Post Access Report

Ultra-Low-Cost Torpedo Anchors for Marine Renewable Energy

Awardee: **RCAM Technologies, Inc. DBA Sperra**
Awardee point of contact: **Mason Bell**
Facility: **Sandia Laboratories Drop Tower Facility**
Facility point of contact: **Budi Gunawan**
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Authors: Mason Bell, Jason Cotrell, Budi Gunawan, Luis Abeyta, Richard Jepsen

EXECUTIVE SUMMARY

The Ultra-Low-Cost Torpedo Anchors (TAs) for Marine Renewable Energy project aimed to evaluate the embedment performance of Sperra's concrete torpedo anchors in sandy seabed conditions, a previously untested environment for torpedo anchors. Conducted under the Testing and Expertise for Marine Energy program, the project utilized the 300-foot Drop Tower Facility at Sandia National Laboratories in Albuquerque, NM. The objective was to validate reinforced concrete TAs as a cost-effective and low-carbon alternative to conventional steel torpedo anchors while maintaining equivalent or superior performance in real-world conditions. By integrating a retrievable steel booster with concrete fin assemblies, the study explored the potential for concrete torpedo anchors to provide robust, scalable, and sustainable anchoring solutions for offshore renewable energy applications.

The testing campaign consisted of 14 drop tests, comparing the performance of concrete and steel torpedo anchors in saturated sandy soil, a challenging environment where torpedo anchors have historically been excluded due to perceived limitations in embedment potential. Three concrete fin designs were fabricated with varying torpedo fin attack angles of 45°, 52.5°, and 60° to assess the influence of fin geometry on embedment depth and stability. Each torpedo anchor was subjected to free-fall drop tests from heights ranging from REDACTED, achieving impact velocities between REDACTED. Data collection was performed using high-speed cameras, accelerometers, and load cells, measuring penetration depth, impact forces, retrieval forces, and embedment behavior to determine the feasibility of concrete torpedo anchors in cohesionless sandy seabeds.

Results demonstrated that concrete torpedo anchors achieved embedment depths comparable to the steel reference anchor, confirming that concrete can match the performance of steel while offering significant cost and carbon reductions. The 45° fin attack angle achieved the best penetration, making it the preferred configuration for future design optimizations. Retrieval forces varied across designs, with peak efficiencies on the order of 3 achieved, even with anchors not fully embedded, indicating promising results for further optimization. Notably, this project represents the first experimental validation of torpedo anchors in cohesionless sandy soils, a seabed condition often deemed unfit for torpedo deployment. These results suggest that torpedo anchors can be expanded for use in a broader range of seabed conditions, opening new possibilities for offshore renewable energy anchoring in previously excluded regions. This study provided critical experimental validation for Sperra's concrete torpedo anchor technology, demonstrating its cost-effectiveness, sustainability, and viability in sandy seabeds. The findings will inform numerical modeling improvements and design refinements to further optimize embedment performance and pullout (holding) capacity.

Moving forward, this research will focus on enhancing numerical models to improve penetration predictions for torpedo anchors in sandy soils. Further testing will explore additional design variables, including anchor mass, fin geometry, impact velocity, and different soil compositions. A full-scale field demonstration will be a crucial next step in validating long-term performance under operational marine conditions. The success of this project highlights the commercial potential of concrete torpedo anchors, supporting their adoption of wave energy and offshore marine renewable applications. By offering comparable performance to steel at a fraction of the cost and carbon footprint, this research advances scalable, sustainable anchoring solutions for the growing offshore energy sector.

1 INTRODUCTION TO THE PROJECT

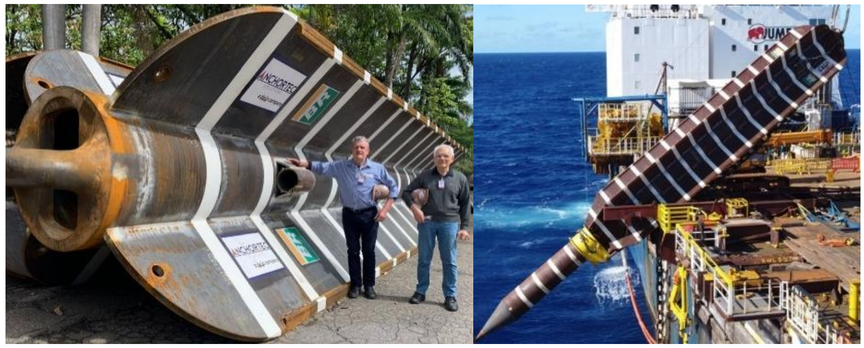

Figure 1. 100-ton steel torpedo anchor for the oil and gas industry. Smaller units will be appropriate for marine energy's lower loads.

Torpedo anchors (TAs) represent a significant innovation in marine anchoring technology, originally developed by the Brazilian oil and gas company Petrobras in 1996 (**Figure 1**). This development was driven by the need for more cost-effective anchoring solutions in deep water, where traditional methods like drag anchors, gravity anchors, and piles proved expensive. Characterized by their pile-like structure, TAs are uniquely designed for installation via the kinetic energy they acquire during a free fall of 30 to 150 meters through seawater before penetrating the seabed. For installation, a TA is suspended vertically at a predetermined height above the sea floor and then released (**Figure 2**). This process allows the anchor to embed itself typically to a depth of at least twice its length, ensuring a robust and stable mooring solution. The design and installation method of TAs make them an optimal choice for deepwater applications, offering advantages in terms of both efficiency and cost-effectiveness.

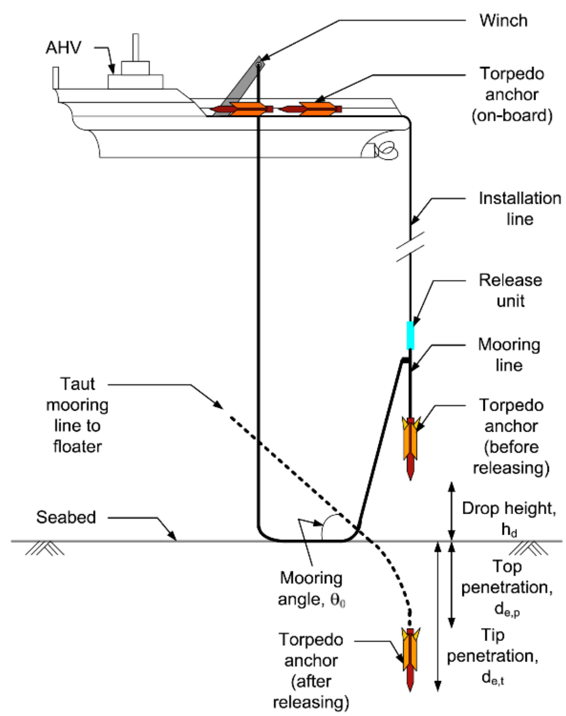

Figure 2. Illustrative installation method for torpedo anchors. Source: Hossain et al. (2014).

TAs are a promising anchor type for US marine energy deployments because they 1) provide high omnidirectional load capacities that are suitable for all mooring configurations, mooring line materials, and floating structure types, 2) locate during installation with a high degree of accuracy and certainty, 3) are well proven in oil and gas applications, 4) install quickly, quietly, and efficiently, 5) embed in a variety of seabed soil types commonly found in the US including normally consolidated clays and calcareous sand, and 6) have potentially superior resistance to seismic events.

The conventional steel TA stands as a proven solution in the offshore anchoring domain, particularly within the oil and gas industry (**Figure 1**). Over 2,000 conventional steel TAs have been successfully deployed, demonstrating their adaptability across a range of load capacities for applications such as floating oil platforms, risers, and umbilical cables. Fabricated from 2-inch to 3-inch-thick steel fins and rolled-pipe, conventional steel TAs are typically filled with concrete, steel, or lead ballast to achieve the desired weight and hydrodynamic stability. A summary of TA characteristics from literature is provided in (**Table 1**).

Despite their proven effectiveness, the adoption of conventional steel TAs in the US, especially for marine energy deployments, has been limited. This is mainly due to the high costs associated with steel and lead ballast, as well as a general lack of experience with these anchors in the US market. Additionally, the significant metal content in conventional steel TAs leads to a substantial carbon footprint, and their production often involves imported materials or overseas manufacturing.

Table 1. Summary of TA pile characteristics from literature.

Author	Medeiros (2002)	Brandão et al. (2006)	Lieng et al. (2010)	O'Beirne et al. (2015, 2017a, 2017b)	Sturm et al. (2011)	Wang et al. (2016, 2018)
Location	Marlim, Campos Basin, Brazil	Albacora Leste Field, Brazil	Goja, North Sea	Erne - Northern Ireland	Norwegian Troll Field	Shanghai Jinshan Port, Jangsu Yangcheng Lake and Zhejiang Yueqing Port Soils
Water depth	200 -1000 m	1195; 1180; 940 m	358 - 371 m	3 - 19 m	300 m	1g lab condition
Soil	NCC and OCC	-	Lightly OCC	Very Soft NCC	Lightly OCC	NCC
Water content	-	-	21 - 68%	270 - 520%	-	27 - 77%
Liquid limit	-	-	-	180 - 345%	-	-
Plastic limit	-	-	20.8 - 36.4	-	-	-
% of Fines	-	-	-	95%	75 - 95%	-
Strength profile	Su = 5 + 2z	-	-	Su = 1.5z (z= 0 to 1.5); Su = 2.25 + 0.8z (z - 1.5 to 3)	Su = 5 kPa (z = 0 to 2.5); Su = 5 + 2.69z (z = 2.5 to 15)	0.65 - 3 kPa
Sensitivity	-	-	2 - 3	1.9 - 2.6	5.5	1.182 - 2.270
Scale model	Prototype	Prototype	Prototype	1:20; 1:100	1:3	1:65 to 1:180
Diameter	0.762 - 1.066 m	1.07 m	1.2 m	60 mm; 6 mm	0.4 m	19; 25; 32 mm
Weight	240 - 950 kN	98 tonnes	80 tonnes	203 N;	28.55 kN	0.187 - 0.894 kg
Length	12 - 15 m	17 m	13 m	0.75m; 75 mm	4.4 m	0.095 - 0.352 m
Fluke	0	0.9 m x 10 m	4 m wide	4 No's	4 No's (0.5 m x 1.6 m)	4 No's extended 2/3rd of length
Tip embedment	29 m in NCC; 13.5 m in OCC; 15 m in calcareous sand; 22 m in seabed soil	9; 16; 17.5 m	24 & 31 m	1.1 - 1.9 m (L_{anchor} = 750 mm) 85 - 110 mm (L_{anchor} = 75 mm)	7.4 and 8.7 m	0.095 - 0.545 m
Terminal velocity	-	16.3; 23; 24 m/s	24.5 & 27 m/s	-	-	-
Impact velocity	10 - 22 m/s	-	-	0 - 6.7 m/s; 16.41 - 16.92 m/s; 25 m/s (example application)	12.8 - 15 m/s	3.13 - 7.00 m/s
Drop height	30 - 150 m	40 - 135 m	50 & 75 m	0 - 19 m	> 50 - 75 m	0.5 - 2.5 m
Anchor tilt	-	3; 9; 5 degrees	< 2 degrees	2.5 degrees	5 to 8 degrees	-
Pull-out capacity	1400 - 7500 kN	6088 kN	700 tonnes	-	-	Varies
Tip angle	-	30 and 60 degrees	-	-	-	30 degrees

Sperra's (formerly RCAM Technologies) ultra-low-cost TA (**Figure 3**), represents an advanced and innovatively designed TA. This system comprises a steel central shaft, referred to as the booster, which was reused across multiple drop tests to evaluate its effectiveness in repeated deployments.. Complementing this, a set of reinforced concrete fins are integrated into the design. During the installation process, these components operate in unison, acting as a singular TA unit. Once embedded in the soil, the booster is designed to be retrievable, leaving only the concrete fins within the seabed. This feature significantly reduces the amount of residual material per anchor, optimizing for both environmental impact and material efficiency. The booster's design contributes to the anchor's enhanced performance. By reducing the projected area of the booster shaft, higher terminal velocities were achieved in drop testing, allowing for deeper penetration in cohesionless sandy soils. This attribute is especially advantageous in mixed soil conditions and in shallow water depths, extending as shallow as 30 meters.

Additionally, reinforced concrete fins are manufactured using cost-effective, locally sourced concrete materials. For the TEAMER test campaign, Sperra fabricated three concrete TAs, each featuring distinct fin attack angles of 45°, 52.5°, and 60° to evaluate the effect of fin geometry on embedment performance. 3D printing is beneficial for crafting the anchor's fins, where precision manufacturing complex geometries is paramount. As such, the use of automated, robotically controlled 3D printing is a key aspect of Sperra's TA design, allowing for the efficient and precise fabrication of complex shapes while eliminating the costly formwork required in traditional concrete casting. For the TEAMER test campaign, plastic molds were 3D printed using a large format plastic printer for casting reinforced the fins. In larger scale versions an outer shell referred to as "stay-in-place formwork" can be 3D concrete printed and reinforced concrete is cast in the voids.

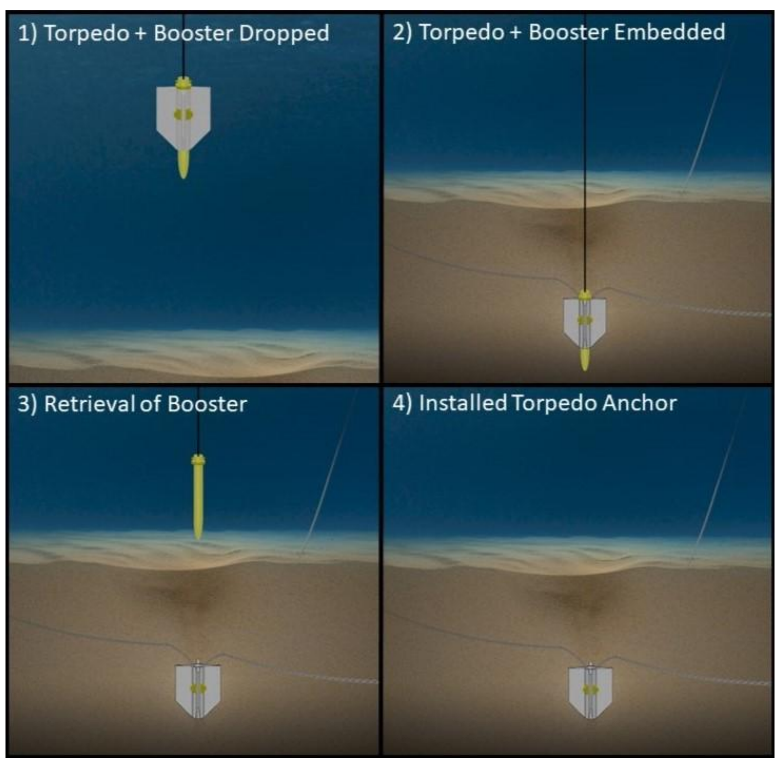

Figure 3. Artist's rendering of installation procedure for Sperra's ultra-low-cost TA.

This TEAMER project aimed to investigate the embedment performance and vertical load capacity of Sperra's innovative ultra-low-cost TAs in sandy soils, focusing on their applicability for anchoring marine energy devices such as wave energy converters. Testing was conducted at Sandia National Laboratories in Albuquerque, New Mexico using their 300-foot Drop Tower Facility. During testing, each TA specimen was raised to a calculated height, ensuring that upon release, its impact velocity mirrors that of a descent through water, targeting an anticipated penetration depth of up to 2 meters. Following their free-fall each TA impacted a pit of saturated sand prepared to replicate field-representative seafloor conditions to the extent practical within a controlled test environment. The specimens' actual penetration depths were measured and compared against the estimated depths. The analysis provided critical data to assess how specific features influenced the anchor's embedment performance. The installed cost of Sperra's TAs is projected to be substantially lower than traditional anchors, accelerating marine energy deployments in the US by reducing balance-of-system costs, installation times, CO_2 emissions from manufacturing and installation of anchoring systems, and easing anchoring logistics through more efficient design and installation methods. TAs are well proven in the oil and gas industry as a reliable anchoring solution in deep-water with primarily clayey or mud/sand cohesive soils. However, sandy soils and scaling the TA technology for use in marine energy installations like wave energy presented several design challenges that have never been explored experimentally. The primary design challenge is ensuring and accurately characterizing TA embedment performance in more difficult cohesionless sandy soils, such as those tested in this project at shallower depths (60-100 m) present on the US west coast.

2 Roles and Responsibilities of Project Participants

2.1 Applicant Responsibilities and Tasks Performed

The applicant, Sperra, was responsible for the following:

1. **Project Management:** Sperra assigned a project manager to oversee the entire test plan, test parameters, and ensure the soundness of the experimental design.
2. **Experimental Design:** Sperra was responsible for designing the experimental setup, including the selection of TA specimens, specifying the test parameters, and working with the network facility to include necessary instrumentation in design.
3. **TA Fabrication:** Sperra fabricated four TA fin specimens with distinct fin attack angles of 45°, 52.5°, and 60°. Three were concrete and the fourth was a steel reference. The test articles had approximate dimensions of 1 m long by 0.85 m wide and a mass of 154-290 kg. Sperra subcontracted and oversaw the fabrication of a single 200 kg, 1.65 m long retrievable steel booster and reference steel anchor weighing 154 kg that consisted of the central shaft, fins, and padeye.
4. **Shipment of TAs:** Sperra coordinated the shipment of the fabricated TA specimens from their facility at Alta Sea at the Port of Los Angeles to Sandia in Albuquerque, NM for testing, ensuring proper logistics and documentation.
5. **Data Collection and Analysis:** The tests were witnessed and oversaw by the project manager assigned by Sperra. Sperra provided input on the data collection process and reviewed the results after testing was completed. This included analyzing high-speed video footage, manual penetration depth measurements, and impact velocity data. Sperra determined the drop height for subsequent testing after reviewing previous test results.
6. **Final Reporting:** Sperra led the development of this final post-access report, following the TEAMER specific post-access reporting guidelines.

2.2 Network Facility Responsibilities and Tasks Performed

The network facility, Sandia, was responsible for the following:

1. **Test Facility Management:** Sandia managed the test facility and provided the necessary infrastructure and equipment for conducting the drop/impact testing.
2. **Data Acquisition:** Sandia was responsible for data acquisition during the experimental tests, utilizing high-speed video cameras and triaxial accelerometers. Sandia worked with Sperra to fabricate a 3D printed instrumentation box, ensuring proper installation, calibration, and operation of the instrumentation attached to the back end of the TA specimens retrievable steel booster. The test data collected included drop height, embedment depth, time-series angular displacement, acceleration, and velocity, specimen static force, specimen vertical pull-out force. Acceleration was measured using an accelerometer and derived from high-speed video cameras.
3. **Experimental Testing:** Sandia performed a total of 14 drop/impact tests of the TA specimens according to the experimental design created by Sperra. Sandia ensured the proper and safe functioning of the drop-release mechanism at the 300-foot tower, the vertical trolley guided system, the soil pit, and other testing equipment.
4. **Data Processing and Performance Assessment:** Emphasis was placed on measuring embedment depth, inclination, and vertical pull-out capacity to evaluate the effect of each innovative feature on the TAs performance. Sandia conducted initial data processing of the collected experimental data using their in-house code.
5. **Final Reporting:** Sandia collaborated with Sperra to compile the experimental results, findings, and analysis into this final report. Sandia contributed to the analysis of TA performance and provided technical input in the reporting process.

3 Project Objectives

The objective of this project was to gather data from experimental drop/impact testing of Sperra's ultra-low-cost TA. Data collected from this test was used to:

1. Compare experimentally measured penetration depths to pre-test numerical estimates for TAs in cohesionless sandy soils.
2. Demonstrate TAs as a viable anchoring solution for marine energy deployments.
3. Assess the performance and validity of TAs installed in shallow water with sandy soil types.
4. Characterize the impact that individual TA features have on the overall embedment performance.
5. Evaluate the structural integrity of Sperra's TA manufacturing process.

Validating Sperra's innovative TAs for anchoring marine renewable energy systems, focusing on shallow waters with sandy soil types, was a key objective in this study to confirm the efficacy and applicability of TAs under the specific demands of the marine energy industry. The project conducted a series of 14 drop tests with both steel and concrete TAs, evaluating embedment performance in a saturated pit of sandy soil at Sandia's 300-foot drop tower. The study provided insight into how variations in fin geometry, including 45°, 52.5°, and 60° fin attack angles, affected embedment performance. These results are being used to refine numerical penetration models and assess necessary design modifications for future TA deployments.

Successful completion of the test campaign confirmed that concrete TAs could embed in cohesionless sandy soils but with penetration depth variability influenced by anchor fin geometry and impact conditions. The study examined concrete anchor performance relative to a steel reference anchor, providing comparative data on embedment efficiency and retrieval forces. These investigations helped to identify the most effective design configurations for deeper embedment, optimal inclination, and enhanced stability and holding capacity. The performance metrics evaluated included:

- **Numerical Model Accuracy:** Comparing experimentally measured penetration depths to pre-test numerical predictions to validate penetration estimation methods for cohesionless soils.
- **Anchor Efficiency:** Assessing embedment characteristics and retrieval forces to inform future anchor geometry optimization.
- **Anchor Viability:** Assessing the practicality and effectiveness of TAs as anchoring solutions in marine energy deployments, with a focus on shallow, sandy environments.
- **Embedment Performance Analysis:** Examining the influence of varying fin geometries and impact velocities on embedment performance.
- **Structural Integrity Post-Impact:** Observing the resilience and durability of TAs after impact, ensuring they meet operational demands.
- **Cost and Environmental Impact:** Demonstrating that concrete-based TAs can potentially reduce installed costs and lower CO_2 emissions compared to traditional deadweight anchors.

4 Test Facility, Equipment, Software, and Technical Expertise

The testing was conducted using the 300-foot drop tower located in Albuquerque NM, on Kirtland Air Force Base, inside Sandia's Tech Area III operated by SNL Department 1531 (Mechanical Environments), one of the two drop towers located within the Sandia Lake Facility Complex (**Figure 4**). The drop towers provide a controlled environment for testing a wide variety of small and large test items. These towers were built in the 1950s and 1960s to support ballistic testing of weapon programs. In 1983, a 57.3 m by 36.6 m water tank, with a 15.2 m water depth (named Sandia Lake Facility/Water Impact Facility) was built in between the two towers to support the Space Shuttle program's R&D. NASA approached Sandia to investigate why space shuttles' external fuel tanks were sinking in water once jettisoned during launch and to propose solutions. Sandia has a dedicated team that plans and runs experiments at this facility.

The tower consists of a square-narrow frame tower measuring 4-feet by 4-feet by 300-feet tall. Its main cable is anchored on to the ground at one end, passes over the top of the tower, and anchored to a cantilevered counterweight at the other end of the cable. The main cable trolley is attached on to the main cable via a set of sheaves making it mobile along the main cable. One end of the remote operated

Figure 4. The two towers (left), the vertical trolley guided system (middle), and one of the space shuttle program tests at the facility (right).

hoisting winch cable is attached to an electric cargo hook which was used to lift and release the fins and booster from the provided drop heights. In a similar manner, the same winch, cable, and cargo hook were utilized to lift and remove (pull-out) the booster and fins from the plaster sand after each test was completed.

Test specimens were attached to the trolley in desired test orientation and maintained the orientation on impact with any deviations in angle measured via photometrics. The trolley guided system is well-suited for testing systems and components that require precise and repeatable impact conditions at impact velocities of 100 ft/s (30.5 m/s) or less. For the project, the impact target was a container of sand that saturated with water to mimic ocean seafloor conditions. At this stage of experimentation, the sand container was not placed inside the lake. This allowed for better control of the sand layer preparation so that experimental results could be used to better understand the basic characteristics of the TA embedment, without adding additional complexity and costs to the scope of testing.

5 Test or Analysis Article Description

The work performed through TEAMER involved manufacturing and drop/impact testing of four (instead of seven as originally planned) subscale TA prototype specimens in a controlled laboratory environment. Each specimen had a retrievable steel central shaft, also known as a booster, and a set of concrete or steel fins. Three of the four TAs were made from reinforced concrete, utilizing large format additively manufactured formwork (**Figure 5 a**) and cast concrete techniques (**Figure 5 c**) to cast robust and ultra-high performance reinforced concrete fins utilizing the capabilities of Sperra's state-of-the-art 3D printing facility at AltaSea in the Port of Los Angeles (**Figure 5 b**). The fourth specimen was fabricated and welded from steel plate and used as a reference to a full steel version (**Figure 8**, bottom left). Sandia Laboratories' Drop Tower Facility provided a vertical trolley guided system, allowing precise and repeatable impact conditions at various impact velocities. During experimental testing, each TA specimen was dropped multiple (at least 3 per specimen) times from different heights, with each a specified drop height corresponding to a desired impact velocity.

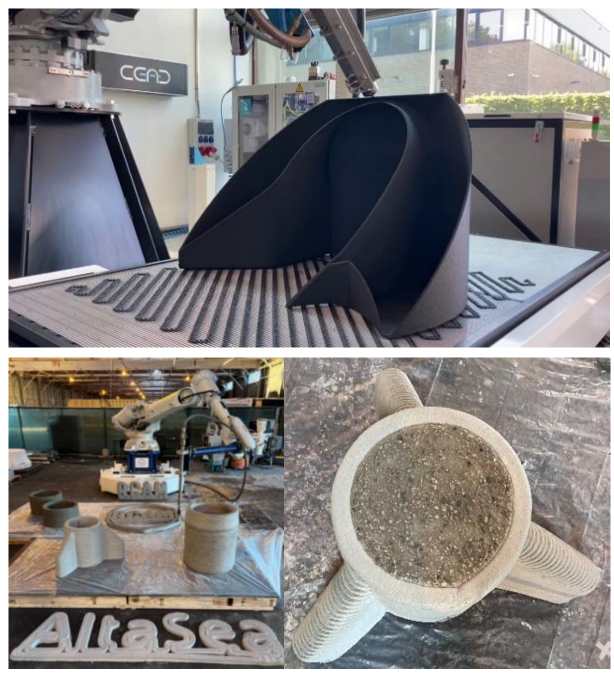

Figure 5. a) Large format plastic pellet extruder purchased by Sperra. Source: CEAD Group (*top*). **b)** Sperra's port-side R&D 3DCP facility located at AltaSea at the Port of LA (*bottom left*). **c)** 3D concrete printed TA proof-of-concept stay-in-place formwork TA printed at AltaSea *(bottom right).*

The dimensions of the test articles are approximately 1.65 m long by 0.85 m wide, with a mass ranging from 154-290 kg each. The dimensions and key parameters are labeled in (**Figure 6**) and the design matrix for each specimen is summarized in (**Table 3**). These dimensions have been selected to optimize the size of the TAs for 1-to-5-tonne load capacity, suitable for medium-sized wave energy converters and various other marine energy applications as determined by Sperra's market research. Additionally, a 3D printed instrumentation box was outfitted to the back end of the TA retrievable steel booster to accommodate the inclusion of 3 on-board triaxial accelerometers and data acquisition system for data collection during experimental testing. The test articles' finalized geometry, material properties, mechanical function, and other relevant technological characteristics were refined over several months prior to fabrication by Sperra, ensuring manufacturability and structural performance.

For the tests, four distinct TA specimens will be evaluated, each incorporating different innovative features. The term "innovative" in this context refers to design elements and manufacturing techniques that diverge from conventional steel TA designs, primarily in terms of fin geometry, thickness, attack angle, and the manufacturing process. The selection of these specific variations and the scale at which they are applied was informed by a two-fold approach. First, a comprehensive literature review was conducted as outlined by (**Table 1**), which provided insights into the current state and limitations of conventional TA designs. This review helped identify potential areas of innovation, particularly those that could benefit from additive manufacturing techniques. Second, a preliminary assessment of the manufacturability of TAs using additive manufacturing techniques was performed. This assessment not only evaluated the feasibility of producing these variations but also helped in determining the scale at which these changes could be effectively implemented. The metric for assessing the appropriateness of the range of variation focused on balancing manufacturability and potential performance enhancement. Each feature's variation was chosen not only for its theoretical contribution to the TA's performance but also for its practicality in fabrication. The combination of academic insights and practical manufacturability considerations ensured that the selected parameters for variation were not only innovative but also grounded in realistic engineering and production capabilities. The effectiveness of these variations was assessed through a series of performance metrics captured during

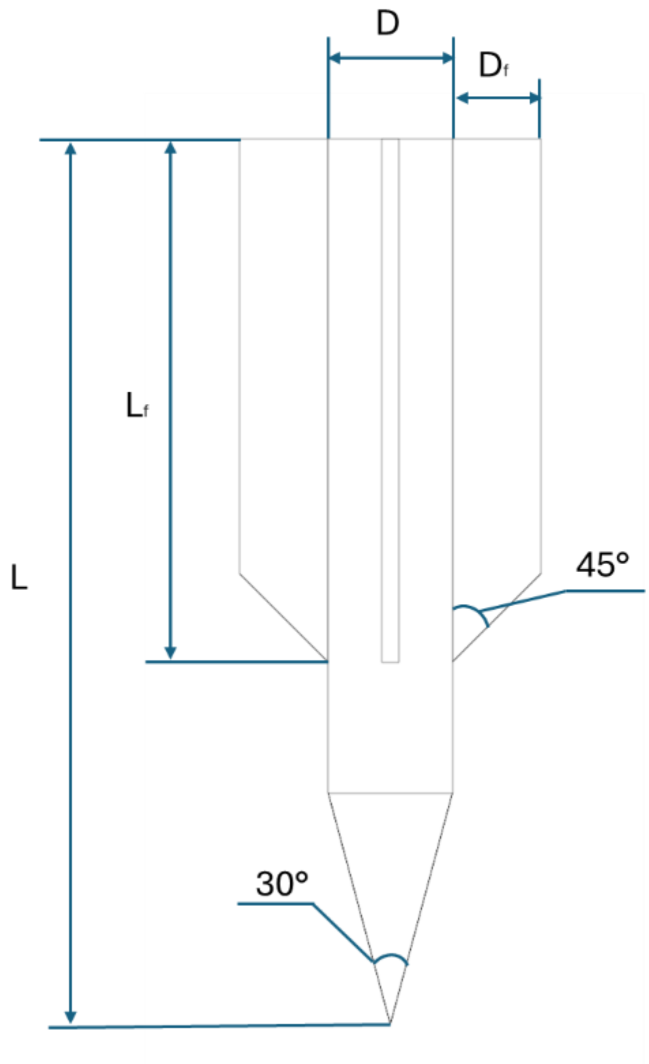

Figure 6. Key geometric parameter definitions of TA for use in **Table 3**. Fin attack angle = 45°.

experimental drop/impact testing. These metrics include, but are not limited to, embedment depth, structural integrity post-impact, and overall efficiency of the anchor (pullout force divided by static force). By comparing the performance outcomes of these varied designs, the project aimed to validate the choice of parameters and the scale of their variation, ensuring that they contribute meaningfully to the advancement of TA technology for marine energy applications.

Test Units: The test units consisted of two types of materials: steel and concrete. The three concrete anchors used on the tests were designed and fabricated with three different angles of impact seen in (**Figure 8**)**.** The single steel anchor was designed and fabricated with thinner fin blades in comparison to the concrete anchors making it easier to penetrate the sand. The three concrete fin attack angles were 45°, 52.5°, and 60°, and the steel fins were made with a fin attack angle of 45°. Both sets of anchors, concrete and steel were designed and fabricated to be used in conjunction with the steel booster to form the anchor assembly.

REDACTED

Figure 7. Photographs of each step for fabrication of test specimens performed by Sperra.

Concrete Anchors - 45° Angle

Concrete Anchors - 52.5° Angle

Concrete Anchors - 60° Angle

Steel Anchors 45° Angle

Booster & Slice Recorder

Anchor Assembly

Figure 8. Photographs of test specimens highlighting their configuration

6 Work Plan

6.1 Experimental Setup, Data Acquisition System, and Instrumentation

Sandia sourced and prepared the target soil pit, a steel culvert with a diameter of 3-m and a height of 3.81-m, filled with saturated sand. The sand's properties were carefully selected to closely resemble those at the PacWave South wave energy test facility near Newport, OR. Sediment classification studies by Goldfinger in 2014 and TerraSond in 2018 indicated that local sediments near PacWave South, predominantly medium-grained sand with an average size of 364 micrometers over 117 samples, are representative of the Oregon shelf. This includes some shell debris and a minor amount (less than 2%) of silt. To ensure the replicability and consistency of testing conditions, the state of the sand in the pit was characterized and managed carefully. The sand used for testing had a mean particle size of 508 microns, based on a sieve analysis conducted before the test campaign. Before the first impact test, the saturated sand was prepared to reach a uniform density with depth, with baseline measurements taken for reference. After each test, the sand was leveled and the cavity formed by prior impact test was filled with a rake. Core samples were taken before testing and after six drop tests to analyze density changes in the sand bed. Density measurements averaged 2.01 g/cm³ throughout the testing program, indicating generally consistent preparation of the soil pit across the test series and no measurable change in bulk density between drops in the upper layers of the pit where cores were taken. The sand was not remixed between each drop as initially planned, but was periodically monitored for particle movement and compaction effects. While acknowledging the importance of boundary conditions in experimental design, it is essential to recognize that the operational limits of the test facility and the size constraints of the soil pit introduced some variability in penetration depths between successive tests. However, consistent application of these limitations across all tests ensured that relative differences in TA design and test parameters remained valid for comparative analysis. The dimensions of the soil pit were chosen to provide a sufficiently large testing environment, to minimize boundary effects. This size was determined based on the expected behavior of the TAs upon impact and the need for a realistic simulation of field conditions. While the container cannot replicate the infinite expanse of a seabed, its dimensions were deemed adequate for the scope of the tests, primarily focusing on the initial impact and penetration behavior of the anchors. Achieving true similitude in subscale prototype testing of a complex, nonlinear, and pressure-dependent soil system is inherently challenging. Dimensionless parameters such as the Cauchy, Cavitation, Bond, Reynolds, and Froude numbers are commonly used to characterize dynamic systems like this but cannot all be simultaneously matched at reduced scale. Rather than attempting full similitude, the objective of this test program was to maintain consistency across all trials by using uniform soil preparation methods, anchor geometry, drop procedures, and instrumentation. This allowed for reliable comparison between specimens. While we acknowledge the limitations of subscale modeling in capturing the full complexity of soil-structure interaction, this internally consistent approach provides a robust basis for evaluating relative embedment behavior and informing future full-scale development. The drop testing was conducted utilizing the main cable trolley system at the 300-foot tower to suspend and release the TAs from multiple heights above the soil pit, providing precise control over impact velocity. Drop heights varied from REDACTED, corresponding to achieved impact velocities ranging from REDACTED, respectively. Impact angles and velocities were confirmed using high-speed video analysis.

Each TA specimen tested was equipped with three triaxial accelerometers in the aft of the retrievable booster, with one serving as a redundant data collection device. However, due to electrical connection failures and data recorder issues, acceleration data was lost in several tests (see **Section 7.2**). Based on testing experience with impact and penetration events, it was anticipated that likely there would be much higher "shock" peaks in the acceleration measurements. Therefore, the Endevco 2000g Piezoresistive accelerometers were selected, weighing 1.5 grams each and having a sensitivity of 100mV/g, to capture the impact shock, as well as the subsequent vibration immediately after impact. Data was recorded through a 7-gram on-board DTS Slice Nano data recorder. The recorder was hardened to shock and vibration.

Additionally, impact events were being recorded using three 4k high-speed video cameras, providing a third redundant data capture method. Data recording relied primarily on high-speed photometric analysis due to accelerometer data loss. These diagnostics captured key embedment performance variables including time-series impact deceleration and velocity, angular displacement, and embedment depth. Embedment depth was further verified post-drop by measuring the tip depth before retrieval using a tape measure. Following each drop, the retrievable steel booster was extracted vertically from the soil, and the pull-out force measured using a telehandler-mounted electronic load cell rather than the originally planned vertical trolley's built-in load cells. The booster recovery forces ranged from approximately 200 kg (equal to the booster's self-weight) to peak values over 581 kg, representing a 2.9x increase over its weight alone. The embedded concrete fins were then similarly extracted, and the pullout force was measured. The collected data is instrumental in understanding each TA specimen's embedment performance, booster retrieval demands, and ultimate vertical pullout capacity. These experiments de-risked the application of TAs in sandy soils for wave energy deployments and yielded insights for future design optimization and TA embedment model development. The sensors were calibrated by Sandia's primary standards lab. Sandia utilized its in-house data fusion and processing platform, identical to the setup used for weapon qualification experiments, to analyze sensors and photometric data.

Detailed testing, measurement and instrumentation requirements were developed through discussions between Sperra and Sandia after the test plan was approved by TEAMER, summarized below:

Test Requirements: The test requirements were to conduct a series of unguided, free-fall drop tests using a combination of steel fins, concrete fins, and a steel booster (solid steel cylinder). To meet the test requirements provided, the 300-foot drop tower main cable, and trolly were set up and configured on the main cable at a predetermined distance and height provided in (**Figure 9**). In addition to the main cable trolly configuration, a steel 3-m diameter by 3.81-m-tall culvert filled with plaster sand with the proper size range (~508 microns) up to a 3-m high saturated with standing water approximately 5-cm above the sand. The culvert containing the sand was located directly under the main cable trolley to raise and drop the TA and booster on to the center of the culvert from three different drop heights.

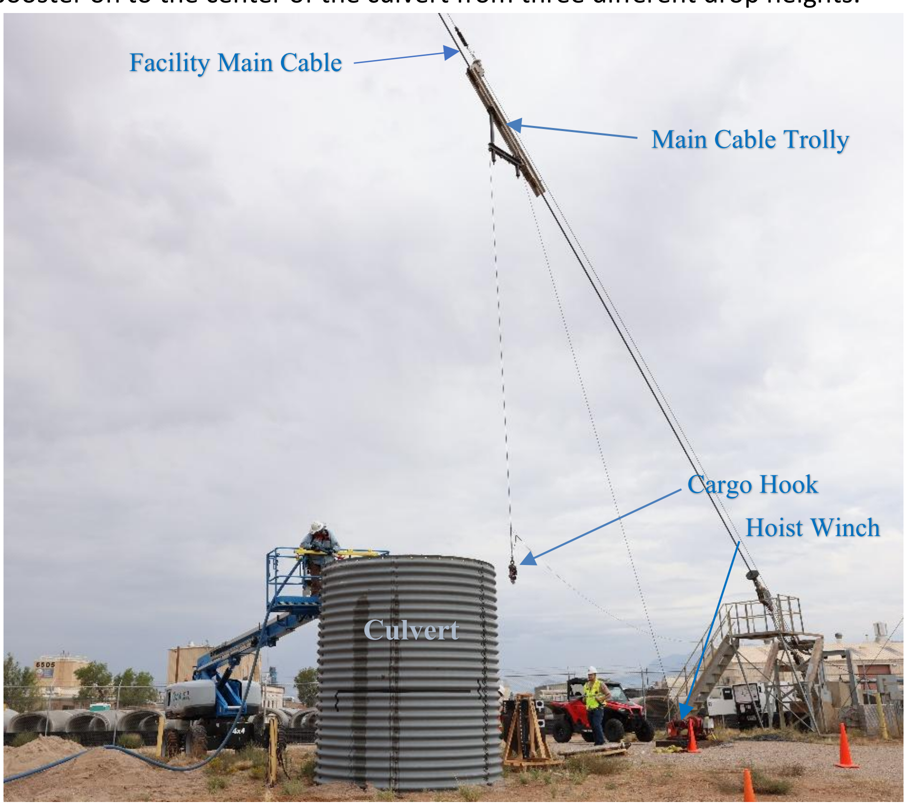

Figure 9. Main Cable and Trolly Configuration

After the fins and booster were set up on the TA stand, two adjustable Kevlar slings (4082 kg capacity) were attached to the top of the fins and looped through a remotely operated electric release hook which was attached to the hoisting winch cable. After the test hazard area was confirmed clear and safe, the anchors containing the booster were raised using the winch to predetermined drop heights as specified in (**Table 5**). After the height was confirmed, the electric release hook was activated, dropping the units into the center of the sand filled culvert. The drop heights, impact speed, and impact angle obtained during the impact are provided in (**Table 5**).

Instrumentation Requirements: Sandia's Department 1531 was responsible for the planning, installation, preparations, transducer selection, wiring, setup, checkouts, data recording, posttest data review, and quick views. To obtain the test data requested, a Nano Slice data recorder, 4 single-axis Endevco 2K accelerometers, two accelerometers aluminum block, interconnecting cables, terminal block, and a Lithium Polymer battery (11.1V, 2200mAh) were configured into a 16.83-cm long by 7.62-cm wide by 6.35-cm deep 3D printed box provided in (**Figure 10**). The 4-Endevco accelerometers were mounted onto an aluminum block in the X , Y, and Z axis to capture the impact information. A sampling frequency of 100kHz was employed to capture the acceleration data. The fourth accelerometer provides redundancy to the acceleration measurement in the direction of the impact (X). After the slice recorder, battery, and supporting devices were configured in the box, the box lid was attached and secured on to the box using 4-corner screws and electrical tape around the lid and box edges. After the lid was secured to the box, the instrumentation box was then attached to the top end of the booster using glass tape around the booster and box to assure the box and lid would survive the impact. (**Figure 10**) shows the location and configuration of the instrumentation box on the booster.

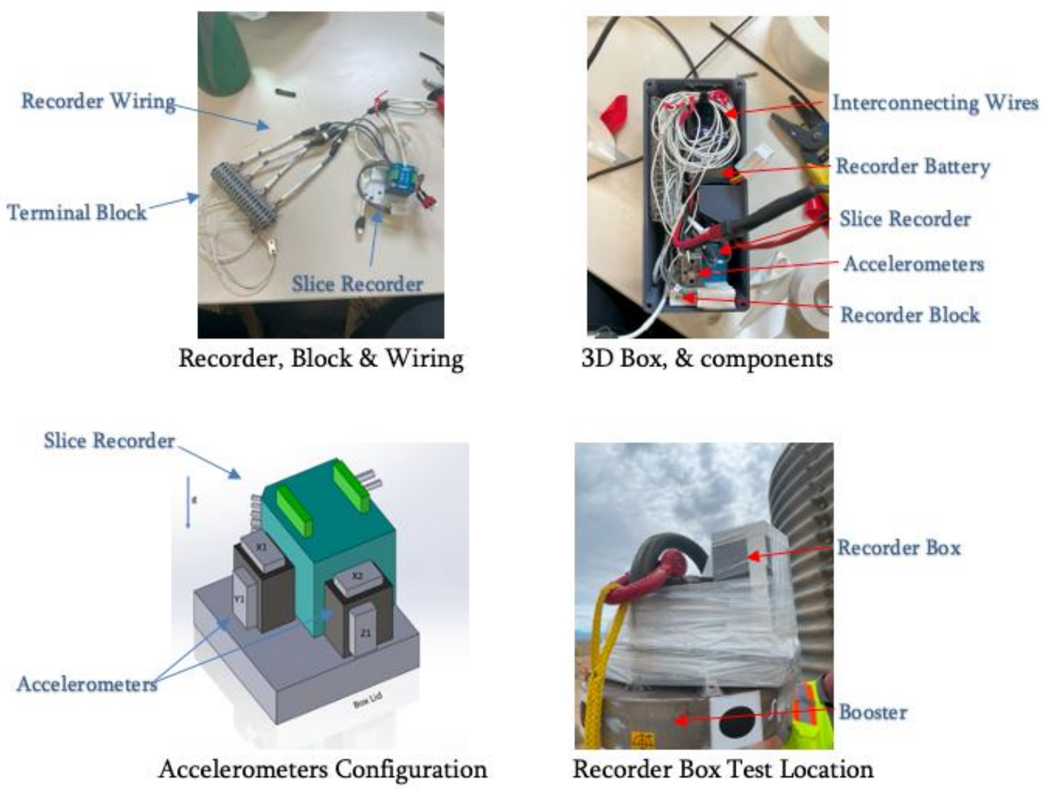

Figure 10. Instrumentation Data Recorder and Configuration Location

Photometrics Requirements: The photometric requirements for the Sperra TEAMER Torpedo Anchors were to prepare and set up a combination of high-speed video cameras and GoPro's at the 300-foot drop tower test complex to capture the anchor test unit's behavior and performance during the drop tests series. The test information such as impact speed, impact angle and penetration are of high importance to the customer. The information gathered from each of the tests will provide vital information needed to make decisions on future design, modification and/or improvements. The high-speed cameras used on the Sperra drop tests were set up and configured in orthogonal views approximately 90° apart and approximately 15.24-m (south camera) and 9.14-m (east camera) away from the culvert and impact area. In addition to the 3-high-speed video cameras, a set of GoPro cameras were set up and configured on the main cable trolley directly over the culvert and on the culvert top to obtain visual impact information on each of the tests. The anchors were arranged with numerous photo stickers and markers at areas of interest on the fins and other parts of the assembly for digital image correlations. Still photography was also taken from numerous directions and locations to document the pre-test setup and post-test results. The speed and resolution for the high-speed cameras used to obtain the test results are provided in (**Table 2**). The camera's layout and orientations for the tests conducted at the 300-foot drop complex are provided in (**Figure 11**). The video data obtained from the high-speed photometrics video cameras during the Sperra Anchor tests were impact speed and angle of impact. The video camera's coverage was taken from two different orientations arranged on orthogonal views.

Table 2: High Speed Video Measurements Resolution

Test	Camera	Impact Speed	Impact Angle
All (14)	East Camera Location	± 0.15 m/sec	± 1.0º
All (14)	South Camera location	± 0.15 m/sec	± 1.0º

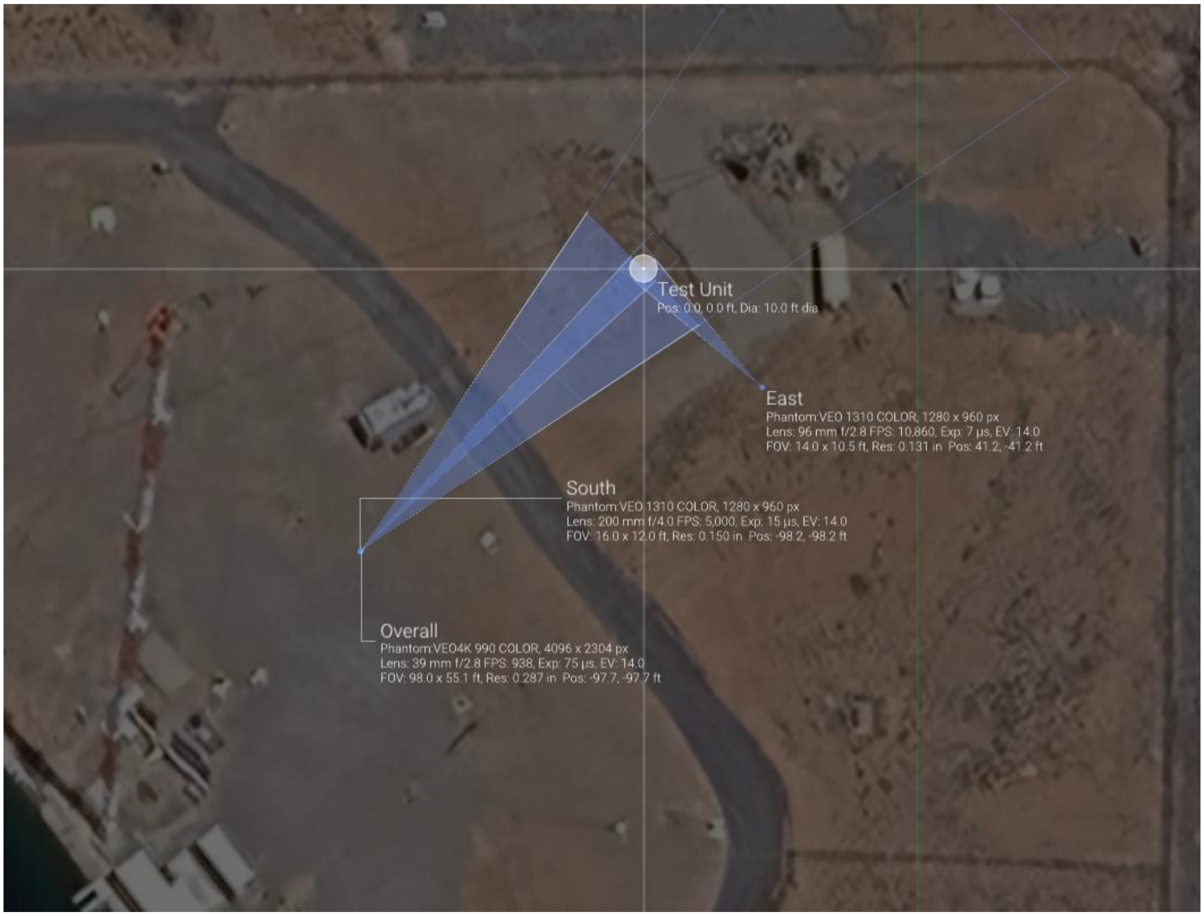

Figure 11. Photometrics Camera's Layout

6.2 Numerical Model Description

The specified drop height for each specimen was determined using a series of theoretical frameworks for conventional TAs used in oil and gas applications. While these frameworks were developed for undrained clays, the penetration process in sandy soils is expected to occur under high strain rates that will lead to undrained shearing conditions. The theoretical framework included an estimation of hydrodynamic terminal velocity and a predictive formula for penetration depth and corresponding anchor capacity developed for clayey soils by O'Loughlin et al. (2004), which was adapted for cohesionless sandy soils in consultation with geotechnical experts at the University of California, San Diego (**Figure 12**). In particular, the undrained shear strength profile with depth was estimated from the friction angle. While this approach provides a good estimate of the change in undrained shear strength with depth, the magnitude of the undrained shear strength does not consider possible changes in pore water pressure during shearing, so the magnitudes of undrained shear strength need further experimental validation. The model also considers the impact of shearing rate on the undrained shear strength and the impact of soil drag on the pile penetration, both of which need to be better studied in sands. The numerical predictions were compared against experimental results to assess the accuracy of penetration depth estimations and inform future design optimizations. As will be noted, the model generally overpredicted the penetration depth. However, the difference between the achieved and predicted penetration depth was within 0.5 m, which is reasonable and can be refined through future research. A detailed breakdown of the numerical calculations and penetration analysis of torpedo anchors, including model assumptions, input parameters, and performance estimations, is provided in (**Appendix A**).

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Figure 12. Specimen 1 inputs (*top left*) to Euler's solution to OLoughlin et al 2004 penetration depth estimation (*top right*) adapted for cohesionless loosely compacted sand geotechnical conditions shown as a graph (*bottom*) of penetration with respect to velocity of the TA. Using this model, each test specimen's impact velocity resulting in 2 m penetration was determined and included in (**Table 3**) and (**Table 5**).

6.3 Test and Analysis Matrix and Schedule

Approximately 21 tests were originally intended to be carried out with 7 different TA specimens, each subjected to varying impact speeds. The actual number of tests consisted of 4 different TA specimens each subjected to varying impact speeds for a total of 14 tests, included in (**Table 5**). Fabrication was limited to three concrete specimens and one steel reference specimen because the testing campaign required accommodating all seven would have exceeded the available time and resources. Reducing to three specimens allowed for multiple drops per anchor at varying heights, enabling a broader range of impact conditions and a more informative dataset for assessing embedment performance. The series commenced with an impact speed aimed at achieving an estimated penetration depth of 2 meters. Following the initial test, the impact speeds for each subsequent specimen were adjusted to achieve the ideal penetration depth for the next two tests. This adaptive approach allows for a more refined understanding of the relationship between impact velocity and penetration depth, essential for assessing the performance characteristics of the TAs under different conditions. The facility conducted approximately 3 tests per day, facilitating the completion of the entire test series within a one-week period. The anticipated matrix of design considerations for the seven TA specimens is comprehensively detailed in (**Table 3**). This matrix outlines the specific parameters and configurations for each test, ensuring a systematic and thorough examination of the TA designs and their impact behavior. Specimens 2, 3, 6, and 7 were excluded from testing due to budgetary constraints of the test facility. A steel reference was included as a control. Specimens 1, 4, and 5 were selected for experimental drop/impact testing.

Table 3. TA drop test specimen design matrix. Dimensions defined in (**Figure 6**)

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6.4 Safety

This project adhered to stringent safety procedures and protocols at every stage, ensuring the well-being of all personnel involved. No injuries or incidents occurred during any part of this project. Sperra, during the manufacturing and shipping of the TA specimens, operated a fully OSHA-compliant facility. This adherence to safety standards included comprehensive Injury, Illness, and Prevention Programs as mandated by California law. These programs encompassed various safety measures and protocols to mitigate workplace hazards and ensure the safety of all employees. In preparation for the testing phase at Sandia, all involved parties, including Sperra personnel, were required to familiarize themselves with critical safety documents pertinent to testing at the facility. These documents included the Safety Case, Primary Hazard Screening, Job Safety Analysis, and Operating Procedure. Sandia organized an online Q&A session, allowing Sperra and other participants to gain a thorough understanding of the safety requirements and procedures specific to the testing environment prior to testing. During the actual testing campaign, daily safety briefings were conducted with all personnel on site. These briefings reviewed potential hazards, risks, and appropriate mitigation procedures. They also covered the necessary Personal Protective Equipment required for that day’s activities. This daily review ensured that all team members are consistently aware and prepared for the specific safety considerations of each day's testing schedule. Furthermore, a detailed log file was maintained to record the activities conducted during each measurement day. This log served as a record of adherence to safety protocols and procedures, providing an audit trail for safety compliance.

The test units did not contain any hazardous materials except for the onboard Slice data recorder which required a single Lithium Polymer battery which didn’t contain hazardous toxic chemicals. During testing, the battery was placed inside a 3D printed box in conjunction with the slice recorder and accelerometers. The slice recorder’s Lithium Polymer battery typically lasted 2 to 3 hours which was long enough to conduct 3 tests consecutively without having to remove and open the box between tests.

6.5 Contingency Plans

To ensure the successful execution of the project despite potential risks, a comprehensive contingency plan was established. This plan outlined specific actions to be taken in response to various scenarios that could have impacted the test campaign:

- Poor Weather Conditions: In the event of inclement weather leading to postponement, Sandia will endeavor to reschedule the testing to future dates. Flexibility in the testing schedule and proactive communication with all parties involved will be key to managing delays effectively.
- Destruction of Specimens Upon First Impact Tests: To mitigate the risk of specimen destruction upon initial impact, Sperra will conduct detailed structural analyses of each design to ensure robustness against intended impact forces. Additionally, a thorough visual inspection of each specimen will be performed prior to each drop test to identify and address any potential structural weaknesses.
- Resetting Test Pit Between Tests: After each test, the sand will be leveled and the cavity formed by prior impact test will be filled with a rake. Before the first impact test, the saturated sand will be prepared to reach a uniform density with depth, with baseline measurements taken for reference. Core samples will be taken before testing and after multiple drop tests in the campaign to analyze and quantify any density changes in the soil pit.
- Photometric Camera System Calibration: The photometric camera system will undergo a thorough calibration and testing procedure prior to the start date of the project. This ensures accurate data collection and reliable performance throughout the testing campaign.
- Instrumentation Failure: In case of an identified failure or malfunction of any key instrumentation during testing, backup equipment will be readily available. This includes spare accelerometers, data recorders, and high-speed cameras. Quick replacement and recalibration procedures will be in place to minimize downtime. However, during testing, accelerometer malfunctions were not immediately detectable during testing, and data corruption was only identified after the fact during post-processing. As a result, some tests lack usable accelerometer data. In those instances,

redundant data collection provided via photometrics was used to extract velocity, angle, and acceleration values to ensure continuity in the dataset.

- Data Integrity Issues: Regular data backups will be performed to prevent loss of information. In case of data corruption or loss, redundant data collection systems, like secondary accelerometers and additional video footage, will be used to reconstruct or verify the lost data.
- Personnel Safety Concerns: In the event of a safety incident, immediate action will be taken according to Sandia's emergency response protocols. Regular safety training and drills will be conducted to ensure team preparedness.

6.6 Data Management, Processing, and Analysis

6.6.1 Data Management

The test data collected during each test was initially stored on the instrumentation control laptop. Post-testing, Sandia securely transferred and stored this data on a secured SharePoint site. This approach ensured both immediate accessibility for preliminary analysis and long-term secure storage. The data structure will be systematically organized to facilitate ease of access and analysis. Metadata accompanying each dataset includes details such as test date, specimen identifier, test conditions (like impact speed and soil conditions), and instrumentation specifics. This metadata is crucial for ensuring that the data can be accurately interpreted and utilized in future analyses.

Table 4. Outline of the data and format that have been submitted to the Marine and Hydrokinetic Data Repository (https://mhkdr.openei.org/submissions/605).

Data Type	Description	Format Submitted
Raw Unfiltered Time History	Initial data as captured during the tests, without any processing or filtering.	Comma-Separated Values
Filtered Time History	Data post-application of filters to remove noise or irrelevant frequencies.	Excel Sheets
Drop Height Calculations and Field Measurements	Analytical embedment formulas to calculate desired drop height of each test and corresponding field-collected data for actual depth of embedment.	Excel Sheet
Photometrics	High-speed and resolution video footage paired with velocity, acceleration, and angle variation.	MP4 Files

6.6.2 Data Processing

The data-processing methods for this project were comprehensive and systematic, ensuring accuracy of the data collected. Initially, all data from each test was saved in its raw format before undergoing any analysis, thus preserving the data's original state. Following each test, a quick review of this undisturbed data was conducted to identify necessary analysis processes and check for any anomalies or inconsistencies. Throughout the testing phase, a range of data processing techniques were applied as required. This includes evaluating raw, unfiltered time history data and employing filters to generate filtered time history plots shown in (**Appendix C**). Redundant data collection, quality assurance and control procedures were integral to the project. This started with verifying the entire recording system, including transducers and cables, through regular checks and calibrations of the instrumentation. The data acquisition system also underwent testing to confirm its reliability in accurately capturing and storing test data. The use of redundant data collection systems, like secondary accelerometers and photometrics, added another layer of quality control, allowing for cross-verification of data. Due to accelerometer data loss in multiple tests, primary data analysis relied more heavily on high-speed photometric tracking of impact angles, velocities, and penetration depths.

7 Project Outcomes

7.1 Results

The drop test requirements and results for all 14 tests are summarized in (**Table 5**), and included in detail in (**Appendix A**), providing a detailed comparison of impact velocities, penetration depths, and retrieval forces. The 45° fin angle consistently achieved the best penetration, reinforcing its suitability for future designs. Peak retrieval efficiencies on the order of 3 were achieved, even when anchors were not fully embedded, indicating strong holding capacity and opportunities for further optimization. The high-speed photometric data captured detailed impact velocities, penetration depths, and retrieval forces, providing a robust dataset for analysis. All MP4 files containing photometric recordings of each drop test are included in (**Appendix B**).

Table 5: Drop Test Requirements and Results from **(Appendix A)**

Test #	Test Date	Fin's Type	Drop * Height	Impact Speed Photo	Impact Angle (East/South)	Fins ** Penetration (Tape)	Booster Recovery Force	Fins Recovery Force
1	9/16/24	Steel	REDACTED	REDACTED	REDACTED	REDACTED	REDACTED	REDACTED
2	9/17/24	Steel	REDACTED	REDACTED	REDACTED	REDACTED	REDACTED	REDACTED
3	9/17/24	Steel	REDACTED	REDACTED	REDACTED	REDACTED	REDACTED	REDACTED
4	9/18/24	Concrete	REDACTED	REDACTED	REDACTED	REDACTED	REDACTED	REDACTED
5	9/18/24	Concrete	REDACTED	REDACTED	REDACTED	REDACTED	REDACTED	REDACTED
6	8/18/24	Concrete	REDACTED	REDACTED	REDACTED	REDACTED	REDACTED	REDACTED
7	9/19/24	Concrete	REDACTED	REDACTED	REDACTED	REDACTED	REDACTED	REDACTED
8	9/19/24	Concrete	REDACTED	REDACTED	REDACTED	REDACTED	REDACTED	REDACTED
9	9/19/24	Concrete	REDACTED	REDACTED	REDACTED	REDACTED	REDACTED	REDACTED
10	9/20/24	Steel	REDACTED	REDACTED	REDACTED	REDACTED	REDACTED	REDACTED
11	9/20/24	Steel	REDACTED	REDACTED	REDACTED	REDACTED	REDACTED	REDACTED
12	9/20/24	Concrete	REDACTED	REDACTED	REDACTED	REDACTED	REDACTED	REDACTED
13	9/20/24	Concrete	REDACTED	REDACTED	REDACTED	REDACTED	REDACTED	REDACTED
14	9/20/24	Concrete	REDACTED	REDACTED	REDACTED	REDACTED	REDACTED	REDACTED

* Anchor drop height measurements were taken with a Total Station. (manual mode)

** Anchor low and high sides penetration measurements were taken from the top of the anchor fin's edges to the top of the sand on both sides **(**L-Fins low side, H-Fins high side)

Sand Properties: The test bed for the impacts was composed of Plaster Sand for mixing in plaster products from JPR Gravel in Rio Rancho, New Mexico. A sample was obtained for particle size measurement prior to delivery. A sieve analysis showed that the sample has a mean size of 508 mm with a distribution shown in (**Figure 13**) when delivered and (**Figure 15**) once installed in the soil pit. Based on the information from the sieve analysis, the soil can be classified as a poorly graded sand (SP).

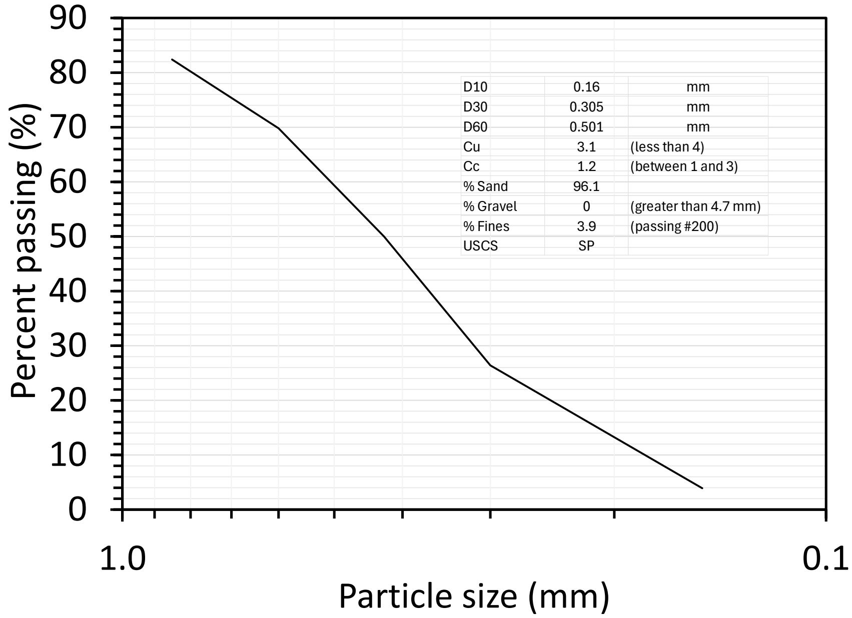

Figure 13. JPR Sand particle distribution for sample prior to delivery.

Figure 14. Picture of 10-15 cm depth sample after being dried in the oven.

Core samples were taken from the culvert at the beginning and after 6 drops to represent the as delivered and placed sand properties. The samples were taken while fully saturated with at least 2 inches of standing water on top. The samples were sliced into 5 cm sections and then weighed wet and dried for over 48 hours at 60 °C and then weighed dry. While a drying temperature of 105 °C is standard for geotechnical testing, a lower temperature was used due to limitations of the available field equipment. To compensate, samples were dried for an extended period to ensure complete removal of pore water. (**Figure 14**) shows a picture of a sliced sample in a weigh boat. The density of both cores averaged about 2.01 g/cm^3 with depth and are shown in (**Tables 6** and **7**). Two samples were then taken for sieve analysis to check for particle size of the as delivered/placed sand. One sample was near the surface (0-5 cm slice) and one at depth of 10-15 cm. They had a mean size of 485 and 498 µm respectively. While these samples represent only a small portion of the total pit depth (~4.1%), they were intended as quick spot-checks to confirm that the placed material matched expectations. Particular focus was given to the upper layers, where anchor impact occurred and where compaction effects would be most pronounced. The core samples did not reach soil in the area near the torpedo pile tip, so any densification in this region was not quantified. Any such densification may have led to an increase in soil shear strength with each test and a reduction in the depth of the penetration.

Table 6. Initial Density Measurement

Depth (cm)	Wet Mass (g)	Dry Mass (g)	Water Content	Density, ρ (g/cm^3)
0-5	455	370	0.189	**1.997**
5-10	455	375	0.178	**2.024**
10-15	310	255	0.180	**2.018**
15-20	255	210	0.180	**2.019**

Table 7. Density Measurements after 6 Drop Tests

Depth (cm)	Wet Mass (g)	Dry Mass (g)	Water Content	Density, ρ (g/cm^3)
0-5	575	465	0.193	**1.987**
5-10	470	385	0.183	**2.012**
10-15	390	320	0.182	**2.014**
15-20	340	280	0.179	**2.021**

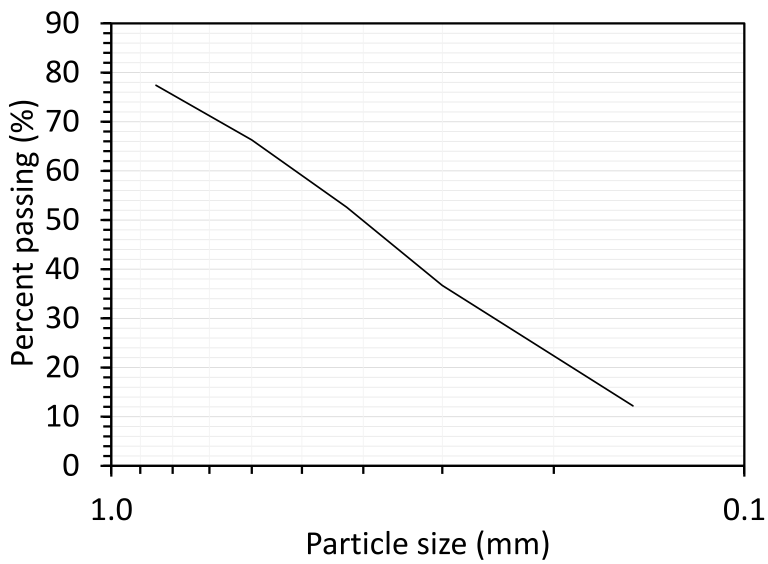

Figure 15. Sand as delivered size distribution at 10-15 cm depth

Instrumentation Results and Data: The Diversified Technical Solutions (DTS) Nano Slices were used as an onboard data acquisition method to record four Endevco-2k accelerometers data. These Endevco accelerometers were mounted on aluminum blocks inside a 3D printed box that was strapped to the aft end of the booster. The DTS Nanos were powered by an onboard Lithium Polymer battery rated at 11.1V, 2200mAh. For testing, the battery was connected, the test recording started, and the box sealed with glass tape and electrical tape. The time of the drop was recorded so that post-test the relevant section of data could be pulled from the 2–3 hours period. The first several tests were successful, however after repeated testing, the terminal block connections began failing due to the impact events and thin wires. In addition, the same data recorder/battery setup was used for multiple tests without continuity checks to avoid test delays. The long-term times with the high sample rate led to some failures in the downloads and loss of data. These issues led to loss of some test data. Ultimately, six tests consisting of 4-channels per test were successfully collected and reviewed.

The accelerometer data measured was that of the booster since that is where the instrumentation box was mounted on to. In the results, there is a small increase in acceleration over the period of about 1 second that is believed to be the cargo hook release event. Then there is an event on the order of 10-20g's in the X direction that is the first impact of the booster. Milliseconds later, there is a second event with high g's that is expected to be the ringing of the booster colliding with metal on metal with the anchor tube. The X-direction Accelerometers were mounted such that positive X was up. There were also "Y" and "Z" accelerometers which were relative to the position of the box and orientation of the booster. They, however, captured acceleration from any sort of tilt. (**Figure 10**) provides photos of the Slice recorder, components, configuration inside the 3D box, and box placement on the booster. The time history plots provided here are for preliminary "quick views" purposes and not for analysis. The raw data files obtained from the 6 recorded tests were provided to Sperra. The six test plots provided in (**Appendix C**) are from the first three tests conducted from three different drop heights using the steel anchor which had a 45° fin angle. The following three tests were also conducted from the same three different drop heights using the concrete anchor with a 45-degree fin angle but much thicker fins. The drop information related to the 6 tests such as drop height; impact speed and orientation are provided in (**Appendix C**)**.** Additionally, an example of photometric measurement results is shown in (**Figure 16**).

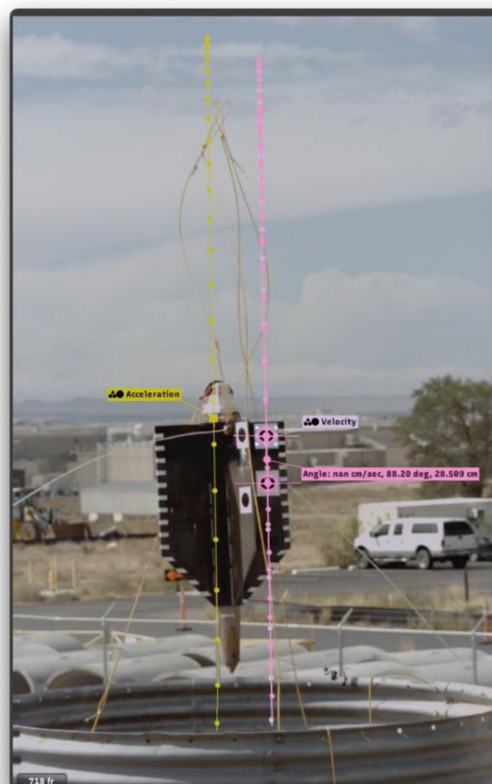

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Figure 16. An example of velocity, angle and acceleration values derived from photometrics data available for download in (**Appendix B**).

7.2 Lesson Learned and Test Plan Deviation

The project successfully validated key aspects of Sperra's TA design and provided experimental data on embedment behavior, retrieval forces, and anchor stability in cohesionless sandy soils. The project was considered as complex, compared to typical TEAMER projects at Sandia. It involved 15+ staff from multiple departments within Sandia (due to the multiple expertise required), a formal internal project review and acceptance process, and a rigor environmental and safety review. A significant amount of time was devoted to planning, procurement, designing the test measurement, instrumentation and execution, to ensure that the project objectives were met.

Several key lessons that will help improve the execution of future testing programs are shown below:

- The test plan provided a good detail of the planned testing, however, due to the complexity of the project there were still some uncertainties on the technical design and execution of the test specimen and testing, which ultimately affected the scope of the work that could have been done with the proposed funding amount. Resolving these details required significant efforts, which could not have been covered before the project budget was approved for usage, i.e. when TEAMER approved the revised test plan (end of March 2024). By mid- June 2024, the project team learned that the number of drop tests to be performed had to be reduced from 21 to around 14, to fit the project budget. As such, the number of drop tests and specimens was also adjusted, with the original plan calling for seven specimens and 21 drop tests. More tests could have been performed, but intermittent weather events also caused weather delays on one of the testing days for about 2 hours. This required modifications to the test matrix, prioritizing variations in fin attack angles while omitting some originally planned configurations such as variable fin thickness and a trial of stay-in-place 3D concrete printed formwork.
- The 185-foot drop tower was unavailable for the scheduled test dates, and the testing was moved to the 300-foot tower, requiring modifications to the drop setup. While this change did not fundamentally alter the test objectives, it did affect the configuration of the release mechanism and data collection setup. The 185-foot tower was scheduled to have an inspection around the selected TA testing dates, as there was a concern about the safe load limit on the main cable. To not delay the test, the project team agreed to move the test to the 300-foot tower. Earlier coordination with the facility would have allowed more time to adapt to this change and refine the test plan accordingly. However, it is understood that this is not always possible, due to the urgent nature of the inspection and that safety risk was involved.
- Accelerometer data was only obtained for 6 of the 14 performed drops due to electrical connection failures and data management limitations. The first several tests were successful; however, after repeated impact events, the spring-loaded terminal block connections began failing due to shock loading and the use of thin-gauge wiring. The original connection method was selected to allow rapid sensor interchangeability in the field, but this reduced mechanical robustness under repeated high-acceleration impacts. Following identification of the issue, the terminal connections were replaced with permanent wired connections to improve durability for the remainder of testing. In addition, during the final days of testing, the same data recorder and battery configuration was used for multiple drops without intermediate continuity verification in

order to avoid delays at the test facility. Because the accelerometer compartment (Figure 10) was designed as a sealed, battery-powered remote system in anticipation of full embedment in a saturated sand bed, incoming data were not monitored in real time. As a result, electrical failures were not identified until post-test download and inspection, and contingency measures relying on immediate fault detection were not activated during active testing. The remote, waterproof design required autonomous operation and continuous recording, which generated multi-hour, high-frequency datasets. The large file sizes required extended download times between test days, and in some instances led to software instability and corruption of select data files. While this configuration ensured environmental protection of the instrumentation, it limited real-time verification capability and increased operational risk. Future testing should incorporate live or buffered signal monitoring, strain-relieved and shock-hardened wiring, and trigger-based recording to significantly reduce unnecessary data volume. Consideration should also be given to cable-connected systems where feasible, allowing continuous power supply, real-time data streaming, and immediate verification of sensor integrity. Additional redundancy measures may include secondary accelerometer systems, independent power sources, and parallel data acquisition systems. Although some accelerometer time histories were lost, acceleration was also measured using the redundant high-speed photometric tracking system as developed by the Contingency Plan in Section 6.5. Photometric-derived kinematics provided velocity, impact angle, and acceleration estimates for all tests. As such, no critical impact performance data were lost for any drop, though the dataset is less robust than originally intended.

- The drop release mechanism also introduced unexpected variability in test results. The hook system used to release the torpedo anchors did not always disengage both ends simultaneously, leading to an initial misalignment in some drops. This misalignment propagated throughout free fall, affecting impact orientation (up to ~7 degrees from vertical) and increasing the surface area that contacted the soil, which in turn influenced embedment performance. A more precise, controlled release mechanism should be implemented in future tests to ensure uniform drop alignment and minimize variability in penetration results.
- There were also insights gained into sediment properties and potential compaction effects. Repeated dynamic penetration events in granular soils inherently induce shear, fabric disturbance, and volumetric strain. While bulk density measurements from core samples taken outside the central impact zone did not show measurable changes in average density during the test program, samples were not extracted from the center of the impact region. As such, localized increases in density within the most highly disturbed soil cannot be ruled out, and progressive densification of the sand layer after successive drops is considered likely. In addition, maintaining a constant water level above the soil surface while minor leakage occurred at the base of the tank likely generated a downward seepage gradient. This downward seepage force would have increased effective stress in the soil layer and may have contributed to increased penetration resistance over time. Future testing should incorporate targeted density sampling within impact zones where feasible, continued sieve analysis to monitor particle crushing, and monitoring of hydraulic boundary conditions to better characterize evolving soil state under repeated dynamic loading.
- Additionally, the test plan called for measuring retrieval forces using the built-in load cells at the tower, but instead, retrieval forces were measured using a telehandler-mounted electronic load

cell. This adjustment allowed for accurate force measurements despite the change in equipment. Despite each of these deviations, the test campaign successfully met its primary objectives, providing valuable data on embedment performance, retrieval forces, and TA stability in sandy soils. The findings will inform future anchor design optimizations, numerical model refinements, and field deployment strategies.

8 CONCLUSIONS AND RECOMMENDATIONS

The project successfully validated key aspects of Sperra's TA design by completing each of the project objectives:

1. Compare experimentally measured penetration depths to pre-test numerical estimates for TAs in cohesionless sandy soils.
2. Demonstrate TAs as a viable anchoring solution for marine energy deployments.
3. Assess the performance and validity of TAs installed in shallow water with sandy soil types.
4. Characterize the impact that individual TA features have on the overall embedment performance.
5. Evaluate the structural integrity of Sperra's TA manufacturing process.

The results confirmed that fin geometry significantly influences embedment depth, with the 45-degree fin angle achieving the best penetration. This reinforces the importance of optimizing fin design for future TA deployments. The retrievable steel booster system performed as expected, demonstrating the feasibility of reusing a central shaft to reduce material costs and environmental impact. One of the key conclusions from the test campaign was that the soil conditions were stiffer than anticipated, resulting in shallower penetration depths compared to numerical model predictions. This discrepancy necessitated a reduction factor in the penetration model to better align future predictions with observed performance. Moving forward, additional calibration of soil resistance parameters will be required to improve numerical modeling accuracy. This will be done both through the further development of the theoretical framework mentioned above, including refinement of the undrained shear strength profile of the sandy soil, the effects of penetration rate on the shear strength of the sandy soil, the soil-anchor interface characteristics, and the drag of the sand on the anchor. In addition, this study may use more advanced simulations like the discrete element method (DEM) coupled with computational fluid dynamics (CFD). The CFD-DEM approach may also permit consideration of the loss in energy associated with surface tension at the air-water interface. Another important finding was the impact of drop misalignment caused by the release mechanism. The observed deviations in impact orientation directly affected embedment performance, indicating that a more precise drop system is required to ensure uniform, repeatable results. Future tests should implement a mechanically stable release mechanism that guarantees even disengagement of the anchor. The test campaign also highlighted the need for improved instrumentation reliability. While high-speed photometric tracking provided useful penetration and velocity data, the loss of accelerometer data in several tests prevented an evaluation of the deceleration of the anchor during penetration when it was not visible to the cameras which underscores the importance of redundant measurement systems. Future experiments should include backup accelerometers, independent data loggers, and enhanced pre-test calibration procedures. Based on these findings, several recommendations for follow-on work have been identified. Future testing should expand parametric studies to assess the effects of different soil compositions, anchor masses and geometries, and drop velocities. Conducting field deployments in a real marine environment will be critical for understanding long-term performance under oceanic loading conditions. Additional drop tests could also be repeated under controlled conditions to validate drop accuracy and misalignment over multiple test sequences. Overall, this test campaign successfully provided the necessary experimental validation to advance the development of cost-effective, scalable anchoring solutions for marine renewable energy applications. The data collected will directly inform next-generation TA designs, numerical model refinements, and field deployment strategies, ensuring continued progress in offshore anchoring technology.

An article about the project was written and published on Sandia's LabNews (**Figure 17**). In addition, a journal manuscript that highlights the outcome of a WPTO Phase I SBIR and this TEAMER RFTS 9 project is currently being prepared: REDACTED To be submitted to: REDACTED

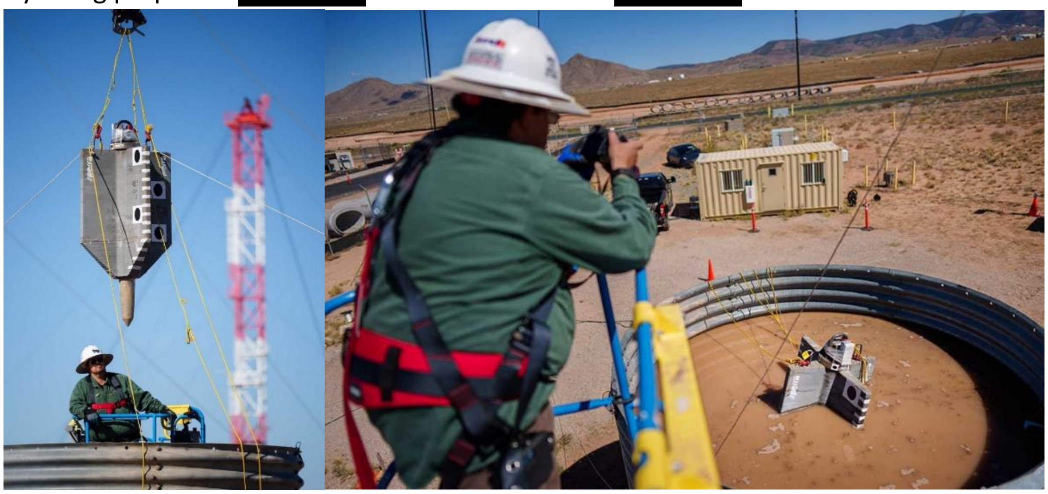

Figure 17. Photographs from an article written by Sandia LabNews about this TEAMER project. (https://www.sandia.gov/labnews/2024/10/17/the-big-drop/) Photography Credits: Craig Fritz

9 REFERENCES

References have been included throughout the document following each citation to ensure proper attribution and traceability of sourced information.

10 ACKNOWLEDGEMENTS

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11 APPENDICES

APPENDIX A: NUMERICAL PENETRATION ANALYSIS AND DROP TEST RESULTS OF TORPEDO ANCHORS

Includes a detailed breakdown of the numerical calculations and penetration analysis used to estimate the embedment performance of torpedo anchors in cohesionless sandy soils. Additionally, this appendix contains the full results from the drop tests, including measured penetration depths, impact velocities, and retrieval forces, allowing for direct comparison between numerical predictions and experimental outcomes.

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APPENDIX B: PHOTOMETRICS MP4 TEST DATA FILES

REDACTED	REDACTED	REDACTED	REDACTED	REDACTED	REDACTED
REDACTED	REDACTED	REDACTED	REDACTED	REDACTED	REDACTED
		REDACTED	REDACTED		

APPENDIX C: ON-BOARD INSTRUMENTATION DATA. QUICK VIEW TIME HISTORY PLOTS.

Test 1 – Steel Fins 45° (REDACTED) Full Data: REDACTED

REDACTED

Test 2 – Steel Fins 45° (REDACTED) Full Data: REDACTED

REDACTED

Test 3 – Steel Fins 45° (REDACTED) Full Data: REDACTED

REDACTED

Test 4 – Concrete Fins 45° (REDACTED) Full Data: REDACTED

REDACTED

Test 5 – Concrete Fins 45° (REDACTED) Full Data: REDACTED

REDACTED

Test 6 – Concrete Fins 45° (REDACTED) Full Data: REDACTED

REDACTED