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Innovative Suction Anchor System (SAFL) with Extendable Fastening Legs: Design, Prototype Development, and Initial Field Testing in Soft Seabed Environments

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ABSTRACT: The article introduces the innovative seabed anchor system SAFL (Suction Anchor with extendable Fastening Legs) and presents the results of the research team's initial tests. Traditional seabed anchors often struggle to maintain stability in soft seabed environments, limiting their effectiveness in various marine applications. This breakthrough system is specifically designed for anchoring objects in such conditions. The project aims to develop an anchor that, once embedded in the seabed, deploys lateral, extendable legs to significantly enhance its holding capacity. The research team successfully developed a SAFL anchor prototype and conducted preliminary field tests. The initial results not only demonstrate the effectiveness of the SAFL system but also lay the groundwork for significant advancements in marine engineering and offshore construction, enabling more reliable and efficient anchoring solutions for a wide range of marine applications.

1 INTRODUCTION

Seabed anchors, also known as ground anchors, are essential tools for securing various underwater structures, such as buoys, piers, and floating vessels (including ships, boats, sailboats, and motorboats). They are particularly important for large floating units that require stability and cannot be freely moved by water currents or wind. To address these challenges, the SAFL (Suction Anchor with extendable Fastening Legs) seabed anchor system has been developed. These anchors were deployed in Lake Raduńskie as a replacement for previously used concrete-filled buckets—colloquially referred to as 'pigs'—which failed to perform effectively, resulting in the drifting of attached buoys and the moored surface vessels.

2 ANCHORS AND SEABED ANCHORS

Bottom anchors and seabed anchors are typically made of metal and consist of several fundamental components, including the main body, arms, claws or blades that embed into the seabed, and a shackle or eye for attaching the anchor line or chain. When an anchor is lowered to the bottom, its claws or blades penetrate the substrate due to the vessel's weight and the tension in the line or chain. As the vessel moves, the increasing tension causes the anchor to embed more deeply into the seabed, resulting in a more secure hold. Anchors and seabed anchors are crucial for ensuring the safety of vessels during stationary periods on open water, providing stability and preventing uncontrolled drifting caused by wind, waves, or currents.

Examples of typical anchoring solutions using various types of bottom anchors for offshore structures are presented in Figure 1 and Figure 2. Anchoring systems used in offshore structures are generally categorized into gravity anchors and embedded anchors. Figure 1 illustrates embedded anchors, including the SAFL system (a hybrid of a traditional suction caisson and a helical anchor) designed for use in anchoring navigational markers (e.g., fairways) and securing mooring buoys for small boats, sailboats, kayaks, and other surface vessels.

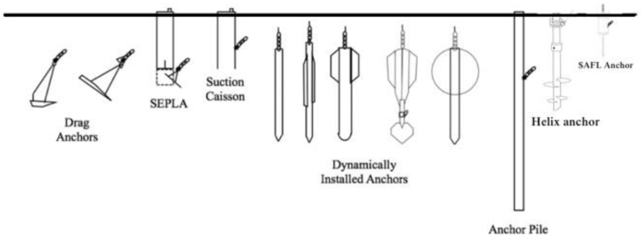

Figure 1. Embedded anchors. Source: own study based on [1, 12, 13, 14].

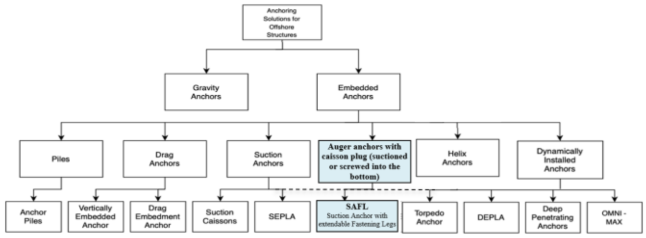

Figure 2. Anchoring solutions for Offshore Structures. Source: own study based on [1].

Gravity anchors (see Figure 2 and Figure 3) – This type of anchor relies on its own weight to secure a floating structure to the seabed. Typically made of heavy materials such as steel, concrete, or cast iron, gravity anchors achieve significant mass, enabling them to provide reliable holding capacity. They are primarily used in applications where a permanent and secure anchorage is required—such as for large marine structures including oil rigs, navigation buoys, or vessels stationed in a fixed location for extended periods. Gravity anchors are also employed in areas with hard seabed, where other types of anchors may struggle to penetrate or where a retrievable anchoring solution is preferred to minimize seabed disturbance [2,3].

Figure 3. From left: Gravity Anchor, Deadweight Anchor, DEPLA Anchor, OMNI MAX Anchor. Source: Own study based on [2, 3, 9, 10, 11].

Suction caissons (see Figure 1) – Also known as suction anchors or suction pile anchors, these are a modern type of anchor widely used in the maritime industry, particularly for securing large offshore structures such as oil rigs, wind turbines, and other heavy marine installations. They operate on the principle of negative pressure, which is generated within the anchor to pull it deeply into the seabed, ensuring a highly secure hold. A suction caisson consists of a large cylindrical body with an open bottom that is placed on the seabed. The caisson is typically made of durable material—usually steel—and features a wide base to maximize contact with the seabed [4].

SEPLA-Type Anchors (Suction Embedded Plate Anchor) (see Figure 1 and Figure 2) – This type of anchor combines two anchoring technologies: suction caissons and plate anchors. It is an advanced system used in the offshore industry, particularly in deepwater environments. A SEPLA anchor consists of two main components: a plate anchor and a suction chamber. The plate anchor is a large, flat element that embeds itself into the seabed, while the suction chamber—typically cylindrical in shape—is mounted above it. Negative pressure is applied to draw the entire structure deeper into the seabed until the plate reaches the desired embedment depth. SEPLA anchors integrate the advantages of both plate and suction technologies, making them one of the most effective anchoring solutions for heavy offshore structures. Owing to their strength and adaptability to various seabed conditions, SEPLA anchors are a preferred choice for many deepwater applications [5].

Drag Anchors (see Figure 1 and Figure 2) – Drag anchors are among the most commonly used types of anchors, particularly in marine environments. Their design and operating principle make them highly effective for securing floating structures such as ships, oil rigs, and offshore installations. A drag anchor typically consists of one or two arms (called flukes) and a shank. The flukes may be fixed or pivoting, allowing for improved penetration into the seabed. At the end of the anchor is a stock, which serves as the attachment point for the anchor line or chain. Drag anchors operate by moving along the seabed, during which the flukes dig into the substrate, gradually burying deeper and generating increasing resistance, eventually bringing the vessel or structure to a stop. This type of anchor performs best in soft seabed conditions, such as sand, silt, or clay [6].

Anchor Piles (see Figure 1) – Anchor piles are used to secure large structures such as oil platforms and subsea installations. They are embedded into the seabed by driving or pressing them in using specialized equipment. Due to their mass and anchorage depth, they generate strong resistance through friction with the seabed. An anchor pile is connected to a floating structure or offshore installation via robust cables or chains, which are attached to its upper section [7].

Torpedo Anchors (see Figure 1 – dynamically installed anchors) – Torpedo anchors are classified as dynamically installed anchors and are primarily used in deep-water applications. Featuring a torpedo-like, streamlined shape, they accelerate when dropped into the water and penetrate the seabed upon impact, embedding themselves without the need for additional mechanical assistance. A key consideration in selecting this type of anchor is conducting a seabed survey, as torpedo anchors are most effective when deployed on soft substrates [8].

Deadweight Anchor (see Figure 3) – Also classified as dynamically installed anchors, deadweight anchors are primarily used for the permanent anchorage of offshore structures such as navigation buoys, docks, oil platforms, and other installations requiring a stable, immovable position. These anchors typically feature a simple design and are made from heavy materials such as concrete, steel, or reinforced concrete. Their shape can vary, typically resembling a cube, cylinder, or other basic forms, with mass being the key factor in ensuring stability [9]. DEPLA Anchors (Dynamically Embedded Plate Anchor) (see Figure 3) – Developed in Western Australia, DEPLA is a hybrid anchor that combines the features of plate anchors and dynamically installed anchors. It does not require additional machinery for installation and is highly resistant to vertically directed forces. DEPLA anchors are typically deployed at depths greater than 500 meters, reaching speeds of approximately 25 m/s upon deployment, which allows them to embed into the seabed to a depth up to three times their own length. Due to its design, DEPLA can withstand very high loads, making it an ideal solution for large and heavy offshore structures. The plate anchor component ensures exceptional stability, which is crucial in variable and harsh marine conditions. It is suitable for a wide range of seabed types, from sand to clay [10].

OMNI MAX Seabed Anchors (see Figure 3) – OMNI MAX anchors belong to the category of gravity-installed anchors and are considered among the most efficient anchor types available today. They combine the characteristics of dynamically installed anchors and suction caissons, with the key difference being their ability to withstand significant forces not only in the vertical direction but also from any angle around their axis. This feature provides a major advantage, particularly in terms of durability and stability under storm conditions, making them highly effective for securing offshore structures in challenging marine environments [11].

Helix Anchors (see Figure 1 and Figure 2) – A helix anchor (also known as an auger or screw anchor) consists of a steel, screw-like shaft with integrated welded bearing plates, which is installed directly into the seafloor. These anchors are suitable for a wide range of substrate types [12]; however, both the installation procedures and design configurations are adapted to the specific characteristics of the underlying material. Helical anchors are generally unsuitable for harbor areas characterized by highly mobile sediments, where prolonged exposure may result in the anchor becoming uncovered over time. Helix anchors are widely regarded as one of the most environmentally sustainable types of seabed anchors due to their minimal spatial footprint and negligible interference with marine fauna [12]. They are significantly smaller and lighter than alternative anchoring systems, offering additional operational advantages. Furthermore, according to engineering calculations, a helix anchor drilled four meters into a sandy substrate can withstand a torque of 20 to 50 tons, depending on the sediment properties [13, 14].

3 SAFL ANCHOR SYSTEM DESIGN

In 2024, the Student Special Interest Group of Underwater Research 'SeaQuest,' operating under the Department of Navigation at the Maritime University of Gdynia, received funding from the Ministry of Science and Higher Education for the project titled 'Innovative Anchoring System with Side-Deployable Clamping Arms SAFL.' The project, assigned the number SKN/SP/602624/2024, is being carried out as part of the 'Student Circles Create Innovations' program, based on an agreement dated May 14, 2024. The project leader is Capt. Grzegorz Rutkowski, who is also the supervisor of the Student Special Interest Group 'SeaQuest.'

4 SAFL CONCEPT

During a CMAS P3 diving course held in 2023 at Lake Raduńskie, near the Stella Maris Resort in the village of Sznurki in the Kashubia region, members of the Student Special Interest Group of Underwater Research 'SeaQuest' encountered a significant issue with the mooring of small vessels. The prevailing method involved the use of so-called 'pigs' (see Fig. 4, right) – gravity-based anchors consisting of large plastic buckets filled with concrete and placed on the lakebed. However, these improvised anchors proved ineffective in securing watercraft, as kayaks and other small vessels frequently drifted away due to wind and water currents. This instability not only caused inconvenience for vessel operators, who had to repeatedly reposition their boats, but also highlighted the broader inefficiency of existing mooring solutions. Recognizing the need for a more reliable anchoring system, the research team was inspired to develop an innovative bottom anchor design aimed at enhancing stability and effectiveness in inland water mooring applications.

After conducting market research on available bottom anchors, it was found that there was a lack of suitable solutions for anchoring and/or mooring small surface vessels in both inland and marine waters. At that point, our supervisor, Capt. Grzegorz Rutkowski, proposed the development of innovative bottom anchors (suction-ejector type) with side-deployable clamping arms. These arms would increase the anchor's holding power, enabling stable positioning of small surface vessels and secure mooring to buoys.

The aim of the project was to develop and validate the functionality of an innovative suction-ejector seabed anchor, named SAFL (Suction Anchor with extendable Fastening Legs). Once positioned in the seabed substrate, where it is screwed in, driven, embedded, or optionally covered with stones, gravel, or sand, the SAFL anchor utilizes a hydro-ejector system. This design allows for more effective mooring of small surface vessels (such as boats, yachts, pedal boats, etc.), floating navigational markers (e.g., in the IALA buoyage system), as well as other surface and/or underwater objects and ocean engineering devices, including hydrometeorological measuring equipment, fishing nets, and chemical barriers (e.g., oil spill containment booms), keeping them securely anchored in a stable position.

This led to the creation of a project under the same name, assigned the number SKN/SP/602624/2024, as part of the 'Student Circles Create Innovations' program. The program outlined the following objectives for its implementation: (1) Conducting development work aimed at creating an innovative product. (2) Facilitating the transfer of the product to the business sector and the socio-economic environment. (3) Promoting the scientific development of the circle members. (4) Acquiring basic diving training skills necessary for testing the innovative product in real-world conditions and for further research activities. (5) Enhancing the quality of research conducted by the scientific circle and presenting the research results.

The project implementation period was set for 12 months, with the completion date scheduled for May 14, 2025. During this time, our group was tasked with preparing the necessary technical documentation for the SAFL devices, creating several prototypes of the SAFL bottom anchors, and conducting water-based strength tests on them.

5 PROTOTYPE DEVELOPMENT

After completing the basic diving training (P3 CMAS), which our students underwent between May and June 2024, members of the Student Special Interest Group of Underwater Research ‘SeaQuest’ produced the first 10 prototypes of the SAFL bottom anchors (see Fig. 4) and deployed them in the bed of Lake Raduńskie. These anchors were tested throughout the summer, from May to September 2024, successfully securing various surface vessels (an Omega-class sailboat, a pedal boat, a kayak, and a rowboat) under different hydrometeorological conditions (strong currents, storms, squalls, and rain). This phase of the project is now complete, and the use of SAFL bottom anchors has yielded very promising results. All the anchors proved to be highly stable and resistant to the hydrometeorological disturbances present in the tested water body.

Figure 4. On the left, the first prototypes of SAFL bottom anchors anchored in the bottom of Lake Raduńskie in May 2024, used for mooring small watercraft at the Stella Maris center in Kashubia. On the right side is the old gravity anchor known as ‘pig’ (plastic bucket filled with concrete). Source: Internal materials of NKBP ‘SeaQuest’ – May 2024.

6 NEXT PROJECTS AND PROTOTYPES OF DEVICES

The main goal of the SAFL project is to create an innovative product with a wide range of applications in water transportation. The desired outcome is the effective mooring of small surface vessels (such as boats, yachts, pedal boats, kayaks, etc.), floating navigational markers (such as buoys in the IALA buoyage system), and other surface and/or underwater hydrotechnical objects (such as floats, nets, and measuring devices) in a stable position relative to the seabed.

The SAFL bottom anchor was initially envisioned as a screw-in type anchor, installed by screwing it into the seabed using suction-ejector devices operated with the assistance of divers. Once installed, it would be embedded in the bottom of the water body (whether sandy or muddy) or optionally covered with dredged material (such as sand or gravel). This design aims to keep the object in a stable anchoring position relative to the seabed, even when subjected to various external disturbances, particularly those caused by wind, water currents, and waves. The hose exiting the pump on the boat is connected to the SAFL anchor.

With the help of a diver, who positions the anchor on the seabed while the pump is running and sucking sand into the main body of the anchor, its interior is filled. The design of the screw, featuring spirally welded, sharp elements on the shaft (optionally, an auger fixed to the bottom of the anchor), allows the anchor to rotate around its own axis, causing the SAFL anchor to embed itself into the seabed. Once the screwing process is complete, the diver attaches a line to secure the buoy to the anchor. The main body of the anchor is filled with sand, preventing lateral movement due to water currents and waves. Meanwhile, the protruding parts of the anchor, shaped in a streamlined manner, are sealed (for example, with a valve or a wooden plug) to prevent upward movement, thus ensuring that the anchor does not escape from the seabed. In the sealed anchor, a vacuum is created, keeping the anchor securely embedded in the seabed. Projects of various SAFL bottom anchors are shown in Figure 5.

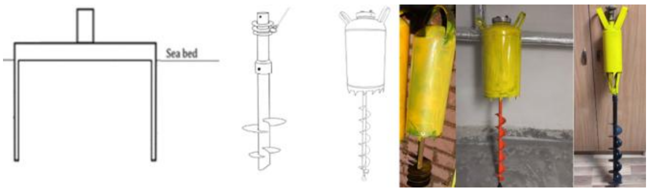

Figure 5. From left: ‘Umbrella 1’ SAFL, ‘Umbrella 2’ SAFL, SAFL Flange Anchor. Source: Internal Materials of the Student Special Interest Group of Underwater Research ‘SeaQuest’.

The process of securing the ‘Umbrella 1’ SAFL anchor requires a pump and a hose connected to the anchor. Once placed on the seabed, the anchor, with the assistance of a diver, sucks sand into its main body. Dredged material (silt and sand) begins to flow into the paddles of the propeller, weighing down the side claws, which then start to open outward, increasing the anchor's effective holding power in the seabed. As the anchor’s weight increases due to the accumulation of dredged material (silt and sand), the paddles and/or side claws become more deeply embedded in the seabed. A chain or, optionally, a line for securing mooring buoys to small vessels is attached to the securely positioned SAFL anchor. In this setup, the paddles of the anchor help prevent horizontal movement. Additionally, the ‘V’-shaped design of the paddles and their embedding in the seabed are intended to enhance the anchor's holding power and protect it from pulling forces.

The ‘Umbrella 2’ SAFL anchor features mechanically deployed claws activated by a screw system. This design ensures the secure anchoring of various objects, particularly in soft and unstable substrates. Its construction draws inspiration from the natural anchoring mechanisms of certain plants, which spread their roots to maintain stability in the substrate while withstanding various external disturbances. A key advantage of the SAFL ‘Umbrella 2’ anchor is its reusability. The screw mechanism allows for multiple deployments and recoveries, making it highly effective for repeated use. The anchoring and disanchoring processes are relatively simple, and its versatility opens up broad applications in fields such as hydraulic engineering, sailing, diving, and research activities. This anchor is likely to exhibit a high level of safety and reliability, effectively withstanding external disturbances caused by currents, wind, and waves.

The next prototype of the SAFL anchor incorporates a flange located on the main shaft, near its stem. This flange serves as a resistance element, significantly enhancing the anchor's adhesion to the substrate (the bottom of the water body). The anchoring process is facilitated by a suction or fire-fighting pump connected via a hose to the anchor, allowing for the suction of bottom sediment (mud and sand) to fill the area around the anchor and its side claws, as well as the resistance flange. This ensures the substrate enters the flange's interior.

The external parts of the flange extend in all four directions. When filled with sand, the flange prevents vertical movement, effectively stopping the anchor from being pulled upward from the seabed. A key advantage of the SAFL Flange anchor is its high resistance to forces attempting to dislodge it from the substrate. The anchoring setup concludes with a chain or line connecting the SAFL Flange anchor to a floating mooring buoy. This design offers robust resistance against dislodgement, thanks to the shape of the resistance flange, which also reduces the anchor's susceptibility to rotation under heavy loads.

7 FINAL PROJECT AND PROTOTYPE

During the course of the project, prototypes of the 'Umbrella 1,' 'Umbrella 2,' and 'SAFL Flange Anchor' were constructed with modified designs, primarily by extending their length to facilitate installation. These prototypes are shown in Figure 6. However, empirical testing revealed significant inefficiencies, particularly related to installation difficulties, such as considerable resistance during installation, which made them less practical for field applications.

During the testing, the research team also assessed the holding capacity of the prototype 'SAFL Screw-In Anchor'. This anchor, featuring a design similar to that of a helix anchor, proved to be easy to install. It consists of a hollow tube and an interchangeable auger, allowing for the testing of multiple variants with different auger diameters. Augers with larger diameters were relatively difficult to screw into the ground, as they tended to displace and churn up the surrounding soil rather than penetrate it efficiently. In contrast, anchors equipped with smaller-diameter augers demonstrated holding capacities of several hundred kilograms.

Consequently, due to the installation difficulties encountered with the 'Umbrella 1', 'Umbrella 2', and 'SAFL Flange Anchor', further development shifted towards the anchor depicted in Figure 6, labelled as 'f'. This anchor effectively combines the beneficial attributes of suction caisson anchors and helix anchors (see Fig. 7) and was proven to be highly effective during the first test conducted in Lake Raduńskie in May 2024.

Figure 6. Prototypes of SAFL bottom anchors; a – prototype of 'Umbrella 1' anchor, b – prototype of 'Umbrella 2' anchor, c – initial prototype of 'SAFL Screw-In Anchor', d and e – prototypes of 'SAFL Flange Anchor', f – prototype of 'SAFL Screw-In Suction Anchor'. Source: Internal materials of Student Special Interest Group of Underwater Research 'SeaQuest' - January 2025.

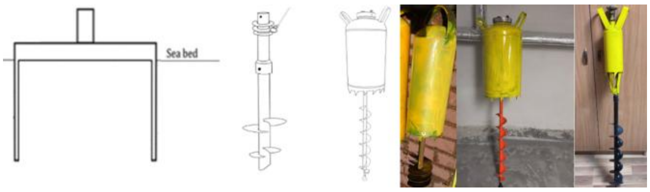

Figure 7. From left: Suction Caisson, Helix Anchor, SAFL Screw-In Suction Anchor prototypes. Source: Own study based on [4, 12, 13, 14], internal materials of Student Special Interest Group of Underwater Research SeaQuest.

The new anchor design effectively combines the advantages of suction caisson and helix anchors by integrating a suction-assisted installation method with a helical embedding mechanism. This approach ensures rapid and precise placement, akin to helix anchors, while providing high holding capacity and resistance to both vertical and lateral forces—characteristics typically associated with suction caissons. The suction feature facilitates smooth penetration into the seabed without excessive force, allowing for accurate positioning. Meanwhile, the helical component firmly anchors into the substrate, enhancing stability and resistance to external disturbances such as currents, waves, and wind-driven loads. The research team continues to refine the project to optimize the anchor's performance and aims for the final prototype to be eligible for patent protection.

8 CONCLUSION AND FUTURE WORK

The first SAFL anchor prototypes showed promising results during initial tests conducted in 2024, which directly led to the development of new, refined models and the ongoing enhancement of the original project concept. These positive outcomes continue to inspire our research team, fuelling further innovation and optimization. Currently, we are conducting tests to evaluate the holding capacity and reliability of the latest anchor designs, with the goal of completing this phase by May 2025. Detailed test results and analyses will be published in future studies. Ultimately, our goal is to secure patent protection for our innovative anchoring solution, laying a strong foundation for its practical applications in maritime and offshore engineering.

ACKNOWLEDGEMENTS

The Student Special Interest Group of Underwater Research 'SeaQuest' would like to express our sincere gratitude to the reviewers for their thoughtful evaluations, valuable comments, and the time they dedicated to reviewing our work. 'SeaQuest' is currently involved in the research project No. SKN/SP/602624/2024, titled 'Innovative Anchoring System with Side-Deployable Clamping Arms SAFL,' which was submitted as part of the 'Student Circles Create Innovations' competition organized by the Ministry of Science and Higher Education. We hope that this new project will receive additional financial support, enabling us to continue our research efforts on the SAFL project (Suction Anchor with Extendable Fastening Legs) as well as on other ongoing projects such as the flexible diving bell Batychron [18], the mobile underwater diving support base (MUDS base) [15, 16, 17], the mobile electromagnetic mooring system (MEMS) [19], and several other initiatives. These projects have the potential to greatly benefit marine transport systems, particularly in underwater operations for exploratory and tourist diving, all while ensuring life safety and the protection of the marine environment.

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