Anchor Installation for the Taut Moored Tidal Platform PLAT-O

Nick Cresswell*[1], Jason Hayman*, Andy Kyte*, Andy Hunt*, Penny Jeffcoate*

*Sustainable Marine Energy Ltd

Trinity Wharf, Trinity Road, East Cowes, Isle of Wight, U.K., PO32 6RF

[1] nick.cresswell@sustainablemarine.com

***Abstract* - High energy tidal stream sites exert large loads on offshore structures, due to the relationship between velocity and the high density of seawater and the resulting hydrodynamic forces. Tidal turbine support structures must withstand high loads to harness the most lucrative tidal sites. Traditional monopile or jacket structures require substantial foundations to support the loads from large scale tidal turbines. An alternative is to moor a platform to the sea bed using anchors and mooring lines. Such platforms can be free-surface floating or suspended in the water column, such as a taut-moored platform.**

Sustainable Marine Energy's (SME) PLAT-O buoyant platform is an example of a taut-moored platform which can support smaller scale turbines or instrumentation packages. The platform, and the four small anchors used to secure the device's mooring lines, are lightweight at ~1/70th of the mass per installed MW of alternative technologies. This paper presents the application of drilled anchors for supporting taut-moored tidal platforms, and their applicability in high yield tidal energy sites.

The type and installation methodology of such anchors is dependent upon the geology of the bed rock. Bed surveys must be conducted to determine the appropriate anchor type and installation technique for the local geological and bathymetric conditions. The installation methods for SME's anchoring technologies have been designed to minimise the cost of installation, requiring only a small support vessel and an Anchoring Remotely Operated Vehicle (aROV). The aROV can be used to install anchors at a high flow tidal site over one slack water period.

This paper presents some of the geotechnical considerations for anchor design and installation. The paper also describes the applicability of drilled anchors for use with small scale turbine platforms, appropriate installation methods employed and testing undertaken.

***Keywords* – Taut-Moored, Rock Anchor, Screw Pile, Foundations**

I. INTRODUCTION

It is estimated that the UK could supply between 15 and 20% of its electricity demand from tidal energy [1]. The key obstacle to the delivery of commercially acceptable tidal energy generation is the capital cost associated with the development of tidal energy schemes [2]. The primary drivers of the cost of a tidal energy scheme are the cost of the turbine unit and the cost of the supporting structure and installation of the turbine unit, each accounting for approximately 40% of the total project capital cost [3]. The cost of the turbine, drivetrain and associated electrical equipment is driven to a large extent by the power rating of the device [4], the cost of the supporting structure and installation are dependent upon the structural configuration which is selected [5].

In order to reduce the cost of tidal energy it has been suggested that a change of configuration away from bottom mounted turbine support structures with piled or gravity bases could lead to cost reductions in the system capital cost [5], a trend already under way in the offshore wind industry [6]. This has led to the development of turbine systems, for both wind and tidal, mounted on buoyant structures which are secured to anchoring points at the seabed [6]–[8]. This configuration reduces capital cost as the structure and foundations do not need to withstand the large moment generated from the thrust forces acting at a distance from the foundations, with the forces now transferred in tensile mooring lines directly to the anchoring point [9].

The anchoring points to which the mooring lines are secured are commonly gravity bases, which require costly installation methods, requiring large, expensive vessels for monolithic foundations or protracted operations with smaller vessels for modular designs [7], [10], [11]. An alternative solution is to utilise the local geology to provide the anchoring point by drilling an anchor into the seabed [8]

In order to develop their PLAT-O tidal energy platform Sustainable Marine Energy (SME) have developed two anchoring solutions to address mooring requirements in two different geological conditions. A helical screw pile anchor was designed for use in seabeds comprised of gravels, sands or clay, and for harder geology a rock anchor was developed.

Helical screw pile anchors have been used for many years to provide foundations in a number of fields, with a developed understanding of their operation [12]–[15]. The use of screw pile foundations for marine renewable energy has been previously suggested due to their low cost, high load holding capability, and rapid and quiet installation [16], [17]. The testing of full scale screw piles for use on marine renewable devices has not been previously reported.

Rock anchors are an established geotechnical solution with analysis methods which are well developed [18], [19]. Drilled and grouted rock anchors, or micro-piles as they are sometimes referred, have been suggested previously for marine renewable energy [20], [21]. The use of a drilled-only rock anchor is a concept which has not previously been investigated.

This paper examines the conditions in which screw pile and rock anchors can be employed, their load holding capability and the installation methodologies.

II. ANCHOR INSTALLATION

Anchor installation in the case of both helical screw piles and rock anchors is achieved using an Anchoring Remotely Operated Vehicle (aROV). The aROV, as seen during rock anchor testing in Fig 1, is a marinised drilling rig controlled and powered via an umbilical providing hydraulic power and control from a surface vessel.

The most significant modifications to the aROV are: a replacement hydraulic valve pack in a pressure compensated, oil filled chamber; pressure compensation for the drilling heads; and a high resolution underwater camera system to facilitate remote drilling control. The modified aROV underwent a significant period of operational testing on land in both the helical screw pile and rock anchor configurations to ensure that operations could be performed without direct visual contact.

In order to drill, the aROV is loaded with an anchor on the surface and deployed overboard by crane from the deployment vessel. Due to the low mass of the aROV (5t in air), deployment and control are possible from a small vessel such as a multi-cat.

Fig 1: Loaded AROV in rock anchor configuration during land based testing in Orkney

Once on the seabed, the anchor is drilled into the substrate using high torque hydraulic motors, thereby eliminating the need for loud percussive drilling for both screw pile and rock anchor installation. Once the anchor has been drilled to depth the aROV is retrieved in the case of the screw pile. In the rock anchor case, the anchor is pre-tensioned and the aROV is retrieved. The full procedure for the drilling of one rock anchor, which is the more onerous of the two anchoring operations, takes approximately one hour from the point where the aROV leaves the vessel to the point at which it returns. Deployment of an anchor is therefore possible within one slack water period.

III. HELICAL SCREW PILES

A. *Anchor Overview*

The helical screw pile was developed as part of the Screw Anchors for Marine Energy Devices (SAMED) project in conjunction with Marine South East and ABC Anchors. The screw anchors, as seen loaded on the aROV in Fig 2, are formed of a central shaft onto which profiled steel sections are welded to form the screw. The screw pile is of a multi-helix type, with the shaft diameter stepping up midway along the length of the shaft to increase the lateral bearing capacity of the pile at the top end, where the majority of the lateral load is transferred to the seabed [22].

Fig 2: Loaded AROV in screw pile configuration prior to testing at Yarmouth

The installation of screw pile anchors is achieved using a high torque hydraulic motor to spin the anchor about its axis and another pull down motor to apply the thrust to drive the anchor into the seabed at a predetermined rate. The advancement rate for the anchor is set so it is driven at one pitch spacing per revolution.

The helical screw pile is configured for use in sand, gravel and clay seabed conditions, initially designed for use during trials of PLAT-O offshore from Yarmouth on the Isle of Wight. The limiting conditions for the installation of a screw pile anchor are that the soil must be sufficiently soft to allow for the pile to be fitted and have sufficient mass and strength to resist the forces applied. The assessment of the bearing capacity of screw pile anchors is covered in depth by Ghaly et al. [12], [13].

B. *In-situ Testing*

1) *Geotechnical Test Conditions*

Testing of the helical screw piles was undertaken in a test pit created on land, based upon core sample results from site. The core sample data was extrapolated across the site with the aid of sub-bottom profiling. The sub-bottom profiler track was set to pass through each of the core sample test locations and each of the anchor points. The depths of the layers in the soil at the core sample locations via the sub-bottom profile data were verified using the actual depths obtained from the core samples. The layer depths at the anchor locations were then resolved using the sub-bottom profile data.

In order to achieve realistic conditions within the test pit, a location was chosen with matching underlying clay and a pit was dug. The geotechnical conditions at the Yarmouth site, which were replicated in the test pit, were a top layer of medium dense coarse flint gravel with some sand and shell fragments and a clay layer beneath. The depth of the gravel over the site was found to vary during the sub-bottom profiling and the test pit was therefore created with gravel at two depths. The depths chosen were the minimum gravel depth extrapolated over the site of 1.45 m, and the maximum gravel depth of 2.40 m.

The conditions at site are also highly linked to the seabed nature of the site and it was therefore necessary to take account of this in the testing. In order to reproduce the conditions as far as possible the pit was flooded to replicate the effect that the pore water pressure will have on the anchor behaviour and capacity.

2) *Test Method*

In order to test the capacity of the anchors in the test pit two anchors were installed within the test pit, a schematic of which can be seen in Fig 3. The test pit steps down in the centre, meaning that the gravel is at two depths, to mimic the most extreme upper and lower depths of gravel on site. Anchor A was driven into the shallower gravel end of the test pit, with 1.45 m of gravel depth, with Anchor B being driven into 2.40 m of gravel.

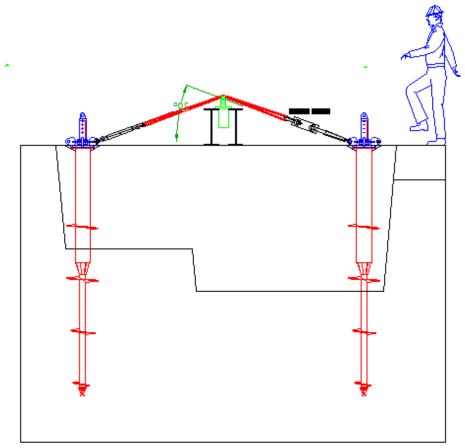

Fig 3: Schematic view of the test pit used for helical screw piles, with Anchor A on left and Anchor B on the right

The test was set up such that the two anchors were connected by a chain, with a hydraulic ram mounted to a frame in the centre. The spacing between the anchors was selected so as to remove influence of the anchors on one another and to remove any influence from the supporting soil for the test frame. The ram was connected to the anchors via chain, with a load cell inserted between the ram and the anchors. The ram pressure was increased and the line tension was increased to the mooring line tension value required for the test. Manual control of the ram pressure was used to control the line tension during the test.

The anchors were installed vertically, rather than inclined along the axis of loading to maximise their holding capacity, so as to mimic the deployment at site. The precise angular positioning required to install inclined anchors being beyond the capability of the first generation aROV.

A cyclic load test at the maximum expected line load was conducted on the helical screw pile to reproduce tidal cycling on the foundations during PLAT-O's deployment at Yarmouth on the Isle of Wight. This test involved the periodic loading and unloading of the pile from the minimum operational line tension of 9.8 kN to the maximum operational mooring line tension of 53.0 kN. These loads correspond to downstream and upstream line loads respectively on the device with the turbines operating on the limit of their cut out velocity. The test load cycling was undertaken with a period of 4 minutes, with the load changed at a rate of ~4 kN/s, with 111 cycles completed, which is equivalent to 56 days of tidal periods on site.

3) *Test Results*

The results of the testing undertaken in the pit can be seen in Fig 4. These results show that the helical screw pile anchor was capable of withstanding the maximum expected mooring line loads during deployment at Yarmouth, assuming similarity of the underlying seabed conditions. The anchors can be seen to initially displace as the load is taken. After around 10 loading cycles the rate of increase of the anchor displacement drops off and the peak displacement during each cycle begins to plateau.

The overall trends in the displacement, which can be seen in Fig 4, are broadly similar between the two anchors, as would be expected for such similar ground conditions using identical anchors. There is a greater displacement range seen in the case of Anchor A over each load cycle, particularly during the initial ten load cycles.

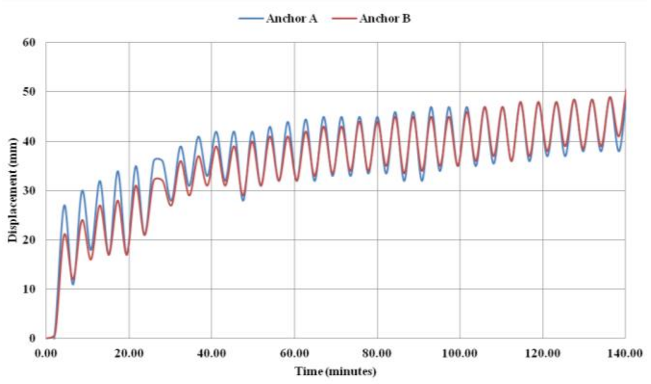

Fig 4: Corrected horizontal displacement history for the helical screw pile cyclic load test on Anchors A & B

The increase in the displacement range could be explained by the difference in the geotechnical conditions. Anchor A, which has the greater displacement, has less gravel along its length and more clay. This occurs due to the difference in friction angle between the two soil types and the greater load holding capacity generated by the increased depth of gravel.

The effects of the soil behaviour when loaded over time are clearly then important in the assessment of the anchor's holding capacity. This also suggests that care should be taken to gradually load the anchors prior to applying peak loads.

4) Anchor Applicability

Helical screw piles can be used in a variety of soils and ground conditions. The anchor's load holding capacity is highly dependent on the bulk density and friction angle of the soil [12], [13] and so the anchor is particularly well suited to sites with compacted gravel type conditions. The anchors capacity is also a function of the anchor geometry, particularly the shape and arrangement of the helical plates. The ability to scale anchors means that anchors can be utilised in a range of soil type seabed conditions, with lighter or weaker soil being approached with the use of an anchor with either a greater embedment depth or an increased shaft diameter. In order to design a helical screw pile a thorough understanding of the geotechnical conditions at site is required. The gathering of this data is best achieved through a comprehensive geotechnical investigation procedure.

5) Gravity Anchor Comparison

When compared to a gravity based foundation, the helical screw pile provides an efficient solution. Using the deployment of PLAT-O at Yarmouth as an example, a gravity based mooring system and helical screw pile are compared. The use of a gravity based mooring point, assuming a seabed friction coefficient of 0.5 and a factor of safety of 1.5, would require a mass of 18.1 tonnes per anchor point. The helical screw pile has a mass of ~300 kg. Installation of piles can be performed rapidly using the AROV operating from the deck of a multi-cat, with the material cost of each mooring point being 21% of that for equivalent gravity based systems with additional reductions in operational costs.

A summary of the comparative costs of a gravity based anchor and the helical screw anchors is given in **Error! Reference source not found.**. These costs are approximate example values and provide a high level indication of costs. This shows that the total cost of deploying a four-point mooring system is approximately 17% less when using screw anchors compared to gravity anchors. This results in a substantially more cost efficient system for anchor deployment.

TABLE 1

COST SUMMARY FOR GRAVITY AND HELICAL SCREW ANCHORS

Parameter	**Gravity**	**Helical Screw**
Mass	4 x 18.1t = 72.4t	5.6t (aROV) + 4 x 300kg = 6.8t
Material	Steel shot + frame @ ~£495/t + £2k = £37.8k High density concrete @ ~£590/t = £42.7k	£30k
Marine Ops	Multi-cat £5k /day * 4 days	Multi-cat £5k /day * 4 days
TOTAL	~£60k	~£50k

IV. ROCK ANCHORS

A. Anchor Overview

The Raptor 100 rock anchors utilised for the deployment of PLAT-O#1 at the European Marine Energy Centre (EMEC) were developed with Rockbit Ltd. The anchors, as seen in Fig 5, are formed of an inner stem and outer casing which are free to rotate and move axially relative to one another. The outer casing is initially retracted, with both the inner stem and outer casing rotating to drill to depth. Once the required depth is reached the outer casing continues to drill down, propelled by rams on the drill head. The movement of the outer stem causes the fingers at the base to splay. When the fingers are fully deployed the anchor is pre-tensioned by rotating the nut on the inner stem using the drill head, thereby pulling up and applying tension to the centre stem and reacting this against the splayed fingers into the bedrock.

The rock anchor is designed for use in solid geology, where the load holding capacity of the anchor is primarily determined by the friction angle of the bedrock into which the anchor is drilled. Determination of the friction angle and shear strength of the rock is driven to a large extent by the Rock Mass Rating (RMR) of the associated geology. The friction angle determines both the volume, and therefore mass, of rock and the area of the shear surface which are mobilised. Rock with a greater friction angle enables a greater load bearing capacity for the anchor. The theory behind rock anchor design is provided by Yang [19].

Fig 5: Raptor 100 rock anchors

B. *In-situ Testing*

1) *Geotechnical Test Conditions*

Extensive testing of the rock anchors was undertaken in a quarry in Finstown, Orkney, to ensure testing was as close as possible to the geological conditions on site at EMEC. The conditions found at site, which were mirrored in the quarry, were exposed surface level bedrock formed of siltstone/mudstone of the Rousay Flagstone Formation with little sediment on the surface. The similarity of the rock between the site and the quarry was confirmed by a local independent geological expert. The bedrock was considered to be in a fair condition, with moderate fracturing present. An underwater image of the bedrock during installation of the anchors can be seen in Fig 6, which also shows that there is no damage to the surrounding rock mass during the installation process.

The key rock strength parameters were taken on site through borehole data and testing of the recovered cores. These were then compared to site data from the test site. The key rock strength parameters which are replicated between the test site and the borehole data are summarised in Table 1.

TABLE 2

KEY GEOTECHNICAL PARAMETERS AT SITE

Variable	**Value**	**Units**
Rock uniaxial strength	32.8	MPa
Rock mass rating	55.0	-

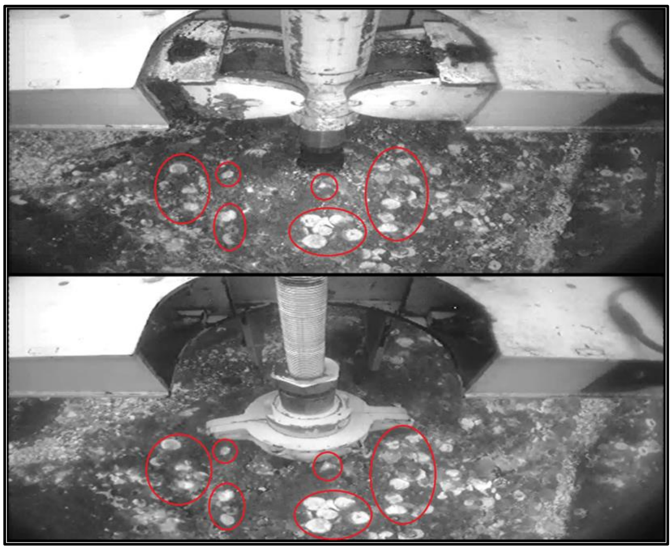

Fig 6: Bedrock at site during installation of anchors

2) *Test Method*

There were three tests completed for the rock anchors: a vertical load test, cyclic loading tests and a peak load test. The test setup for the vertical load test can be seen in Fig 7, with the frame setup directly above the rock anchor. The frame was designed such that the feet of the frame were located outside the assumed cone of rock mobilised by the anchor to resist the uplift [19], [23]. A ram was then used to apply a vertical load in seven increasing cycles, to 186.4, 274.7, 372.8, 461.1, 549.3, 647.5 and 735.8 kN respectively, aiming to arrive at the failure load of the rock mass. The load was calculated using the geometry of the ram and the hydraulic system pressure.

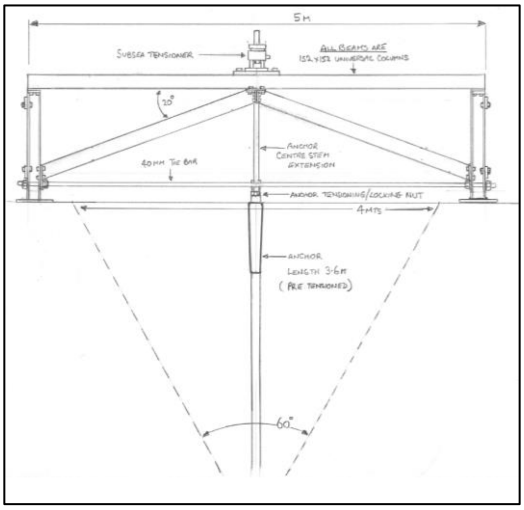

Fig 7: Test setup for Raptor 100 anchor vertical load test

The setup for the cyclical and peak load tests of the rock anchor can be seen in Fig 8. The test was set up with two anchors drilled into the rock at the quarry with a frame between them. The separation distance was set such that the frame, which held a hydraulic ram, was situated out of the cone of rock mobilised to provide the uplift capacity of the anchors. A chain was rigged between the two anchors and run over the top of a hydraulic ram. The hydraulic ram was used to provide a vertical force which acted to induce a line tension at the expected mooring line angle of PLAT-O. The line tension was measured using a calibrated load cell fitted into the chain assembly.

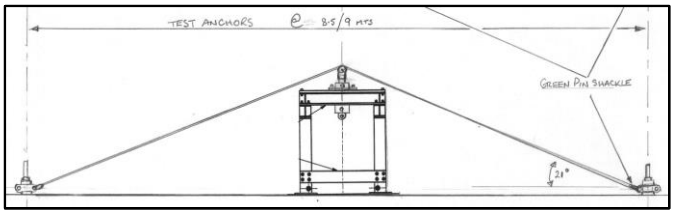

Fig 8: Test setup for Raptor 100 anchor cyclic and peak load tests

The cyclic load tests were conducted to mimic wave loading, with a line tension varying from 147.1 kN to 196.2 kN over 1000 cycles for one test and from 274.7 kN to 314.0 kN over 600 cycles for the second. The line tensions here are considerably higher than those on the helical screw pile anchors due to EMEC presenting a much more aggressive tidal flow regime for the PLAT-O device and loads therefore increasing. The line tensions used here were equivalent to a line tensions representing the harshest operating cases. The anchor head displacement was recorded during the tests.

The peak load test was conducted to a maximum load of 740.0 kN, which was the factored peak line load expected on an upstream line during a line loss event on the other upstream line. The load was applied in a series of eight increasing load cycles over 1 minute each, with the load increasing by 1/8th of the maximum load each cycle. The anchor head displacement and applied load were recorded during the test.

3) *Test Results*

The test results for the rock anchor vertical load test can be seen in Fig 9. It can be seen here that the rock anchor peak vertical displacement is linear until 647.5 kN, with hysteresis noted when the load is dropped between cycles.

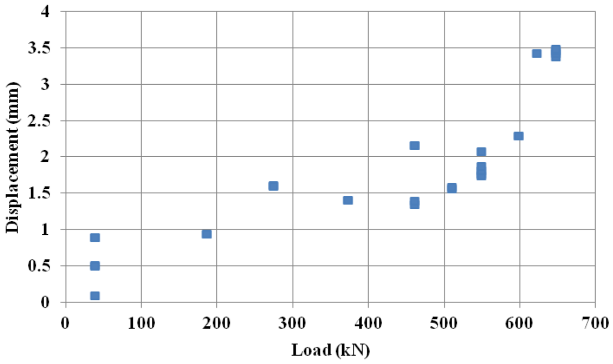

Fig 9: Displacement against load for the rock anchor vertical load test

The scale on the load axis of Fig 9 can be seen to end at 647.5 kN rather than the full test load of 735.8 kN. This is due to failure of the rock anchor due to uplift of the rock mass at a load of approximately 667.0 kN. This represents a significant factor of safety against the design uplift load, which suggests that the assumed rock cone uplift model is conservative as has been noted in previous research [19], [23], [24]. This discrepancy is due to the neglecting of the shear strength of the rock mass in the calculation of the uplift capacity.

The displacement against time results from the cyclic load tests can be seen in Fig 10. The anchor loading procedure values were not recorded for the higher load tests. The results show that after the displacement during initial loading of the anchor, the cyclic loading had very little effect on the position of the rock anchor head in either the horizontal or vertical directions. As might be expected the displacements noted in the higher load case were greater than those noted in the lower load case. What displacement there is can be largely attributed to the deflection of the anchor itself rather than changes in the rock's bearing strength.

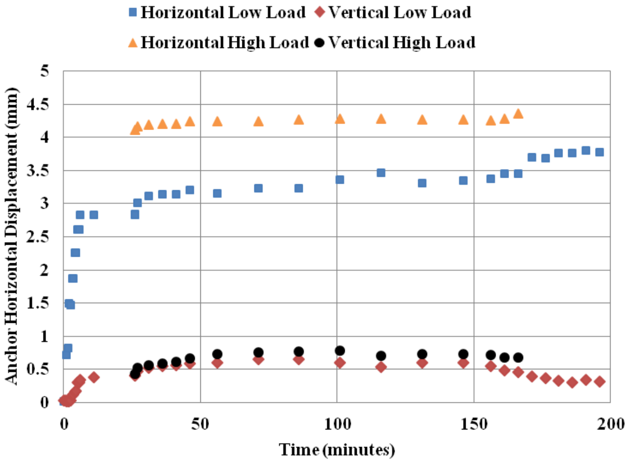

Fig 10: Displacement history for the rock anchor cyclic load tests

There is some evidence of minor settlement of the rock anchor in the more lightly loaded case from around 180 minutes onwards. This settlement of approximately 0.25 mm occurs gradually over around 10 minutes before the anchor once more settles.

The results shown in Fig 10 provide confidence that the cyclic loading is not causing weakening of the rock and that the ultimate load holding capacity of the anchor will not be significantly affected by repeated cyclic loading at lower loads as there is no significant movement of the anchor head over the duration of the test. There is a future plan for longer term cyclical load testing and monitoring of the anchor head positions.

The results from the peak load test can be seen in Fig 11, which shows the history of displacement against load over the test cycles. As would be expected from the angle that the line load is applied and the design of the anchor, the vertical component of the displacement is considerably lower than the horizontal component.

The results show that there is minor hysteresis in the anchor displacement as the load increases over each progressive cycle. The overall trend shows a linear increase of the anchor head displacement with the applied load. The absence of any significant deviations from the peak load to displacement trend shows that there has not been any significant rock fracturing resulting in a loss of bearing capacity as the load increases.

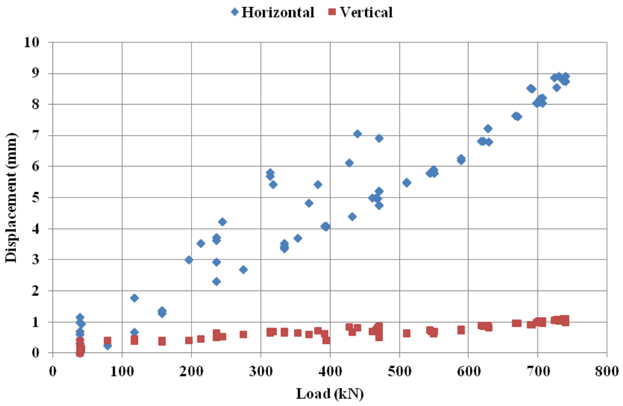

Fig 11: Load against displacement for the rock anchor peak load test

The trend of the relationship between the load and displacement, even at the highest applied loads, shows that there is additional load holding capacity in the anchors above that which it was designed to withstand. This can be seen as there is no evidence of significant rock fracturing leading to significantly increased displacement at low load. This was further verified by the visual condition of the rock mass after testing, with evidence of only limited local fracturing at surface level.

4) *Anchor Applicability*

Rock anchors can be utilised wherever solid geology is present on site. The holding capacity of the anchor is directly dependent upon the rock type and the state of the rock on site [19]. The anchor design parameters can be modified to accommodate a range of rock type and loading conditions. In order to design a rock anchor it is necessary to have an understanding of the geological conditions on site, which is best achieved via a thorough geotechnical investigation.

5) *Gravity Anchor Comparison*

The Raptor 100 anchors used for PLAT-O at EMEC have a mass of 260 kg and are able to withstand a load of 740.0 kN. In contrast, the use of gravity based mooring point, assuming a seabed friction coefficient of 0.5 and a factor of safety of 1.5, would require a mass of at least 392.0 tonnes per anchor point. The mass of material to be transported to site, including the mass of PLAT-O, is therefore 69.6 times greater in the case of a gravity based system. The scaling up of a rock anchor is likely to further increase this factor as the mass of a gravity based foundation increases in a cubic relationship to holding capacity. In contrast the relationship for a rock anchor is almost linear due to the increased holding capacity being derived from the mobilised rock cone increasing to the cube of the length.

Also, the limited resource which is required to drill an anchor can be seen clearly in Fig 12, which shows the aROV being recovered onto the deck of a multi-cat at slack tide after drilling an anchor subsea. Due to this simplicity there are clear incentives operationally, due to reduced installation cost and the limited weather windows on tidal sites, to move from a gravity based to an anchor based mooring system.

A summary of the comparative costs of gravity anchors and the Raptor 100 anchors are provided in

TABLE 3. This shows that the total cost of the Raptor100 system is approximately 10%, or less, of a gravity based system. The number of marine operations due to the amount of material required is not feasible with a small vessel and so large vessels are required, which are less available and more expensive. Additionally, at the end of an anchor life cycle the marine operations would be incurred again, so the overall cost would increase. This shows that the cost benefit of using the rock anchor system is substantial.

V. CONCLUSION

The results of the tests for the helical screw piles and rock anchors have shown that the holding capacity of the two anchor types developed for PLAT-O are able to restrain the worst design line load cases. The reported tests also show that the anchors are able to operate in cyclic loading conditions without degradation in their performance. The low total displacements seen in the tests show that there is additional capacity to withstand loads above the values tested.

Further testing of the rock anchors is currently being planned to evaluate the ultimate load capacity of the Raptor 100 anchors. There is also work planned to investigate the longer term settlement of rock anchors under load.

The ease of installation and low cost compared to the use of alternative gravity based anchors make the use of anchors as foundations attractive for the reduction of system capital and installation costs for tidal energy devices. This is particularly true of the rock anchor, where a large holding capacity per unit mass is mobilised through use of the underlying strata.

Fig 12: aROV being recovered at slack tide after anchor drilling subsea

TABLE 3

COST SUMMARY FOR GRAVITY AND RAPTOR 100 ANCHORS

Parameter	**Gravity**	**Raptor 100**
Mass	4 x 392t = 1568t	5.6t (aROV) + 4 x 260kg = 6.6t
Material	Steel shot @ ~£495/t = £776k High density concrete @ ~£590/t = £925k	£60k
Marine Ops	Multi-cat £5k /day * 45 days (max lift 35t) Rig vessel £15k /day * 8 days	Multi-cat £5k /day * 6 days
TOTAL	~£900k - £1150k	£90k

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