GeoWAVE

Geotechnical design solutions for the offshore renewable wave energy industry

Final Publishable Summary Report

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The research leading to these results has received funding from the European Union Seventh Framework Program (*FP7/2007-2013*) under grant agreement no. 287056

1 EXECUTIVE SUMMARY

Although Wave Energy Converter (WEC) technology is mature, the wave energy industry is still reliant on using anchoring and mooring solutions that have been developed for the offshore oil and gas industry. Compared to this established industry, the design life of a WEC and its moorings is much longer than the temporary periods for floating oil and gas facilities and the WEC must respond dynamically to wave loading (rather than being kept as motionless as possible) in order to generate electricity. These challenges are exacerbated as the proportion of the installed costs associated with moorings and anchors for a WEC are an order of magnitude larger than that for a floating oil and gas facility (20% vs. 2%). Previous WEC demonstrators have employed conventional mooring and anchoring arrangements. Whilst the associated costs can be borne by a demonstration project they would be prohibitively expensive for a fully commercial wave farm with tens or hundreds of WECs. These unique requirements require specifically adapted mooring and anchoring solutions for WEC installations. This is the technical challenge that has been addressed by GeoWAVE, so that widespread deployment of WECs on a commercial scale becomes viable.

The GeoWAVE Consortium has developed a new holistic mooring solution, combining recent technological advances in mooring and anchoring components. This has involved bringing together SMEs with novel products including an in-line elastic tendon/damper that can be optimised to minimise loading in the mooring lines and tune the hydrodynamic performance of the WEC (Seaflex AB, Sweden), and a novel drop-anchor that can be used in challenging cohesionless seabed conditions (sand), is geotechnically efficient (for low cost) and can be installed more easily, cheaply and precisely (GeoProbing Technology, Norway). At various points, a third SME has either been a wave energy developer (Wavebob, Ireland, followed by Pelamis Wave Power Limited, UK) or a consulting engineering firm working in the offshore sector (Cathie Associates, Belgium) to provide specialist expertise regarding the ultimate application of the new solution to WEC station keeping.

Three research partners provided expertise in geotechnical engineering for the anchors (University of Dundee, UK; University of Western Australia, Australia) and in hydraulic engineering for the moorings (University College Cork, Ireland). State-of-the-art experimental facilities were provided for testing of the new mooring and anchoring components including, for the first time, a unique combination of wave basin and geotechnical centrifuge modelling facilities, allowing the new mooring line performance to be characterised in the wave basin, with the test data being subsequently applied to model anchors in the centrifuge tests. This was supported by numerical and analytical modelling.

From the outputs of the six work packages, GeoWAVE has redefined the state-of-the-art for mooring WECs at challenging cohesionless seabed sites. A new mooring configuration, consisting of taut mooring lines, coupled with Seaflex tendons and an efficient drop anchor has been shown to perform reliably under the dynamic loading of extreme sea states and potentially reduce costs by between 40-60%, compared to existing mooring and anchoring arrangements. Design and costing methods that

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can be used to implement the new solution have also been developed, removing a significant technical hurdle to installation of commercially viable wave energy farms.

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2 Project Context and Objectives

2.1 Context

Although Wave Energy Converter (WEC) technology is developing, the wave energy industry is still reliant on using anchoring and mooring solutions that have been developed for the offshore oil and gas industry. There are significant economic differences associated with moorings and anchoring for WECs compared with oil and gas facilities; approximately 18% of the installed wave energy costs are associated with the station-keeping of WECs, compared with only 2% for an installed floating oil production facility.

The very low relative costs associated with anchoring oil and gas facilities has affected the way existing mooring and anchoring technologies have been developed. As the anchors and mooring are such a small proportion of the cost of producing a barrel of crude oil, cost-savings in the mooring/anchoring system have little effect on the bottom line. Secondly, the anchors and moorings are responsible for keeping a far larger proportion of the capital expenditure safely in position and also play a significant role in ensuring the health and safety of persons on board the facility. The overall incentive to take any innovative risks to cut costs for floating oil and gas facilities is therefore very low indeed and anchoring and mooring designs have been very conservative as a result. Existing and historical WEC demonstrator installations have employed conventional mooring and anchoring arrangements. Whilst the costs associated with these conventional mooring and anchoring systems can be borne by a demonstration project where the aim is to prove the WEC technology, these costs would be prohibitively expensive and economically unviable for a fully commercial wave farm with up to 200 WECs, operating in deeper waters (> 100 metres). The wave energy industry cannot afford to inherit this conservatism and will need to reduce the larger proportional cost association with the anchors and moorings so that widespread deployment of WECs on a commercial scale becomes viable. Therefore specifically adapted mooring and anchoring solutions are required for the wave energy industry. For shallow water mooring (for example, between 50-100m), designing a flexible mooring is extremely challenging. Conventional catenary moorings cannot provide sufficient flexibility for wave energy converters. However, in the GeoWAVE project, we have shown that utilising elastic components in the shallow water mooring can provide the necessary flexibility for the mooring system, so to significantly reduce the loads on the mooring lines and thus the loads on anchors.

Only in recent years, as wave energy developers are making efforts to overcome technical problems associated with the energy conversion aspects of WECs, has attention turned to mooring and anchoring requirements. Whilst a number of numerical and experimental studies have addressed mooring configurations, research on anchors has been confined to literature reviews. Furthermore, these studies have not attempted to address the complex loading regime imparted by a WEC to the anchor, the required design life, nor the economic considerations of WEC anchoring systems relative to those used for oil and gas installations. The mooring requirements for WECs will be different in several respects and poses the following unique research challenges:

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1. WECs require permanent moorings since the design life of a WEC will greatly exceed the five years, which is typical for a long-term mooring installation of a floating oil and gas facility;
2. WECs have a dynamic response to wave or wave group loadings, and this may be critical for the functional requirements of the WEC when it and its mooring are considered together as a coupled system; the choice of mooring design can significantly influence how wave power is extracted and how such systems are operated and maintained;
3. The sole mooring requirement for a floating oil and gas facility is to keep the it stationary, whereas a WEC must be permitted to move relative to the waves so that power can be extracted, whilst also keeping the WEC in the pre-defined profile during extreme storm events.
4. Economic returns for an installed WEC are much lower than for an oil and gas installation, such that the economics that govern the current mooring and anchoring systems employed by the offshore oil and gas industry are prohibitive for the wave energy industry.

These unique requirements highlight the need to develop specifically adapted mooring and anchoring solutions for WEC installations. This is the technical challenge that has been addressed by GeoWAVE.

Floating facilities can be anchored to the seabed by catenary or taut-line moorings Catenary moorings arrive horizontally at the seabed, transmitting predominantly horizontal loads to the anchoring system whilst taut-leg moorings arrive at an angle to the seabed, transmitting both horizontal and vertical load components (Figure 1). The reduced mooring line length in taut line configurations results in significant installation cost savings and they are also better for load sharing between adjacent lines than catenary moorings. However, the restricted elongation properties of taut mooring lines are likely to cause problems when used in WEC applications as do not allow for inevitable tidal variation or unimpeded motion of the WEC to produce electricity. Additionally, at sites where seabed soils may be relatively thin and overlying rock, the limited elasticity will result in high anchor loads and required capacities, which may be difficult to provide. GeoWAVE has therefore considered incorporating an 'elastic tendon' component within a taut-line, which contributes beneficially to the motion independence of the WEC (a requirement for optimal power conversion) and reduces anchor loads in both operational and storm conditions, allowing smaller anchor to be used.

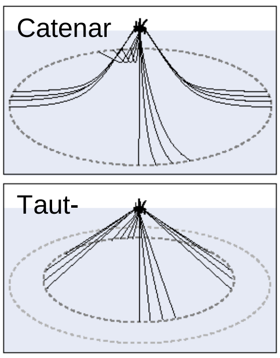

Figure 1: Catenary and taut-line mooring systems.

The problem of selecting an appropriate anchor for WECs is particularly problematic in view of the complex dynamic cyclic loading imparted to the anchor from a WEC. These effects may be

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detrimental to anchor capacity over the very long WEC design life (typically 30 years) compared to a temporary oil and gas production facility, depending on the soil type and the magnitude of the cyclic loading to the pull-out capacity of the anchor. There is therefore a risk that cyclic loading (particularly during strong storms) degrades the anchor capacity below its design value, causing the anchor to fail and the WEC to break loose. The consequences of a WEC breaking free within an array of devices include severe physical damage to surrounding WECs, power transmission lines and other marine infrastructure. More importantly it would have significant negative effects on public acceptance of the reliability and acceptance of wave energy.

The overall aim of GeoWAVE was therefore to remove the technical and economical hurdle of mooring WECs to the seabed, thereby providing new and significant business opportunities for the SMEs in the consortium.

2.2 Project Objectives

The scientific and technological objectives of GeoWAVE, outlined in the Description of Work, have been addressed as follows:

1. To investigate the most suitable mooring configurations and components for Wave Energy Convertors that will minimise anchor loads, motion impedance and required anchor burial depth;
2. To provide performance data for a new generation of technically efficient anchors that will quantify expected anchor geometries for a given mooring configuration, water depth and seabed profile;
3. To utilise the new performance data from Objective 2 to develop and calibrate design methods for anchor installation, in-service performance and station keeping of a WEC;
4. To utilise design methods from Objective 3 and performance data from Objective 2 to develop costing methods for mooring and anchoring WECs at a particular site, permitting an economical viability assessment;
5. To conduct offshore testing to collate field data and verify design methods from Objectives 3 & 4.

2.3 Project Team

A highly experience team of European academic and industrial organisations was assembled for the GeoWAVE project. The project team is introduced below:

University of Dundee (DUN) The Geotechnical Engineering Research Group at the University of Dundee was formed in 1997 to advance the research portfolio of Civil Engineering. The University of Dundee was rated as the best Civil Engineering department in Scotland in the recent Research Excellence Framework (REF) and 3rd overall in the UK. This ranking was enhanced by a strong geotechnical engineering research group

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and specialist facilities including the geotechnical centrifuge facility, which will be used in GeoWAVE. The centrifuge has recently received a €0.5M upgrade, through the Northern Research Partnership and the labs a €1.0M upgrade through the ERDF. The research group currently includes five members of academic staff with complementary skills covering physical modelling (both 1-g and centrifuge modelling), numerical modelling (finite element analysis) and soil modelling (advanced soil testing and constitutive modelling), supported by 11 doctoral and post-doctoral researchers. Both mechanical and electronic technical support is available in the department to undertake the work required to develop any specialist equipment and instrumentation required for GeoWAVE. Over the past five years the research group has held numerous research grants on topics of soil-foundation interaction and Geoenvironmental engineering through Research Councils UK, totalling approximately €0.7M. The group also previously coordinated the FP6 "QUAKER" project and the named researchers on this proposal (see below) have recently participated in a Joint Industry Project to develop an innovative new grillage foundation for installing lightweight seabed infrastructure.

The principal responsibilities of DUN were:

- **WP1 leader**
- **WP5 leader**
- Project Coordinator (WP1)
- Numerical modelling (WP2)
- Centrifuge modelling (WP3)
- Synthesis of centrifuge and numerical modelling/results (WP3/5)
- Development of design methods (WP5)
- Dissemination (WP6)

THE UNIVERSITY OF WESTERN AUSTRALIA
Achieve International Excellence

The University of Western Australia (UWA) The Centre for Offshore Foundation Systems (COFS) located at The University of Western Australia was established in 1997 as an Australian Research Council Special Research Centre by Professor Mark Randolph, in response to challenges associated with seabed sediments off the coast of Australia. Since 1997, COFS has developed into the largest and most prolific research group in offshore geotechnics worldwide, establishing an outstanding

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reputation for the quality of both its research and experimental facilities, as well as its services to local and international industry. With a team of 18 academics, 16 technicians, 6 administrative staff and 20 postgraduate research students, COFS represents the world's largest concentration of internationally recognised researchers and modelling facilities focused on offshore geotechnics. COFS funding for 2010 was over $10 million, of which approximately half was derived from industry sources. COFS has been funded by the Australian Research Council as part of the Special Research Centre programme, and is now part of the Australian Research Council Centre of Excellence for Geotechnical Science and Engineering.

The world leading geotechnical centrifuge facilities at COFS are regularly used by geotechnical designers to assist the establishment of site-specific soil-structure interaction parameters for the design of offshore seabed infrastructure worldwide. Examples of major industry clients for COFS in 2010 include Exxon Mobil, BP, Chevron and Woodside Energy. In addition to providing geotechnical design assistance to industry for site specific projects, COFS has led and partnered in several large international joint industry projects (JIPs) including the DeepStar JIP the SAFEBUCK JIP, the CSIRO Cluster Collaboration and the MERIWA JIP on submarine slide – pipeline interaction. There are numerous examples of COFS' research findings from these JIPs being codified in American Petroleum Institute and International Standards Organisation documents. Five members of COFS' current staff are members of the American Petroleum Institute and International Standards Organisation committees responsible for developing international design guidelines for the oil and gas and renewable energy industries.

The principal responsibilities of UWA were:

- **WP3 leader**
- Centrifuge modelling (WP3)
- Synthesis of centrifuge and numerical modelling/results and field data (WP2/3/4/5)
- Development of design methods (WP5)
- Dissemination (WP6)

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University College Cork, Ireland
Coláiste na hOllscoile Corcaigh

University College Cork (UCC) The Hydraulics and Maritime Research Centre at University College Cork was established in 1979. It is a centre of excellence within Ireland for Ocean Renewables and Coastal Engineering providing support to the maritime industry as well as fundamental research and development. The staff of 35, all at least MSC qualified and with industrial/commercial experience have a full mix of engineering skills from naval architecture to electrical engineering. UCC have experience of instrumentation and data acquisition at a number of scales from tank tests through to full scale deployment. The Centre houses the only facilities for wave simulation in Ireland with a Wave Flume and an Ocean Wave Basin. These facilities have recently (2009-2010) undergone a €2.5m upgrade, giving them state-of-the-art capabilities. The Centre also has its own supercomputing facilities as well as a suite of numerical modelling packages, both Industry standard and bespoke. UCC are partners in 7 FP7 ocean energy projects, a testament to their expertise in wave energy. UCC are responsible for producing a test and evaluation protocol standard that has been adopted as part of Ireland's Ocean Energy Strategy. UCC sit on several standards committees or Ocean Energy at national and international level, and are co-founding member of The European Ocean Energy Association.

The principal responsibilities of UCC were:

- **WP2 leader**
- Numerical and analytical modelling (WP2)
- Input on specification of wave basin testing (WP3)
- Development of design methods (WP5)
- Specifying and conducting wave tank tests (WP3)
- Synthesis of physical and numerical modelling/results (WP3/5)
- Dissemination (WP6)

Lloyd's Register
LIFE MATTERS

Lloyd's Register EMEA (LR) The Lloyd's Register Group is an organisation that works to enhance safety and to approve assets and systems at sea, on land and in the air. They check that assets and systems work so that people and communities around the world can get on with everyday life. They set, uphold and apply high technical standards of design, manufacture,

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construction, maintenance, operation and performance across many sectors to the benefit of many businesses.

Their participation in GeoWAVE is to review project results from a certification perspective. Their role is relevant as they are involved in the certification and review of many offshore mooring systems around the world for various types of vessels, platforms and other offshore infrastructure. Their work on such mooring projects starts at the conceptual design stage, through to site specific investigations, design and witnessing of installation and commissioning activities. Recent mooring project experience includes: floating, production and offloading vessels for Soekers Sable development (South Africa), Wafa (Libya); a missile platform for the French Navy and numerous loading buoys offshore Algeria. Experience in renewable energy includes: extensive involvement in wind farm projects offshore Northern Germany and tidal for Atlantis Resources and Neptune Renewable. These projects have used a variety of anchor types including drag anchors, anchor piles and gravity bases.

The principal responsibilities of LR were:

- Review project results from certification perspective (WP6)
- Dissemination (WP6)

CATHIE ASSOCIATES

Cathie Associates SA (CA) Cathie Associates provides geotechnical engineering design services to the oil, gas and energy industries, primarily in the offshore sector:

- Specialisation in geotechnical analysis and design
- Construction support including project management and site supervision
- Pile driving monitoring
- Numerical analysis

They serve clients who design, install and operate offshore, near shore and onshore facilities. Typical projects include geotechnical characterisation of the seabed and pile, suction caisson or anchor design for all kinds of offshore structures. They are heavily involved in the offshore renewable energy industry specifying and supervising investigations, and developing foundation concepts. Their associates have a

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combined total of over 50 years of experience in offshore geotechnics, foundation engineering, piling, anchoring, jackup stability, trenching, and associated aspects of offshore construction.

Cathie Associates role in GeoWAVE will consist of reviewing proposed anchoring concepts with a view to marine installation feasibility, and dissemination of the results within their network of clients, as well as more widely at conferences and exhibitions. Their technical reputation and knowledge of the offshore industry will enhance the credibility and value of the project outcomes.

The principal responsibilities of CA were:

- **WP6 leader**
- Review project results from offshore industry perspective (WP6)
- Dissemination (WP6)

Seaflex®
www.seaflex.net

Seaflex AB (SFX) Like most inventions, the SEAFLEX mooring system came about by chance. In the 1960s, Bertil Brandt, a Swedish innovator active within the mining industry, invented a highly durable compound rubber. In 1968, Brandt visited a fishing harbour in Cannes where he witnessed the chaos that occurred when fishing boats berthed. This inspired the idea for a simple and secure rubber mooring arrangement with specially manufactured rubber straps. Realising the potential of his invention, Brandt continued to develop a secure anchoring system on his return to Sweden. Bertil's son Lars, now continues the family business as the president of Seaflex. The first pontoon was moored with SEAFLEX in 1975. Today there are several thousand SEAFLEX systems in use around the world. Over an eight-year period, Seaflex increased its sales by an average of 30% per year and doubled its staff. Ninety percent of all sales are exports. The traditional markets in Europe and the United States have in recent years been joined by new and expanding markets in the Middle East and Asia. This is further evidence of Seaflex's expansion capabilities.

The principal responsibilities of SFX were:

- Technical coordination and support for all activities related to the SFX component (WP2/3/4/5)

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- Review of numerical output (WP2)
- Specification of Seaflex characteristics (WP2/3)
- Review of design methods (WP5)
- Dissemination (WP6)

GeoProbing Technologies (GPT) GPT is a technology developer and provider of innovative anchor solutions for offshore floating structures such as oil and gas production platforms. To date GPT's concepts have focused on mooring such structures in deep waters where soft seabed clay sediments are prevalent. GPT are involved in this project because they acknowledge that there is a strong need for a cost effective anchoring solution for mooring of smaller structures in shallow waters in which granular soils e.g. sands, are more frequently encountered. An appropriate cost effective anchoring method for these types of soils will call for a different technical solution to those that are used in soft clay sediments. Presently there exist alternatives that can be applied successfully but installation costs render them prohibitive, especially when considering new technology such as renewable wave energy sources where costly anchoring may threaten their viability. GPT's contribution to the project is to develop anchoring solutions that are built upon existing anchoring solutions.

The principal responsibilities of GPT were:

- **WP4 leader**
- Technical coordination and support for all activities related to anchors (WP2/3/4/5)
- Field testing (WP4)
- Specification of physical model testing requirements (WP3)
- Review of physical modelling test data (WP3)
- Review of design methods (WP5)
- Review of anchor capacity (WP2/3/5)
- Review of soil data (WP4)
- Installation procedures for field tests (WP4)
- Dissemination (WP6)

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3 Main Scientific and Technological Results

3.1 Project Overview

To achieve the required significant advancement beyond the current state-of-the-art as follows:

1. ***A fully coupled response to the technical problem was adopted.*** As the motion response of the WEC dictates the loading regime in the mooring lines and ultimately the loads applied to the anchors, the overall problem requires a fully coupled solution. For the first time, GeoWAVE brought together expertise on WECs, moorings, anchors and engineering within the marine environment.

2. ***Provision of state-of-the-art experimental facilities***: the GeoWAVE consortium provided a unique combination of advanced physical modelling facilities to obtain realistic experimental data for the anchors and moorings that is verifiable at full scale. This included application of geotechnical centrifuge modelling, which has been employed extensively by the oil and gas industry. A centrifuge rotationally spins a soil sample to increase the self-weight stresses within the soil such that the up to 60 metres of a “real-world” soil deposit can be accurately simulated. This was coupled with ocean wave basin testing of an existing scale model of the Pelamis WEC device with existing and new mooring designs, to provide mooring load information for the centrifuge modelling. Wave basins allow full control over the actual sea states produced and have been extensively used by ocean energy device developers to simulate the response of their conceptual or prototype WECs in active sea-states.

3. ***Advancement on commercially available numerical models for moorings***: GeoWAVE has developed new dynamic simulation models and improved available modelling techniques to include provisions for dynamic conditions appropriate for WEC applications.

A Seaflex elastic damper mooring component (supplied by SME partner Seaflex) has been incorporated within a taut line mooring arrangement, allowing reduced pre-tensions (reducing anchorage requirements) and providing beneficial elongation properties for optimisation of machine movement and dynamic characteristics. This has been combined with a cost effective and technically efficient new type of drop-installed plate anchor (DPA Mark III, supplied by SME partner Deep Sea Anchors/GeoProbing Technologies), allowing station keeping of WEC devices in geotechnically more marginal locations (shallow seabed soils). The anchor adopts a thin ‘blade-like’ design which increases penetration potential in sand compared with existing dynamically installed anchor designs. The anchor features a plate at the lower end attached to an upper removable follower The DPAIII is drop-installed in a similar manner to other dynamically installed anchors, but utilises the upper removable follower to provide the necessary additional mass to achieve the required anchor embedment. Following embedment, the follower is retrieved to the installation vessel for reuse in the next installation, leaving the plate anchor vertically embedded in the seabed.

GeoWAVE was organised into 6 work packages as indicated below (and shown in Figure 2):

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- Work Package 1 (WP1): Project management
- Work Package 2 (WP2): Numerical and analytical modelling
- Work Package 3 (WP3): Physical modelling
- Work Package 4 (WP4): Offshore field trials
- Work Package 5 (WP5): Development of design and costing methods
- Work Package 6 (WP6): Dissemination, knowledge transfer & IP exploitation

The subsequent sections will summarise the main scientific and technical outcomes from the core technical work packages (WP2 – WP5 inclusive).

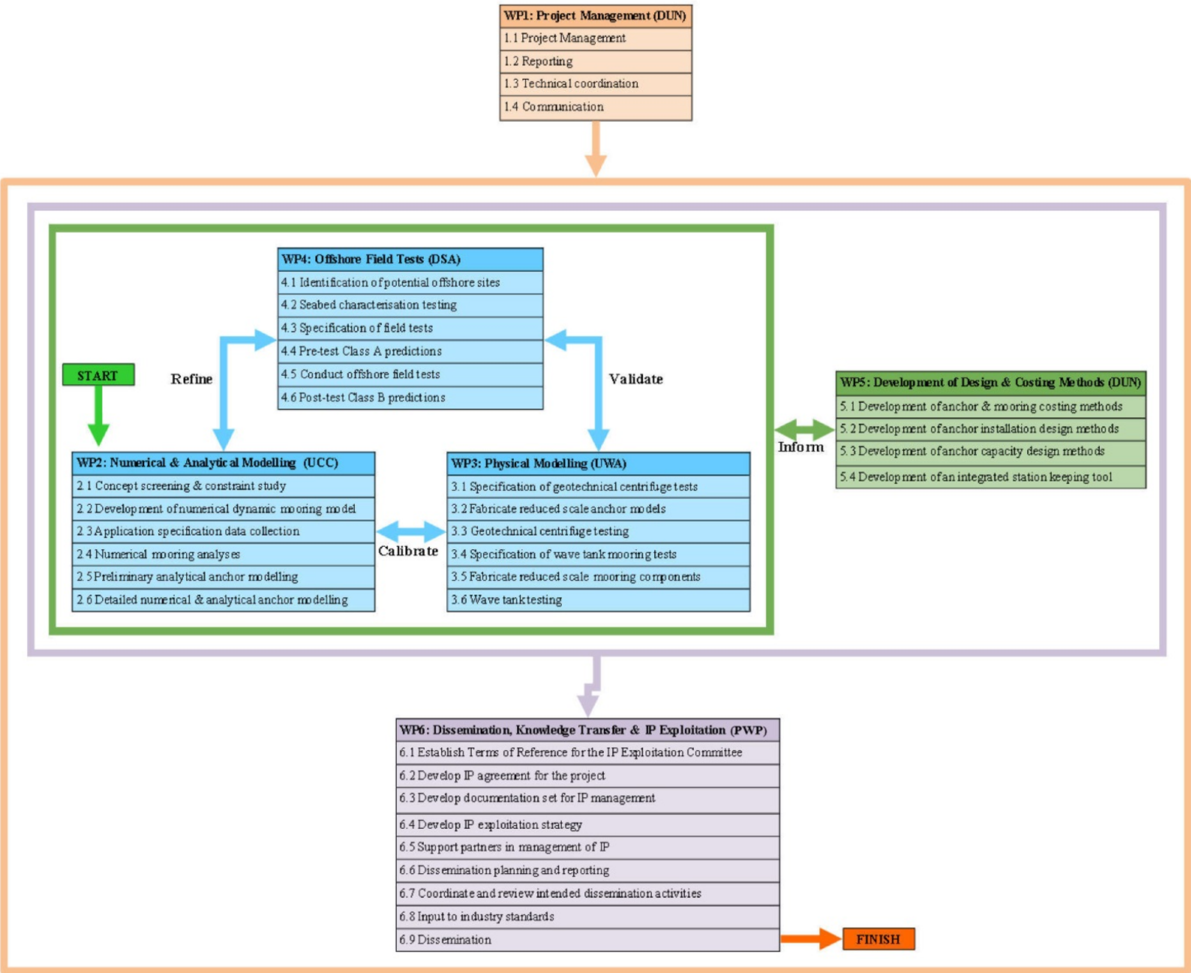

Figure 2: Interdependence and work flow between work packages.

3.2 WP2 Numerical and analytical modelling

Work package 2 covered numerical modelling and computer simulation work associated with both the anchor and mooring components of the system. This work was used to:

(i) provide an initial state of the art review to focus project effort onto the most promising anchor and mooring combinations (D2.1);

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(ii) allow specification of the optimal Seaflex element design (D2.3) for use with WECs (via the numerical model developed and validated against test data in D2.2) and therefore design/optimise the physical model tests to make best use of the available time in the wave basin;
(iii) investigate the long-term performance, i.e. the potential for fatigue failure in both the new mooring arrangements (D2.4) and the new anchor types (D2.5);
(iv) provide fundamental performance data of the anchor underpinning design methods developed for the new anchors in WP5 (D2.5).

Deliverable D2.1 (D2.1) reviewed currently available and emerging mooring line and anchor technologies and evaluated their comparative performance, in terms of their suitability for mooring single WECs and arrays. Due to a change in partner from Wavebob (WVB) to Pelamis (PWP) part-way through the project, this study was undertaken for a point absorber type WEC (WVB) and a line attenuator type WEC (PWP), though the latter is the final version of record. Compared to the current concept of a three-point catenary line + drag anchor mooring, the potential for significant cost savings was identified early in the project Evidence from the literature and some preliminary analyses suggested that this could be achieved by moving to a three-point taut line + drop anchor system. The benefits of such a system would:

1. Reduced cost (and seabed footprint) by using taut-lines;
2. Reduced cost by using more efficient anchors that are dynamically installed, saving both capital and operational cost;
3. Further cost reduction in terms of anchor size by utilising an elastic tendon component (e.g. Seaflex) to reduce line loads.

The potential for cost saving was subsequently verified by the final costing exercise conducted in WP5, D5.4. These results were used to focus subsequent activities in WP2 and WP3 for a typical line loading of 200 t in dense nearshore sand, representing a highly likely performance specification for future arrays of WECs. In particular, that:

1. The optimal configuration of the Seaflex tendons (e.g. numbr of hawsers) would need to be identified.
2. Although suction caisson anchors may provide improved performance compared to existing solutions, given the additional cost associated with installation and the low level of experience of installing such anchors in dense sands a drop anchor will offer an improved solution within the existing mooring due to lower installation costs provided it can be shown to have a similar (or better) geotechnical performance.
3. dynamically embedded drop anchors currently only existed for use in cohesive soils, so the geotechnical capacity and performance of higher-risk new-generation dynamic anchors (DPA III) would need to be determined via centrifuge and numerical modelling, with emphasis being placed on anchor installation (particularly installation depth, which is key to capacity) and performance in coarse-grained deposits.

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In **Deliverable 2.2** (D2.2) a numerical model of a single Seaflex tendon element was developed and validated against existing loading and unloading experimental test data provided by Seaflex and further static and dynamic testing undertaken as part of GeoWAVE. The numerical model was essential to subsequently design a new larger array of tendons, sized for the loading induced in the mooring of a large WEC. The new experimental tests, conducted at the Hydraulics and Maritime Research Centre (HMRC, UCC). included constant speed ramp type tests (constant speed stretching and compression) and sinusoidal tests, more representative of the dynamic loading induced by waves within an offshore environment.

The experimental tests demonstrated the many beneficial characteristics of Seaflex components over synthetic ropes of similar stiffness, including:

1. flexibility, to reduce mooring line loads (and thereby potentially reduce anchor sizes);
2. ability to smoothing motions, potentially elongating of the lifecycle of the mooring components in the marine environment;
3. hysteresis, resulting in velocity-dependent damping, which could mitigate sudden 'snap' loads which might otherwise overload the anchors. Up to 180 times the energy dissipation per cycle was observed for the hysteretic element compared to an elastic element having the same backbone stiffness but no hysteresis.

An example of the fit of the model developed to a number of cycles of sinusoidal test data for a Seaflex tendon is shown in Figure 3.

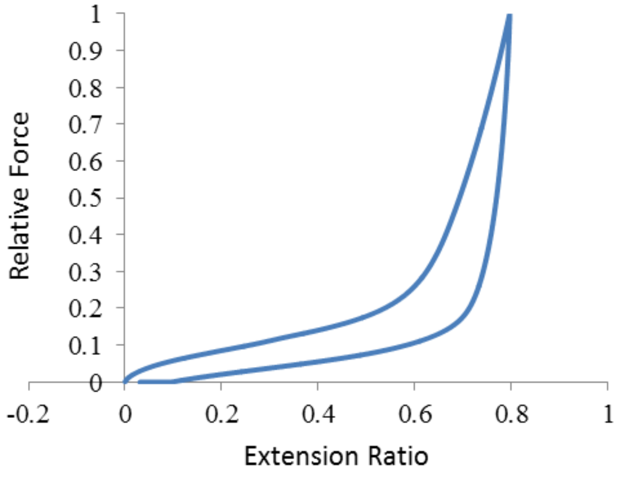

Figure 3: Validation of numerical model of the highly non-linear Seaflex tendon.

This beneficial hysteresis behaviour identified and quantitatively modelled in D2.2 presented significant challenges in subsequent simulation/numerical modelling of a complete mooring system incorporating Seaflex elements because existing commercial software packages, such as Orcaflex and ANSYS AQWA, have not offered the capacity in modelling the hysteresis behaviour. As a result, an in-house code was been developed at the Hydraulics and Maritime Research Centre (HMRC), University College Cork, Ireland which was used to conduct mooring simulations (**Deliverable 2.3**, D2.3) that were subsequently used in sizing new Seaflex units for the wave basin tests conducted in WP3.

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The code was validated against ANSYS AQWA for applications without Seaflex units (to ensure the mooring dynamics were properly captured) and the numerical model for the Seaflex tendon was then implemented. Example simulations of generic catenary and taut leg moorings with and without Seaflex elements were also provided in this D2.4, to provide guidance for subsequent use, e.g. in the preliminary design evaluation of a mooring system (see Figure 4).

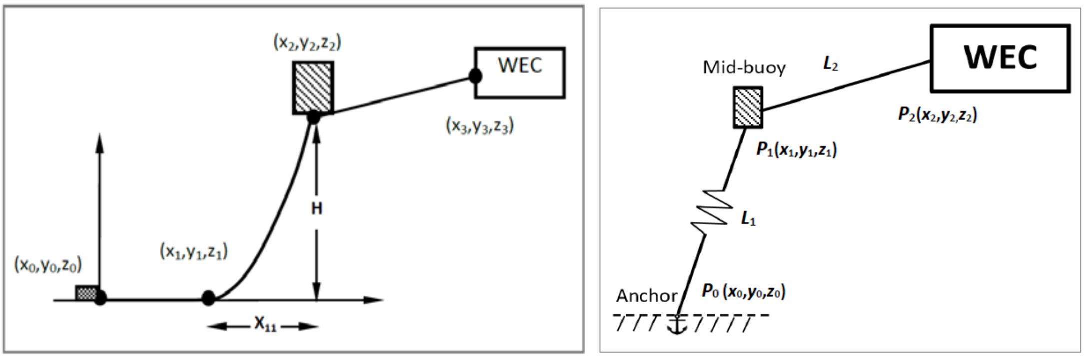

Figure 4: Simplified conventional mooring (left) and new taut-line + Seaflex (GeoWAVE) configuration (right)

Having investigated comparative performance between the current and newly proposed mooring arrangements and demonstrated the potential benefits of the new arrangements, **Deliverable 2.4** (D2.4) provided further investigation into the long term performance of the new Seaflex elements of the proposed moorings within the dynamic marine loading environment. Two main aspects were studied, namely: (i) the potential for vortex induced vibration (VIV) given that multiple Seaflex tendons would need to be situated in close proximity; and (ii) fatigue life analysis of the individual tendons under the expected loading.

As a vortex is shed due to flow of water past a bluff body (in this case, a cylindrical Seaflex tendon), owing to the pressure difference, forces in the in-line and cross flow direction are generated causing an oscillatory vibration. As a result vortex induced vibration is a possible cause of fatigue failure for submarine structures. CFD simulations for VIV presented in D2.4 showed that vorticity cannot be well developed between closely spaced parallel tendons (Figure 5). In the worst case considered, the maximal force acting on the component was relatively small compared to the magnitude that would be required to have a significant influence on the fatigue life of the component. Hence, the distance between the components may be more decided by the practical consideration, rather than the fatigue life implications of VIV.

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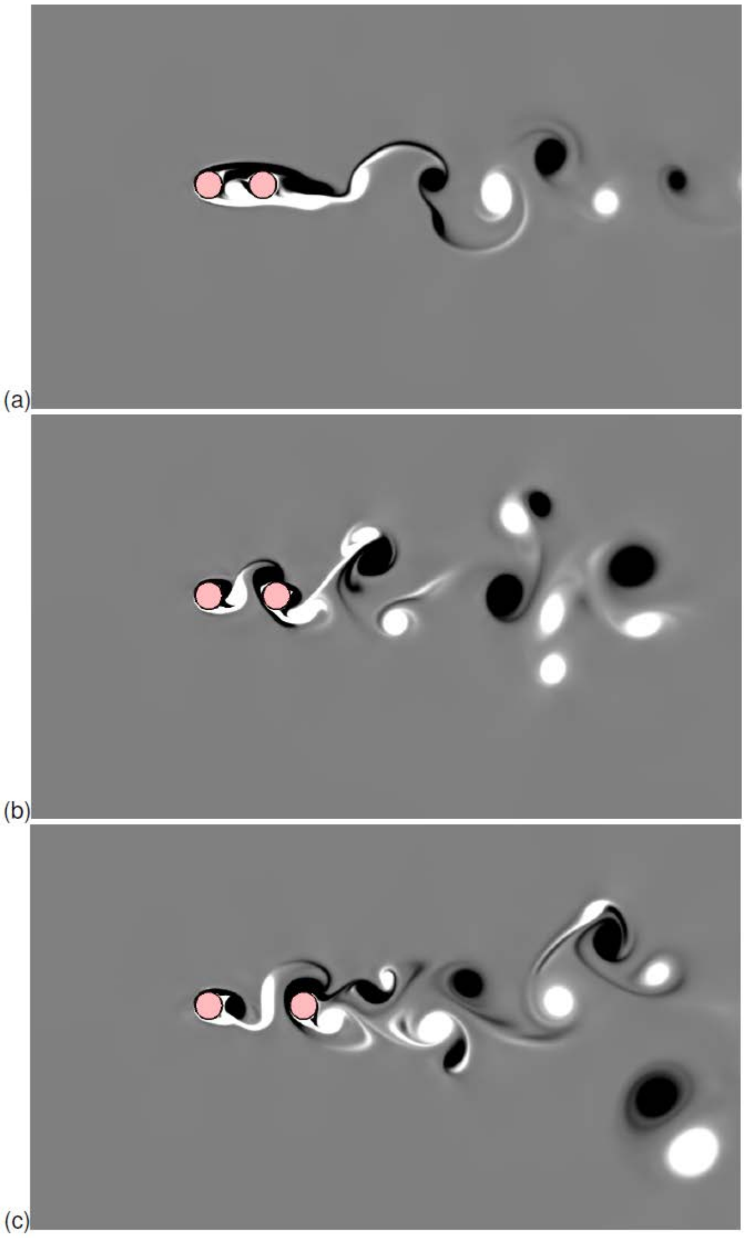

Figure 5: Vortex shedding around closely-spaced Seaflex tendons, from CFD

Having demonstrated that VIV-induced forces are negligible from a fatigue point of view, it remained to consider the fatigue life under the larger in-line forces generated within the mooring system. By the time this section of D2.4 was being undertaken, experimentally measured data from the wave basin testing programme (WP3, D3.3) were available. This test data was used to define the loading regime in preference to the preliminary numerical modelling data from D2.3.

According to the Seaflex AB product quality check, every Seaflex product (batch in production) must pass a survival test. In the survival condition test, the component has to pass the 100,000 cycle test with the maximum extension of 80%. Combined with data from the component breaking test (in N = 1 cycle) this data can be used to define a magnitude of a cyclic stress (S) against number of cycles to failure (N) curve (i.e., an S-N curve). As this is a standard product test, this data will be available for all tendon elements produced. As the component has not actually reached its fatigue limit in N =

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100,000 oscillations (assuming it has survived), definition of the fatigue curve based on this test data will be conservative. The experimental data from the wave basin tests for the Pelamis P2e WEC having the new GeoWAVE taut line arrangement including Seaflex elements that were optimised for the peak loading expected, indicated that the fatigue life of the Seaflex components in the mooring system will easily be sufficient in all sea states considered, even considering the largest waves occurring all year round.

Deliverable 2.5 (D2.5) focussed on numerical simulation of the performance of the anchor, both under static and cyclic loading, using 2-D and 3-D Finite Element Modelling (FEM). This is the anchor component analogue of the Seaflex tendon modelling from D2.2 and D2.3, and also considered estimations of fatigue performance in a similar framework to D2.4.

The suitability of the soil model used was first confirmed by validating 2-D FEM against available analytical solutions and Limit State analyses for anchors buried in dense sands which arose from D2.1 as the most likely seabed soil conditions for future WEC arrays. Subsequent 3-D modelling (Figure 6) provided the first estimates of pull-out capacity of a new dynamically embedded anchor (DPA-III) for use in sands, and provided performance data that was subsequently used in developing the anchor design methods of WP5. This data confirmed the potentially high holding capacities of suitably embedded anchors that was identified in D2.1. Mapping of 2-D load-displacement curves onto the more computationally expensive 3-D curves provided a potential route for more efficient future analysis of other seabed cases through the use of quicker 2-D analyses. Cyclic simulations of pre-tensioned anchors also provided data for estimating S-N curves based on a limited amount of anchor deformation that could be used in fatigue assessments of the complete new GeoWAVE mooring + anchoring system (DPA-III + taut line + Seaflex) alongside those for the new Seaflex elements from D2.4, and pre-existing curves for the mooring line element.

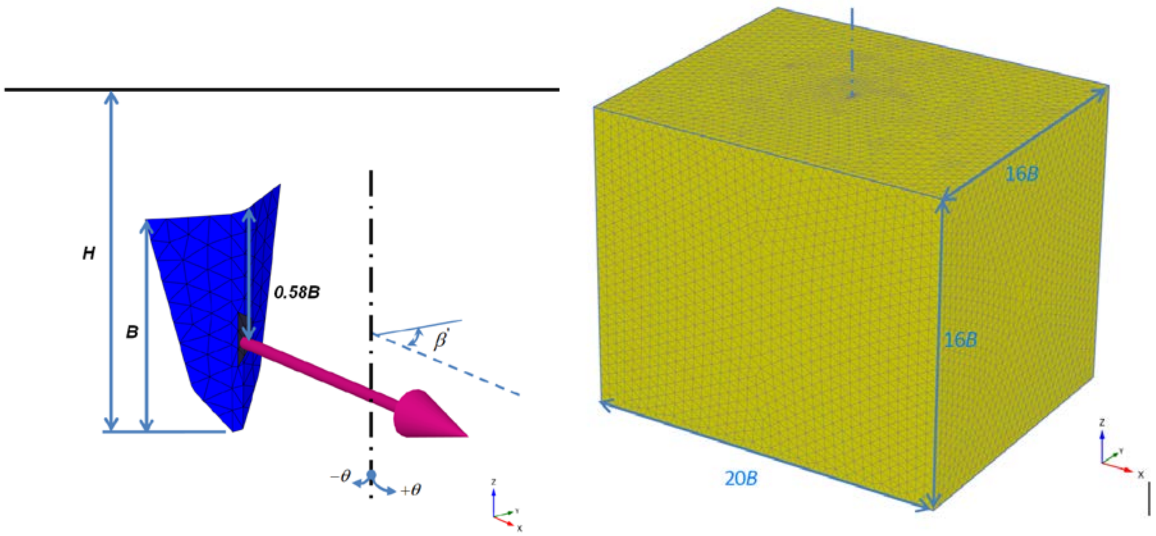

Figure 6: 3-D FEM model of DPA-III (anchor plate)

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3.3 WP3 Physical modelling

Work package 3 complemented the numerical work of WP2 by conducting physical model testing of the newly proposed mooring system and the new DPA-III type anchor. In both cases the approach adopted was scaled physical model testing, conducted in either a wave basin (mooring components above the mudline) or a geotechnical centrifuge (anchor components below the mudline). GeoWAVE was unique in bringing these two complimentary physical modelling approaches together to be able to study the complete mooring and anchoring system. Previous studies relating to mooring of WECs and other floating renewable energy devices has focussed solely on the mooring above the mudline and has neglected anchor performance. The tasks included:

(i) wave basin testing at a scale of 1:29 of an existing sophisticated model of the Pelamis P2e WEC under a range of regular and irregular sea states, and moored with either conventional catenary moorings or the new taut line + Seaflex configuration developed in GeoWAVE (D3.3);

(ii) fabrication of reduced scale anchor models (D3.1), followed by centrifuge testing at scales between 1:50 and 1:100 of the drop embedment process and subsequent monotonic and cyclic loading of the installed anchors (D3.4).

At the outset of the project another deliverable (D3.2) was originally included, to develop 1:50 scale models of the Wavebob point absorber WEC for the wave basin testing. However, with the loss of Wavebob and the accession of Pelamis, the existing model of the P2e line attenuator could be used, making D3.2 obsolete.

Use of a wave basin and appropriate scaling of the test model for similitude of the non-dimensional Froude number produces model scale results that when scaled up using the appropriate scaling laws, will represent the behaviour of a full scale prototype for all behaviour above the mudline (i.e. in the water column). This is at a fraction of the cost of full-scale testing. Similarly, use of a geotechnical centrifuge to produce an elevated acceleration field permits stress similitude at homologous points between a small scale model and the full scale prototype, such that geometrically scaled models again represent the behaviour of full scale prototypes, at a fraction of the cost of full scale testing.

In **Deliverable 3.3** (D3.3), the existing Pelamis P2e scale model owned by PWP was tested with a variety of mooring configurations in the Plymouth COAST wave basin. This facility was used instead of the HMRC wave basin due to the larger size of the P2e model compared to the 1:50 scale point absorbers considered at the outset of the project. The tested mooring configurations included three catenary mooring systems and three taut mooring systems (see Figure 7). In each case, tests were done considering a basic catenary or taut arrangement, and newer GeoWAVE arrangements in which either the stiffness only behaviour of the Seaflex units was simulated, or both stiffness and damping characteristics were realistically simulated. To simulate the Seaflex units realistically, a novel combination of inelastic and O-ring components was developed (see Figure 8).

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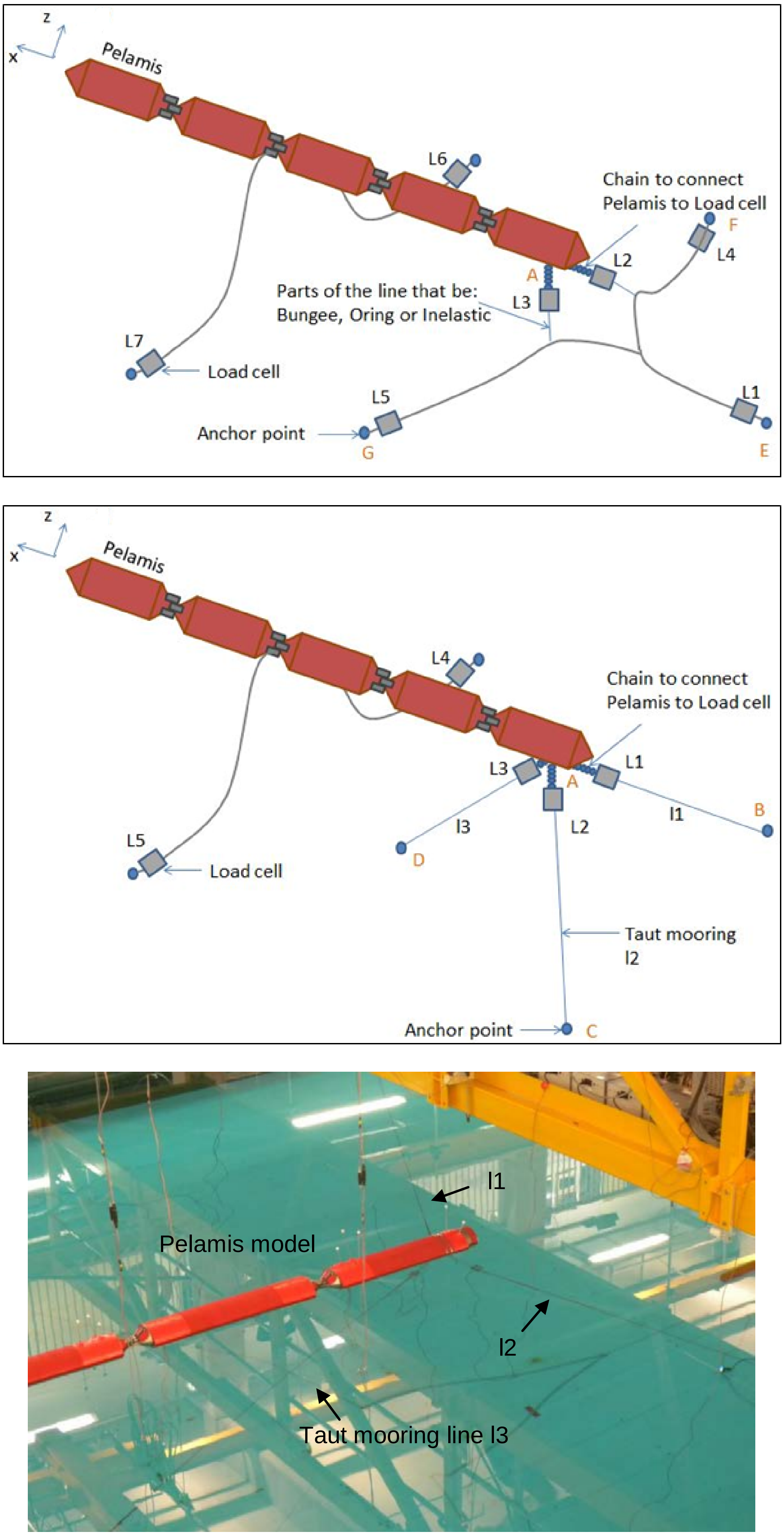

Figure 7: Wave basin testing: existing catenary arrangement (top); new GeoWAVE taut arrangement (middle); 1:29 scale model in the COAST wave basin (bottom)

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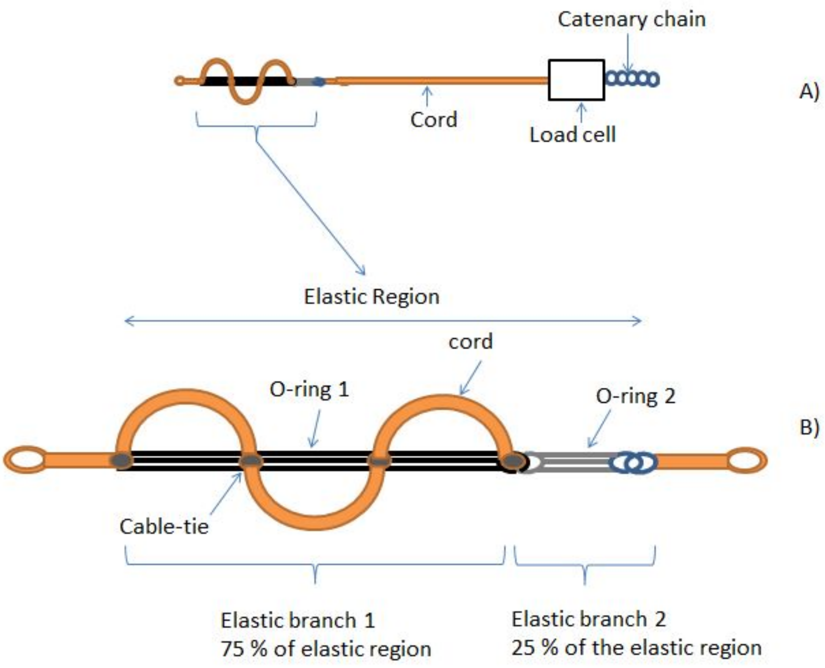

Figure 8: Physical model analogue of a Seaflex damper.

From the data analysis, the following conclusions were drawn:

1. Elastic components applied in the catenary mooring could increase the mooring flexbility, thereby reducing the mooring forces on the mooring lines and on anchors, and allow a larger excursion in irregular waves;
2. Significant further reduction of the loads in the mooring lines was achieved by using a taut line arrangement (lines at 30 degrees to the horizontal). For example, the maximum dynamic force in the taut mooring tested was approximately one third of that in the original catenary mooring. In addition, the taut-leg mooring also limited the excursion of the device. This is very beneficial for the design of both the mooring and anchoring systems. The much reduced loads could allow smaller mooring lines and anchors, which in turn would reduce the cost of installation of the mooring system;
3. The application of the taut-leg moorings to the Pelamis wave energy converter did not change the heave and pitch motions which were the main motion modes for power conversion; hence the new taut mooring system will not have negative effects on power conversion;

Given the significant hydrodynamic benefits identified for the new GeoWAVE taut line + Seaflex listed above, the centrifuge testing programme (described below) tested anchors loaded dynamically under both catenary and taut line configurations.

Deliverable 3.1 (D3.1) detailed the fabrication of the reduced scale anchor models (see Figure 9). required for the geotechnical centrifuge testing. **Deliverable 3.4** (D3.4) subsequently used these models to simulate the drop embedment process (1:100 scale tests) and anchor capacity tests (1:50 scale). The centrifuge tests involved a total of 72 tests performed between August 2013 and August 2014 in twelve samples; 14 anchor embedment tests in two samples and 58 anchor capacity tests in

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ten samples. Typical test arrangements are shown in Figure 10. From this testing, the following conclusions were drawn:

1. The DPA-III anchor was found to embed between 0.9 and 2.2 times the lower plate length (Figure 11), depending on the density of the seabed sand, mass of the follower and achievable impact velocity. These embedments were higher than previous DPA designs in coarse-grained soils, verifying that the new design is an improvement for use in such seabeds. The achieved embedments suggested high holding power based on the initial numerical simulations (D2.5). The final embedment depth was found to increase with decreasing relative density and increasing mass ratio and impact velocity.
2. The monotonic capacity of the anchor (Figure 12) was been investigated considering different normalised padeye eccentricity normal to anchor ratios, loading inclination at mudline (i.e. representing different mooring configurations) and tip embedment ratios. The maximum achievable peak monotonic capacity corresponded to a high padeye eccentricity and a horizontal loading angle at mudline (catenary mooring), making this mooring configuration optimal from a geotechnical standpoint. The use of a taut line mooring (β = 30°) was of secondary preference with an expected reduction in the monotonic or cyclic peak capacity of up to 43% compared with the catenary mooring. However, the applied line loads will be reduced by 66% in this case based on the wave tank testing (D3.3, see above).
3. The cyclic capacity tests of the DPAIII suggested that cyclic loading of either a regular or irregular form (of up to 15 simulated storms) could increase the subsequent pull-out capacity by between 20-40% for a catenary mooring or 5-30% for the taut line case. The irregular cases demonstrated the effectiveness of including a Seaflex by using measured mooring line loads from the wave tank test data (D3.3) for 'rigid' mooring lines (not including a Seaflex mooring line component) and 'soft' mooring lines (including a Seaflex mooring line component). Unlike the rigid case, the Seaflex connection was able to sustain the cyclic loading without failing at the end of the storm sequence. Also, the magnitude of the cyclic loads were lower and consequently smaller anchors may be used.

The conclusions presented are valid for the soil conditions tested (saturated dense silica sand) and the geometry of the DPA investigated. While it is believed that the conclusions can be qualitatively extrapolated to other sandy seabeds, the anchor geometry for optimal drop and the resulting capacities would need to be re-established as a function of the soil characteristics and any change in anchor geometry.

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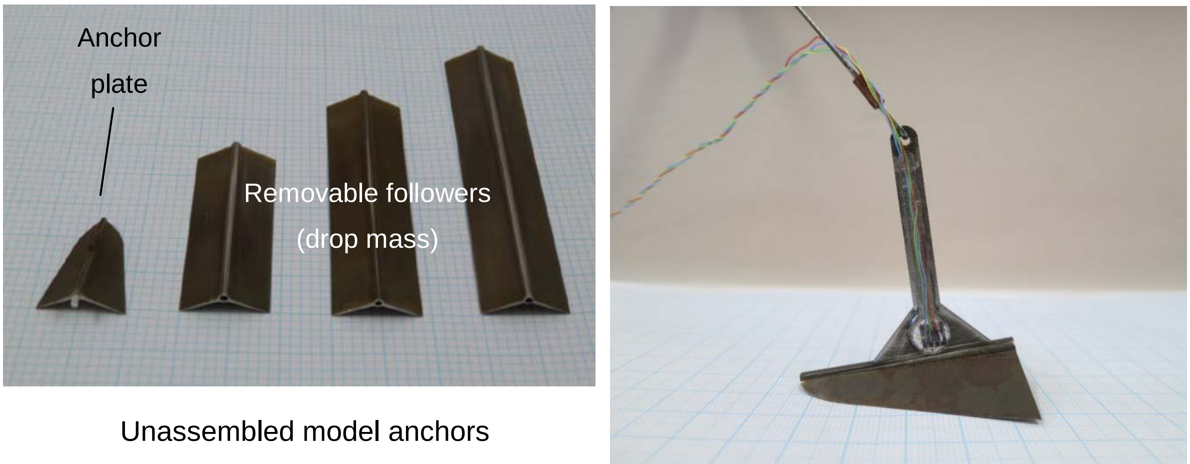

Unassembled model anchors

Figure 9: Scale model anchors for centrifuge testing: with removable followers for embedment tests (left) and an instrumented anchor plate for capacity testing (right).

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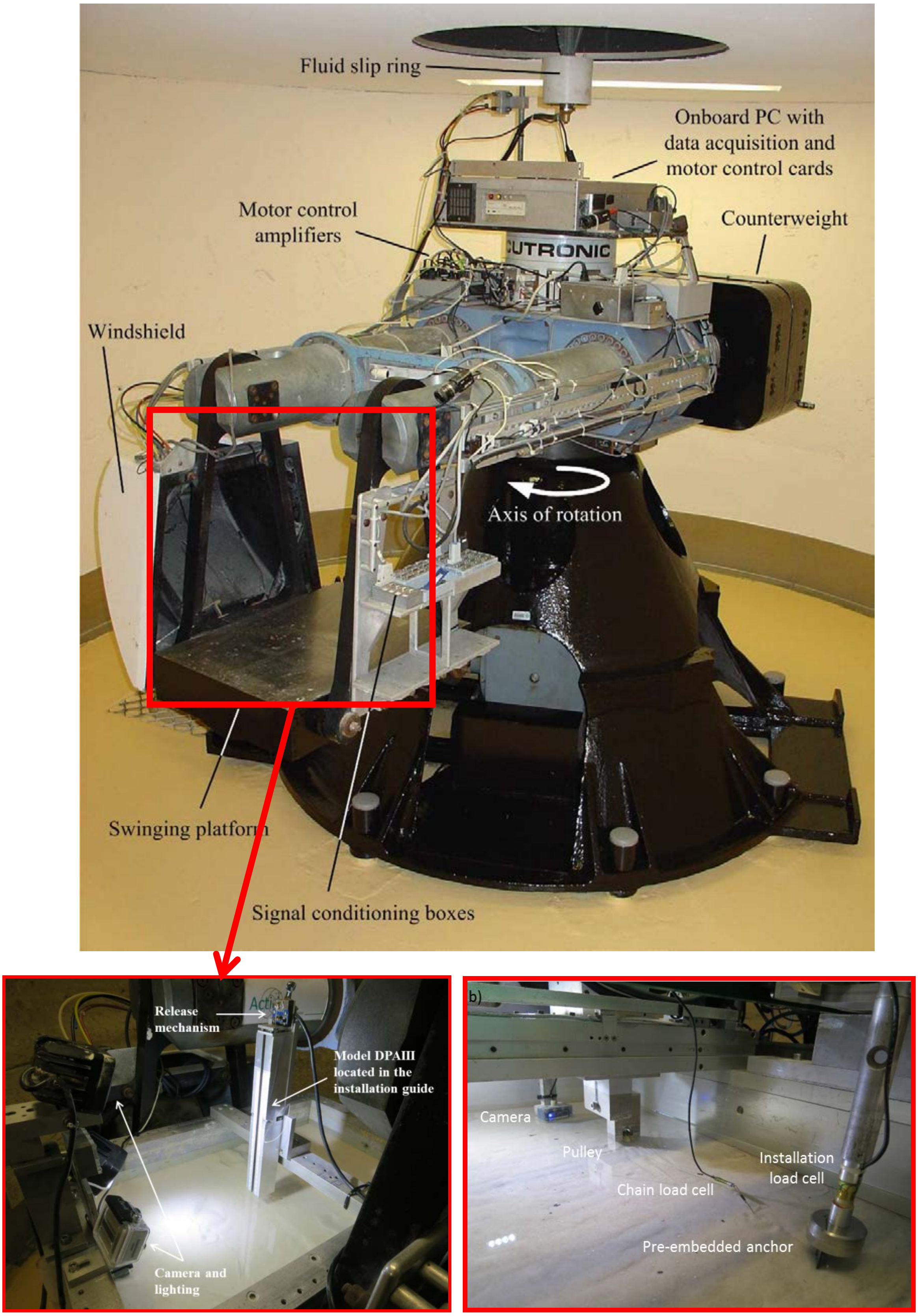

Figure 10: Geotechnical centrifuge at UWA, showing embedment test set-up (bottom left) and capacity arrangement (bottom right).

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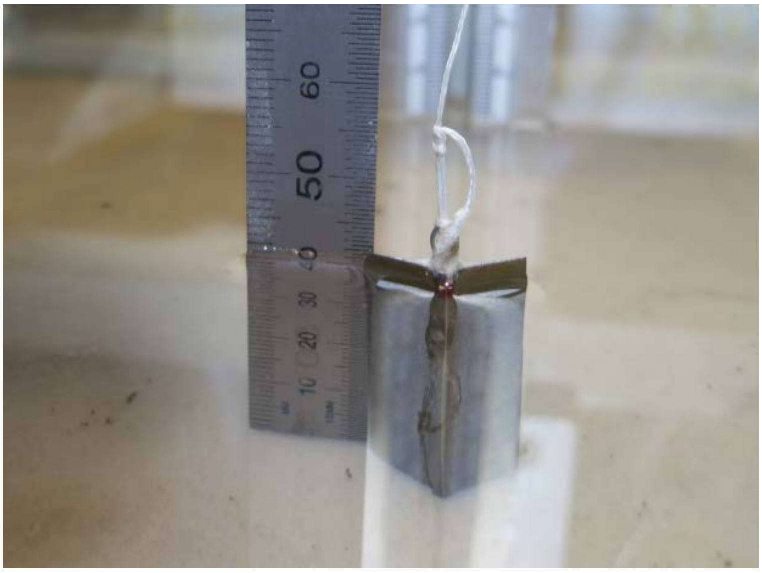

Figure 11: Embedded anchor after drop (the top of the follower can be seen above the mudline)

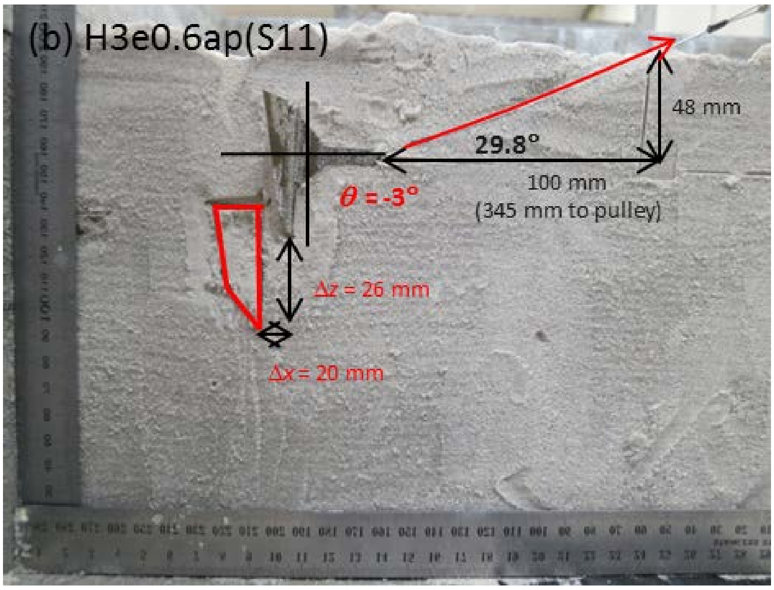

Figure 12: Sectioned model showing anchor configuration in soil at peak capacity (initial position shown in red)

3.4 WP4 Offshore field trials

Work Package 4 covered field testing of the new DPA-III anchor system at sea. This was conducted at a site representative of locations for future offshore wave energy arrays, namely the Eurepean Marine Energy Centre (EMEC) full scale wave site, which is 2.5 km off the coast of Billia Croo, Orkney in the UK as shown by Figure 13, with water depths between 45 and 55 m.. The tasks included:

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(i) Assessment of the geotechnical characteristics of the seabed at the test site and identification of optimal drop locations for the tests (D4.1), followed by estimation of the anchor capacities ahead of the field tests (D4.2);

(ii) Offshore field tests of a scale model anchor including drop installation at sea followed by anchor extraction for capacity (D4.3).

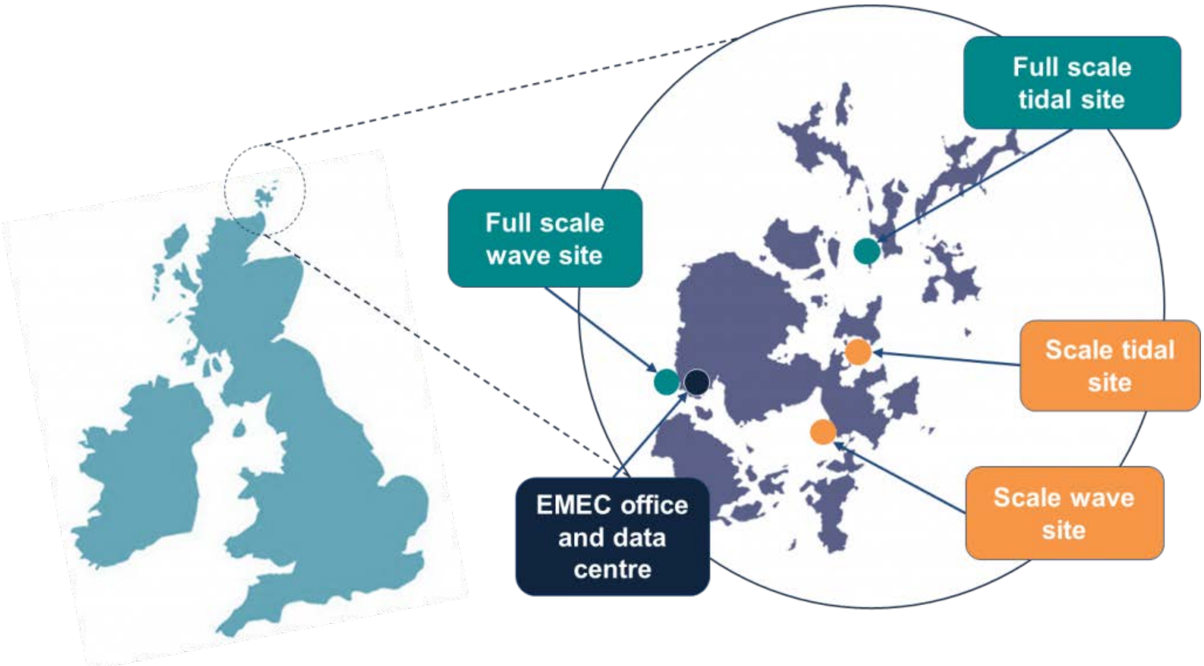

Figure 13 Site location (http://www.emec.org.uk/facilities/)

Deliverable 4.1 (D4.1) presented a geotechnical interpretation of pre-existing geotechnical site investigation data, gathered by RJ McLeod Limited at the EMEC test site during December 2002 and provided to the GeoWAVE consortium by PWP. Based on this data (which included 16 cone penetration tests, CPTs; 16 vibrocores and a programme of geotechnical laboratory index tests), the seabed can be described as mainly coarse grained. The refusal of a number of CPTs at shallow depth and limited recovery of a number of vibrocores towards the south of the site suggested that the soil was shallow in places and underlain by bedrock, representing exactly the kind of marginal seabed conditions that GeoWAVE aimed to address.

Comparing the field CPT data to that in the centrifuge allowed two potential test zones to be identified for the field tests. The first location consisted of loose underlain by medium dense to dense over the expected penetration depth of the scaled DPA-III anchor. At the second contrasting location, the seabed was more varied, but generally described as medium dense to very dense sand over the depth of interest at some locations, but with hard layers at shallower depths at other locations.

Deliverable 4.2 (D4.2) outlined the Class A predictions of the monotonic pull-out capacity of a reduced scale field DPA-III type anchor at the two potential test locations identified at the EMEC test site in D4.1 for idealised soil conditions (Figure 14). These were conducted using the 3-D Finite Element procedures described in detail in Deliverable D2.5 (Work Package WP2), but with the anchor modified to include a bridle loading arrangement designed to increase capacity based on the

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observations from the centrifuge test programme (D3.4). So as to be more useful as a guide to the subsequent field testing, particularly in terms of sizing equipment, simulations were conducted for a range of embedment depths between 1 – 3 anchor lengths, encompassing the range of embedment depths achieved in the centrifuge tests (D3.4).

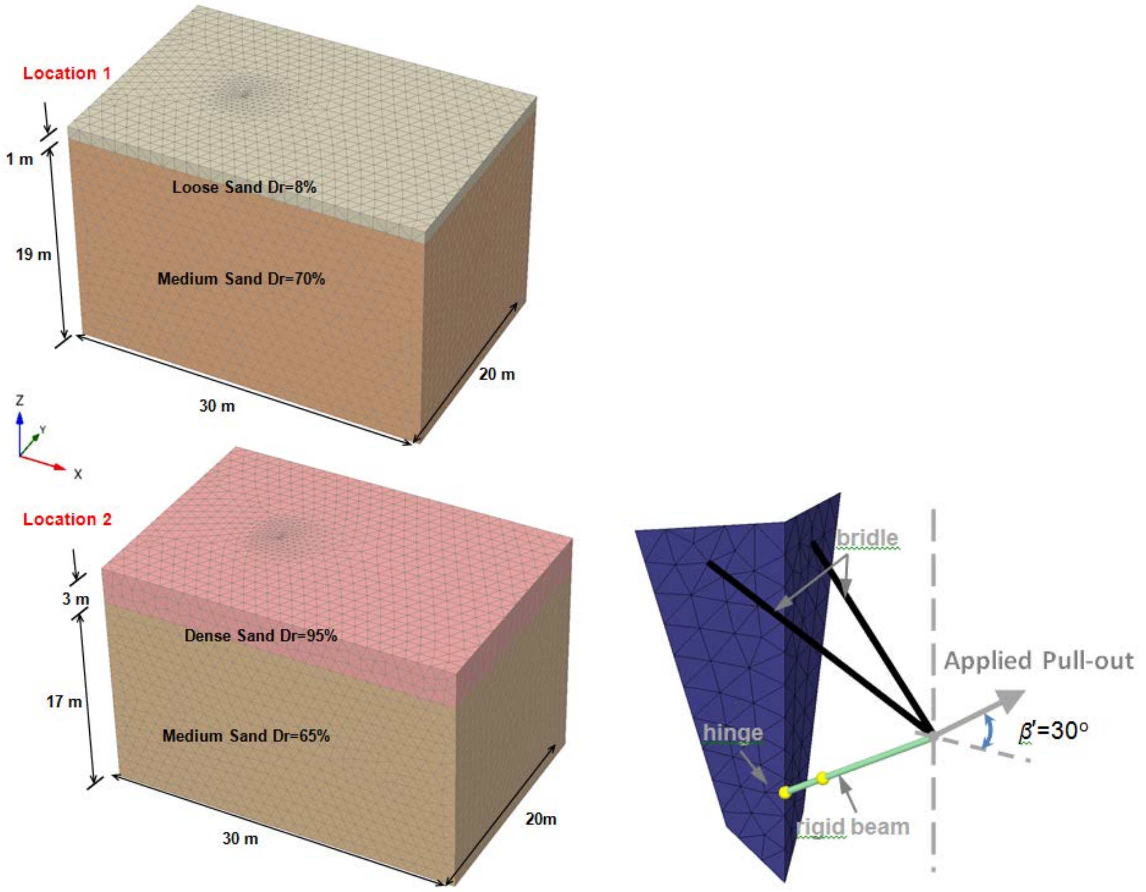

Figure 14 FEM models of idealised field site seabed conditions and test anchor with bridle

Finally, **Deliverable 4.3** (D4.3) reported the field trials of the reduced scale DPA-III anchor at EMEC, conducted in July 2015. A 1:2.5 reduced scale anchor with detachable follower was designed, fabricated and employed for the field trials, as shown in Figure 15. This had a total length (anchor + follower) of 2.75 m, with a plate (anchor) height of 1 m. The overall anchor mass was 425 kg. A guide frame that keeps the anchor in a vertical position for a limited but sufficient drop distance until it attains a necessary critical velocity to maintain stability, was also designed and fabricated. The anchor and guide frame components were manufactured by Pentland Precision Engineering Ltd, Edinburgh, UK.

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Figure 15 Assembled anchor/follower with bridle arrangement at EMEC (without guide frame)

The assembly included three independent instrumentation units that measure accelerations and rotations during installation and anchor loading. These included: (1) a data logger, developed and built by UWA as part of GeoWAVE that was housed in the anchor plate that measures rotation of the plate as it is loaded using a tri-axis MEMS accelerometer; (2) an Inertial Measurement Unit, incorporating a second data logger that measures accelerations along three orthogonal axes and rates of rotations about the same three axes using a tri-axis MEMS accelerometer and 3-component component MEMS gyroscope during free-fall in the water column and embedment in the soil; and (3) an instrument container at the top of the follower which holds a data logger developed by GPT that measures accelerations along three orthogonal axes for redundancy.

The DPA-III centrifuge tests (D3.4) show that the plate anchor is strongly susceptible to moving vertically through the soil when loaded (developing minimal capacity) unless the padeye (line connection point) is located at a sufficient eccentricity from the plate. This was incorporated within the field test anchor through the use of a three line bridle (see Figure 14). The three lines come together at a common connection point that serves at the anchor padeye.

GeoWAVE hired the "Green Isle" vessel from Green Marine in Orkney (http://greenmarineuk.co.uk/), a Damen Multi Cat® 2712, along with Remotely Operated Vehicle (ROV) support from Roving Eye Enterprises to observe and document the anchor-mooring line configuration before anchor release

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and to observe seabed conditions before and after anchor penetration. A 10 stage rigging procedure to prepare the anchor for drop at sea was developed and 10 drop tests were conducted from between 10-18 m drop height above the seabed, over a period of 2 days of testing which was the limit of the available test time which could be accommodated within the project resources.

Although the experimental procedures worked as planned and the anchor appeared to be hydrodynamically stable during free-fall in water (Figure 16), the anchor failed to achieve embedment depths of the order achieved in the preceding centrifuge tests. The limited embedment depth, which prevented anchor capacity being generated, is considered to be due to a combination of (a) stronger than anticipated seabed sediment at the test site, which was not at the recommended test locations (established from CPT records) due to EMEC licensing constraints which emerged after delivery of D4.1 and D4.2 and (b) an overall anchor mass that was at the lower bound of the range considered in the centrifuge tests. The decision to elect for a smaller (and hence lighter) follower was driven by concerns associated with the strong tidal currents at the test site, which could have push over the embedded anchor as it touched down. Although sufficient embedment was not achieved in the trials, the field trials have proven that the anchor is hydrodynamically stable and validated the drop installation procedure. This is complimentary to the centrifuge test data reported in D3.4, which demonstrated that the anchor can achieve embedment depths sufficient to generate significant anchor holding capacity.

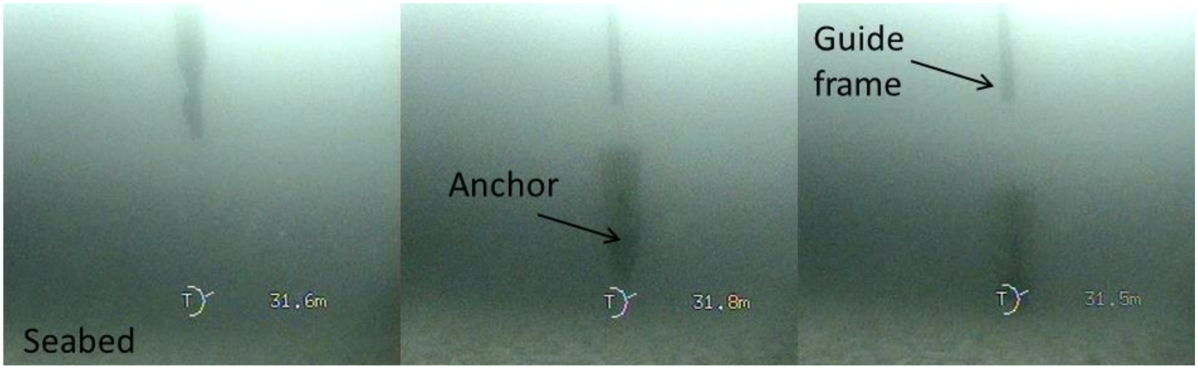

Figure 16 Stills from the ROV video capture for Test 4

3.5 WP5 Development of design and costing methods

Work Package 5 synthesised the new technical understanding gained through the research activities outlined in WP2 – WP4 into a toolkit for practical application to the design of mooring and anchoring systems for WECs. This included:

(i) Quantifying the costs of the newly developed mooring and anchoring systems (D5.4) and benchmarking this against existing approaches (D5.1, later revised in D5.4 to account for partner change;

(ii) Developing analytical methods for predicting the embedment and capacity of a new DPA-III type anchor (D5.2);

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(iii) Developing an integrated station keeping tool – a suite of tools for sizing the mooring and anchoring components for a given application (D5.3), providing information for subsequent costing (using the tool developed in D5.4).

Deliverable 5.1 (D5.1) produced quantified costs for the proposed deployment of the Wavebob point attenuator WEC which was the initial device under consideration by the consortium. This was based on the mooring configuration for its deployment in the Pilot Zone off the coast of Portugal, where the water depth is approximately 55 m. With Wavebob's subsequent departure from the project, the costs were re-quantified for the Pelamis line attenuator WEC; this was included in Deliverable 5.4, rather than re-issuing D5.1.

Deliverable 5.2 (D5.2) outlined the analytical methods developed during GeoWAVE that can be used in the design of a DPA-III drop anchor in sand. This included an analytical installation model, which uses a finite difference method to incrementally solve the equation of motion for penetration of the anchor into the seabed during the drop phase, while the follower is still connected. The result of the installation analysis is the penetration depth as a function of soil properties and anchor dimensions, which forms an input to the anchor capacity model which is also described in the deliverable. This consists of a kinematic model for determining peak monotonic anchor pull-out capacity (once the follower has been removed) that incorporates the behaviour of the embedded anchor line within the seabed and the loss of embedment which occurs up to the peak capacity being reached. These methods were validated using the available centrifuge test data from D3.4, which is currently limited to dense sand conditions as (i) FEM data was only available for these conditions; and (ii) centrifuge data which included observations of anchor line angle and loss of embedment was also only available for these conditions for the validation. Further 3-D FEM for different soil conditions would allow extension of the capacity model to other cohesionless materials, now that the methodology has been established.

The methods formulated in D5.2 were implemented into an integrated station keeping tool in **Deliverable 5.3** (D5.3). This incorporates:

1. A digital tool for extracting seabed property information from offshore piezocone penetration test (CPTU)data, such as that conducted at the EMEC field test site;
2. A digital tool for assessing anchor penetration depth for a given design of anchor which utilises the soil property information from tool (1);
3. A digital tool for determining the anchor performance under loading corresponding to the embedment determined using tool (2);
4. A digital tool for assessing the touchdown stability of the anchor, i.e. the resistance to toppling under the action of any near-seabed currents as it begins to penetrate the seabed, for the size of anchor providing sufficient capacity, as verified using tool (3).

In their current form, the tools are configured for assessing a given design of anchor; however the analyses may be re-run for different conditions to iterate towards an ideal set of design parameters for a particular application. If the pull-out capacity is too low for the applied mooring line forces from the

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WEC, or if the maximum installation current is too low to provide a practically realistic window for installation it is considered best to increase the follower mass as much as possible while keeping the centre of mass as low as possible on the follower and minimising changes to its width and length, to maximise penetration while minimising the effect on stability against toppling. If the required pull-out capacity cannot be achieved using a practical follower, the anchor cand be increased in size.

Having developed the tools for assessing the performance of one of the new anchors, **Deliverable 5.4** (D5.4) described the formulation of a spreadsheet costing model: 'Costing_methods.xls'. This estimates capital expenditure (CAPEX) of the components included within a complete mooring spread, which requires the material and size of the mooring lines to be determined based on the line arrangement, water depth and the expected loadings from the WEC, along with an approximate sizing of the anchors based on the seabed properties and loadings from the mooring lines. The approximate anchor size so determined can be used as the starting point for the detailed anchor performance analyses following D5.3.

Having defined the sizes of all of the components, a database of the cost of each element as a function of its size was defined, so that the CAPEX cost of any size mooring spread and anchoring system can be estimated. OPEX costs are defined as a percentage of the CAPEX costs and can be set individually for the different design options to account for differences in installation procedure between the different methods. The cost database is fully editable, so the tool can be updated as costs change in the future (e.g. due to inflation or cost savings due to new production techniques). The spreadsheet tool then summarises the sizes and costs for a range of different mooring/anchoring design options. These include:

- using 'existing' technologies (catenary mooring + gravity or drag anchors);
- using existing catenary moorings with the new DPA-III anchor technology;
- using a newer taut-line mooring arrangement with the new DPA-III anchor technology;
- using the full GeoWAVE arrangement, i.e. taut line + Seaflex units + DPAIII anchor.

An example set of results was presented for a nominal line tension of 400 kN (40 t) at a site having water depth of 50 m and a dense sand seabed (RD = 80%). Treating the drag embedment case as the 'existing' benchmark, if only the anchoring component of the technology developed in GeoWAVE is employed (DPA-III) within a catenary arrangement, there may or may not be savings made, depending on the embedment that can be achieved with the DPAIII, and whether savings in fabrication of the new anchors can be made through economies of scale when an array is considered with many anchors compared to a one-off fabrication. Any savings in cost would be in addition to other advantages of utilising DPAIII technology when installing an array, including obtaining precise positioning and potentially having cheaper installation. Adopting the fully holistic solutions that GeoWAVE set out to obtain, optimising both the mooring and anchoring components, even if relatively shallow embedment is achieved on the anchor, combining the taut line with the Seaflex units results in smaller, cheaper lines and smaller, cheaper anchors, reducing the overall cost by between 40% - 60% compared to a 'current' catenary + drag embedment case, depending on the embedment achieved by the anchor.

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3.6 GeoWAVE Objectives Addressed

The specific **scientific and technological objectives of GeoWAVE**, outlined in the Description of Work, have been addressed as follows:

1. To investigate the most suitable mooring configurations and components for Wave Energy Convertors that will minimise:
    a. anchor loads, thereby minimising component costs,
    b. motion impedance and hence maximise potential power conversion (of a Pelamis WEC),
    c. required burial/penetration depth (linked to lower anchor loads).

A new mooring configuration has been developed consisting of a 3-point taut line arrangement including Seaflex elements. This was shown to (a) reduce the loads transmitted to the anchors (D3.3); (b) optimise motion impedance (D2.3 and D3.3) and (c) would result in lower required penetration depth due to the lower line loads (D3.3).

2. To provide performance data for a new generation of technically efficient anchors that will quantify expected anchor geometries for a given mooring configuration, water depth and seabed profile.

An extensive database of centrifuge test data has been provided to quantify embedment ultimate pull-out capacity and performance under dynamic loading representative of storm loading (D3.4). Field test data has provided data on hydrodynamic performance during the drop phase and demonstrated that this is stable.

3. To utilise the new performance data from Objective 2 to develop and calibrate design methods for:
    a. anchor installation,
    b. in-service performance of the moorings and anchors,
    c. an integrated station keeping tool for the WEC.

Design methods have been developed to assess (a) anchor installation (D5.2); (b) in service performance of the moorings (D2.2, D2.3 and D2.4) and anchors (D2.5 and D5.2); and (c) implemented within an integrated station keeping tool (D5.3).

4. To utilise design methods from Objective 3 and performance data from Objective 2 to develop costing methods for mooring and anchoring WECs at a particular site, permitting an economical viability assessment.

The research leading to these results has received funding from the European Union Seventh Framework Program (*FP7/2007-2013*) under grant agreement no. 287056

A spreadsheet costing method has been implemented that can quantify the costs of conventional and new GeoWAVE mooring & anchoring systems and provide a comparative assessment to support decision making.

5. To conduct offshore testing to collate field data and verify design methods from Objectives 3 & 4.

Offshore field testing was conducted (D4.3) but due to a combination of limited time on site, unexpected seabed conditions which limited penetration and strong current which generated instability on touchdown, it was not possible to conduct any pull-out testing.

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4 Potential Impact, Main Dissemination Activities and Exploitation of Results

4.1 Potential impact

The EU has set challenging targets for the percentage (20%) of its energy requirements that must be sourced from renewables by 2020 (COM, 2007). The wave energy resource that lies along Europe's western seaboard is amongst the highest in the world, making renewable wave energy one of the more obvious sources for achieving these targets. The European Commission estimate that there is the potential for 10 GW to be installed by 2020 (COM 2008), which represents 3.1% of the estimated European wave energy resource (Pontes and Falcao, 2001) and 0.5 – 0.8% of the estimated global wave energy resource (Thorpe, 1999). A more conservative estimate assumes that 1.8 GW would be installed by 2020 and that the 10 GW target would be met in 2026 (Figure 17). **1.8 GW of installed capacity would correspond to 1,800 P2e WECs, 5,400 anchors and 5,400 Seaflex components.** Hence, there is a very significant new market that GeoWAVE will open for the SME partners who will now be strategically placed to exploit this opportunity and to become both EU and international leaders in this new industry.

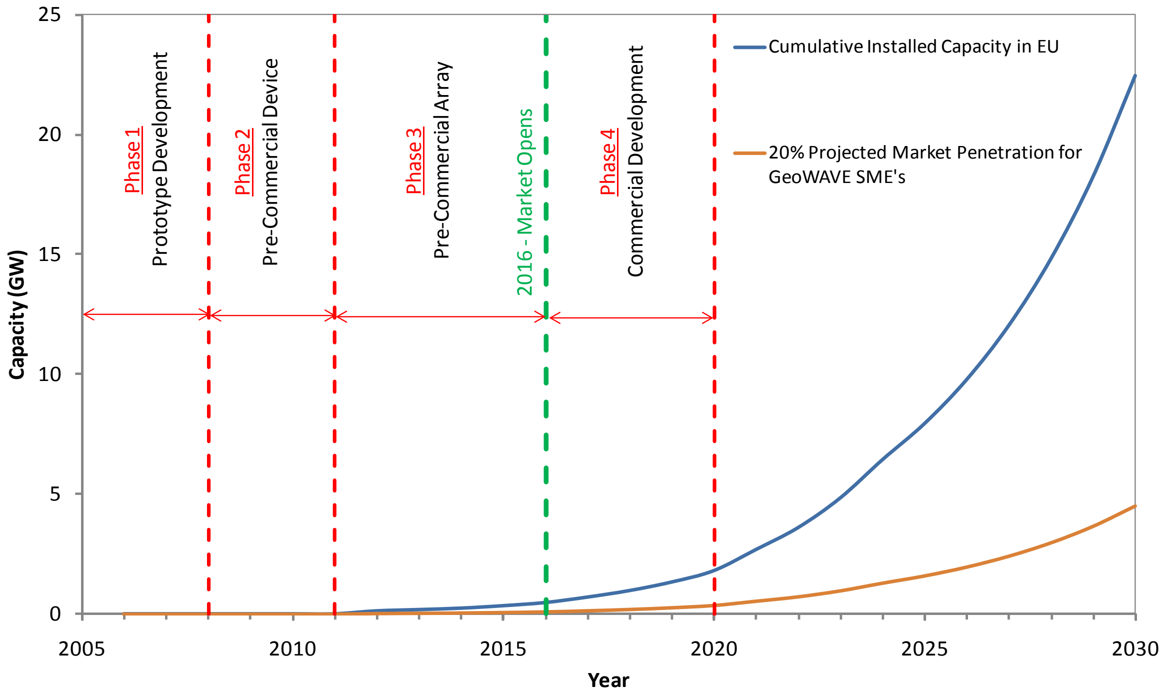

Figure 17 Projected EU market growth

The GeoWAVE project has redefined the state of the art of mooring and anchoring WECs, providing a new holistic solution which improves WEC performance, minimises cost and has been shown to provide reliable capacity, even when subject to dynamic loading. This new mooring and anchoring solution and related project IP is fully owned by the SMEs in the consortium. This will ensure that the

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project outcomes can be commercialised, thereby overcoming some of the remaining significant technical barriers for the further development of the wave energy sector.

Considering that current WEC devices are rated at around 1 MW, adopting a conservative projection of 1.8 GW of wave energy by 2020, infers that 1,800 WECs would be required to meet this medium term target. In terms of anchor and Seaflex mooring component sales, each WEC would typically be moored using a 3 point principal arrangement at the nose of the device, with 3 anchors and 2 taut line connections. Assuming the same 20% market penetration, means that 1,080 anchors and 720 Seaflex moorings would be required to meet the 1.8 GW projection for wave energy by 2020. Both GeoProbing technology and Seaflex are market ready and have excellent commercialisation channels. They will be able to begin exploitation of this market opportunity when future wave farm sites are developed. Although the anchor and mooring components and configurations have been developed around the Pelamis P2e WEC by GeoWAVE, the performance data and design methods are transferrable to other WEC systems. As such, Deep Sea Anchors/GeoProbing Technology and Seaflex will be in an excellent position to realise significant sales opportunities with other WEC developers.

Wave energy is expected to provide 2 direct jobs related to the WEC foundation elements (i.e. moorings and anchors) for every MW of installed capacity EU-OEA (2010). Adopting the previous 20% market penetration of 1.8 GW of wave energy by 2020 corresponds to a potential combined increase of 720 employees at GeoProbing Technology and Seaflex by 2020. In addition, their involvement in the technical aspects of the work packages and ownership of the design methods arising from GeoWAVE will increase their industrial competiveness and innovation capacity for other offshore applications such as floating wind turbines, oil and gas and offshore aquaculture.

The potential size of the offshore wave energy market by 2020 will also create significant opportunities for Cathie Associates to provide the geotechnical engineering consultancy and design for future wave farm developers. GeoWAVE has provided them with unique knowledge and tools for application in this sector, thereby positioning them ahead of their competitors in the renewable energy sector, which is currently focussed on offshore wind and tidal energy systems. The new technology developed through GeoWAVE will allow them to deliver anchoring solutions which are more cost effective and with improved dynamic performance than existing systems, helping them to win tenders and facilitating the impact for GeoProbing Technology and Seaflex mentioned above.

The project outputs will also be relevant to other offshore applications, the most significant of which is offshore wind energy. The European Wind Energy Association have ambitious targets of 20 GW of offshore wind energy by 2020. Some of this installed capacity will be in water depths greater than 50 m, where it becomes more economical to use floating rather than fixed wind turbines. Although the number of floating turbines that will be installed by 2020 cannot yet be quantified with any certainty, a conservative estimate of 10% corresponds to 800 2.5 MW wind turbines, which would likely be anchored with a 4 line, 4 anchor arrangement. As before, assuming a conservative 20% penetration

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in the floating offshore wind turbine market would result in an additional 640 anchors and Seaflex units.

The vast wave energy potential along Europe's western seaboard offers the EU an opportunity to evolve from a region heavily reliant on imported energy to one that not only fulfils its own energy requirements, but also exports its expertise and technology globally, thereby having a wider European impact. Meeting the medium term EU projection of 10 GW generated from ocean energy sources by 2020 would benefit the EU economy in the following ways:

1. **Creation of a new manufacturing industry**: renewable energy technologies already account for a turnover of €20 bn and have created 300 000 jobs COM (2008). A 20% share for renewables is estimated to mean almost a million jobs in this industry by 2020 – more if Europe exploits its full potential to be a world leader in this field. In addition, the renewable energy sector is labour intensive and reliant on many SMEs, spreading jobs and development to every corner of Europe. By installing 10 GW of wave energy by 2020, wave energy would represent 4% of the overall renewable energy mix in 2020, with increasing growth after 2020 as technologies mature. The share of job creation by 2020 is therefore likely to be of the order of 40,000 jobs across the EU (i.e. 4% of one million jobs in renewable energies).
2. **Security of energy supply**: the EU dependence on imported energy has risen from 20% at the signing of the Treaty of Rome in 1957 to its present level of 50%, and the European Commission forecasts that imports will reach 70% by 2030. If energy trends and policies remain as they are, the EU's reliance on imports will jump to 84% for gas consumption and 93% for oil by 2035. Europe is already paying the price of energy dependence. According to the European Commission, the EU's gas import bill alone increases by €15 billion annually for every $20 increase in price of a barrel of oil.
3. **Reduction in the EU's carbon footprint**: the EU has the rather ambitious target of 20% share of renewable energies in EU energy consumption by 2020. Recent studies indicate a CO_2 avoidance of 300 kg for every MW of installed wave energy (EU-OEA, 2010). Installing 1.8 GW of wave energy by 2020 would save 1.3 Mt/year.

4.2 Main dissemination activities

As will be outlined in the discussion of exploitation of the project results below, much of the output from GeoWAVE is highly commercially sensitive and is currently being explored for the potential to submit patent applications associated with both Seaflex units optimised for WEC application and the new DPA-III (anchor design and installation procedure). Nonetheless, non-sensitive elements of the research conducted have been disseminated as outlined below:

General information about the project has been disseminated via the project website and three international press releases. The key findings from the wave tank testing, namely the demonstration that the new GeoWAVE proposed moorings can significantly reduce mooring line (and hence

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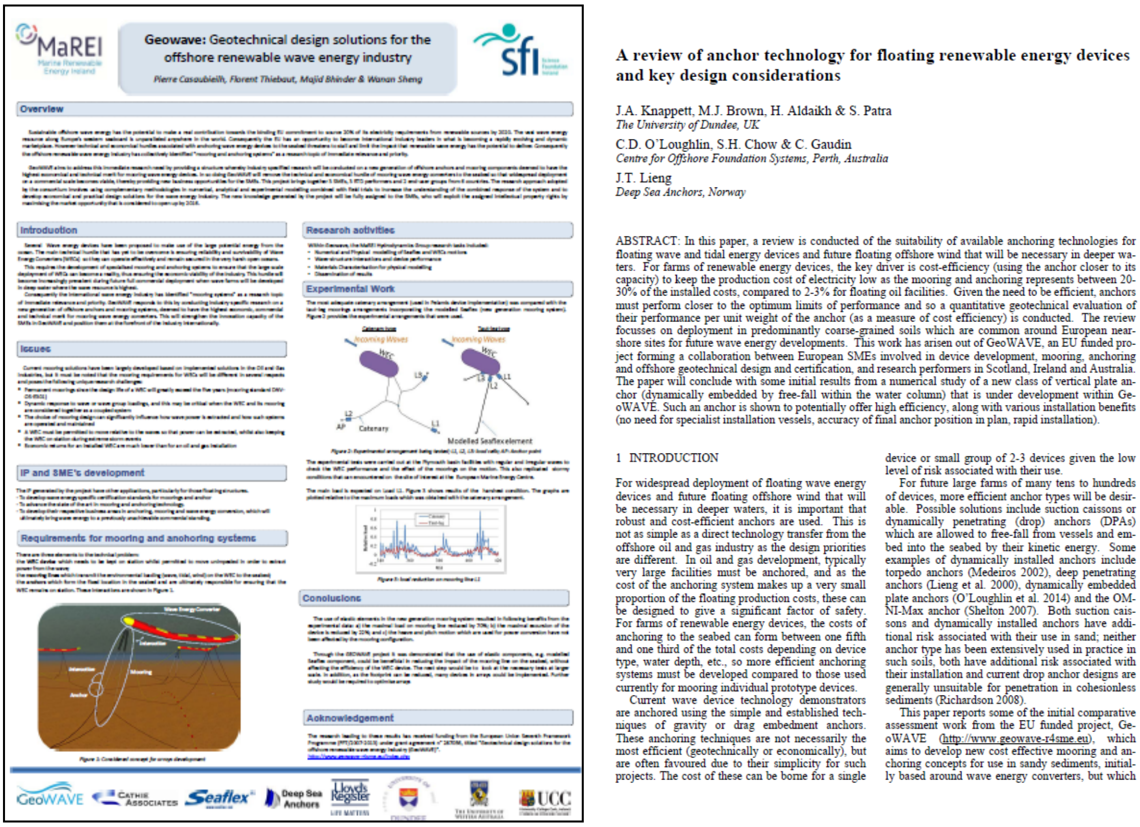
anchorage) load has been presented in a normalised form to avoid releasing sensitive performance and sizing information on the Seaflex units at RENEW 2014, the 1st International Conference on Renewable Energies Offshore (Lisbon, Portugal). The geotechnical benefits of drop installed plate anchors compared to existing solutions has also been disseminated in a normalised form at ISFOG 2015, the 3rd International Symposium on Frontiers in Offshore Geotechnics. In both cases a scientific paper was published and presented orally to an international audience at the conference or symposium. A poster has also been prepared (Figure 18).



A review of anchor technology for floating renewable energy devices and key design considerations

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ABSTRACT: In this paper, a review is conducted of the suitability of available anchoring technologies for floating wave and tidal energy devices and future floating offshore wind that will be necessary in deeper waters. For farms of renewable energy devices, the key driver is cost-efficiency (using the anchor closer to its capacity) to keep the production cost of electricity low as the mooring and anchoring represents between 20-30% of the installed costs, compared to 2-3% for floating oil facilities. Given the need to be efficient, anchors must perform closer to the optimum limits of performance and so a quantitative geotechnical evaluation of their performance per unit weight of the anchor (as a measure of cost efficiency) is conducted. The review focusses on deployment in predominantly coarse-grained soils which are common around European near-shore sites for future wave energy developments. This work has arisen out of GeoWAVE, an EU funded project forming a collaboration between European SMEs involved in device development, mooring, anchoring and offshore geotechnical design and certification, and research performers in Scotland, Ireland and Australia. The paper will conclude with some initial results from a numerical study of a new class of vertical plate anchor (dynamically embedded by free-fall within the water column) that is under development within GeoWAVE. Such an anchor is shown to potentially offer high efficiency, along with various installation benefits (no need for specialist installation vessels, accuracy of final anchor position in plan, rapid installation).

1 INTRODUCTION

For widespread deployment of floating wave energy devices and future floating offshore wind that will be necessary in deeper waters, it is important that robust and cost-efficient anchors are used. This is not as simple as a direct technology transfer from the offshore oil and gas industry as the design priorities are different. In oil and gas development, typically very large facilities must be anchored, and as the cost of the anchoring system makes up a very small proportion of the floating production costs, these can be designed to give a significant factor of safety. For farms of renewable energy devices, the costs of anchoring to the seabed can form between one fifth and one third of the total costs depending on device type, water depth, etc., so more efficient anchoring systems must be developed compared to those used currently for mooring individual prototype devices.

Current wave device technology demonstrators are anchored using the simple and established techniques of gravity or drag embedment anchors. These anchoring techniques are not necessarily the most efficient (geotechnically or economically), but are often favoured due to their simplicity for such projects. The cost of these can be borne for a single device or small group of 2-3 devices given the low level of risk associated with their use.

For future large farms of many tens to hundreds of devices, more efficient anchor types will be desirable. Possible solutions include suction caissons or dynamically penetrating (drop) anchors (DPAs) which are allowed to free-fall from vessels and embed into the seabed by their kinetic energy. Some examples of dynamically installed anchors include torpedo anchors (Medeiros 2002), deep penetrating anchors (Lieng et al. 2000), dynamically embedded plate anchors (O'Loughlin et al. 2014) and the OMNI-Max anchor (Shelton 2007). Both suction caissons and dynamically installed anchors have additional risk associated with their use in sand; neither anchor type has been extensively used in practice in such soils, both have additional risk associated with their installation and current drop anchor designs are generally unsuitable for penetration in cohesionless sediments (Richardson 2008).

This paper reports some of the initial comparative assessment work from the EU funded project, GeoWAVE (http://www.geowave-r4sme.eu), which aims to develop new cost effective mooring and anchoring concepts for use in sandy sediments, initially based around wave energy converters, but which

Figure 18 Example poster & paper

4.3 Exploitation of Results

Deliverable 6.2 presented the plan for use and dissemination of the results, concentrating on the two main products in development by SME partners responsible for these products, Seaflex and GeoProbing Technology. This considered both exploitation directly within the wave energy sector and also a broader analysis of the project work to determine whether there may be additional commercialisation opportunities for the SME partners. This was conducted using a SQUADRON™ analysis, i.e. considering:

- Segmentation
- QUality requirements
- Attractiveness
- Deliverables

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- Ranking
- Operationalising
- New income streams

The primary target markets (eight have been identified) for the products and services are defined below.

Product/Service	Application Area			
	a) WECs	b) Floating wind turbines	c) Offshore bioculture	d) Fish farms
1. Seaflex Mooring Element	✓	✓	✓	✓
2. DPAIII Anchor	✓	✓	✓	✓

The intended primary role of Pelamis Wave Power in this project was to assist in the development of mooring and anchoring systems which have the potential to improve the economics of commercial scale wave farms. The motivation therefore was to increase the available mooring component options from which to choose during mooring design. The mooring designs will always be site specific and project specific so the systems developed here may not always be applicable however having additional options and particularly overall life-cycle cost reducing options will be advantageous in increasing the economic performance or viability of projects. The advantage to Pelamis was therefore in having cost reduction options rather than new or additional revenue streams however in some cases a substantial reduction in mooring cost could be viewed as an enabling step towards project viability. Once Pelamis left the project, the motivation for the project did not change but the SME partners who benefit are different.

Seaflex and GeoProbing Technology have still benefitted in terms of development of their respective mooring/anchoring components and installation techniques allowing them to exploit their use within floating renewable energy systems. Cathie Associates stepped in as an SME partner at a late stage after PWP withdrew. As a consultant, CA will exploit the IP generated to offer new services related to anchor design and thus station keeping.

The SME partners fully own all Intellectual Property (IP) generated during the course of the project. Since the SMEs do not compete within the industry supply chain there are no IP conflicts between the partners. It is the partners' view that they will make the most of the project outcomes by collaborating on future WEC installation contracts. Cross-licencing the GeoWAVE IP rights will be implemented as necessary for future installation contracts.

Seaflex own the new IP that has been generated in deliverables D2.2, D2.3, and D3.3, and a proportion of D5.3 and D5.4. Through GeoWAVE, the performance of the Seaflex mooring component has been quantified under the complex cyclic loading regime imparted by WECs. The scale of the mooring component that is needed in order for the mooring to adequately perform over the design life of the WEC has also been determined. Seaflex will exploit this new IP by producing improved moorings and certifiable mooring designs for use with WECs. Seaflex are currently

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investigating whether this can form the basis of a new patent application that would enhance their patent portfolio and allow them to ring-fence the inventions that underpin the company's mooring systems.

GeoProbing Technology own the new IP that has been generated in deliverables D2.5, D3.4, and a proportion of that in D5.2, D5.3 and D5.4. Their anchor range is protected by patent numbers 625766 (USA), 307553 (Norway) and 1 042162 (EPO registered), principally for use in cohesive soils. However the claims covered in these patents are directed more to the performance of the anchors in mooring offshore oil and gas facilities. The research deliverables assigned to GeoProbing Technology (D2.5 & D3.4) and the associated IP could be exploited by Deep Sea Anchors by filing patent applications based on new fields of application (such as for use with WECs) and also for improvements to their existing inventions. GeoProbing Technology are currently exploring the potential for new patent applications around the plate-type design of the new DPA-III for use in sands and the installation procedure.

Cathie Associates owns a proportion of the new IP that has been generated in D5.2, D5.3 and D5.4. As a geotechnical specialist consultant, the IP generated in this project will provide Cathie Associates with improved understanding and methods for the design of anchoring systems.

There are currently no existing or anticipated business agreements which may impose limitations on the subsequent exploitation or information or inventions generated as a result of the project. As both the Seaflex and anchor components are currently being explored in terms of their suitability for patent applications, the publication of project results within the public domain has been somewhat limited.

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5 Project Details

Title	**GeoWAVE: Geotechnical design solutions for the offshore renewable wave energy industry** (GA no. 287056)
Coordinator	**University of Dundee** United Kingdom
Consortium	**University of Western Australia** Australia **University College Cork** Ireland **Lloyd's Register** United Kingdom **Cathie Associates** Belgium **Seaflex** Sweden **GeoProbing Technology** Norway
Duration	3rd September, 2012 – 2nd August, 2015
Funding Scheme	SME-2011-1: Research for the benefit of SMEs
Budget	EU contribution: €1,129,100.00
Website	http://www.geowave-r4sme.eu/
For more information	geowave@dundee.ac.uk

The research leading to these results has received funding from the European Union Seventh Framework Program (*FP7/2007-2013*) under grant agreement no. 287056

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The research leading to these results has received funding from the European Union Seventh Framework Program (*FP7/2007-2013*) under grant agreement no. 287056