PFOW Enabling Actions Project: Sub-sea Cable Lifecycle Study

February 2015

This report has been published by The Crown Estate as part of its Enabling Actions work to support development of the Pentland Firth and Orkney waters wave and tidal projects. The Crown Estate commissioned the European Marine Energy Centre (EMEC) Ltd to complete the work which aims to accelerate and de-risk the development process, looking at a range of key issues. Under the Enabling Actions Programme, work is selected, commissioned and steered by The Crown Estate in close discussion with the PFOW project developers.

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Acknowledgements

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1. Executive Summary

In March 2014, EMEC received funding from The Crown Estate to collate and review information about the integrity of sub-sea cables installed at the EMEC wave and tidal test sites to help inform on their performance in high energy environments. EMEC sub-contracted submarine cable specialists Engineering Technology Applications Ltd (ETA) to carry out this review.

This report provides a summary of the review undertaken by ETA, and is intended for publication to inform the marine renewable energy industry on factors affecting the integrity and performance of sub-sea cabling, including conclusions from the review and an opinion on the status of the cables in relation to age, tidal and wave environments. Pertinent recommendations for any further work in this area are also made.

The key aim of the cable review project was to improve the industry's understanding of how best to specify and manage subsea cables for wave and tidal current projects, by investigating how the cables installed at the EMEC test sites have been performing since installation. Life-spans currently reach 10 years on the wave cables.

The sub-sea cables installed at the EMEC test sites appear to be in general good condition, with some serving wear within a few areas of significant strumming risk. Each of the cables was reviewed in terms of installation methods, faults, operational life and electrical and ROV surveys. By comparing data from risk analysis calculations (that are usually carried out prior to installation) and actual damage to the cables, it was possible to understand the accuracy of predictive calculations.

Analysis of areas of suspensions on the EMEC cables has shown that there is a strong correlation between predictions utilising existing calculation methods and actual wear observed.

It is clear that frequent strumming causes rapid deterioration of cable serving, with instances of wear being greater and more distinct over areas of suspension than other areas of the cables. It is reasonable to conclude therefore that cable lifespan could be expected to be significantly reduced if strumming frequently occurs. The report has concluded that the greatest risk to sub-sea cables is the effect of tidal currents leading to cable strumming and instability.

Findings relating to cable movement were inconclusive, being obscured primarily by wear caused by installation operations and discoloration on rocks caused by bunched loose serving. There is some indication that cable movement occurred in the areas where industry standard calculations (taken from DNV standards) predicted. This confirms (to some degree) that calculation methods are broadly effective.

Suspensions and kinks due to the installation process have also occurred at the EMEC site and have required subsequent remedial work.

Recommendations to developers therefore include, to;

- Carry out calculations: In sites with high tidal flow, strumming is a key concern and may result in significantly reduced life for sub-sea cables. Risk of strumming should be assessed at an early stage and mitigated where possible. As there appears to be a correlation between the calculations using standards and damage observed, while unconfirmed, focus should be on controlling primary factors such as angle to tide (therefore, maintaining the cable as close to parallel to the tide, where possible), and length of suspension (DNV RP F105 states that cable suspensions with a length less than 30 times the diameter of the cable are not considered to be significant, i.e. at risk of strumming (the standard describes that length/diameter <30 exhibits '*very little dynamic amplification*'). This study therefore focused on suspensions greater than 3 metres)

- Complete detailed site surveys: A detailed knowledge of the seabed (using, for example, side scan sonar and ROV surveys) and thorough route planning will help to understand and minimise the risks to a cable

- Optimise route to avoid key risks for mitigation: When planning sub-sea cable installations, routes parallel to the tidal flow will reduce the risk of strumming if suspensions are formed. Due to the threat of significantly reduced service life, longer routes requiring extra cable that avoid strumming risk by maintaining the cable parallel to the flow, following natural features of the seabed or avoiding particular areas, may prove economically advantageous as they may help minimise the necessity for repair. Cable routing should also consider any effect that the bathymetry or seabed features may have in sheltering or preventing lateral movement of the cable (it should be noted that strumming requires the free flow of the current around the cable, if the cable becomes sheltered within seabed features it may be protected, and thus laying in-line with seabed features will also help prevent suspensions forming). Laying with extra slack should be considered where high risk suspension is predicted (however, with caution in high tidal environments)

- Increase protection: Cable armouring will help to protect a cable in high energy environments and up to quadruple armouring is available (beyond this the stiffness of the armouring makes transportation, logistics and installation more difficult and more expensive)

- Budget: Where strumming risk cannot be avoided, the cost of a reduced cable life should be taken into account within the project budget. Anecdotal evidence suggests life spans of cables can be effectively halved and even reduced to as little as 6-8 years. While the EMEC study has not confirmed this, and the cables at this site appear to have largely out lasted the 6-8 year minimums, this evidence should not be discounted. Inter-array cables, the routes of which cannot be varied as readily as those of the export cables, may often be under high risk of strumming and hence the recovery and replacement of these cables on a shorter time frame should be considered

- Monitor and inspect: Post-lay inspection should be integral to operations in tidal environments in order to assess risks to the cable, and should where possible involve assessment of strumming risk. Strumming risk can only be assessed in real detail once a cable has been laid and actual suspension can be observed. This information can be compared to calculations completed prior to installation to confirm if damage is occurring where predicted or if there is an unexpected issue. While mitigation methods in the planning stages may help limit damage, surveys will be required to assess if the cable is at risk. Remedial work to reduce suspensions may be necessary and has previously proved effective

2. Introduction

In March 2014, EMEC received funding from The Crown Estate to collate and review information about the integrity of sub-sea cables installed at the EMEC wave and tidal test sites to help inform on their performance in high energy environments. EMEC sub-contracted submarine cable specialists Engineering Technology Applications Ltd (ETA) to carry out this review.

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This report has been published by The Crown Estate as part of itsenabling work to support development of the Pentland Firth and Orkney waters wave and tidal projects. This work aims to accelerate and de-risk the development process, looking at a range of key issues. Work is selected, commissioned and steered by The Crown Estate in close discussion with the project developers.

The European Marine Energy Centre Ltd (EMEC) was established in 2003 and is the first and only facility of its kind in the world, providing developers of both wave and tidal energy converters (technologies that generate electricity by harnessing the power of waves and tidal streams) with purpose-built, United Kingdom Accreditation Service (UKAS) accredited open-sea performance testing facilities. EMEC is located in the Orkney Islands off the north coast of mainland Scotland, and has two principal grid-connected test sites, one for testing tidal energy converter devices and the other for testing wave energy converter devices.

Whilst EMEC's primary focus is the provision of services to industry for the rigorous testing of marine energy convertor systems (MECS), it also participates in a variety of national and international research projects aimed at providing the industry with essential information to progress. This includes projects aimed at industry-related problems that can be tackled in some generic capacity.

For more information on The Crown Estate's work in wave and tidal energy, see http://www.thecrownestate.co.uk/energy-and-infrastructure/wave-and-tidal/ or contact waveandtidal@thecrownestate.co.uk

For more information on EMEC's work in wave and tidal energy, see www.emec.org.uk or contact info@emec.org.uk

3. Background

Commercial wave and tidal energy generation sites in the Pentland Firth and Orkney waters (PFOW) and around the UK are now entering initial planning phases, and supporting information and data on how sub-sea cables perform in these high energy environments will be required by both project developers and investors alike in order to progress successfully.

To date there has been very little published information on how sub-sea cables survive and perform in high energy sites. The EMEC test sites currently have 12 sub-sea electrical cables installed, for which a considerable amount of information is available from regular inspections and testing. The oldest cables have been installed for approximately 10 years, and are installed at varying angles to waves and tidal currents in high energy locations. EMEC has carried out numerous routine remotely operated vehicle (ROV) surveys for structural integrity of the cables, and also has data from comprehensive electrical testing throughout the period that the cables have been installed. This information is expected to be of use to wave and tidal developers entering the commercial planning phase in PFOW and elsewhere in the UK.

The key aim of the cable review project was to improve the industry's understanding of how best to specify and manage subsea cables for wave and tidal current projects, by investigating how the cables installed at the EMEC test sites have been performing since installation.

2.1 Scope of Work

As mentioned above, the primary deliverable of the project is a report summarising the information available from the EMEC site and providing analysis, conclusions, and recommendations for future work based on this data. This summary report includes:

- A short review of existing cable integrity information relating to the wave and tidal energy sector and guidance available to developers
- A summary of the information available from EMEC
- Selection of which EMEC sub-sea cables were subjected to detailed review
- Review of survey data for the selected EMEC cables, to include summary of:
    - Serving wear
    - Spans/tight bends
    - Cable armour
    - Anthropogenic interactions
    - Cable movement
- Review of cable performance data covering:
    - Electrical – voltage/resistance tests
    - Communications – Optical Time Domain Reflectometer (OTDR) tests
- Consideration of factors affecting cable performance on selected cables, including:
    - Seabed type
    - Current speed and wave loadings
    - Cable usage
    - Cable to cable comparisons
- Conclusions and recommendations for further work

2.2 Methodology

To date, sub-sea cable installations in marine renewables areas have been guided by evidence that is broadly anecdotal, and by the use of codes and standards centred on pipeline stability (notably DNV RP F-109), the accuracy of which has never been tested in these specific applications. As a primary goal then, this study sets out to assess the efficacy of current techniques against the real world evidence available from the EMEC test sites.

In order to accomplish this, where possible the expected risks were set out independently and prior to the assessment of the cable condition in order to ascertain any difference between expected condition, and actual status. In comparing actual wear to expected risk, this study will aim to identify if and where current models fall short and ascertain if any further variables affecting the cable need to be accounted for. A key strength of the EMEC data is that the cables have been installed at different times, often using varying techniques. By identifying cables in comparable conditions that have been installed in different ways this study will attempt to expand the list of variables to include installation parameters and thus provide conclusions and advice to future developers.

The primary tools used to assess risk to the cable have been standard vortex induced vibration calculations used to assess the risk to the cable from strumming, and DNV RP F-109 utilised to assess cable stability (i.e. the likelihood of bodily movement).

Vortex induced vibration calculations are in general governed by three dimensionless groups: the reduced velocity, the stability parameter and the Reynolds number. The principle variables assessed are velocity of the current flow perpendicular to the cable and the natural frequency of a suspension, each of which is affected by further variables. Current flow velocity perpendicular to the cable is a function of the typical flow velocity (reduced when the cable is in greater water depths) and angle of the cable to this flow. Natural frequency of a suspension depends on its length, tension in the cable, and various cable parameters such as weight. The diameter of the cable is also taken into consideration in reference to the interaction of the current with the cable. Calculations show the necessary depth averaged current required to initiate strumming at different multiples of the natural frequency. Cables calculated to strum at lower current velocities, often reached at the site, were seen as being at higher risk. The level of risk of strumming calculated was compared to actual observable damage on the survey footage (such damage was categorised on a comparative scale in order to enhance comparison between suspensions).

The variables covered by DNV RP F-109 are similar to those for vortex induced vibration calculations. This standard provides calculations for determining whether a cable is horizontally or vertically stable in specific wave and current conditions. The calculations look at variables including average conditions, depth of cable, the interaction of wave and tide, and cable size in order to ascertain the forces experienced by the cable. Cable weight and seabed material are then used to assess the likelihood of movement. Cables were assessed at varying points across a range of conditions to determine conditions necessary for movement, and together with weather data this was used to ascertain the risk to the cable. This again was compared to visible damage at specific points, and along the length of the cable route.

It should be noted that there are some limitations with the data that may limit the scope of the conclusions of this study. The primary limitation is on quantifying the level of wear to the cables; while major risks (e.g. stability, strumming) can be quantified with ease, this is not the case for the *results* of these phenomena. Electrical test data yields results that are, in the most part, binary (pass/fail) and as no cable failures have been reported to date this information is unlikely to yield a detailed quantitative conclusion. Wear information instead comes from observed wear from survey footage which is subject to interpretation and limited by how well areas have been captured in the ROV surveys; information will therefore come from primarily qualitative sources. EMEC does however have a wealth of survey footage, present and historical, which will allow sufficient objectivity to be imparted by a comparative approach. Limitations will be identified where possible and highlighted as recommendations for further study and investigation.

2.3 Brief Overview of State of the Art in Design for Reliability of Sub-sea Cables

The lifetime of a sub-sea cable is governed by the deterioration of the insulation material properties under the influence of a combination of temperature, electric, chemical and mechanical stresses. Over time, these factors decrease the dielectric strength of the cable, ultimately leading to failure. Protecting the dielectric insulation layer is achieved using water blocking sheaths made of polymeric or metal materials. These materials also protect the cable against mechanical damage during cable transport and installation.

As detailed in Figure 1 below, the protection of the insulation layer is achieved using a number of additional outer layers. These consist of the armour (usually made of steel wires) which provides tension stability and mechanical protection particularly during installation and from external aggression due to fishing gear and anchors. Double layer amour is sometimes used to provide added protection. To protect the armour from corrosion the final outer layer of the cable consists of hessian tapes, bitumen and yarn or polypropylene strings.

1. Conductor: copper, circular stranded compacted, longitudinal water-tight by filling with a sealing compound (optional)
2. Conductor screening: extruded semi-conductive compound
3. Insulation: EPR
4. Insulation screening: extruded semi-conductive compound
5. Screen: copper tapes
6. Fillers: polypropylene strings
7. Binder tapes
8. Bedding: polypropylene strings
9. Armour: galvanised round steel wires, single or double wire armouring
10. Serving: hessian tapes, bituminous compound, polypropylene strings

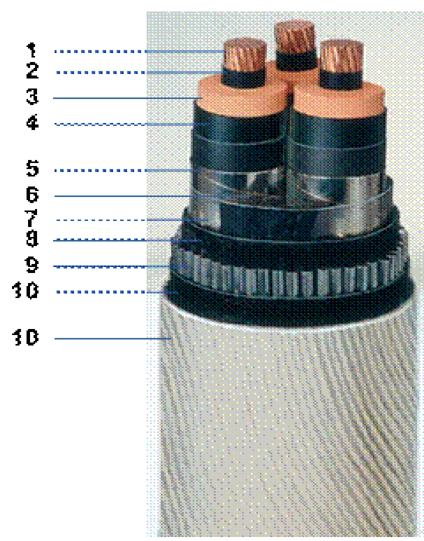

Figure 1: Construction of submarine power cable

2.4 Other Work in this Field: Health Management System for Sub-sea Cables

Dr. David Flynn of Heriot-Watt University (HWU) has led an 18 month project funded by Scottish and Southern Energy to investigate a first generation health management system. The team developed a monitoring collar and desktop analysis tool to monitor sub-sea cables in-situ and to predict the remaining useful life (RUL) of a cable. Utilising a 15 year historical data base, it was identified that 70% of cable failure mechanisms were attributed to external/environmental factors. The current state of the art in cable monitoring utilises either, or in combination, online electrical condition monitoring and distributed temperature and strain (DTS) measurements via fibre optics. These systems cannot monitor the failure modes associated with corrosion, abrasion and third party impacts, e.g. shipping. Therefore, current commercial systems only support the monitoring of 30% of the failure modes. This new health management system focuses on the majority share of failure modes, as shown in Figure 2 below, but with a sensor agnostic architecture that enables the integration of commercial monitoring systems.

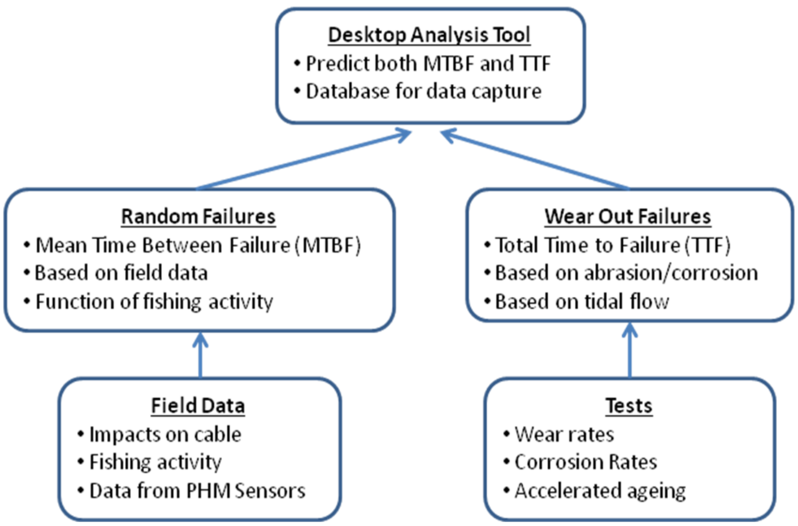

Figure 2: Failure modes covered by the sub-sea cable Health Management System

Within Phase 1 (12months) of the project the team investigated a condition based health monitoring system to monitor the degradation of sub-sea cables due to abrasive wear. This phase of the project demonstrated:

- Experimental technique to gather wear data for armour material
- Model to predict cable movement based on defined tidal current
- Model to predict wear in the amour over time
- Embedded sensors that gather data on movement of the cable
- Communications between the sensors and an embedded micro-controller containing the wear model
- Communications between the sensors and the shore

The above developments were undertaken to deliver a new monitoring technology that was retro-fit-able to new and legacy sub-sea cable installations. Data on cable dynamics and the processes of scour, abrasion and corrosion on the seabed at the time of development did not exist.

The reliability of sub-sea cables can be considered using the classical 'bathtub' curve which demonstrates different failure rates against time in service (see Figure 3 below). Initially, there may be a high rate of failure with a new sub-sea cable design due to poor design and manufacturing defects. Sub-sea cable manufacturers aim to have manufacturing procedures in place that would eliminate these failures. The second phase as known represents random failures, which for sub-sea cables would be due to unforeseen incidents such as third party impacts due to fishing activity. The final phase is wear-out, which for sub-sea cables would be failures due to abrasion and corrosion.

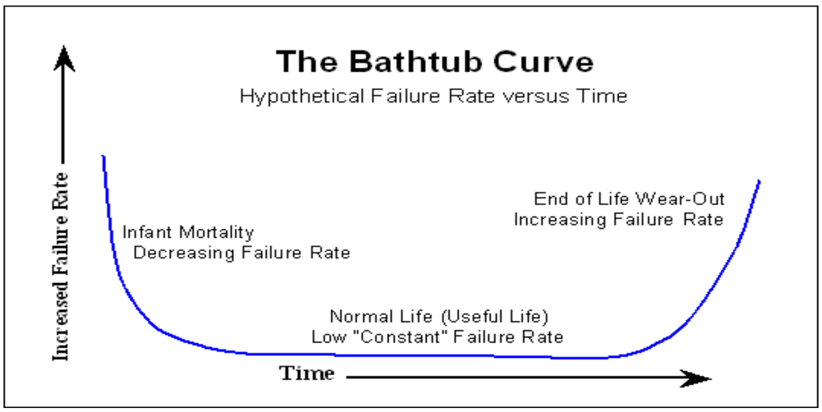

Figure 3: Bathtub curve for reliability

A brief review of the available literature demonstrates that sub-sea cable manufacturers undertake a number of tests to qualify a cable before shipping to customers. These tests are detailed by Thomas Worzyk in the book *Submarine Cables (pages 136-148)* where accepted standards (International Electrotechnical Commission (IEC), etc) are used. These tests focus mostly on electrical and thermal behaviour of the cable. The main standard for mechanical testing is documented in *CIGRE Electra 171* which is used to test torsional and bending stresses in cables, particularly to assess their strength during installation.

Cable abrasion and corrosion rate measurements are detailed in IEC 60299 standard. In the abrasion test, a cable is measured through a mechanical rug test using a steel angle dragged horizontally along the cable. This test was designed for the cable in the laying operation; hence it does not reflect the abrasion behaviour of the cable when it moves along the seabed in the working environment.

Hence in assessing the overall reliability/life of a cable design before deployment, a number of factors such as those detailed above need to be considered. A desktop tool to assess probable lifetime and risks of failure in a specified sea environment will need to consider all of these factors. At present, HWU has designed and developed a first generation of such a tool (see Figure 4 below). To HWU's knowledge there is currently no other analysis tool available that can predict the expected lifetime of a sub-sea cable when subjected to defined seabed conditions and tidal flows. During blind testing this system predicted the accuracy of cable RUL within one month. Future work will focus on expanding the historical database, integrating additional data from commercial monitoring systems, scaling up the monitoring hardware, and validating the system against a larger case study set.

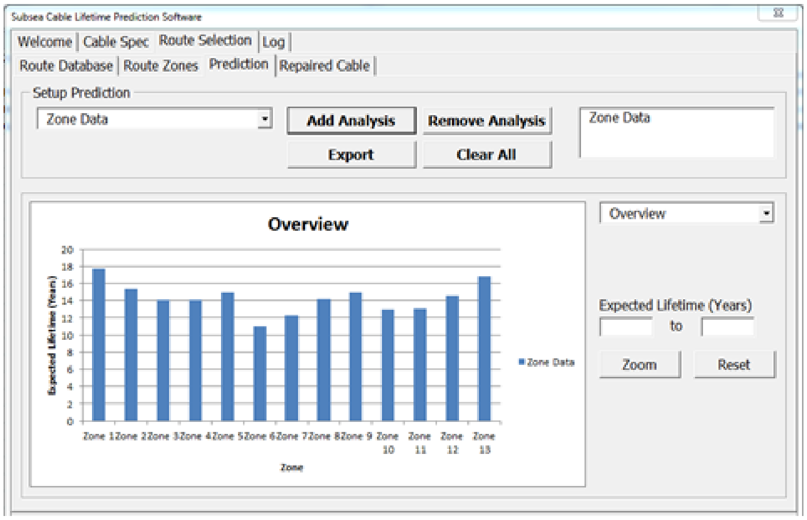

Figure 4: Sub-sea cable lifetime prediction tool developed by Heriot-Watt University

The tool uses knowledge from historical failures, rates of material degradation, modelling of cable displacement and in-situ cable monitoring enable a prediction of the RUL of a given cable zone. Different cable types in different environments can instantly be compared to enable the optimal planning of cable type and route.

4. Cables in High Energy Environments: Current Knowledge

Submarine cables are typically designed with a design life of 25 years or more, but are not normally subjected to strong tidal currents or the aggressive conditions associated with wave and tidal energy sites.

In general, power cable failure data is not readily available but the International Council on Large Electric Systems (CIGRE), an International Association of large utilities, have attempted to collate data reported by cable owners and manufactures. It is thought that this data will have limitations as not all faults are reported. The key points of the CIGRE study can be summarised as follows:

- Of all cable faults reported, around 50% were due to fishing and anchoring, and risks at the EMEC site are low all the way along the cable route
- Average failure rate for all types of submarine power cables are 0.1114 faults/100 km/year
- The major part of these failures occurred after nearly 10 years and more in operation
- A reduction in fault rates have been observed from a previous CIGRE study (this is attributed to most new cables being buried to a depth of at least 0.5m and improved survey leading to better route design)

This, and other similar reports, constitutes the extent of formalised data available on power cable faults; none of this is directly applicable to wave and tidal energy test sites. At present, all context specific data is purely anecdotal and comes from a very limited collection of circumstances.

For surface laid power cables around Scotland, where aggressive conditions are common, a service life of around 18 to 24 years is expected. In areas where cables are laid perpendicular to strong currents in rocky conditions however, these have been known to fail in much shorter timescales. Anecdotal evidence suggests that in some high tidal areas around Scotland where cables are laid on the surface and perpendicular to the tide they have failed 6 to 8 years after installation. It is suspected that these cables are not only laid perpendicular to the tide but also under relatively high residual tension, leading to large suspensions which are the cause of failure (due to vortex induced vibration). No formal figures have been released for these cables.

Further evidence for significantly reduced service life can be taken from the experiences with the submarine cables laid between Rockport, Maine and the islands of North Haven and Vinalhaven (which has been dubbed the world's worst submarine cable). Here, the 17km of cables had been laid over a number of areas of rugged bottom, the worst of which was a 15m high rock outcrop with near vertical walls on both sides (after 13 years in service, the first fault occurred in the area of this outcrop). It is worth noting that this cable was single armoured.

It is difficult to draw ultimate conclusions from this anecdotal data, and thus predictions relating to service life of cables can rarely be made as the conditions of lay can only be speculated upon. It can only be said that it *appears* that service life will be reduced. In this regard, with extensive survey information, and site specific current information, the data relating to EMEC sub-sea cables could provide a significant improvement in predicting sub-sea cable life.

5. Cable and Site Information

EMEC operates two grid-connected full scale test sites, one at Billia Croo on the western edge of Orkney Mainland (wave energy test site), and the other at the Fall of Warness to the west of the island of Eday (tidal energy test site). In addition to these grid-connected test sites, EMEC also operates two 'scale' test sites to allow developers to test prototype scale versions of their technologies and deployment techniques in less challenging conditions. Figure 5 below shows the locations of the EMEC test sites.

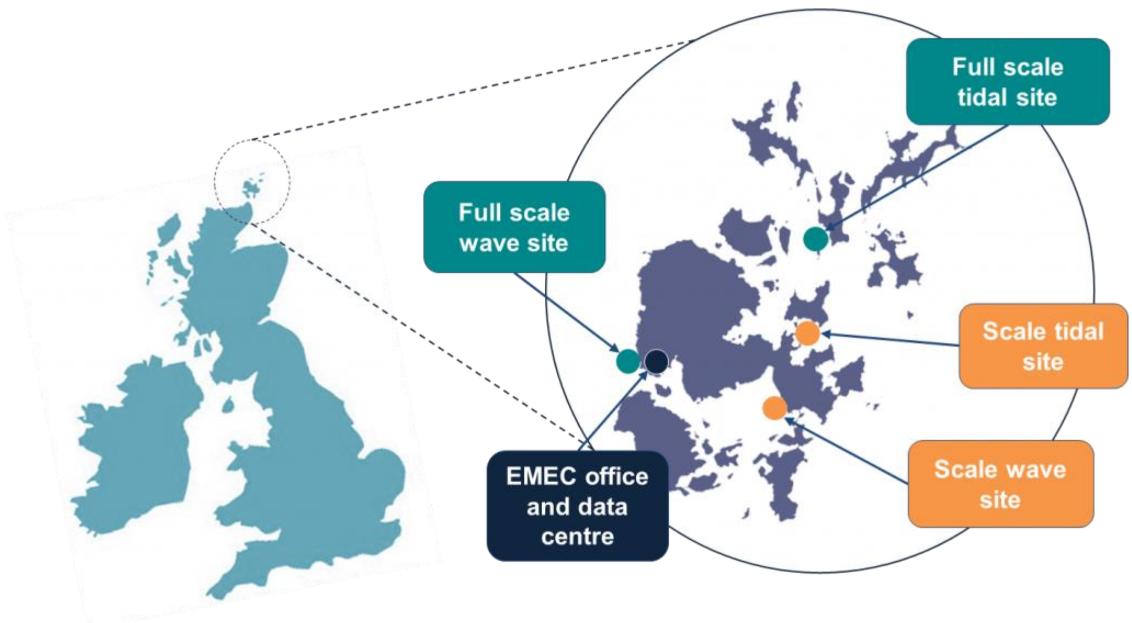

Figure 5: Graphic showing location of EMEC test sites

4.1 Wave Energy Test Site

The EMEC wave energy test site was constructed in 2003 with the installation of four sub-sea cables, and is ideally placed at Billia Croo on the western edge of the Orkney Mainland. Subjected to the powerful forces of the North Atlantic Ocean, it is an area with one of the highest wave energy potentials in Europe, with an average significant wave height of 2m – 3m, but reaching extremes of up to 17m (the highest wave recorded by EMEC so far). An additional berth was established in 2010, and the site now consists of five cabled test berths in up to 70m water depth (four at 50m, one at approximately 70m), located approximately 2km offshore and 0.5km apart. In addition to this, a near-shore berth is situated closer to the substation for shallow water projects.

Figure 6 below shows the extent of the EMEC wave energy test site at Billia Croo (dashed lines) together with the approximate route of the five sub-sea cables (red lines).

The EMEC wave energy test site is characterised by dramatic seabed topography, and with the cables laid in relatively high tensions (estimated 1.5-2t) across this they hang mostly in freespan, in some areas touching down briefly every 20-30m.

The current profile at the wave energy test site is also significantly different. As opposed to a single directional tidal current, the water flow is influenced by the wave activity at the site. Tidal flow itself is indicated to be relatively low, with a large component of the current coming from the waves. Overall current direction is therefore highly variable and must always be assumed to act in worst case at 90º to the cable (this should be roughly true of tide-only currents for W2 and W3 as the tidal direction is North-South, and the cables are laid East-West). Current velocity is also highly variable at the wave energy test site, as it is dependent on wave height.

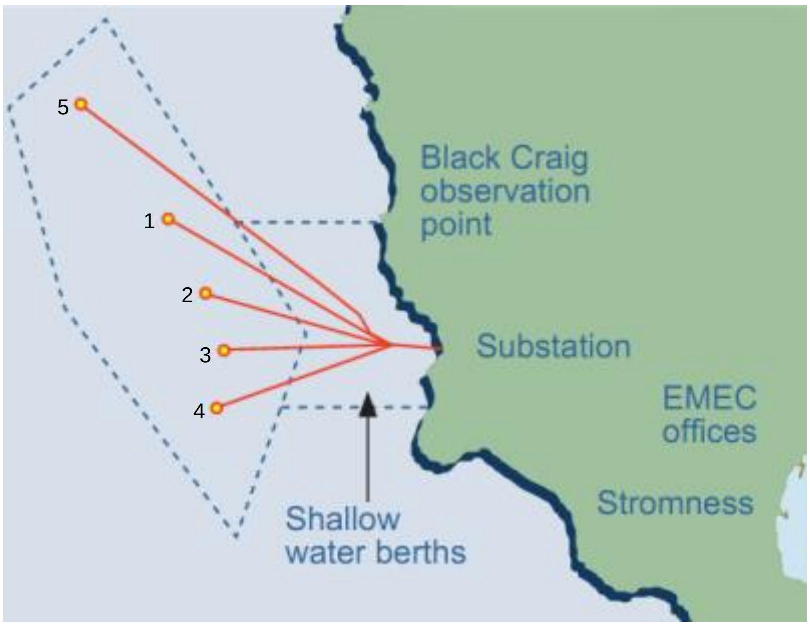

Figure 6: Graphic showing area of the EMEC wave energy test site at Billia Croo, Orkney

4.2 Tidal Energy Test Site

The EMEC tidal energy test site at the Fall of Warness is situated just west of the island of Eday, lying in a narrow channel between the Westray Firth and Stronsay Firth. As tides flow from the North Atlantic Ocean to the North Sea, they quicken as they are funnelled through Orkney's northern islands. The site was chosen for its high velocity marine currents which reach almost 4m/sec (7.8 knots) at peak spring tides.

The first sub-sea cables were installed at the site during 2006, at depths ranging from 12m to 50m in an area 2km across and approximately 4km in length. The site now accommodates eight cabled test berths (the cable nearest to the shore, cable 8, was installed by an EMEC client, and is not included in this study). Each 11kv sub-sea cable extends to the middle of the tidal stream from EMEC's substation at Caldale in Eday, from where it is routed to the individual test berths. Figure 7 below shows the extent of the EMEC tidal energy test site at Fall of Warness (dashed lines) together with the approximate route of the eight sub-sea cables (red lines).
At the tidal test site, the 60% depth averaged current at the site reaches speeds approaching 4 m/s on the spring tide, and decays with depth according to the 1/7 power law. Typical day to day peak current is around 2.6 m/s. Current flows on the line between 330/340º and 150/160º (accounting for a minor difference between flood and ebb). This is affected by some seabed

features, and in particular Seal Skerry in the area of T4, but it was largely assumed to be consistent for this study.

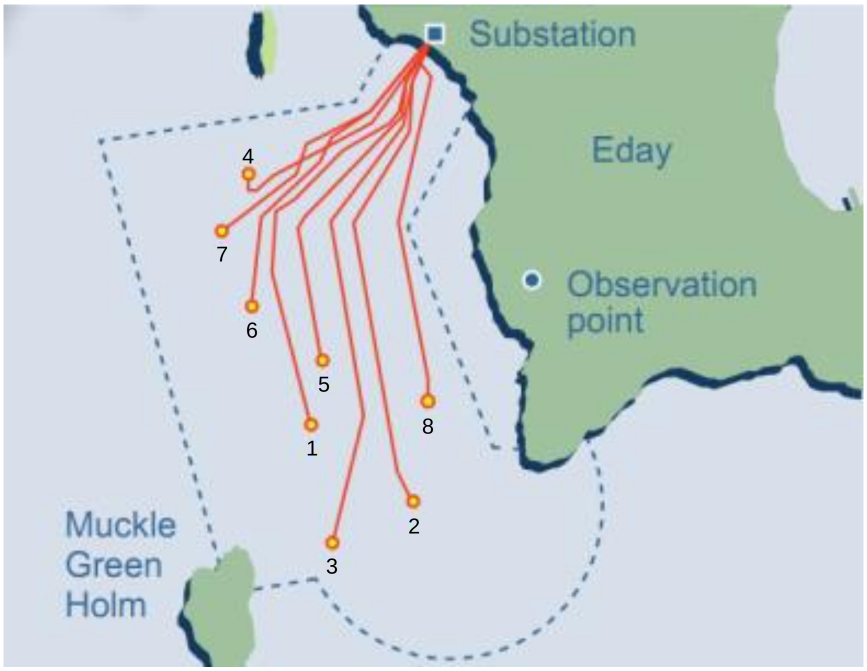

Figure 7: Graphic showing area of the EMEC tidal energy test site at Fall of Warness, Orkney

4.3 Cable Details

The cables at the wave energy test site at Billia Croo and the tidal energy test site at the Fall of Warness are broadly similar, with an 11kv cable running from an onshore substation out to each open-sea berth.

The cables are wet-type composite cables consisting of three Ethylene Propylene Rubber (EPR) -insulated stranded copper power cores designed for alternating current; three 2.5mm^2 copper signal/pilot trip cables; and a 12-core single-mode fibre-optic bundle. Each cable is then armoured with two layers of galvanised steel wire. Cables were provided by AEI Cables Ltd (wave energy test site cables) & Pirelli/Prysmian Group UK (tidal energy test site cables).

In 2010, a UK Department of Energy and Climate Change (DECC) funded project enabled EMEC to increase the berth capacity by installing new cables. These cables, built by Draka in Norway, are of a similar specification to the cables described above, but are cross-linkable polyethylene compounds (XLPE) -insulated and include an additional 4 core 4mm^2 auxiliary power cable. Two additional cables were installed at the tidal energy test site and one at the wave energy test site, using a total of 12km of newly procured cable.

The cables were laid as standard sub-sea cables on the sea bed. As the cables approached the shore, in 15m of water, ductile iron cable protectors were attached. At the low water spring tide mark, each passes into a trench dug 1.2m into the seabed and beach. On shore, the cables are fed into a manhole and then into an electricity substation. At the seaward end, each cable, when not occupied by a developer, is terminated using a specially designed end-cap.

Table 1 and Table 2 below provide a summary of the sub-sea cables installed at EMEC to date, showing intervention history and data available for each cable.

Fall of Warness Tidal Energy Test Site							
	Cable 1	**Cable 2**	**Cable 3**	**Cable 4**	**Cable 5**	**Cable 6**	**Cable 7**
1. Cable type							
Manufacturer	Pirelli	Pirelli	Pirelli	Pirelli	Pirelli	Draka	Draka
Construction	DWA fully flooded	DWA fully flooded	DWA fully flooded	DWA fully flooded	DWA fully flooded	DWA semi-flooded	DWA semi-flooded
Insulation	EPR	EPR	EPR	EPR	EPR	XLPE	XLPE
Csa	Cu 120mm2	Cu 120mm2	Cu 120mm2	Cu 120mm2	Cu 120mm2	Cu 120mm2	Cu 120mm2
2. Date of installation							
	Aug-Oct 2005: Two known kinks.	Aug-Oct 2005	Aug-Oct 2005	Aug-Oct 2005	Aug-Oct 2005: Recovery gear lost, cable tangle at end	2010: Note 4.	2010: Laid with J+S end fitted.
3. Outline of interventions and use							
	July 2008: Cable end disturbed as result of barge run-off.	June 2008: Cable end moved laterally to allow foundation works.	July 2008: Damage due to barge run-off.	2007: cable Lifted, relocated to developer's device, pulled in through J-tube. Several cable handling operations within this scope, see note 3.	2006: Unsuccessful attempts to recover cable, thought to have had limited contact with cable.	Aug 2010: Cable lifted, moved, connected to client sub-sea structure. (Note 5)	Sep 2013: Cable lifted, moved, spliced to client cable management system.
	July 2010: Cable lifted, tested, cut back approx. 900m to remove kinks, tested again.	July 2008: Damage due to barge run-off.	Aug 2009: Damage due to anchor drag during operations.	2007 - present: Cable energised at 11kV	Sept 2010: Cable lifted, unknown length removed, J+S test end fitted.	Oct 2010: Cable disconnected from sub-sea structure	
	Aug 2010: Cable lifted, kink removed, 1km repair length spliced to end.	Jan 2010. Approx. 180m damaged cable removed, 200m Developer's 8kV	Oct 2010: Cable lifted, 650m damaged cable removed, 600m repair length		20-Sep to 11-Oct-10: Cable energised at 11kV	Apr 2011: Cable reconnected to sub-sea structure	

		umbilical spliced on.	fitted c/w J+S test end, laid temporarily on seabed, retrieved and re-laid on desired route 2 weeks later.				
	Oct 2011: Cable lifted, short client cable (100m of Draka 120mm2) spliced on. Kink thrown in repair length.	August 2010 - present: Cable in service at 6.6kV	Oct 2010 - 17-Jul-13: Cable energised at 11kV (J+S test end)			Nov 2011: Cable disconnected from sub-sea structure	
	Dec 2011: Nacelle connection (may have disturbed the splice)						
	Dec 2011 - Jan 2013: In service, variable voltage and frequency up to 6.6kV.						
	Jan 2013: Nacelle removed (may have disturbed the splice).						
	Aug 2013: Cable lifted, cut back beyond kink, new repair length added.						

	Aug 2013: Nacelle reconnected.						
	Aug 2013 – present: In service, variable voltage and frequency up to 6.6kV.						
4. Electrical test data available							
	2005 - 2010: note 0	2005 - 2010: Note 0	2005 - 2010: Note 0	2005 - 2007: Note 0	2005 - 2010: Note 0	2005 - 2010: Note 0	July 2010: Tests as note 2
	July 2010: Tests as note 1	2008: Various tests associated with cable ops and damage, mostly optical.	2008: Various tests associated with cable ops and damage, mostly optical.	2007: IR and dc pressure test prior to energisation	Sept 2010: Test as per note 2	July 2010: Post-installation tests to 5kV	Feb 2012: Tests as note 2, cable unterminated onshore.
	Aug 2010: Tests as note 1.	Jan 2010: Client tests including VLF to 12.7kV	Oct 2010: Test as per note 2		Feb 2012: 5kV IR test	Aug 2010: Client handover tests to 5kV	Mar 2013: Tests as note 2 after onshore termination.
	Oct 2011: Tests as note 2 at handover to client.				Apr 2013: 5kV IR test		July 2013: Tests as note 2 at handover to client
5. Resource data available							
	Wave Height every 100m(M)	Wave Height every 100m(M)	Wave Height every 100m(M)	Wave Height every 100m(M)	Wave Height every 100m(M)	Wave Height every 100m(M)	Wave Height every 100m(M)
	Period every 100m(M)	Period every 100m(M)	Period every 100m(M)	Period every 100m(M)	Period every 100m(M)	Period every 100m(M)	Period every 100m(M)
	Direction every 100m (M)	Direction every 100m (M)	Direction every 100m (M)	Direction every 100m (M)	Direction every 100m (M)	Direction every 100m (M)	Direction every 100m (M)
	Current speed every 100m (M)	Current speed every 100m (M)	Current speed every 100m (M)	Current speed every 100m (M)	Current speed every 100m (M)	Current speed every 100m (M)	Current speed every 100m (M)

	Current direction every 100m (M)	Current direction every 100m (M)	Current direction every 100m (M)	Current direction every 100m (M)	Current direction every 100m (M)	Current direction every 100m (M)	Current direction every 100m (M)
	ADCP (at specific location)	ADCP (at specific location)	ADCP (at specific location)	ADCP (at specific location)	ADCP (at specific location)	ADCP (at specific location)	ADCP (at specific location)
	Waverider buoy (at specific location)	Waverider buoy (at specific location)	Waverider buoy (at specific location)	Waverider buoy (at specific location)	Waverider buoy (at specific location)	Waverider buoy (at specific location)	Waverider buoy (at specific location)
	Bathymetry at 2m resolution	Bathymetry at 2m resolution	Bathymetry at 2m resolution	Bathymetry at 2m resolution	Bathymetry at 2m resolution	Bathymetry at 2m resolution	Bathymetry at 2m resolution
6. ROV data available							
	2006 offshore	2006 offshore	2006 offshore	2006 offshore	2006 offshore	2010 offshore	2010 offshore
	2009 offshore	2008 offshore	2008 offshore	2007 offshore	2008 offshore	2012 inshore	2012 offshore
	2010 offshore	2009 offshore	2009 offshore	2008 offshore	2009 offshore	2013 offshore	2012 inshore
	2010 inshore	2010 inshore	2010 inshore	2009 offshore	2010 inshore		2013 offshore
	2012 inshore	2011 offshore	2010 offshore	2010 inshore	2010 offshore		
	2013 offshore	2011 inshore	2011 offshore	2010 offshore	2012 offshore		
		2013 offshore	2013 offshore	2011 offshore	2013 offshore		
				2011 inshore			
				2013 offshore			
7. Cable Routes							
	SW from substation	SW from substation	SW from substation	SW from substation	SW from substation	SW from substation	SW from substation
	S from 30m contour	S from 30m contour	S from 30m contour	Roughly follows 20m con	S from 30m contour	SW to beyond 30m con	SW to beyond 30m con
			SW from 50m contour	west of turbine		South after 30m con	South after 30m con
				east back to turbine			
				Complex route offshore		Complex route offshore	Complex route offshore
Notes:							
Note 0:	Cables originally laid with Pirelli pulling head, not able to accept high voltage test.						
Note 1:	Tests include continuity, IR at 5kV, VLF at 12.7kV and partial discharge. Also OTDR.						
Note 2:	Tests include continuity, IR at 5kV and VLF at 12.7kV. Also OTDR.						
Note 3:	First move introduced kink.						

	Kink removed, tested, reported.
	Second move to platform, then incremental pull-in.
	Cable easing works.
Note 4:	Cable 6 laid with client's own end fitment. Client advised 5kV max test voltage.
Note 5:	Client did not use an umbilical. Some issues with management of slack cable.

Table 1: Summary of sub-sea cables installed at the EMEC tidal energy test site, Fall of Warness, Orkney

Billia Croo Wave Energy Test Site					
	Cable 1	**Cable 2**	**Cable 3**	**Croo Cable 4**	**Cable 5**
1. Cable type					
Manufacturer:	AEI	AEI	AEI	AEI	Draka
Construction	DWA fully flooded	DWA fully flooded	DWA fully flooded	DWA fully flooded	DWA semi-flooded
Insulation	EPR	EPR	EPR	EPR	XLPE
Csa	Cu 50mm^2	Cu 50mm^2	Cu 50mm^2	Cu 50mm^2	Cu 120mm^2
2. Date of installation					
	2003	2003	2003	2003	2010
3. Outline of interventions and use					
	2004: First device trials at 11kV. Cable lifted to make bolted connection to client's umbilical within oil-filled junction box.	2006: Cable lifted to fit Henley pulling head (Note 0)	2006: Cable lifted to fit Henley pulling head (Note 0)	2006: Cable lifted to fit Henley pulling head (Note 0)	June 2012: Cable handover to client.
	2006: Cable lifted to fit Henley pulling head (Note 0)	2010: Cable lifted, J+S test end fitted	Jan 2010: Cable lifted for testing. Recapped with modified Henley end.	2010: Cable lifted, J+S test end fitted	July 2012: Cable lifted for splicing of client umbilical.
	2006: Cable lifted to splice on client umbilical.	2011-12: Several cable operations to achieve a successful splice of new umbilical			Sep 12: Client umbilical parted in severe weather.
	2007: Device trials at 6.6kV	2012- present: Device trials at 6.6kV			June 2013: Cable lifted, umbilical replaced.
	2010: Cable lifted to splice new umbilical				2014: Cable in use.
	2010 – present: Device trials at 6.6kV				
4. Electrical test data available					
	2006: Various IR tests at splicing	2010: Tests as Note 1	2010: Tests as Note 2	2010: Tests as Note 1	June 2012: Tests as note 2 prior to handover to client

	2007: Various IR tests	2011-12: Tests as Note 2 at splicing	2010 – present: A small number of IR tests at 1kV.	2010 – present: A small number of IR tests at 5kV.	2012 – present: A small number of IR tests at 5kV.
	2010: Tests as Note 2 at splicing				
	2010 - 2013: Continuity and IR data as Note 3 from 15 device deployment cycles	2012-present: Continuity and IR data as Note 3 from 12 device deployment cycles			
5. Resource data available					
	Wave Height every 100m(M)	Wave Height every 100m(M)	Wave Height every 100m(M)	Wave Height every 100m(M)	Wave Height every 100m(M)
	Period every 100m(M)	Period every 100m(M)	Period every 100m(M)	Period every 100m(M)	Period every 100m(M)
	Direction every 100m (M)	Direction every 100m (M)	Direction every 100m (M)	Direction every 100m (M)	Direction every 100m (M)
	Current speed every 100m (M)	Current speed every 100m (M)	Current speed every 100m (M)	Current speed every 100m (M)	Current speed every 100m (M)
	Current direction every 100m (M)	Current direction every 100m (M)	Current direction every 100m (M)	Current direction every 100m (M)	Current direction every 100m (M)
	ADCP (at specific location)	ADCP (at specific location)	ADCP (at specific location)	ADCP (at specific location)	ADCP (at specific location)
	Waverider buoy (at specific location)	Waverider buoy (at specific location)	Waverider buoy (at specific location)	Waverider buoy (at specific location)	Waverider buoy (at specific location)
	Definition of Surf zone	Definition of Surf zone	Definition of Surf zone	Definition of Surf zone	Definition of Surf zone
	Bathymetry at 2m resolution	Bathymetry at 2m resolution	Bathymetry at 2m resolution	Bathymetry at 2m resolution	Bathymetry at 2m resolution
6. ROV data available					
	2006 inshore	2006 offshore	2006 offshore	2006 offshore	2010 offshore
	2008 inshore	2008 inshore	2008 inshore	2008 inshore	2011 inshore
	2008 offshore	2008 offshore	2008 offshore	2007 offshore	2013 offshore
	2009 offshore	2009 inshore	2009 inshore	2008 offshore	
	2011 offshore	2009 offshore	2009 offshore	2009 inshore	
	2013 offshore	2010 offshore	2011 inshore	2009 offshore	
		2011 offshore	2011 offshore	2010 offshore	
		2011 inshore	2013 offshore	2011 inshore	

		2013 offshore		2013 offshore	
7. Cable Routes					
	West from substation	West from substation	West from substation	West from substation	West from substation
	NW to offshore after gully	NW to offshore after gully	W to offshore after gully	SW to offshore after gully	NW to offshore after gully
Notes:					
Note 0	HV cores cut and capped but not prepared for electrical testing. Tests therefore not possible with henley end.				
Note 1	Tests include continuity, IR at 5kV, VLF at 12.7kV and partial discharge. Also OTDR.				
Note 2	Tests include continuity, IR at 5kV and VLF at 12.7kV. Also OTDR.				
Note 3	tests at connection include continuity through star-wound transformer at device, and 5kV IR all phases together				
Note 4	tests at disconnection include 5kV IR each phase (one up, two down)				

Table 2: Summary of sub-sea cables installed at the EMEC wave energy test site, Billia Croo, Orkney

4.4 Summary of General Cable Condition

The following sections provide a summary of the 12 sub-sea cables installed by EMEC (seven at the tidal energy test site and five at the wave energy test site).

4.4.1 Fall of Warness Cable 1 (T1)

The most recent ROV survey of this cable was carried out in October 2012. The majority of wear identified in the most recent ROV survey of T1 is related to installation issues. A very tight kink is observed in the cable at the offshore end. Nearer the device gravity base there is also a steel bend-restrictor quadrant with a 360 loop of cable around it. The kink was removed in August 2013. Adjacent to this is the terminal J+S box, which at time of survey is spliced onto a jumper cable connected to the turbine. This was disconnected in January 2013, and reconnected in August 2013. The cable is currently energised at variable voltage up to 6kV.

Apparent risks to this cable are mainly from anthropogenic interactions including limited fishing activity and an additional cable crossing which has been protected with grout bags. The condition of the cable appears generally good with no significant areas of damage observed in the 2012 survey.

4.4.2 Fall of Warness Cable 2 (T2)

The most recent ROV survey of this cable was carried out in June 2013. This cable is generally in good condition, as observed from ROV surveys carried out in in 2011 and 2013. There are two significant areas of wear, one due to a cable bight close to the device tripod which has caused serving wear, and the second around 270m from the device tripod, seemingly due to abrasion on the rocky seabed in the main tidal flow. Inshore, the cable is laid over sandy shingle, and has partial burial as well as additional armour.

Apparent risks are largely limited to the rocky seabed in the main tidal flow, and little to no anthropogenic interactions can be observed. The cable does not have any significant rock contacts, or free-spans of any notable scale.

4.4.3 Fall of Warness Cable 3 (T3)

The most recent ROV survey of this cable was carried out in June 2013. This cable is observed to be in good condition with little damage other than minor serving deterioration described by the surveys “as normal loosening of serving in a few places”. The 2011 survey reported one 2m section in which serving separation has caused the armour wires to become exposed; this is not reported on the 2013 survey. The 2013 survey notes that no movement or additional wear is evident between 2011 and 2013.

A number of cable crossings with the Environmental Monitoring Pod cable constitute the only reported anthropogenic risk to the cable, and these have remained stable to the date of the most recent survey (June 2013). Seabed conditions are similar to those of T2 and the cables run along similar routes.

4.4.4 Fall of Warness Cable 4 (T4)

The most recent ROV survey of this cable was carried out in June 2013. This cable sits on some of the most hostile rocky terrain within the site, skirting the southern end of the reef that extends south of Seal Skerry. There are considerable freespans over gullies and tight bends around sharp rock edges with no split pipe protection. There is also evidence of fishing activity in the area with a couple of creels and associated rope wound around the cable. Inshore towards the substation, the 2 newest cables on the site, T6 & T7 cross over T4, with concrete mattress protection.

There are many areas of visible wear on T4 with serving detached and areas of armour wire visible. T4 has been energised since 2007 at approximately 11kV. 300m of the cable was moved in order to facilitate connection operations, and following this move, remedial work was conducted to minimise 'at risk' suspensions. Much of the serving wear is thought to have occurred during cable movement, and little deterioration has been observed since. To date it appears that while there are areas of wear, freespans, rock contacts, and fishing activity, cable performance has not been affected.

4.4.5 Fall of Warness Cable 5 (T5)

The most recent ROV survey of this cable was carried out in February 2012. This cable is regarded as being in very good condition. Recent surveys note an absence of any armour damage, no significant freespans, and only a limited number of point contacts. This cable has not yet been energised.

There are a number of creel ropes crossing the cable, as well a crossing from cable 8 (the EMEC client-owned cable). No damage can be seen from these interactions.

4.4.6 Fall of Warness Cable 6 (T6)

The most recent ROV survey of this cable was carried out in June 2013. This cable was installed as part of the expansion of the EMEC facility in 2010. It lies in close proximity to T4 (which it crosses) and to T7 which was laid at the same time. Post-lay ROV survey observed that the cable was laid at relatively high tensions towards the inshore, compared to T7. In contrast, offshore the cable snakes across the seabed, laid with very little residual tension.

This cable appears to be in good condition. Offshore the cable is laid over rocky edges with many short freespans whereas inshore the cable is well supported in shingly sand. There is a location where the cable is hard up against a small vertical rock face, and another where it appears to be laid in tension around a rocky lump. There is only slight evidence of loose serving or surface attrition to the cable on the entire length.

4.4.7 Fall of Warness Cable 7 (T7)

The most recent ROV survey of this cable was carried out in June 2013. This cable is the second of the cables installed at the tidal energy test site in 2010. It lies in close proximity to T4 (which it crosses) and to T6 which was laid at the same time. Post-lay ROV survey observed that the cable was laid at relatively low tensions, compared to T6.

This cable was the subject of a separate independent survey in 2012 to investigate an anomaly in TDR testing. This survey highlighted many areas of wear and abrasion which was corroborated by the ROV survey carried out in June 2013. While freespans and point contacts are limited (as are anthropogenic interactions) there are areas where cable movement has clearly resulted in significant serving wear on the rocky seabed. No breaks in the armour wires were observed during the survey.

4.4.8 Billia Croo Cable 1 (W1)

The most recent ROV survey of this cable was carried out in July 2013. This cable crosses some dramatic seabed geography close inshore consisting of rock shelves, geos and small cliff edges. This results in some considerable freespans and potential areas of stress on the cable where it is forced to turn over rocky edges. Most of the split pipe protection is obscured in the ROV surveys due to kelp fronds inshore. As the cable enters deeper water, it enters areas of significant burial in sand and shingle waves.

There are several areas in which the serving has worn away and the armour is exposed, and indications suggest that at least one of these is possibly due to anthropogenic interactions. Split pipe protection also appears to have separated from the cable in areas where it is needed, such as a contact with cable W2 (it is believed that most of this occurred during installation operations).

4.4.9 Billia Croo Cable 2 (W2)

The most recent ROV survey of this cable was carried out in July 2013. As with all the wave site cables, W2 passes through a dramatic area of seabed geography towards the landfall, resulting in many unarmoured sharp point contacts and long freespans. While there is serving wear leaving steel wire armour exposed, given the age of the cable the serving remains remarkably intact. No damage to the steel wire armour strands was noted. There is also evidence of a phenomena that was noted in 2011 where there appears to be staining of the rock around areas of serving wear. It is not clear whether this is caused by the loose serving scrubbing the rock clean, or by substances (such as bitumen) being removed from the cable.

There is evidence of considerable anthropogenic interaction with W2 with several chains and ropes lying in close contact with the cable. Serving wear though can most likely be attributed to cable movement and seabed conditions.

4.4.10 Billia Croo Cable (W3)

The most recent ROV survey of this cable was carried out in July 2013. This cable runs through some dramatic seabed geography towards the landfall. There is evidence of serving deterioration, possibly due to slight cable movement around the freespans. There is some evidence of discolouration of rocks around the cable as with the other wave cables.

The loose serving has exposed the wire armour in many places, and there are many locations where the cable is clearly stressed as it passes over sharp rock edges with no split pipe protection. There are a number of clear anthropogenic interactions with the cable but as with W2 the serving wear appears to be largely due to cable movement.

4.4.11 Billia Croo Cable 4 (W4)

The most recent ROV survey of this cable was carried out in December 2012. Inshore of approximately 30m depth, this cable is laid across dramatic rock slabs with many geos and vertical edges, leading to the cable lying mostly in freespan for the first 1000m offshore with many point contacts on rock. Serving wear is visible, with evidence of apparent colouring of the surrounding rock.

There is a particularly long (90m) section of freespan inshore where the cable is suspended between a few rock edges. There is evidence of cable movement (and possible strumming) in this region (rock edges worn fresh & bright where the cable is in contact). Also noted was fresh broken rock under the cable though this could be due to the natural erosion process caused by storm waves rather than attrition from cable movement.

Offshore this cable is stabilised in sand.

4.4.12 Billia Croo Cable 5 (W5)

The most recent ROV survey of this cable was carried out in December 2012. This cable is well armoured inshore from the beach out to 20m depth, and as with all the other wave site cables, W5 passes over some very dramatic underwater geography, with numerous short but high freespans, vertical and horizontal rock edges.

There is an area of (possibly dynamic) sand waves further offshore, where the cable is alternately in total burial and short freespan. Offshore of that, W5 enters total burial in sand for the majority of its length, emerging in the vicinity of the J+S termination box. This cable has a flexible jumper cable leading from the J+S box to a device under test.

No armour damage and very little serving wear was noted throughout the length of W5.

4.5 Cable Selection

After initial review of the data available for all cables, the following cables were selected for more detailed analysis/review:

- Tidal 4 (T4)
- Tidal 6 (T6)
- Tidal 7 (T7)
- Wave 2 (W2)
- Wave 3 (W3)

T4, T6, and T7 are all laid across a similar area of the site in perhaps the most hostile waters. The cables are in close proximity, are laid at varying angles to the tidal flow, and are laid in varying tensions. Cable T4 has been the subject of remedial cable work. Due to the surrounding features the cables have excellent prospects for comparison, as the impact of different variables can be observed within roughly the same conditions.

With regards to the cables at the wave energy test site, conditions are considered fairly similar across the site. Cables W2 and W3 were selected for their close proximity to each other, and the large number of features drawn out from the ROV survey reports. There is also a noticeable difference in the levels of wear on each of these cables.

6. Review of Selected Cables

This section describes the key risks associated with the integrity/performance of sub-sea cables, and summarises how the EMEC cables selected for detailed review (T4, T6, T7, W2 and W3) have been affected by these risks.

5.1 Suspensions (freespans)

Cables do not always lay flat and straight on the seabed, and despite the extensive precautions taken during the laying of sub-sea cables, unavoidable cable *suspensions* or *freespans* may occur due to seabed or installation conditions. Suspensions can form when a cable is suspended between points on an irregular seabed (e.g. rock outcrops), or is held under relatively high residual tension. The chance of damage occurring in sub-sea cables is increased in areas where such cable suspensions occur.

The main risk to cable suspensions is that of cable strumming. Cable strumming is a resonance effect that occurs as current flows over a cable. Periodical irregularities occur caused by vortices which form as a result of the boundary layer between the cable and the current. This is known as vortex induced vibration (VIV) and can cause the cable to vibrate. Cable strumming occurs in areas where a cable is in suspension and the current can flow on all sides. Not all freespans will result in strumming, as strumming will only occur when VIV matches a natural frequency of the cable. Strumming may be predicted from the natural frequency of the cable span, and from current data (see Section 2.2).

Cable strumming can result in movement of a cable at contact points, causing abrasion and mechanical fatigue in the cable, which can both shorten the cable's lifespan. Strumming is a particular problem at tidal energy test sites, as high currents increase the likelihood of vibration, and uneven and rocky seabed that result from the currents (due to the removal of sediment cover by the flow) mean suspensions are common. DNV RP F105 states that cable suspensions with a length less than 30 times the diameter of the cable are not considered to be significant, i.e. at risk of strumming (the standard describes that length/diameter <30 exhibits '*very little dynamic amplification*'). This study therefore focuses on suspensions greater than 3 metres.

It should be noted that in terms of assessing the impact of cable strumming, abrasion can be observed from ROV survey footage but, as areas suffering the most damage are often those in contact with the rock, the extent of the damage is difficult to ascertain. In these situations, targeted diver surveys can be undertaken to provide a clearer picture as these will allow the cable to be viewed from the underside at these contact points. While diver surveys were conducted in 2008 these are too early in the cable lifecycle and not specifically targeted at affected areas. Also, abrasion can have other causes, such as bodily movement of the cable, and therefore abrasion damage is not always indicative of strumming.

5.1.1 Suspensions in EMEC Cables

In analysis of the selected EMEC cables, it was observed that in certain areas of the EMEC test sites, significant lengths of cable lie mostly in suspension. These unavoidable suspensions were formed during the cable installation process, due to seabed conditions. The most significant suspensions along the five selected cables were analysed in detail for their likelihood to strum, with these areas compared to the cable condition visible from the ROV surveys. Figure 8 below shows an example of abrasion to sub-sea cable serving due to strumming.

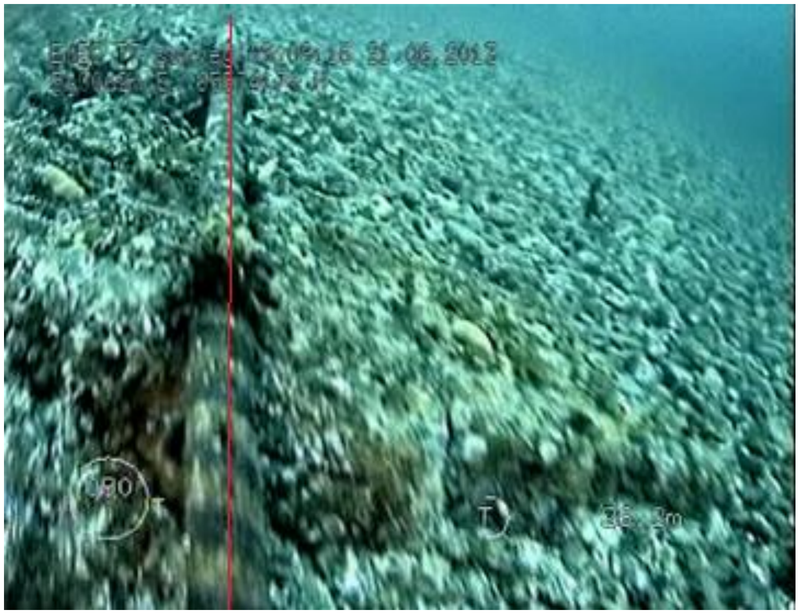

Figure 8: ROV still showing typical abrasion caused by cable strumming

The large number of suspensions at the wave energy test site has been noted in previous surveys and has been subject to additional research conducted by ETA, looking at possible mitigation. Suspensions are therefore typically larger and much more frequent than at the tidal energy test site.

It is clear that strumming poses significant risk to sub-sea cables in tidal environments. This study of the EMEC cables appears to confirm the efficacy of the prediction models; broadly speaking the calculated risk corresponded to the visible condition of the cables. The factors affecting strumming to the greatest degree are current strength, angle of the cable to the tide, and length of suspension, with each carrying significant weight in calculations. Good practice in sub-sea cable laying should consider potential suspension and angle to tide in route planning (laying in-line with tide being of benefit). The distribution of suspensions around specific areas of the EMEC cables also suggests further potential mitigation methods might include:

- Cable laid with minimal residual tension has a better ability to conform to the sea floor. This is already known, with critical lengths between contact points calculable in order to determine whether suspension will exist at a given tension. This study confirms that tension reduction in sub-sea cables is an effective strategy to mitigate cable suspension. It must be noted however that a cable of reduced tension will have a higher likelihood of strumming if suspension is actually present. Also, this technique may not be suitable for laying cables in tidal environments (due to issues with laying slack cable)

* Remedial work carried out by EMEC to reduce suspensions has proved highly effective, with T4 exhibiting no significant suspensions and no significant confirmed wear that can be directly related to strumming since remedial works were completed

* Laying cables in-line with seabed features appears to have an impact on reducing the number and length of suspensions

5.1.2 Conclusions: Suspensions (freespans)

The following conclusions can be drawn from the analysis conducted:

1. In specific areas of cable where calculations suggest that cable strumming would be highly likely, signs of deterioration were visible. The effect of strumming has clearly accelerated damage in some areas, and it is fair to anticipate a decreased service life as a result. While specific failure times are unknown, strumming can be seen to represent a considerable risk. It is worth noting that in these areas, no significant damage to the outer layer of armour wires is visible, although assessment of the condition beneath the cable at the contact point cannot be observed from ROV footage.
2. Current calculation methods seem to accurately represent this risk. Where strumming was expected, deterioration was visible and vice versa. While calculations prove effective and were broadly consistent with the visible conditions of the cable, some variations in answers show that calculations can be limited by the data that is available (often angle to tide was difficult to determine precisely for example, and this has the potential to affect calculated risk). It will be difficult to assess strumming risk at a planning stage as calculation relies on precise data. A wealth of data has been available for this study yet there are still weaknesses in predictions.
3. Limitations in available data mean that information provided here is speculative and based on visual information. Direct assessment of cable movement and vibration has not been possible from the footage, and whether strumming is occurring can only be inferred from cable condition. Direct studies into cable movement at specific points are required in order to confirm these conclusions. Diver swim surveys could also be beneficial in order to provide a closer inspection of the underside of armour wires at damaged areas.
4. Deterioration in areas of cable where strumming is not likely suggests that there are other significant causes of damage. Based on the age and current state of the EMEC sub-sea cables, damage due to other causes appears less aggressive and less of a risk. Proper evaluation of cable condition is limited by the fact that a complete picture of cable condition cannot be achieved through ROV survey alone.
5. The way in which specific cables have been installed appears to have successfully mitigated much of the strumming risk. Low residual tension enables cables to conform better to the seabed profile and avoid spans of significant length. This is not necessarily an applicable 'installation technique' however, as too much slack when laying cables in tide can cause installation issues (e.g. 'looping' of the cable). Low residual tension also increases the likelihood of strumming where suspension is not avoided. Practical

management of suspensions post-lay on T4 seems to have proved an effective solution. Based on calculation criteria, risk is also reduced considerably by aligning cables parallel to the current direction where possible. Alignment to wave direction appears to have reduced strumming risk considerably for cables W2 and W3.
6. Tidal currents appear to pose greater strumming risk than those caused by waves (due to their increased consistency).

5.2 Cable Stability

As well as causing vibration and strumming, tidal flow and wave induced current can also act to move cables from their position on the seafloor resulting in abrasive wear to the cable. The ability of a cable to hold its position on the seabed, and inversely the likelihood that certain tidal and wave conditions will move a cable can be predicted through the use of specific models focussed on 'on bottom stability'. The most widely used and accepted of these is DNV RP F-109: "*On Bottom Stability of Sub-sea Pipelines*" (see Section 2.2). As mentioned above, certain areas of damage on the selected cables appear to have been abrasively worn through some form of movement; such damage has been observed in many areas where strumming has been ruled out, or where the cable is not held in suspension. Also, such instability cannot be ruled out as an alternative cause of wear previously ascribed to strumming, unless damage due to instability can be identified for comparison.

The key variables associated with the stability of cables are current flow and wave conditions, angle to current, cable weight and diameter, water depth, and seabed type. Burial and other means of stabilisation also have a significant effect.

This section sets out to examine the stability of each selected sub-sea cable as far as possible, and to identify and compare any damage that can be seen to have resulted from any instability found.

5.2.1 Cable Stability in EMEC Cables

The EMEC cables have been installed for around 9 years at the time of survey, and serving wear, while common, does not appear to be significant. It is impossible to observe the underside of the cable from the data available, but swim surveys carried out in 2008 noted that wear on these areas was minimal.

Calculations show the three cables studied at the EMEC tidal test site to be stable vertically and horizontally at all angles to tide and depths at peak spring tides. Localised horizontal stability can be affected by suspensions (reduced contact area with the seabed), but there is sufficient leeway in the EMEC data for the cable routes to be assumed stable. DNV RP F-109 also states that vertical stability is improved when the cable is in suspension due to reduced forces experienced by the cable.

Current due to tidal flow alone however is an unlikely state and the fluctuating currents due to waves are key in the question of cable stability. If an average 15 knot South Westerly wind is assumed then Pierson-Moskowitz gives a significant wave height of 1.27m. In this condition, the cable still shows as stable, both vertically and horizontally, in water depths greater than 15m at all angles to current flow.

In winter, wind speeds can reach a higher average of 20 knots bringing a significant wave height of 2.26m. Under these conditions, in 20m water depth the cable will be horizontally unstable at virtually all angles to current. When tide is reduced to a peak average flow of 2.5m/s in these winter conditions, calculations predict that cables become unstable in 20m of water or less, between 105º to 180º and 0º to 40º to the tidal direction, and thus would be moving on nearly every tide where waves were fully formed. At 15m water depth, all angles are unstable and once 25m water depth is reached, stability is re-gained. This is based on a rocky seabed, which covers the majority of the route for EMEC cable T4. Seabed at T6 and T7 is also rocky, but the surface is much rougher.

Based on calculations from DNV RP F-109, significant lengths of T6 and T7 should be unstable in the worst winter conditions. However, little evidence has been seen of any wear due to simple movement along the lengths of either of these cables. This may be explained by the nature of the seabed over which these cables are laid (both cables are laid over significantly sharp rock with a distinct 'grippy' quality). While the standard does account for seabed type to some degree, the nature of this seabed is arguably not represented within it.

Calculations carried out on the cables studied at the EMEC wave test site suggest that W2 is vertically and horizontally stable at all depths above 16m, W3 is stable at all depths above 19m. In extreme wave conditions, both cables are unstable to their maximum deployed depths.

This is consistent with the findings presented from the ROV survey footage, where apparent abrasive wear due to cable movements have been observed. Comparison of serving wear between the general condition of W2 and W3 seem to corroborate with the implied increased risk on W3 as well.

Due to the difficulties associated with assessing the causes of abrasive wear, further detailed analysis from the data available at present provides little additional detail (it is difficult to separate possible abrasion due to movement from potential minor strumming and discolouration phenomena). Also, it is possible that the cables could have received considerable serving wear during installation, recovery, and relocation works (reports from installation and remedial work on T4 note this serving damage as having occurred). Serving wear alone therefore is not necessarily indicative of cable instability. An example of wear possibly caused by cable instability is shown in Figure 9 below.

Figure 9: Possible wear caused by cable movement

It must be noted here as well that stability in the shallow near-shore area where wave forces experienced by the cable are stronger (due to lower water depths) has not been analysed in this study. Ductile iron armour, applied to provide greater stability and protect the cable from the results of instability, conceals any damage the cable may have received. The armour however is intact and thus can be said to be effective. Direct monitoring of movement will provide an insight into how effective the armour is at providing additional stability.

5.2.2 Conclusions: Cable Stability

There are significant limitations in assessing cable movement simply from ROV survey footage, and few firm conclusions can be made using this method. While calculations might suggest that cables should be unstable in specific conditions, actual resultant damage appears minimal for the risk level.

If cable movement is a significant concern, further study options involving the direct monitoring of the cable and more precise inspection could provide the additional data required to form more precise conclusions.

Ultimately, cable movement does not appear to be a considerable risk; however this cannot be confirmed from the data available. The risk of cable movement can be mitigated through route planning (e.g. aligning cable route to tidal current will help improve stability).

The following conclusions can be drawn from the analysis of stability in the EMEC cables:

1. After reviewing the available EMEC cable data, no significant wear that could be attributed to cable movement was observed. Any deterioration due to movement therefore is most likely slow, and risk to cable life minimal.

2. The analysis shows the possibility of movement, and resultant wear on T4, and seems to agree with the results of calculations. However, this wear could also be caused by other phenomena (e.g. some serving wear has been present since installation).
3. Although cables T6 and T7 do not show signs of wear due to movement as might be expected based on calculations, this can be explained by the nature of the seabed over which these cables have been placed. While the standard accounts for differing seabed conditions the range of options is limited, and the (limited) evidence from T6 and T7 implies that greater variation in options may be required.
4. Identifying issues associated with cable movement is somewhat inconclusive, and techniques for direct monitoring of the cables should be applied (particularly during winter months) in order to collect more detailed data. This should also be done on areas utilising the ductile iron armour to assess its effectiveness at providing additional stability.

5.3 Other Risks

As well as the environmental risks posed by the waves and currents, other potentially hazardous factors can affect sub-sea cables. Some of these factors are typically context specific, but have relevance in providing a complete picture of the potential risks to sub-sea cables. The key factors considered in this study are anthropogenic interaction (i.e. other cables, and fishing and anchoring activity) and rock contacts.

5.3.1 Rock Contacts

Rock contacts is the terminology used to denote point contacts between a cable and a solid object, or seabed feature (typically rock) that has not been considered as part of a suspension.

A number of rock contacts were observed from the review of the EMEC cables (see Figure 10 - Figure 12 below).

While the cables appear strained around the contact points, no significant wear was observed in the ROV footage reviewed. This suggests that rock contacts are not a significant threat to the external components of a cable. However, where a cable is under significant stress it could be considered likely that internal damage may occur. Such internal damage cannot be assessed from current information, but given the frequency of rock contacts identified at the test sites (with contacts occurring on all cables reviewed, and similar stresses being observed at freespan touch down points) this is an important area which would benefit from further studies.

Figure 10: Rock contact with cable W2

Figure 11: Rock contact with cable T6

Figure 12: Rock contact with cable T7

5.3.2 Anthropogenic Interactions

As noted in the CIGRE Study discussed in Section 4, fishing and anchoring represents the primary cause of sub-sea cable failure, accounting for in excess of 50% of all power cable faults reported in the most recent period of the study. This section will look at such interactions, alongside other anthropogenic risks to the cables, such as cable crossings. While this kind of activity is essentially context specific, there may be key similarities between activities at the EMEC sites and at other sites, and therefore understanding the key anthropogenic interactions with the cables is highly relevant.

The majority of the anthropogenic interactions observed across the three tidal cables studied have arisen as a result of remedial operations to relieve suspensions, and the installation of concrete mattresses to facilitate cable crossings. There is no obvious damage or wear caused by these interactions. A small amount of interaction with fishing gear is visible, and there is some serving wear around this (see Figure 13 below). However, review of the ROV footage taken in 2009 shows this wear already in place, possibly as a result of installation operations.

A further example of anthropogenic interaction can be seen where cable T6 crosses T4 (see Figure 14 below). In this example the mattress has been incorrectly positioned and T6 is in contact with T4 shown above. While this contact is undesirable, there is no observable evidence of any damage to either cable.

Figure 13: Interaction of fishing creel with EMEC cable T4

Figure 14: Mattress crossing T4 with T6 (cables in contact)

At the EMEC wave energy test site, the study identified several instances of anthropogenic interaction with the cables reviewed. These interactions involved fishing equipment and equipment related to the cable installation operations. Figure 15 below shows a wire-like material, possibly from installation, wrapped around cable W2. This has not caused any damage to the cable.

Figure 15: Wire-like material around cable W2

Figure 16 below shows a wrecked fishing creel next to cable W3. Significant serving wear is visible and, although inconclusive, it seems likely that this was caused by interaction with the creel.

Figure 16: Wrecked fishing creel interacting with cable W3

From analysis of the data available to this study, anthropogenic interaction does not appear to have caused any significant damage to any of the EMEC sub-sea cables reviewed. There is a high likelihood that some of the serving wear observed has been caused by fishing activity. Fishing activity in the area of the test sites is generally light, but the cables are at higher risk since restrictions of the site (nature of the seabed) restrict burial and some other forms of protection. In areas of partial burial in shingle and sand, such light fishing activity is unlikely to cause a problem.

7. Electrical Performance

The 12 sub-sea cables installed by EMEC at the Billia Croo and Fall of Warness marine energy test sites have performed well to date, with no significant failures reported. The cables are subjected to regular electrical testing in order to confirm their operational availability. However, the performance information that can be taken from these electrical test results is limited; deterioration cannot be observed from the majority of electrical test techniques prior to failure, and results are therefore typically binary (pass/fail). The following electrical tests have been performed on the cables at the EMEC test sites:

- Continuity Testing - This is a basic test to determine whether there are any breaks in the cable conductors, and to confirm that current is able to pass through the cable
- Insulation Resistance (IR) Test - IR tests are applied to the power cores and measure the integrity of the insulation between conductors (they are a single point test). Readings are expected to be high (in the region of Giga Ohms). Low readings can indicate a short circuit due to the breakdown of insulation materials
- Very Low Frequency High Voltage Withstand (VLF) - VLF testing assesses the overall integrity of cable insulation by exposing the cores to a specified voltage for a specified period of time. This test is pass/fail, with failure conditions being flashover and ultimate cable failure
- Time Domain Reflectometer (TDR) - TDR checks for inconsistencies in the impedance of a cable by passing an electrical pulse through the conductor. Reflections other than those induced by known features can signify damage to the conductors
- Optical Time Domain Reflectometer (OTDR) - OTDR tests are much the same as TDR tests, but applied to optical fibres. Here a light pulse is used as opposed to an electrical signal

Test results from the above methods confirm that all cables are performing as expected. As no cables have failed to date, no real conclusions can be made about the electrical performance/life-span.

8. Conclusions and Recommendations

A wealth of survey data was been made available to this study, including historical ROV footage covering the lifetime of the sub-sea cables to date. While not without limitation, the ROV footage has provided interesting insight into the behaviour of the cables in the high energy environment of the wave and tidal energy test sites. None of the sub-sea cables installed at EMEC have yet failed, and no significant damage to the armour wire itself was observed in any of the ROV footage.

Broadly speaking, while there is still much study to be done in order to predict subsea cable life at high energy sites such as EMEC, the information from EMEC has highlighted and separated the primary risks posed by these environments. Specific conclusions highlight that the majority of risk in these environments comes from strumming and suspension. Cable movement and instability, rock contact on surface laid cable, and even anthropogenic interaction (although this is highly site specific) do not appear to have posed significant risk to the EMEC cables. While much further study is required to ascertain the true impact of these varying factors, the results then are fairly positive in their implication that where suspension can be avoided cables may have a good chance of surviving to a reasonable service life.

The following conclusions can be drawn and recommendations made from this study.

7.1 Conclusions

- The greatest risk to sub-sea cables is the effect of tidal currents leading to cable strumming and instability. Analysis of areas of suspensions has shown that there is a strong correlation between predictions utilising existing calculation methods and actual wear observed. It is also clear that frequent strumming causes rapid deterioration of cable serving, with instances of wear being greater and more distinct over areas of suspension than other areas of the cables. It is reasonable to conclude therefore that cable lifespan could be expected to be significantly reduced if strumming frequently occurs.

- Findings relating to cable movement were inconclusive, being obscured primarily by wear caused by installation operations and discoloration on rocks caused by bunched loose serving. There is some indication however that cable movement had occurred in those areas where industry standard calculations (taken from DNV RP F-109) predicted it would happen. This confirms (to some degree) that calculation methods are broadly effective. DNV RP F-109 places a large weighting on wave loading and its precedent over tide; there was insufficient data available to analyse this potential issue with DNV RP F-109. Serving wear in areas of suspected movement is moderate at most (minimal compared to strumming), even where cables have been installed for several years. While it was not possible to fully assess the impact of movement-induced wear, it can be concluded that cable movement does not appear to cause significant wear, or rapid deterioration (cables at the wave test site provide significant testament to this, with their current installed life approaching 10 years).

- Little impact was found due to anthropogenic interaction with the sub-sea cables (although this is largely context specific). Rock contacts also pose minimal risk to the cables, and may even serve to stabilise suspensions at some points.

- Valuable work is currently being carried out by Heriot-Watt University in the field of sub-sea cable health management systems. There is potential to develop and validate these systems through collaboration with commercial organisations (see 7.2.1 below).

- In terms of cable life-span, this study cannot provide any firm conclusions, as none of the cables at EMEC have failed to date. The sub-sea cables installed at the EMEC test sites appear to be in general good condition, with some serving wear within a few areas of significant strumming risk. Life-spans currently reach 10 years on the wave cables.

7.2 Recommendations

7.2.1 Recommendations for Further Study

- Monitoring of the cables should be continued (i.e. ROV surveys, electrical testing). The information already held by EMEC is highly valuable, and provides a full historical record of cable condition should any failures occur in the future.

- A study to directly monitor movement of specific sections of cable may help to fill knowledge gaps from this study. At present, likelihood of strumming has only been shown to have a correlation to the level of observable damage on the cable, and this does not explicitly confirm the calculation methodologies. By conducting a study which directly monitors the cable movement, and could be related to specific conditions as opposed to average conditions, the presence of strumming could either be confirmed or excluded. This would allow existing calculations to be assessed directly (as opposed to implied connection to observable damage).

- A further study examining observed wear in key areas more closely (e.g. diver swim surveys) would add value to findings. At present, serving wear has been observed by ROV survey from above the cable, but this does not allow internal wear, or wear actually at the contact point to be explicitly observed. Diver swim surveys could allow the condition of the cable armour wires at contact points to be observed and recorded, and fatigue analysis to assess internal wear could be conducted following the movement study recommended above. This would give a much clearer picture as to the impact of movement on the cables. This may also enable cable life-span predictions to be made.

- Full investigation into the cause(s) of any future EMEC sub-sea cable failure should be made, including detailed examination of the cable. Coupled with the wealth of historical information available, this would prove invaluable for informing future sub-sea cable installations.

- Undertake studies to assess damage to sub-sea cables due to protection mechanisms e.g. rock dumping.

- Studies to assess dynamic rating in terms of the effect of cable remaining useful life due to thermal failures.

- Undertake a detailed study into cable dynamics in order to validate cable displacement estimates and improve future modelling.

- Undertake a geotechnical study within laboratories to better understand the processes associated with scour and obtain higher granularity data on friction forces experienced on cables.

- Unification of existing failure mode databases via strategic alliances e.g. Distribution Network Operators, offshore developers, test centres.

- Validation of a prognostic and health management system against available historical data, utilising the detailed failure mode mechanisms and effect analysis.

7.2.2 Recommendations for Developers

- **Carry out calculations.** In sites with high tidal flow, strumming is a key concern and may result in significantly reduced life for sub-sea cables. Risk of strumming should be assessed at an early stage and mitigated where possible. As there appears to be a correlation between the calculations using standards and damage observed, while unconfirmed, focus should be on controlling primary factors such as angle to tide (therefore, maintaining the cable as close to parallel to the tide, where possible), and length of suspension (DNV RP F105 states that cable suspensions with a length less than 30 times the diameter of the cable are not considered to be significant, i.e. at risk of strumming (the standard describes that length/diameter <30 exhibits '*very little dynamic amplification*'). This study therefore focused on suspensions greater than 3 metres).

- **Complete detailed site surveys**. A detailed knowledge of the seabed (using, for example, side scan sonar and ROV surveys) and thorough route planning will help to understand and minimise the risks to a cable.

- **Optimise route to avoid key risks for mitigation**. When planning sub-sea cable installations, routes parallel to the tidal flow will reduce the risk of strumming if suspensions are formed. Due to the threat of significantly reduced service life, longer routes requiring extra cable that avoid strumming risk by maintaining the cable parallel to the flow, following natural features of the seabed or avoiding particular areas, may prove economically advantageous as they may help minimise the necessity for repair. Cable routing should also consider any effect that the bathymetry or seabed features may have in sheltering or preventing lateral movement of the cable (it should be noted that strumming requires the free flow of the current around the cable, if the cable becomes sheltered within seabed features it may be protected, and thus laying in-line with seabed features will also help prevent suspensions forming). Laying with extra slack should be considered where high risk suspension is predicted (however, with caution in high tidal environments).

- **Protection.** Cable armouring will help to protect a cable in high energy environments and up to quadruple armouring is available (beyond this the stiffness of the armouring makes transportation, logistics and installation more difficult and more expensive).

- **Cost and Budget**. Where strumming risk cannot be avoided, the cost of a reduced cable life should be taken into account within the project budget. Anecdotal evidence suggests life spans of cables can be effectively halved and even reduced to as little as 6-8 years. While the EMEC study has not confirmed this, and the cables at this site appear to have largely out lasted the 6-8 year minimums, this evidence should not be discounted. Inter-array cables, the routes of which cannot be varied as readily as those of the export cables, may often be under high risk of strumming and hence the recovery and replacement of these cables on a shorter time frame should be considered.

- **Monitoring and inspection**. Post-lay inspection should be integral to operations in tidal environments in order to assess risks to the cable, and should where possible involve assessment of strumming risk. Strumming risk can only be assessed in real detail once a cable has been laid and actual suspension can be observed. This information can be compared to calculations completed prior to installation to confirm if damage is occurring where predicted or if there is an unexpected issue. While mitigation methods in the planning stages may help limit damage, surveys will be required to assess if the cable is at risk. Remedial work to reduce suspensions may be necessary and has previously proved effective.

- **Documentation**. Causes of damage should be assessed where possible to inform future operations.

London
The Crown Estate
16 New Burlington Place
London
W1S 2HX
T 020 7851 5000

Edinburgh
The Crown Estate
6 Bell's Brae
Edinburgh
EH4 3BJ
T 0131 260 6070

www.thecrownestate.co.uk
@TheCrownEstate

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