WES KNOWLEDGE CAPTURE

REPORT

WP2 – Offshore Operational Experience

OYKNOW-REP-0001

Revision History:

C2	17/09/15	Incorporate WES comments	M.Holland	D.Naylor	F.Tierney
C1	03/08/15	For submission	M.Holland	D.Naylor	F.Tierney
A1	09/07/15	Draft For Comment	M.Holland	D.Naylor	
Rev	**Date**	**Purpose of Issue**	**Prepared By**	**Checked By**	**Approved By**

CONTENTS

1. PURPOSE

Aquamarine Power has been asked by Wave Energy Scotland (WES) to produce a series of informative knowledge sharing reports. The contract is to facilitate knowledge sharing within the wave energy sector. The aim is to realise cost and time efficiencies by sharing knowledge and lessons learnt from previous experience so that other companies do not have to go through an exercise of learning the same costly lessons all over again.

Aquamarine Power has accumulated a wealth of valuable knowledge and learning through the design, fabrication, installation and operation of the Oyster 1 and Oyster 800 devices. Aquamarine Power recognise that knowledge sharing is a central component for the successful and timely deployment of wave energy projects. As such, Aquamarine Power is keen to share this knowledge for the benefit of the wider wave energy community.

There is a series of 5 reports covering different topics from the experience and knowledge that Aquamarine Power has gained. The topics under contract with WES are:

1. Offshore operational experience;
2. Corrosion & protection in a disturbed water environment;
3. Supply chain (marine components);
4. Tank testing of WECs;
5. Maintainability improvements from Oyster 1 to Oyster 800.

This report covers topic 1 – Offshore operational experience, as listed above.

The ownership of all Foreground IPR generated in connection with this contract shall vest in WES and no reproduction, sale, disposal, licence or disclosure of the Foreground IPR shall be granted or permitted without the prior written consent of WES.

2. LESSONS LEARNT SUMMARY

1. Two methods of constructing multiple pile foundations have been demonstrated at EMEC for Oyster 1 and Oyster 800 that achieve the end goal of drilling and positioning piles with sufficient tolerance to allow the installation of an accurately manufactured Wave Energy Converter (WEC) onto the foundation system.
2. Operations on a wave energy site using small or medium sized jack-up vessels are severely affected by the weather restrictions imposed on crew transfers and on vessel movements.
3. Large jack-up vessels with on-board accommodation that are capable of weathering all forecast conditions can operate 24/7 and deliver encouraging installation times for drilled pile foundations.
4. Large diameter single pile foundations are feasible and attractive in terms of reducing seabed dependency and installation costs and durations.
5. Installation of a large Oscillating Wave Surge Converter (OWSC) can be safely achieved, but careful consideration must be given to the installation weather conditions, device dynamics (during installation) and ballasting arrangements. There are substantial challenges in the use of crane barges for this type of installation.
6. Large WECs can be successfully installed onto the subsea using ‘float in / ballast down’ techniques without the need for large, expensive, crane vessels.
7. Attention has to be paid to the design details that prevent movement of grouted connections during the grout curing period and the seals that retain the grout in the annulus.
8. Vessel capability on Orkney was sufficient to complete all maintenance activities on the Oyster test sites.
9. Operations are inherently weather sensitive, and lack of planning can lead to inefficient time offshore.
10. Simple, robust procedures lead to an improved quality in task plan writing.
11. Onshore run-throughs of equipment and hardware lead to improvements in understanding and ease of installation.

12. Plan for daily diving activities should take into account diver core skills, experience and on-bottom time.
13. Mooring survivability and usability can be improved with simple modifications to riser and pennant wires.
14. Equipment can be used repeatedly submerged in seawater if particular attention is paid to its specification, maintenance and Quality Control process.
15. Equipment which can be used in a variety of different situations, such as a Hydraulic Power Unit (HPU) which powers many tools or the Magdrill which can drill a variety of hole sizes, should be available during all offshore maintenance operations.
16. Successful, safe and efficient diving operations are dependent on the availability of the correct tooling.
17. Communication from vessel to shore is a critical part of Safe Systems of Work (SSOW), ensuring the diver is working on safely isolated systems.

3. KNOWLEDGE AND LESSONS

Aquamarine Power has been developing the Oyster technology for a period of 10 years. Aquamarine Power has performed extensive Research & Development (R&D) activity and built, installed and operated two prototype machines (Oyster 1 and Oyster 800) and more recently have conducted two consecutive product improvement campaigns targeting areas for improvement from previous 'lessons learnt' activities.

Through the successful execution of two full scale device installations (Oyster 1 and Oyster 800), and consecutive product improvement initiatives, Aquamarine Power has gained a wealth of knowledge on numerous aspects of offshore operations including offshore planning, supply chain, vessel capabilities and weather limitations. Offshore operations are common to all wave energy developers and the wider community, including the supply chain, will benefit from Aquamarine Power's experiences to date. The following topics are covered in this report:

1. Piling
2. Oyster 1 and Oyster 800 device installation
3. Offshore vessels and weather dependency
4. Offshore planning and preparations
5. Offshore maintenance and tooling

4. PILING

4.1 Foundation Design Overview

Both Oyster 1 and Oyster 800 have been installed at around 15m water depth at the European Marine Energy Centre (EMEC) nearshore site at Billia Croo, Orkney. The seabed is comprised of a thick bed of moderately strong sandstones (Stromness Flagstones) in angled layers. This is a suitable material for drilled pile foundations.

The Oyster 1 design had 4 steel piles approximately 1 metre in diameter. These were drilled through and then connected by grouted connections to a permanent Pile Connection Frame (PCF). The PCF then provided the structural interface for the installation of the WEC.

The Oyster 800 design was substantially changed based on learning from the installation of Oyster 1. Twin piles, 2.75m in diameter, were positioned to the sides of the machine. The PCF was eliminated by incorporating pile sleeves into the baseframe of the WEC.

Piles were also installed for future device concepts (Oyster 801 and Oyster 802). These monopiles are approximately 4m in diameter.

The sections that follow describe the principal lessons that were learnt from the Oyster 1 foundation installation and how these were addressed in the Oyster 800 project.

4.2 Pile Installation Accuracy

Lesson learnt:

Multiple pile foundations have been constructed, using both a permanent and temporary template to achieve the end goal of drilling and positioning piles. These methods have been demonstrated with sufficient precision to allow for the installation of an accurately manufactured WEC onto the foundation system.

Identified problem:

The installation of a multiple pile foundation is not an activity that can practically be achieved to tolerances that are compatible with the direct attachment of a large machine by conventional means (e.g. bolted flanges). Measures must be put in place to control the precision of pile placement and to provide reasonable tolerances in the connection system.

Discussion of the issues:

Any multiple pile foundation system needs to provide a means of achieving a reasonable tolerance on the relative positioning of the piles and a means of accommodating that tolerance within the connection system. For the latter requirement, both Oyster 1 and Oyster 800 have used high strength grouted sleeve connections. These can be designed for many 10s of millimetres (but not 100s of millimetres) of misalignment. A very important consideration can be the verticality tolerance; a very small angle over a tall pile sleeve equates to a significant radial distance.

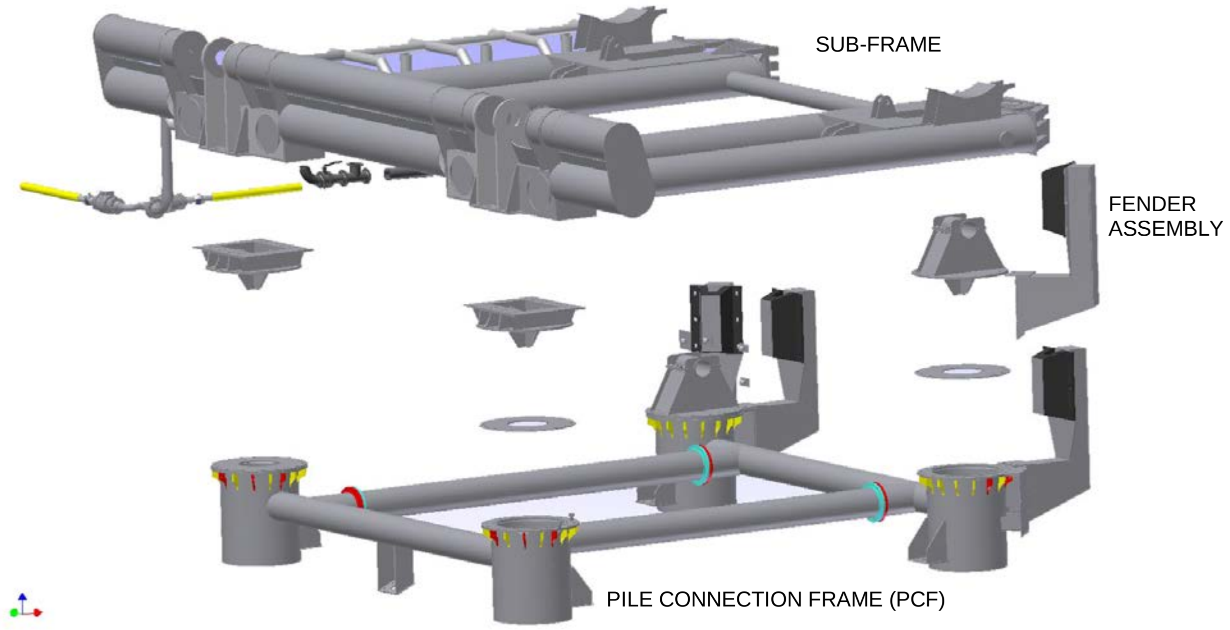

Figure 1 – Exploded view of Oyster 1 interface between PCF and sub-frame

The positioning of the Oyster 1 piles was achieved using a Pile Connection Frame. This permanent intermediate frame was placed on the seabed and levelled. The frontal area of the PCF was relatively small and hence its self-weight provided stability in moderate sea conditions during the drilling and installation operation. A jack- up, with a vertical drilling rig, bored through the 4 pile sleeves before placing the piles and grouting, first into the rock / pile interface and then the pile / PCF sleeve. This approach was successful, but there are (at least) three significant drawbacks:

- The space required for the PCF creates a geometry constraint that may be un-desirable. In the case of Oyster it raises the hinge height of the device reducing power performance and increasing bending moments on the foundation.
- The PCF adds to the CAPEX of every machine.
- Alignment issues are transferred to the interface between the PCF and the WEC.

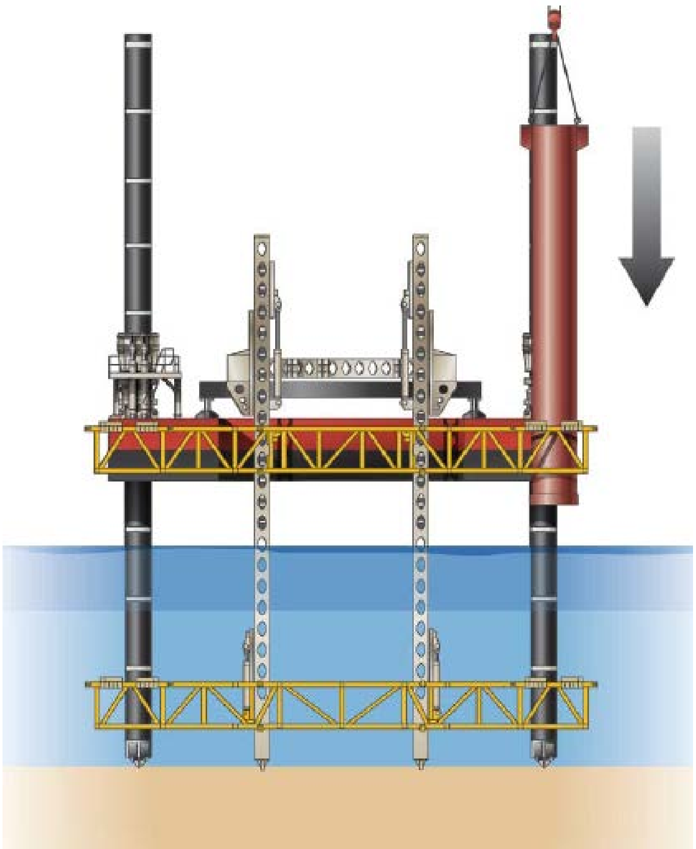

Figure 2 - Illustration of Oyster 800 pile drilling template

The Oyster 800 design addressed these issues by using a temporary drilling template during the drilling and pile installation phases. This template was then removed leaving 2 accurately positioned piles, for later installation of the WEC. The long term CAPEX saving was achieved, although for a one-off device this is offset by the engineering and manufacturing costs of the template. There is a slightly increased risk of the WEC fitting over the piles. This can be mitigated through accurate metrology of the template and of the WEC during manufacture. Again, consideration of how the engineering of the template ensures pile verticality is critical.

4.3 Jack-up Capability

Lesson learnt:

Operations on a wave energy site using small or medium sized jack-up vessels are severely affected by the weather restrictions imposed on crew transfers and on vessel movements.

Large jack-up vessels with on-board accommodation that are capable of weathering all forecast conditions can operate 24/7 and deliver encouraging installation times for drilled pile foundations.

Identified problem:

Small jack-ups, whilst having obvious advantages in terms of day rates and mobilisation costs, have significant operational restrictions when used on a wave energy site.

Discussion of the issues:

The foundations for Oyster 1 were installed using the medium sized jack-up vessel 'Deep Diver' (http://www.seacore.com/downloads/pdf/deepdiver.pdf). A number of related limitations in vessel capability and weather conditions resulted in a significantly extended installation duration:

- There is no on-board accommodation and therefore a crew transfer operation is necessary for every shift. Weather restrictions on crew transfers are substantially tighter than those for drilling operations. Consequently the vessel has to be abandoned at even modest increases in weather conditions due to the risk that crew might become stranded on board.
- The vessel is not rated for surviving storm conditions and can only be moved in fairly calm conditions. It is therefore necessary to take the vessel off the site well before any potential storm event. Even during the summer installation period, this risk can result in loss of a large number of working days.
- The combination of a 4 pile foundation solution and a smaller jack-up barge meant that the jack-up barge had to be re-positioned for the drilling of each pile location. This was a time consuming and weather dependent operation which added significant time and cost to the project. First of all, the weather had to be < 1.2m swell and < 20kts of wind for any positioning to take place. Then each of the 4 jack-up legs had to be securely positioned onto a competent rock seabed. When the jack-up barge was securely in position, personnel access via boat was only allowed in <1.8m swell and drilling in conditions up to 2.5m swell.

As a result of these limitations, it took 49 days to complete the operations to drill, install and grout the 4 x 1.125m piles of Oyster 1.

To counter the issues identified during the Oyster 1 project, Aquamarine contracted a large jack-up, Excalibur, for the Oyster 800 foundation installation (http://www.seacore.com/downloads/pdf/excal.pdf). Excalibur has on-board accommodation and is rated to weather the worst conditions anticipated at Billia Croo during the summer season. 24/7 operations are therefore feasible and were achieved in practice. Successes of this campaign include:

- Drilling, installation and grouting of 2 x 2.75m Oyster 800 piles in 2 weeks
- Drilling, installation and grouting of 4m monopiles (Oyster 801 and Oyster 802) in 6 and 4 days respectively

Further improvements have been identified both in the design and the drilling technology for large monopiles that give good confidence that these durations can be further improved.

Apart from the obvious challenge of day rate and mobilisation costs (particularly for one-off prototype projects) the large jack-up solution posed few operational problems. One issue that is of note however is the importance of jack-up foot positions. Competent, flat rock is required to ensure stability. Finding these conditions over the substantial footprint of a large vessel is restrictive, particularly for a solution (such as Oyster 800) where a particular jack-up orientation is required. Accurate bathymetry, geotechnical information and seabed diver surveys are essential pre-requisites to planning the operation and mitigating the risk that the jack-up cannot find a stable location from which to drill.

4.4 Monopiles

Lesson learnt:

Large diameter single pile foundations are feasible and attractive in terms of reducing seabed dependency and installation costs and durations. They introduce a number of device specific design challenges that have to be carefully considered.

Identified problem:

Multiple pile foundation systems impose significant restrictions on device placement because of the need to locate suitably level seabed over a large area.

Discussion of the issues:

In practise real seabed's, unlike wave tank floors, are rarely flat. This irregularity imposes significant restrictions on physically large systems that have to interface with the seabed. It is desirable to make the connection point as close as possible to the seabed in order to reduce bending moments and, in the case of Oyster, to increase power production.

A single pile (monopile) design has a significantly reduced footprint compared to a multiple pile foundation and therefore gives many more options in terms of device placement. There are a number of advantages as well as disadvantages to the monopile approach.

Advantages:

- Reduced seabed dependency
- Large diameter provides good bending moment capacity.
- Reduced drilling times
- Enables WEC mechanical connection

Disadvantages

- Yaw capacity
- WEC installation (compared to the Oyster 800 design, vertical access to the pile top is not available)
- WEC design (particularly in relation to in situ maintenance access)

5. DEVICE INSTALLATION

5.1 Installation Design Overview

Aquamarine Power have successfully installed 2 large scale WECs at the EMEC nearshore wave test site in Billia Croo, Orkney.

Oyster 1 comprised an 18m x 10m flap mounted on top of a baseframe. In total this machine weighed around 250 tonnes. It was attached to the previously installed Pile Connection Frame (PCF) by 4 large bolted flange connections. Flap and baseframe were locked together during installation. Installation was achieved by partially filling the flap with water so that the machine became negatively buoyant and then lowering into position using a crane barge.

Oyster 800 is a substantially larger machine, with a 26m x 12.5m flap, surrounded by an external baseframe. The baseframe included the pile grout sleeves, thus eliminating the need for a separate PCF. Overall the machine weighs around 1000 tonnes. In a similar manner to Oyster 1, the flap and baseframe were locked together during the installation operation. However, Oyster 800 eliminated the crane barge requirement by towing the machine using its own buoyancy and then sinking it onto the pre-installed piles.

5.2 Oyster 1 Installation

Lesson learnt:

Installation of a large Oscillating Wave Surge Converter (OWSC) can be safely achieved, but careful consideration must be given to the installation weather conditions, device dynamics (during installation) and ballasting arrangements. There are substantial challenges in the use of crane barges for this type of installation.

Identified problem(s):

OWSCs are subject to significant motions (particularly surge) when in a latched down installation configuration, even in calm conditions.

The movement of water within partially filled ballast compartments in response to changes in vessel attitude (free surface effects) can adversely affect device stability during installation.

Crane barges are of limited use in wave environments because of the amplified vessel motions at the end of the crane jib.

Discussion of issues

Oyster 1 was installed with the flap and baseframe locked together in a horizontal configuration. This installation package presented a frontal area of approximately 18m x 4m, which, when suspended from a crane hook resulted in significant surge motions during installation, even in benign conditions. A two stage guidance system was developed during the installation engineering phase to control these motions. The first was a fendering system which the WEC could swing against whilst still a metre or so above its installed position. These rubber fenders restricted the WEC motions to a magnitude where cruciform stabbing guides installed on the base of the WEC could guide the machine accurately into place on the top of the PCF pile sleeves. The final installation accuracy was within +/- 6mm; the radial clearance on the main connection bolt holes.

The flap was constructed from 5 horizontal tubes 18m long x 1.8m diameter. These tubes could be flooded or emptied to alter the overall weight of the WEC. They did not have internal bulkheads. Consequently, installation methods involving partially filled ballast tanks had to be discounted, because the free surface effects rendered them unstable (The water would run to one end of the tank, tipping the device on its end). This was realised during the installation engineering phase which followed the completion of the WEC design itself. This highlighted a risk of having the WEC design separate from installation engineering.

Oyster 1 was installed using a crane barge. This vessel pitched and rolled even in very calm conditions; effects that are amplified at the end of the crane jib. These jib motions have three significant detrimental effects:

- The vertical motion of the jib, combined with those of a secondary floating barge, means that there is a risk associated with lifting a large item off the deck (of the secondary barge). Unless the lifting speed is fast enough the object may re-contact the deck with damaging and safety critical consequences. During the Oyster 1 campaign, the installation method had to be changed to avoid lifting from the deck of a barge in order to overcome this restriction. As a result, Oyster 1 was towed to site, supported by the crane.
- At the point that the WEC is suspended horizontally in the water column, it’s dynamics, including heave motion, are dominated by the local wave particle motions (assuming the negative buoyancy is quite small) which will be different from the crane jib motions. This can result in the crane wire going slack, followed by large dangerous snatch loads. This risk was mitigated for Oyster 1 by installing only in very benign conditions, which significantly limited availability for installation. This lesson was learnt when considering the installation strategy for Oyster 800.
- As the WEC lands out on the PCF, vertical motions can result in large impact forces.

Figure 3 - Installation of Oyster 1

5.3 Oyster 800 Installation

Lesson learnt:

Large WECs can be successfully installed subsea using ‘float in / ballast down’ techniques without the need for large, expensive, crane vessels.

Identified problem(s):

The surge motions that were anticipated during the installation of Oyster 800 demanded a different and more robust means of guidance compared to Oyster 1, which could also broaden the range of installation conditions and reduce the risk of a failed installation attempt.

The WEC needed to be maintained in a horizontal attitude as it was ballasted down and moved vertically through the water column

Installation of such a large machine was not feasible or commercially viable using available crane vessels.

Discussion of issues

The Oyster 1 installation had been exceptionally weather dependent. This needed to be improved for the substantially larger Oyster 800 machine, and is essential for mass installation of commercial machines. To help achieve this, the piles for Oyster 800 were moved from underneath the machine to the sides giving unhindered vertical access to the pile tops. This change had another primary benefit of enabling a hinge position closer to the seabed. Strong, yet compliant, plastic ‘stabbing posts’ were mounted to the top of the WEC pile sleeves. Installation guidance was achieved by mooring the floating WEC over the piles and then lowering the stabbing posts into the top of the piles. Alignment of the WEC onto the piles was thus guaranteed in the subsequent ballasting operation.

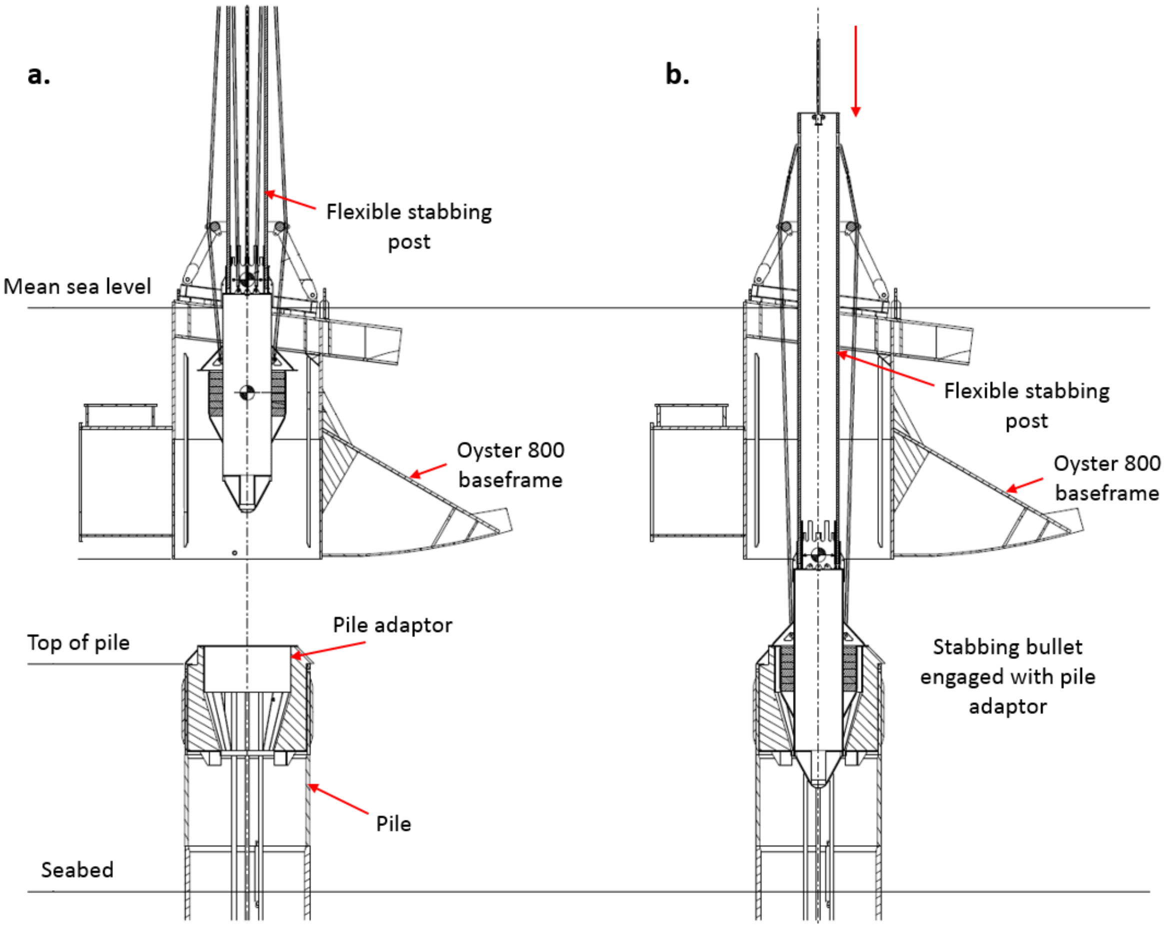

Figure 4 - Illustration of the Oyster 800 stabbing post arrangement. The WEC is positioned over the pile (a.), and the stabbing guide is lowered through the pile sleeve on the Oyster 800 baseframe by varying its buoyancy (b.). The stabbing bullet at the end of the stabbing post engages with the pile adaptor insert. This enables the WEC to be guided into position.

In order to complete a successful installation the WEC had to be maintained in a horizontal orientation as it was ballasted down through the water column. As with Oyster 1, the primary structure of the Oyster 800 flap was comprised of horizontal tubes. This time however the tubes were divided by bulkheads so that the free surface effects were limited and the trim of the device could be maintained. The design was heavier and had less buoyancy at the hinge end, and therefore had a natural tendency to pitch downwards. To counteract this, a temporary buoyancy tube was attached to the hinge end of the machine.

Oyster 800 was successfully installed using the guidance and ballast systems described above, eliminating the need for large, expensive crane vessels.

Figure 5 – Installation of Oyster 800

5.4 Oyster 800 Grouting

Lesson learnt:

Attention has to be paid to the design details that prevent movement of grouted connections during the grout curing period and the seals that retain the grout in the annulus.

Identified problem(s):

To ensure connection strength, grouted connections must be prevented from movement during the grout curing period. This is not trivial when connecting a wave capture device.

Conventional inflatable grout seals can only accommodate a small deviation from co-axial of pile and pile sleeve.

Discussion of issues

The high strength grouted connection between the pile sleeves on the Oyster 800 baseframe and the piles had to be made up with the complete WEC in situ. The flap was kept in the ballasted down configuration for this operation. The WEC was held stable during the grouting operation by a combination of features. Vertical loads were taken by a combination of land out pads within the pile sleeves and temporary installation legs at the opposite (landward) side of the device. Lateral loads were resisted by large diameter (110mm) screws located at the neutral axis of the pile sleeves that were wound in to make contact with the piles.

In a conventional monopile, inflatable grout seals are commonly used to seal the base of the grout annulus in preparation for the grout pore. However, in a multiple pile foundation, where one function of the grouted connection is to accommodate tolerance on position of one pile relative to another, there can be a significant deviation from co-axial of the pile and pile sleeve. Inflatable grout seals are not designed to seal this irregular annulus. A simple alternative solution of a split flange plate bolted onto the pile beneath the sleeve proved to be an adequate solution to this grout sealing problem.

6. OFFSHORE VESSELS

6.1 Vessels and Weather Overview

A multicat is frequently used by Aquamarine Power as the dive vessel on the Billia Croo nearshore test site. Commonly used multicats include the C-Salvor and C-Odyssey owned and operated by Leask Marine. A workboat, the Uskmoor, is also infrequently used. Maintenance activities for both Oyster 1 and Oyster 800 have been designed to be compatible with these standard and readily available vessels.

The weather at the Billia Croo nearshore test site is very changeable, and close monitoring of the forecast is required to ensure it is safe to remain moored on site. Different vessels have different levels of weather sensitivity and mooring capacity. Offshore plans should consider works to be completed at differing water depths, to allow flexibility depending on the weather.

6.2 Vessel Capability

Lesson Learnt:

Vessel capability on Orkney was sufficient to complete all maintenance activities on the Oyster test sites.

Identified Problem(s):

Maintenance activities can be restricted by the stability, crane and mooring capabilities of vessels available.

Discussion of Issues:

Aquamarine Power have used typical medium sized multicats for diving and maintenance operations on the Oyster test site. This class of vessel are around 10m beam and 20-25m overall length. They are typically equipped with a range of winches, deck cranes and bow and/or stern rollers.

The two most frequently used multicat vessels on the Oyster site are the C-Salvor and C-Odyssey, owned and operated by Leask Marine. A workboat, the Uskmoor has also been used infrequently. This vessel is generally avoided however due to limitations in deck space, crane and winching capability and increased weather sensitivity.

The C-Salvor has six winches, which are used for mooring and heavy pull/tow operations. The main towing winch has a Safe Working Load (SWL) of 40te, with five additional tugger winches. The crane is centrally mounted, maintaining good vessel stability during lifting operations. The vessel layout facilitates a large amount of available deck space towards the aft for storage of hardware, an important consideration when planning offshore activities and equipment requirements. It does feature a two-level deck however, which restricts the amount of deck space on the fore deck. Full details on the C-Salvor equipment can be readily obtained from the vessel specification sheet (http://www.leaskmarine.com/vessels/mv-c-salvor/item/download/28_5d4ff3a59d5e1bede2122e7f0298a787).

The C-Odyssey has four winches, with a 60te towing winch and three 15te tugger winches. It has a bow roller and an aft roller. In addition it has two cranes, with a deck crane at the bow and another deck crane at the centre aft. The layout of equipment on the deck of the C-Odyssey must consider that the mooring lines pass across the deck to the central winches. This limits available space for stowage of compressors, Intermediate Bulk Containers (IBCs) and rigging/hardware. Full details on the C-Odyssey can be readily obtained from the vessel specification sheet (http://www.leaskmarine.com/vessels/mv-c-odyssey/item/download/27_bd099ecaea388f6cea17828b4430b10d).

Recovery and installation of the Oyster 800 cylinder modules (23.5te), accumulator modules (4te), and other maintenance activities were successfully achieved using the C-Salvor. These operations are discussed in more detail in OYKNOW-REP-0005 - WES Knowledge Capture - WP6 - Maintainability Improvements.

6.3 Weather Dependency

Lesson Learnt:

Diving operations are inherently weather sensitive, and lack of planning can lead to inefficient time offshore.

Identified Problem(s):

Wave conditions will frequently change on site during the day, contrary to forecast conditions. If there are not sufficient alternative tasks that can be continued, the dive day has to conclude.

Weather assessments should not be solely focused on wave conditions. Wind can be an issue, as this prevents the use of the crane. On the Oyster site, the crane was used to launch and recover a dinghy used for mooring operations. High winds could therefore prevent mooring and a day's diving.

In general, the weather changes very suddenly, and within 15-20 minutes could be unsuitable for any work to take place.

Conditions at the Billia Croo nearshore site are generally calmer in the afternoon/early evening.

Discussion of Issues:

It is important to have a range of tasks available to complete on a day offshore, covering work high in the water column and on the seabed. There is less wave motion on the seabed, meaning that work can be completed in less favourable surface conditions. This ensures that work can take place more efficiently, with 'good' days spent completing critical works high in the water column, supported by seabed works on the 'poor' days.

On days of offshore operations, the dive team consistently left Stromness at 08:00 and stayed on site until 17:00-17:30. The conditions are generally at their calmest after midday. It may be more advantageous to allow night diving, either having two teams to allow 24hr working, or beginning a day at 13:00, and ending at 23:00.

The contract with diving contractor should contain clear, agreed guidelines regarding acceptable wind and wave conditions at the offshore site. For wave and wind predictions, Aquamarine Power use commercial sites, such as Buoyweather and Magic Seaweed, EMEC wave data, and an Aquamarine Power Billia Croo specific forecast. The Aquamarine Power forecast model is a nearshore wave forecasting model, based on freely available meteorology data and the site specific bathymetry. Internet access on-board the vessel enables review of the most up-to-date forecasts in order to make informed decisions about the safety of working conditions.

The decision to operate in marginal conditions is at the discretion of the dive supervisor. At the Billia Croo test site, wave conditions above 1.8m H_s will generally prevent diving from taking place. In addition to being dependant on wave conditions, large lifting operations can be affected by the wind speed. The decision to complete a lifting operation is at the discretion of the vessel skipper. At wind speeds above 25kts, it is not recommended to continue offshore operations as it will not be possible to recover the dinghy used for mooring operations. It is also inherently unsafe to use the dinghy for mooring operations in rough conditions, as the inshore moorings are close to a rocky headland.

At the Oyster 800 nearshore site at Billia Croo, wind direction should be considered when reviewing wave height predictions and planning offshore works. A strong easterly wind will frequently lead to a significant over-prediction of wave height. Wave height predictions tended to be accurate for a strong westerly wind.

7. OFFSHORE PLANNING

7.1 Offshore Planning Overview

There are three important aspects to the preparation for offshore activities. These are the writing and approval of task plans, onshore run-through of offshore procedures, and daily planning.

The task plan is produced in collaboration between the engineering team and the offshore representative, and is distributed to the diving contractor for review and acceptance in advance of the task. It provides the method statement for the offshore activity, giving a detailed breakdown of the task, quality critical details and safety issues. Production of a quality task plan requires all aspects of the operation to be considered in detail. This leads to a better understanding of the nuances of the task, improved offshore efficiency, and identifies all required information to allow safe completion of the work. Feedback on task plans from the offshore team can lead to design and access improvements. Examples of this include the use of bolts instead of studs, including additional lifting eyes or rigging locations, and reaction faces for bolt tightening equipment.

A number of involved or critical tasks are supported by onshore run-throughs of the offshore procedure. This enables feedback from the dive team to be captured and acted upon in good time, where appropriate, to improve the operation. Onshore run-throughs reduce the likelihood of unsanctioned changes being made offshore, which may affect the integrity of the installed hardware, and reduces the time taken to complete operations.

All tasks are planned with thorough consideration of dive skills, qualifications and an awareness of the expected water depths and task durations.

7.2 Task Plan Writing

Lesson Learnt:

Simple, robust procedures lead to an improved quality in task plan writing.

Identified Problem(s):

Task plans often contain too much text without complementary images, which is overwhelming to the reader. This can also obscure critical safety and quality information.

Discussion of Issues:

The adoption of a formal procedure for writing task plans resulted in the production of substantially improved documents in terms of quality and information. Guidance was given highlighting the importance of identifying what is critical to the task at hand, including using pictures to produce an installation storyboard.

The task plan is split into two sections to improve the ease of following by the dive team. The first section contains all essential safety and quality information to complete the task. This includes the equipment list, task specific safety information and hold points, a short pictorial guide to the activity, Critical to Quality (CTQ) hold points, and a feedback section to note down task plan deviations and suggested future changes. The second section includes the detailed procedure, giving additional background information and detailed instructions to enable completion of the task.

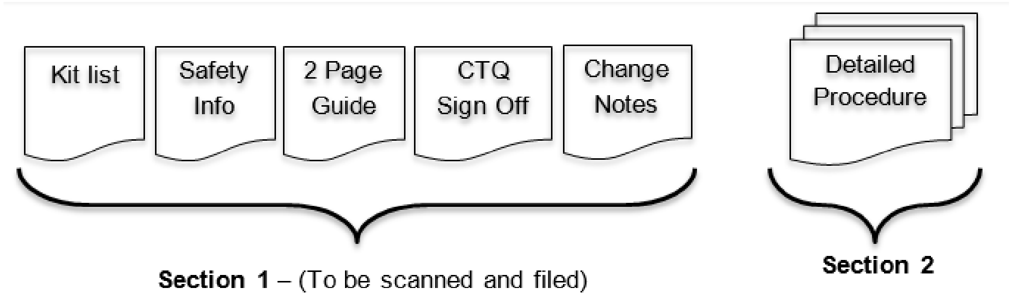

Figure 6 - Task plan structure

Task plan equipment lists include detail on bolt/nut specification and length, rigging, tools required, and equipment location/supplier. This was helpful when getting task plan equipment boxes together, both for requesting equipment from the diving contractor and ordering additional items in good time.

A robust and practical procedure of approving offshore task plans was implemented, with the responsible engineer and dive representative sharing the writing and checking as required, with the lead engineer approving. This checking and approval process maintained a high quality in what had been written, which in turn increased the confidence within the offshore team in following the plan.

It may seem trivial, but a simple improvement to efficiency and quality of offshore activities was achieved by providing a reliable, high-speed colour laser printer in Orkney so that providing hard copies of the most up to date task plan was facilitated.

7.3 Onshore Task Run-through

Lesson Learnt:

Onshore run-throughs of equipment and hardware led to improvements in understanding and ease of installation.

Identified Problem(s):

The offshore team is not always aware of the design details and features in equipment delivered for installation. Frequently, a task would not be completed to the required quality level, or time would be wasted with diver on station while problems were diagnosed using radio and video communications.

Discussion of issues:

Adopting a process of diver onshore dry-runs is beneficial, particularly for non-routine tasks or where there are particular safety or critical quality requirements. The onshore dry-runs covered the main salient points of the task plan, running through methodology, risks and sharing knowledge of how the equipment should be used.

The dive team will frequently offer many ingenious practical solutions which will enable completion of the task. However, they may not have full understanding of some of the engineering or quality requirements imposed during design of the hardware, or the full details of how the hardware is interended to function. These details can often impact the plan for offshore works, and uncontrolled deviation can severly impact the quality of the installation/operation. By completing the dry-run, the input toward practical methods for installation can be reviewed and given due consideration.

The timing of the dry run is important. It needs to be sufficiently early to allow time to modify the task plans and hardware as required, but it also needs to be close enough to the task that the team are engaged in the activity, don't forget details, or are pulled to another job before installation.

One example of an effective onshore run-through was the installation of the modified Oyster 800 sea chest covers. APL's original plan was to lower the covers using the vessel crane, and land them upon stabbing points on the flap structure. Following suggestions from the dive team, a reel of steel wire was added to the top of these stabbing points and passed through the holes on the cover to be secured back to the deck of the vessel. This ensured that the diver could maintain a safe distance to the covers as they were lowered through the water column, and it prevented impact with existing hardware on the flap structure.

Another example of the benefits of onshore run-throughs is in the recovery and installation of the Oyster 800 cylinder modules. Onshore run-throughs and lessons learnt reviews with the dive team enabled continual refinement and optimisation of the procedure. This allowed the operation to be shortened from 10 days at the first removal attempt, to just over 2 days for the final installation.

7.4 Daily Dive Planning

Lesson Learnt:

Plan for daily diving activates should take into account diver core skills, experience and on-bottom time.

Identified Problem(s):

Daily planning does not always consider impact on dive time by dropping to lower water depth. Appreciation of this, and of available diver capabilities, is important to ensure offshore campaigns can be appropriately planned.

Unless on permanent contract, diving contractors will have a number of other jobs ongoing. Where these are viewed as more critical, the more experienced divers may be pulled to these leaving a limited pool available for work on Oyster. This can severely affect efficiency, quality and safety due to a lack of experience within the team.

Discussion of issues:

When planning a day's offshore activities, during a dive a diver can spend approximately:

- 2.5-3 hours at the depth of the Oyster 800 base frame (approximately 28-35ft / 8.5-10.5m).
- 1.5 hours on the seabed (approximately 50ft / 15m).

Full details of on-bottom times can be found through inspection of appropriate dive tables. The APL dive representative used US Navy dive tables, examples of which can be readily found. These tables use imperial units as standard practice. Avoiding going to greater depths, e.g. by performing inspection tasks from above, increases the available dive time.

Daily offshore plans should consider the diver skills required to complete activities, such as inspection, welding and cutting. If five divers are on-board the vessel, four dives will be possible during the day with one diver acting as a standby. The divers should be used accordingly to maximise productivity. To maximise on-bottom time for an experienced diver, it is preferable to recover tools/fasteners dropped to the seabed later in the day with a less experienced diver.

Aquamarine Power and Leask Marine adopted a diver experience rating. Divers are rated as level 1 and 2, with 1 being the more experienced. Based on the activities planned on a particular day, the dive contractor was required to provide a minimum number of Level 1 divers. In 2013 and 2014, the dive vessel was block booked throughout the summer to minimise the need for reactive dive activities and enable long term planning of diving resource to take place, minimising the chances of ending up with an inexperienced crew.

A single offshore representative or offshore engineer who can offer consistent planning and organisation of offshore activities is important, as is having a consistent dive supervisor and dive team.

The offshore engineer/project manager should liaise regularly with dive representative and diving contractor to ensure priorities and diver skill requirements are clearly understood. Dive representatives should have an appreciation of the implications of the tasks being completed, in order that the site is left in a safe condition at the end of each day. When tasks have to be left incomplete, either due to weather or time constraints, assemblies/hardware must be left in a secure condition such that survivability will not be compromised if unforeseen weather conditions prevent return for a number of days or weeks. The outstanding activities for each task are reported in the Daily Progress Report (DPR).

8. OFFSHORE MAINTENANCE ACTIVITES

8.1 Offshore Maintenance Overview

Once onsite, the vessel has to moor up, establish communications to shore and prepare equipment to enable diving to commence.

A simple mooring system was used for Oyster 800, with 4 mooring cans on each corner of the WEC and each connected to a large chain clump on the seabed. Looped back pennant wires at the top of the mooring can were used for the connection to the mooring lines.

Radio communications occur at the conclusion of every dive to give a progress update, making reference to the daily priority list. An onshore radio log is used to record these communications, and updates can be given to other staff. Internet communications are possible between the vessel and shore enabling real time communication of information to all staff.

Tools and equipment used offshore follow a thorough maintenance strategy, and are checked both onshore and offshore prior to use by the diver. Regular tools used include lever hoists, torque wrenches, a Magdrill, a compressor and a variety of hydraulic HPUs.

8.2 Nearshore Vessel Moorings

Lesson Learnt:

Mooring survivability and usability can be improved with simple modifications to riser and pennant wires.

Identified Problem(s):

Moorings were failing at the connection at the base of the mooring can as the hard eye at the top of pennant wires is a weak point in the mooring structure.

Connecting mooring lines to the mooring cans posed a safety hazard in sub-optimal conditions due to the pennant wire loop, used to connect between the mooring rope and the can, being either too short or too long.

Discussion of Issues:

There are four offshore mooring cans on the Oyster 800 site. Two of these are inshore of Oyster 800. A drawing of the inshore mooring arrangement is given below.

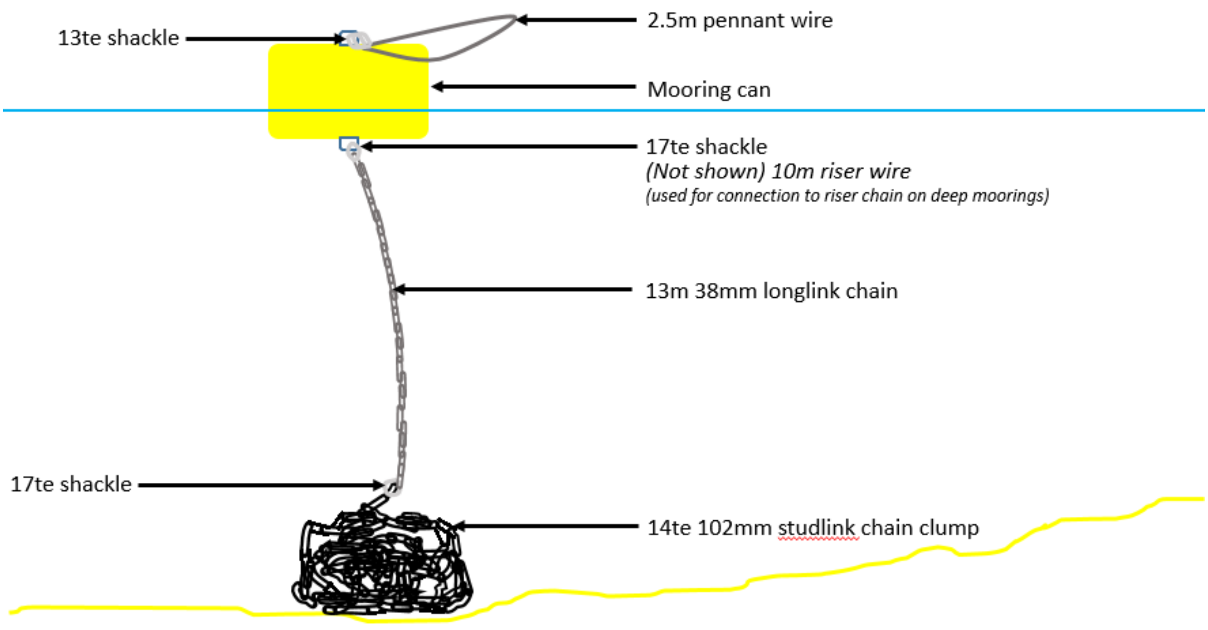

Figure 7 - Illustration of the inshore Oyster 800 mooring arrangement

At the Billia Croo test site, the mooring cans are subject to significant forces. The pennant and riser wires used by APL have a hard eye at either end, with the wire braids exposed and free to rub against the can as it moves in wave conditions. This has led to wear of the wire braid, contributing to failure of mooring lines and loss of station keeping of the mooring can. A simple solution was to weld in place three horseshoe shaped metal brackets around each hard eye. Inspections since installation have shown that these have a positive impact on protection of the wire beneath.

Figure 8 - Horseshoe brackets on pennant wire hard eye

Recent failures of the APL moorings have been a result of failure of the riser chain links. Inspection of the recovered moorings revealed that the can, shackles and riser wires were all intact. Elements of the recovered chain showed fractures in a significant number of the chain links. Temporary moorings have been used during 2015 with positive results, although they come at a high cost which prohibits prolonged use.

Regular mooring inspections are required in order to capture any issues or damage before failure occurs. Quarterly inspections, or inspections in advance of a major maintenance campaign, are required to mitigate against mooring failure. This will provide a greater level of safety assurance and limit potential programme delays which a failure may cause.

The pennant wire loop length has been trialled with 10m, 5m and 2.5m lengths. Operational feedback has led to the selection of a 5m wire (2.5m doubled back) as the optimum length for ease of use and handling by the dive team.

8.3 Use of Offshore Equipment

Lesson Learnt:

Equipment can be used repeatedly submerged in seawater if particular attention is paid to its specification, maintenance and Quality Control process.

Equipment which can be used in a variety of different situations, such an HPU which powers many tools or the Magdrill which can drill a variety of hole sizes, should be available during all offshore maintenance operations.

Identified Problem:

A range of tools are required by the dive team to complete offshore maintenance. These include hand tools, Hydraulic Power Units (HPUs), compressors, hydraulic and pneumatic tools, and lever hoists. Ease and range of use, diversity, and maintenance strategy all have to be considered when specifying equipment in order to maximise effectiveness.

Discussion of the Issues:

Aquamarine Power use Tiger SS11 lever hoists, as these have been designed specifically for use in the offshore environment, with safety features exceeding that of IMCA D 028. Materials and coatings are suitable for seawater immersion, and safety features include a dual brake mechanism and a redundant brake pawl.

A compressor with a flow rate of 8.1m^3/min at 7 bar was used for pneumatic tooling, and with an additional pressure regulator was also used to raise the Oyster 800 flap to the surface during deballasting operations. A Stanley HPU was used to operate all hydraulically-operated tooling. Failures to the Stanley HPU had a significant impact on the number of tasks which could be completed offshore. APL assembled a bespoke HPU with an adjustable pressure flow for offshore hydraulically-operated valve operations. HPU and compressors on the vessel deck were subject to corrosion from sea spray. Fabric covers were unsuccessfully trialled, but a simple solution of using a diesel aerosol spray proved successful in protecting components from salt corrosion.

APL use a number of tools for offshore drilling operations. These include a pistol drill, Magdrill and pneumatic rock drill. The pistol drill is suitable for drilling of small holes (<M12) in soft/thin materials. The Magdrill is powered by the Stanley HPU. It is suitable for larger holes (<26mm), and enables precise drilling into metallic components. It operates optimally on horizontal surfaces. Simple metal drilling templates, fabricated onshore, are used as an aid with the Magdrill. On vertical and painted surfaces there may not enough magnetic pull to maintain position during drilling. The pneumatic rock drill is an onshore drill, adapted for use in subsea conditions. It is used for drilling holes for seabed anchor bolts.

Where the Magdrill is not suitable due to spatial constraints/painted surfaces, Broco burning equipment can be used for rough cutting of holes.

A variety of tools have been used for tightening fasteners on flanges and bolted connections, including torque wrenches, an impact wrench, and hydraulic tensioning tools. The tooling selected depends on the size of the fastener being tightened, the target torque, diver access, the criticality of the joint, and the length of protruding stud. Correctly dimensioned bolts are preferred over studs for flanges, as they enable a torque wrench with a deep socket to be used. Crows-foot adaptors can be used to tighten fasteners with long protruding stud lengths which preclude the use of deep sockets.

There is a benefit to be gained by taking the time to inform the offshore/installation team of the theory behind bolted connections, in order they gain a greater appreciation of the importance of the multiple pass tightening strategy (such as 50%/70%/100%). This understanding will allow time to be apportioned correctly to the flange tightening task during offshore planning. A flange tightening record should be kept, to provide evidence beyond just that of the Daily Progress Report.

8.4 Preparation of Offshore Equipment and Tooling

Lesson Learnt:

Successful, safe and efficient diving operations are dependent on the availability of the correct tooling.

Identified Problem(s):

The cost and time delays associated with incorrect or faulty tooling are very large compared to an equivalent onshore task.

To ensure reliability of offshore equipment, a robust and thorough maintenance strategy must be followed.

Discussion of Issues:

Tooling required for each potential task should be identified and documented, providing guidance to design engineers and for offshore teams. Where new tooling is required, this should be recognised early to allow onshore preparation time and appropriate experience/training to be identified. Detailed equipment information is included in task plans, enabling the offshore team to plan accordingly.

Clashes between tooling and existing hardware during the movement of the tool through its operating range should be avoided wherever possible. 3D CAD models of tooling produced in Solidworks (or similar software), can be tested by the responsible engineer on a full CAD model of the device, to ensure there is sufficient space to operate the equipment. This should be considered during the design stage.

When planning tasks, it should be noted that hydraulic tightening can appear to be a frustratingly slow process. Experience on Oyster 800 is that it takes a diver a minimum of 90 minutes to completely tighten a 20x M36 bolt flange, due to the requirement to complete multiple passes at an increasing torque.

Following use offshore, the tooling is immediately cleaned with fresh water, sprayed with WD40 and left to dry. It is the responsibility of the offshore team to maintain equipment on the vessel. Following return to shore the onshore team repeat the maintenance process, check tooling operation and store equipment such that it is in good condition for the next deployment. Failure to operate will result in the tool being quarantined for further detailed inspection.

Onshore maintenance of all tooling should be completed regardless of offshore submersion, as sea spray can dramatically affect the long term reliability of tooling.

Aquamarine Power have followed a formal offshore lever hoist use and maintenance policy, which was developed with input from the dive representative, offshore engineer, senior engineering team, HSE manager, the equipment supplier (Tiger) and IMCA. Further details about this can be provided on request. Aquamarine Power have not experienced an offshore/operational failure since the adoption of this policy.

8.5 Communications to Shore

Lesson Learnt:

Communication from vessel to shore is a critical part of Safe Systems of Work (SSOW), ensuring the diver is working on safely isolated systems.

Identified Problem(s):

Good and timely communications to shore are an essential requirement to ensure safety and efficiency.

Information was lost by the 'Chinese whispers' effect, with updates being passed down the chain of communication.

Discussion of Issues:

Significant volumes of time can be wasted due to the use of equipment which is not fit for purpose for the activity (such as having to use a spanner instead of a torque wrench), members of the dive or onshore teams not having a thorough understanding of the daily activities, and the timing of work being completed simultaneously onshore.

The daily priority list was sent to all onshore operations staff, ensuring awareness of the tasks being completed offshore. Radio messages were consistently received from the vessel on the completion of each dive, giving an update which related back to the daily priority list to minimise the potential for any confusion. One person had responsibility onshore for the radio each day, and a radio log was implemented to record all communications with the vessel.

There is no internet or mobile phone signal on the Oyster test site. A modem was installed on the primary vessel used on the Oyster site to allow another branch of communication. This was linked to the onshore modem to allow internet access when the vessel was on site. This facilitated communications of images and information via email and skype. This has enabled clarification of tasks or unexpected site conditions by providing an opportunity for a direct line of communication back to engineering staff.

All direct-to-staff internet based communications should be preceded by a radio communication to shore to gain permission for the call. A summary of the discussion should then be given to the onshore radio operator to enable the resolution to be reported in the radio log.

A debrief between APL staff is held at the end of each dive day, and the Daily Progress Report (DPR) is submitted following this. Attendance at the debrief is critical since it is the best, and occasionally only, opportunity for the engineering team to obtain crucial information from that day's activities from the offshore representative. The DPR is submitted to all APL staff every evening of a dive day to update on progress, and is a valuable reference for the engineering team. It covers details of all activities completed, information about tasks still to complete, appropriate pictures, and positive and constructive feedback on task plan/hardware quality.