Marine Micropile Anchor Systems for Marine Renewable Energy Applications

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I. INTRODUCTION

Abstract: The costs associated with current technologies for the mooring, anchoring, or foundation systems of floating Offshore Wind and Marine HydroKinetic (MHK) systems are a disproportionate portion of the total cost of an installed system, and thus of the Levelized Cost of Electricity. New anchor technology has the potential to reduce these costs substantially.

Current anchoring and mooring systems are a substantial and disproportionate portion of the installed cost of renewable ocean energy (ROE) systems, including floating wind, wave and tidal systems.

Published estimates of the costs of ROE anchor and mooring systems range from 25-40% of the installed cost of a system. This clearly has a significant adverse affect on the attainable Levelized Cost of Energy (LCOE). Offshore ROE systems are located in dynamic, high energy marine environments. These environments frequently coincide with the presence of more severe – and even extreme - seafloor conditions, e.g. hard or very dense seafloor sediments, rocky seafloors with or without thin veneers of sediment, steep slopes, and rugged bathymetry – all challenging conditions with respect to anchor and mooring system design and cost. Many locations where installations of ROE systems are being considered have some or all of these characteristics. In some instances, ROE systems will be located in areas where conventional anchoring systems are impractical or unaffordably expensive. Further, some ROE systems require anchoring and mooring in depths at which anchor installation operations from surface ships become difficult and expensive, requiring larger, more capable (and thus more expensive) vessels. In these cases, costly remotely operated vehicle (ROV) operations likely will be required for placement of anchors and connection of moorings.

Micropile anchor technology offers a "game-changing" approach to a broad range of marine anchoring applications that include not only anchors in the traditional sense, but also other applications that require fixing objects to the seafloor. Marine micropiles are appropriate for anchors, foundations and other applications for marine renewable energy systems and many other ocean engineering uses. Marine micropile anchor systems typically comprise multiple, relatively small, hollow micropiles (3-6 cm diameter) that are drilled into the seafloor using an expendable drill bit. Grout is pumped through the hollow micropile, filling the hole around the pile. The micropiles are grouted in place, through a template that then forms the anchor assembly. In other applications, single micropiles are drilled and grouted to anchor pipelines, seafloor junction boxes, renewable energy power aggregation and conditioning units. By contrast, conventional anchors and foundations currently include large diameter mono-piles, gravity bases and steel spread foundations that are secured by large driven or drilled-in piles. For floating structures, drag embedment anchors, piles, direct embedment anchors and clump ("deadweight") anchors are also utilized. One configuration, for example, is a 460 tonne concrete deadweight anchor that costs approximately $500K each. This size anchor requires large, and usually specialized, vessels for transport and installation. Pipelines are often "anchored" by being covered with rock riprap. Other ocean engineering applications often are not anchored at all, or are held down on the seafloor with large weights, concrete mattresses and the like.

II. MICROPILE TECHNOLOGY

Micropile systems are used extensively in terrestrial applications for anchoring, soil reinforcement, foundation stabilization, roof-bolting and numerous other applications. A micropile system comprises several components in addition to the micropile itself, including the expendable drill bits, connectors, and tension plates and nuts. Micropile suppliers

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(of which Ischebeck GmbH in Germany is the world leader) have developed a complete family of micropiles of various sizes and the components and installation equipment for a broad range of applications, all of which to date are terrestrial.

Fig. 1 shows a typical micropile with components, and a sketch of an installed micropile. The micropile is hollow to allow grout to be dispensed at the sacrificial drill bit. Pile segments are connected via couplings to achieve the desired pile length, which can vary from 6 to 20m depending on the soil/rock type and strength.

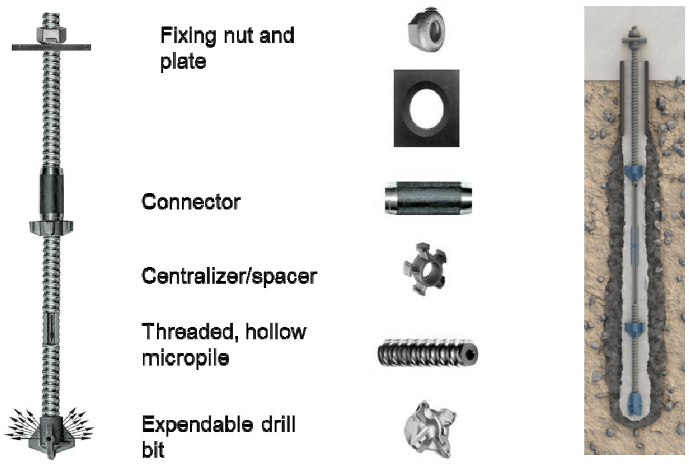

Fig. 1. Micropile with Components

The grout body adheres to the pile and to the anchoring medium and pile capacity typically depends on the bond strength between the grout and soil/rock interface.

Fig. 2 shows a micropile as installed. The most common use of drilled grouted micropile anchors in terrestrial applications is for slope stabilization. In this application, post-process, post-cure, pull testing typically is used to verify the quality of the installation. The consequences of failure are low, the installation costs are comparatively low, and there is a human in the loop to correct any problems that occur during the installation process. In subsea applications, the process and quality assurance methodologies must be much different because the environment is much different. The overhead cost of the at-sea installation process is much higher. It is dominated by the cost of a vessel that is expected to be dedicated to the installation. It is much more expensive (and not practical in many applications) to have a human at the installation site (underwater) where visibility can be extremely poor, currents and wave action can be high, and other challenging conditions can be present.

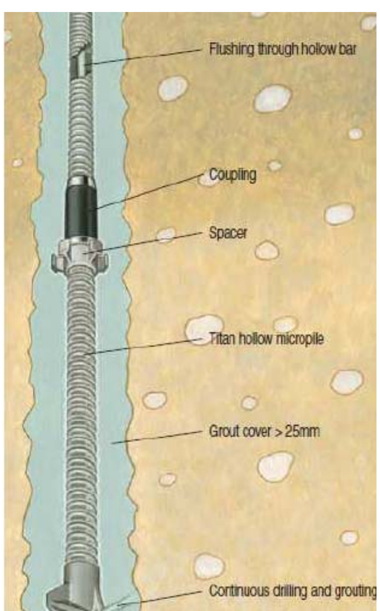

Fig. 2. Drilled Grouted Micropile

III. Marine Micropile Technology Development

Beginning in 2008, a consortium of Sound & Sea Technology, Inc.; Geomarine, Ltd. (now part of UTEC); and Cellula Robotics, Ltd., most recently with US Department of Energy (Award No. DE-EE0003632) and Lockheed Martin Corporation funding, has developed grout compositions and grout injection systems that are suitable for use in the marine environment as a critical element of marine micropile anchor systems. A series of patents have been applied for this technology (references a-c).

The objectives of this project were to:

- Reduce the capital and installation costs of Marine Hydrokinetic (MHK) Systems by developing a lower cost and more flexible anchoring technology to at least Technology Readiness Level (TRL) 4, Proof of Concept
- Perform critical research and development activities that will significantly decrease the costs of anchoring MHK systems in shallower water depths (to 100 meters) and in areas with rocky bottoms
- Expand MHK site selection possibilities, leading to a greater number of available and more optimal locations
- Advance the technology required to remotely attach MHK anchoring and foundation systems to the ocean floor in situations where traditional anchoring technologies are impractical
- Develop a remotely controlled grouting procedure that can be applied to deepwater grouted pile anchor installations with emphasis on a grout delivery control system
- Assess requirements and technologies for a Quality Control and Certification Procedure to validate deep underwater grouted pile anchor installations and conformance with identified environmental concerns

The grouting procedure and the qualification pull test procedure were identified as the key technology areas that required development to advance the concept. We conducted an extensive technology review of currently available grouting methodologies, both terrestrial and marine, to identify promising grout chemistries and grouting procedures. For the pull test, our plan was to use the concept validation tests as an opportunity to develop and prove a pull test apparatus and procedure scalable to the production application.

The project included designs for drilling systems (based on Seafloor Drills technology developed by Cellula) for installation of micropiles in a broad range of applications, some of which are described later in this paper. In addition, this effort developed conceptual marine micropile system designs to assess the feasibility and practicality of marine micropile anchors. In these concepts, several micropiles (the number depending on the holding capacity required) are drilled into the seafloor from a template that becomes the anchor connection. The drilled micropiles are grouted into the seabed. In MHK, tidal and floating offshore wind applications, the drilling and grouting operations are accomplished using a specialized remotely operated system. The anchor installation system is in many respects a specialized Remotely Operated Vehicle (ROV). ROV technology is highly advanced and little development is required for adaptation to the grouted marine micropile anchor application. This project has clearly demonstrated the feasibility of marine micropile anchors for a broad range of applications.

IV. Literature Review

The project thoroughly reviewed the available literature and met with terrestrial micropile suppliers and users to establish the state of practice regarding micropile design codes and practice, test data and test methods, grout specifications, hardware and design concepts.

V. Design Codes and Practices

Small diameter ground anchors have been used onshore for over thirty years, with various countries developing their own codes or standards. In the USA, there has been no national standard or code for rock and soil anchors, although ASTM standards cover material testing. The U.S. Department of Transportation has also produced a comprehensive Geotechnical Engineering Circular on Ground Anchors and Anchored Systems. In the UK, BS8081 “Code of Practice for Ground Anchorages” was published in 1989 and was for a time adopted worldwide, although it has recently been superseded by the Eurocodes.

While currently there are no applicable design codes for marine micropiles, designs based on British Standard BS8081 are probably among the most appropriate to the technology. However, this standard is oriented to onshore applications and is not directly applicable to marine designs. During the course of the project, the technology was discussed with marine certification authorities (American Bureau of Shipping, DNV) who, while highly supportive, have advised that the micropile anchors initially will be considered “novel” and certified accordingly.

VI. Anchor Capacity

As an example, given the novel application, the anchor elements are in boreholes likely designated as “Type A” grouted straight shaft boreholes according to BS8081. The fixed anchor length is designed as embedded in intact (unweathered) rock, based upon the depth of the rock socket. The seabed template is considered to bear onto sediment or weathered rock at the surface of the seabed.

The micropile has a rolled thread similar to a deformed bar, which also controls grout crack widths for durability. Details of a typical product are shown below in Table 1.

VII. Axial resistance

The pull out capacity (Tf) of a Type A anchorage is dependent upon the strength of the material mass and is limited in BS8081 to a grout/rock bond stress of 4 N/mm^2 for strong rock. Similarly, the grout/tendon bond stress is limited in to $2N/mm^2$ for deformed bar.

Thus, the micropile grout bond is critical. When stressed, the anchor theoretically mobilizes a cone of rock above the mid-point of the fixed length. The geometry of the rock cone depends on the degree of jointing, and the inclination of bedding planes. A 60^o cone angle represents a highly jointed or shattered rock, and a 90^o cone angle represents a competent blocky rock. Because shear at the interface between the surface of the cone and the surrounding rock is neglected, a safety factor of unity (FoS = 1) can be taken on the weight of the rock cone, where the rock is horizontally (or sub-horizontally) bedded.

To limit interaction between fixed anchor lengths, a minimum spacing of 1.5m to 2.0m is recommended by BS 8081. Where anchors are spaced so closely, the individual cones overlap to partially cancel each other out, reducing the weight of rock mobilized. To increase the weight mobilized, either the spacing should be increased, or the depth of the cone increased, until the required uplift resistance is achieved.

VIII. Lateral resistance

Substantial lateral resistance of the anchor system can be mobilized via the friction resistance on the steel to soil/rock interface at the seabed and can be enhanced by a spiked or ridged bearing surface to partially penetrate the rock surface or take up irregularities.

The lateral resistance per anchor must be based upon the specific vertical/horizontal load combination. It will be necessary to include a nominal allowance for loss of pre-stress due to fatigue loading and settlement.

TABLE 1. Micropile no. 103/51 NB: maximum working load includes FoS 2.0 on yield

	OD/ID (mm)	**Effective Cross Section Area (mm^2)**	**Ultimate Load (kN)**	**Yield Load (kN)**	**Max Working Load (Te)***	**Nom hole dia (m)**
Micropile Parameters	103/51	5680	3660	2670	136	185

IX. Grout Specification

The literature review identified that certain key grout attributes would be needed for marine anchoring applications, namely:

- Non-shrinkage (expansive properties beneficial)
- Good pumpability
- Good strength (minimum unconfined compressive strength of over 6,000psi / approx. 40kN/mm2 at 28
- days is specified in this application)
- Free of chlorides or other salts (high resistance to chemical attack when cured)

It was found that such grouts typically comprise a blend of Ordinary Portland Cement (OPC), selected fillers, plasticizers, expansion additives and waterproofing admixtures. For subsea placement, the addition of anti-washout properties was also suggested to be beneficial. Finally it was identified that manufacturers would have to be consulted to ensure that none of the chemicals or additives to be used would be harmful to the marine environment.

A detailed grout specification was prepared for the project, covering grout properties, chemical composition and also testing requirements.

Due to quality control issues and the relatively small volumes of grout required for each anchor it was recommended that pre-blended bagged grout be used, and mixed using potable water. This ensures that the QA/QC testing will correlate with manufacturer's recommendations and international design standards.

For mixing the grout, a high speed, high shear colloidal grout mixer was specified. The high-speed shearing action of a colloidal mixer achieves greater hydration of the cement by wetting each individual particle, and mixing time is significantly lower than conventional paddle mixers. This type of mixer provides an extremely efficient and rapid means of producing high quality grout. Additional development will investigate the use of grouts compatible with seawater.

X. Drilled Grouted Micropile Anchor Testing

The objectives of these tests were as follows:

- To advance the application of renewable energy anchoring technology from TRL3 (Proof of Concept) to at least TRL4 (Component Validation in Lab Environment).
- Conduct tests to support the development of a remotely controlled grouting procedure and grout quality control system suitable for marine Grouted Pile Anchor installations.

The test program was as follows:

- The concept for a production remotely operated subsea grouting procedure is described in the next section. The following results have been derived from evaluation of this concept:
  - understanding the effects of the marine environment (salinity, pressure, temperature) on grout setting times is critical
  - grout quality control is important, especially:
    - the ability to perform real-time grout density measurement
    - the ability to perform real-time grout pressure control
- We performed a literature review to learn what data exist on the influence of the subsea environment (temperature, pressure, salinity) on grout-setting time. We found that this issue has been well researched, and there is no need to perform any additional special experiments.
- We identified a candidate density sensor and defined a series of experiments to evaluate its practicality/suitability for subsea grout measurement application.
- We fabricated a simple pressure control apparatus and included testing of this apparatus along with the grout density sensor experiment. These investigations resulted in the following:
  - the off-the-shelf density sensor is easily marinized to operating depths of 100m
  - the sensor readily detects changes in grout density over the range of interest
- We conducted an integrated experiment that included a "gun-barrel" grout-setting test, combined with use of the grout density sensor and the grout pressure control apparatus. The experiment concluded with a pull test.

XI. Design Concepts

The micropiles consist of threaded hollow rods drilled into the seafloor at an adjustable angle and at variable length, depending on the seafloor material and the required axial and lateral foundation fixation holding capacity. The micropiles can be pre-tensioned immediately following installation as a means of significantly enhancing the lateral resistance of the anchor assembly.

Anchor system concepts will typically comprise an array (group) of multiple subsea micropiles, each of diameter about 100 to 150mm, that are drilled into the seafloor from a seabed drilling rig, and then grouted in place, through a template that forms the anchor assembly. The number of micropiles per group would depend on the application loading.

XII. MARINE MICROPILE APPLICATIONS

Installation sites typically are chosen in high energy environments, leading to large hydrodynamic forces on the tools and tooling during installation. While drilled, grouted piles are installed underwater today, the large diameter monopiles typically used to anchor or support tidal, in-river hydro and offshore wind energy generation systems are very different from the micropile technology that is the subject of this paper. A key difference between large diameter monopile installations and Drilled Grouted Marine Micropiles is the number of piles installed (and therefore grouting operations to be completed). Typically there is just one monopile, with no joints, and only one (albeit substantial) grouting operation. With drilled grouted marine micropiles, we expect to install several smaller piles, assembled together in groups of 3 or 4 piles, with typically 8-16 bore holes per anchor assembly, depending on the required holding capacity. For Example, Fig. 4 shows a conceptual drilled grouted micropile anchor system with piles oriented to resist primarily tensile loading at the top. Fig. 5 shows an isometric view of a dual drilling system with an eight micropile template at bottom.

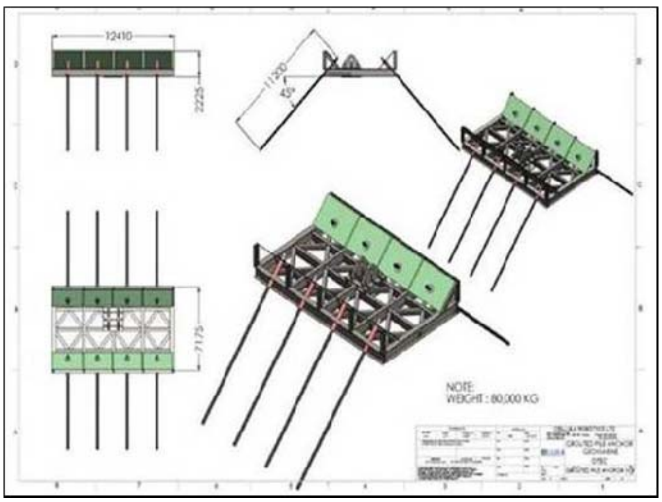

Fig. 4. Conceptual Drilled Grouted Micropile for Directional Loading (Image Courtesy of Lockheed Martin Company)

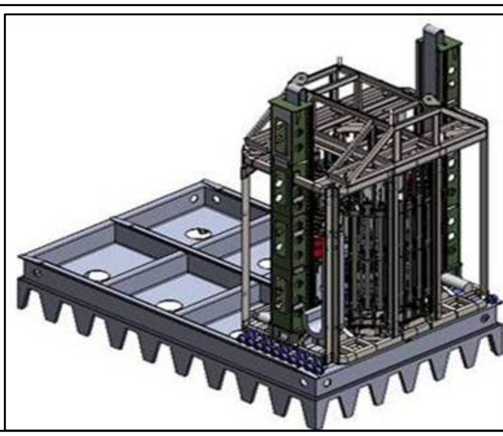

Fig. 5. Rectangular template eight-micropile system

A concept for a tidal energy turbine foundation is shown in Fig. 6. This concept replaces a monopile currently used.

Fig. 6. Tidal turbine foundation using marine micropiles

Fig. 7 shows a design for a micropile anchor for a sensor buoy to be installed off the coast of Oregon. This design is a simple and inexpensive steel template that uses three micropiles.

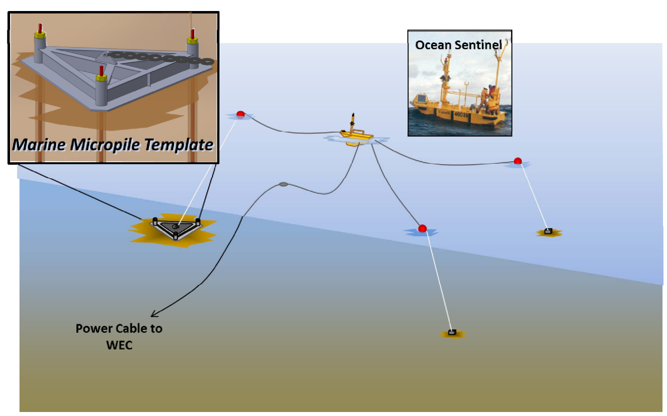

Fig. 7. Simple 3-micropile anchor for sensor buoy

XIII. Production Pile Installation Concept

Elements of a full-scale marine micropile system are shown in Fig. 8. The concept is described as follows:

- An anchor template with pre-located positions for the micropiles is placed over the target anchor location on the seafloor.
- A seafloor drill is situated over the target location of the pile. It holds one or more micro-piles, which it inserts by drilling them into the seafloor.
- The grout delivery system is connected to the drillhead at the top of the pile that is being inserted, allowing the grout to flow through the pile and out the bottom; weak (dilute) grout is used as a flushing fluid during drilling.
- A collar is installed around the pile to capture flushing grout flow rising to the surface around the pile.
- Rich grout is prepared on surface and pumped to the subsea injection point via a subsea throttling valve.
- Fresh water is also supplied from the surface vessel.
- The grout mixture dilution occurs subsea with surface-supplied fresh water. Subsea (rather than surface-based) mixing reduces the time delay between a decision to change the grout/water mix (grout density) and the injection of the modified grout mixture into the hole.

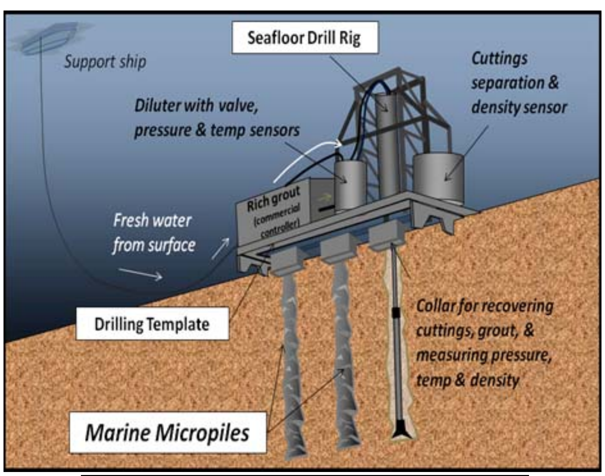

Fig. 8. Marine micropile system elements

- Some combination of water and grout is injected into the hole during insertion of the pile (i.e. drilling), controlled by a throttling valve.
    - Typically, a highly diluted grout is used during the pile insertion (drilling) stage in order to flush cuttings from the hole.
    - Once pile insertion is complete, a rich grout solution (at the final water/cement ratio) is used to anchor the pile.
- The pressure of the grout entering the hole is controlled via a throttling valve situated at the connection between the grout supply hose and the drill assembly. This pressure control function is important in order to avoid over-pressuring the foundation or damaging/ disconnecting the collar.
- When flushing grout exits the hole, the cuttings are separated from the grout, e.g. through a filter.
- The density of the grout is measured as the grout exits the hole. By doing this, we expect to be able to see when all the weak, flushing grout has exited the hole and the hole is completely filled by the undiluted, rich grout.
- Due to environmental concerns in some jurisdictions, we expect to maintain a completely closed loop system, not allowing grout to mix with the ambient seawater until it is cured. This means that the weak flushing grout cannot be simply discharged into the environment, but instead will either be reused, returned to surface through a tube, or deposited into a sealed form at the anchor.

XIV. Cost Comparisons

We have made a number of comparisons of cost between conventional anchoring and foundation systems and marine micropile systems.

Case 1: 1.3MW Tidal Turbine

- Peak Load 1.5MN horizontal
- Load approx 17m above ocean floor thus creating overturning moment
- Current baseline anchor solution – large gravity base
- For conventional pile design assumed a 3 leg jacket structure

Micropile anchor design 40% lower cost ($300K vs $500K)

Case 2: 150kW Wave Energy Converter Buoy

- Peak Load 2MN
- 3-point mooring system
- Load acts on seabed mooring line approx 5-8 degree to horizontal
- Current baseline anchor solution – 3 anchor piles per buoy

Micropile anchor design 55% lower cost ($200K vs $450K)

XV. CONCLUSIONS

Marine Micropile Technology has the potential to reduce the installed cost of many oceanic systems, including marine renewable energy systems, by 15% to 20% or more by replacing traditional anchor and mooring system complexity with a simpler, less expensive and more environmentally acceptable technology, and by reducing vessel and overall installation costs. In addition, MMT is broadly applicable to essentially all marine renewable energy generation and subsurface storage technologies that require a mooring. Further, MMT has broad applicability to other anchoring needs, including expeditionary and remote site logistics systems. The future application of MMT to the MHK industry will lead to improved reliability, survivability, operational availability and financial viability of marine energy systems.

XVI. REFERENCES

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