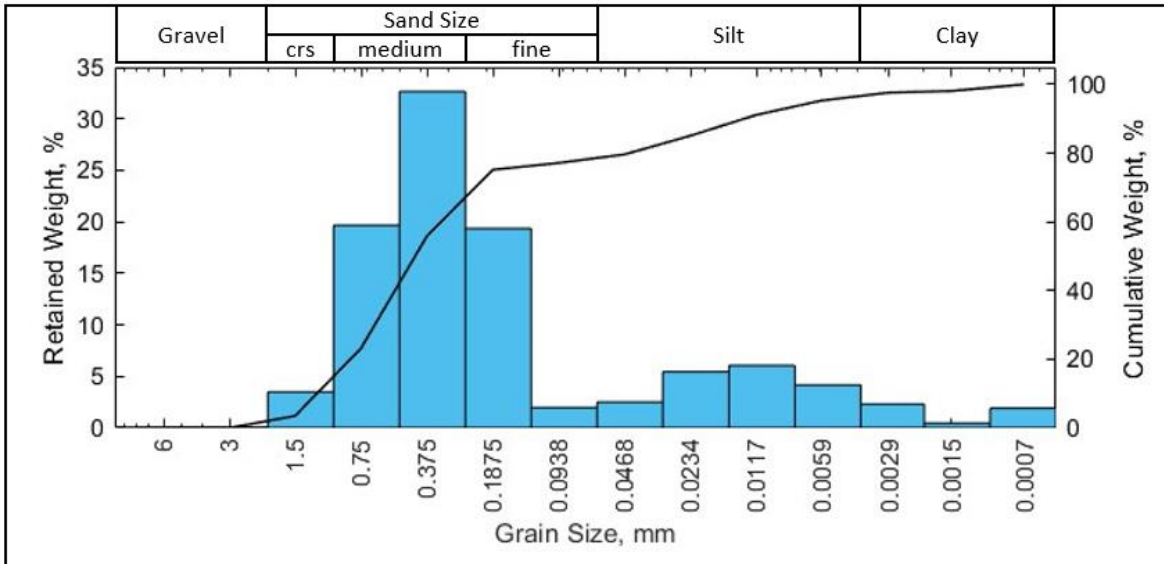
Bottom lander sat on mud later with minimal sinking. Visibility was very poor. Sediment had some cohesion, but divers could easily push their hands into it. Flowrate set to 170 lpm, manipulator had no issues reaching full 0.65 m burial depth, target released, and manipulator recovered without issue.



| Test Data | |
|-----------------------|----------------|
| Water Depth | 9 m |
| Burial Depth | 0.65 m |
| Fluidization Flowrate | 190 liters/min |

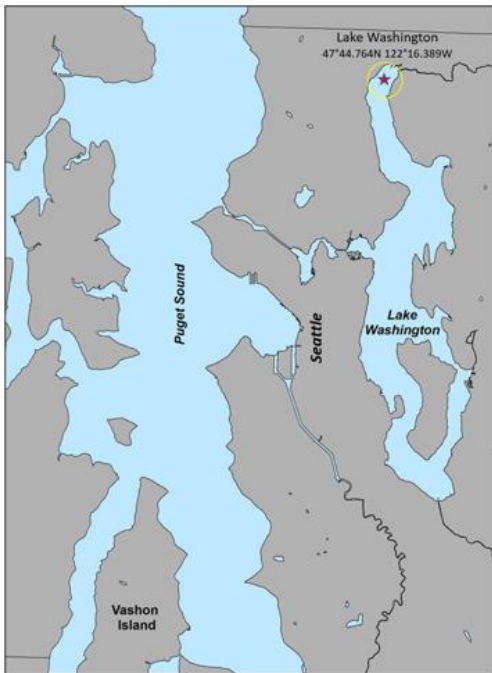


| | | |
|--------------------------|---------------------|-----------|
| Test no. 6 of 6 | Lake Washington, WA | 3/22/2022 |
| 47°44.764 N 122°16.389 W | | |



Test Notes

Same notes as test no. 5. Bottom lander sat on mud later with minimal sinking. Visibility was very poor. Sediment had some cohesion, but divers could easily push their hands into it. Flowrate set to 170 lpm, manipulator had no issues reaching full 0.65 m burial depth, target released, and manipulator recovered without issue.



| Test Data | |
|-----------------------|----------------|
| Water Depth | 9 m |
| Burial Depth | 0.65 m |
| Fluidization Flowrate | 190 liters/min |

