Mooring systems for wave energy converters: A review of design issues and choices

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ABSTRACT

An overview of generic types of wave energy converter (WEC) is presented and their mooring requirements discussed. Mooring system configurations and components from the offshore industry suitable for WEC units are identified. Possible mooring configurations for WECs are discussed and it is argued that not only station keeping but also the overall performance characteristics of the WEC mooring should be considered in the design.

INTRODUCTION

This paper focuses on the moorings for wave energy converters (WECs) which have been identified as a major component of the cost for such systems. For free floating systems, the primary function of the mooring is to keep the WEC on station even in the most severe storm conditions. The cost of the system will be directly related to meeting this requirement, and that of fatigue and abrasion loading, which occurs over a design life of thirty or more years. In addition the mooring system will have a dynamic response to wave or wave group loading, and this may be critical when the WEC and its mooring are considered together as a coupled system. For some WECs this dynamic response, or lack of it, is a key element in the mooring system design. Thus, just as there is diversity among WEC configurations, there is similar diversity among the associated mooring systems and their requirements.
This paper presents an overview of the generic types of wave energy devices and the practical design requirements that WEC mooring systems must meet. It discusses the variety amongst conventional mooring systems and their suitability for WECs. The components that make up typical mooring systems, their function and characteristics are described and discussed.
There is considerable experience of the behaviour and long-term performance characteristics of mooring systems in the offshore industries. Some, but by no means all, of this can be used when selecting mooring system materials and components for WECs. The differences between the mooring system requirements for the offshore industry and those for WECs are explored.

Author's Biography

Robert E. Harris has a Civil Engineering Degree (BSc) and a PhD in Offshore Engineering from Heriot-Watt University. He has been a Research Engineer at the Institute of Offshore Engineering, a Lecturer in the Department of Offshore Engineering (subsequently Civil & Offshore Engineering) and is currently a Lecturer in the School of Life Sciences. He is a member of the Institute of Marine Engineering, Science and Technology and a Chartered Engineer.

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OVERVIEW OF GENERIC TYPES OF WAVE ENERGY CONVERTER

The station keeping of a WEC is closely linked to its design principle and a categorisation of the principles is considered important in order to define feasible station keeping options. In the literature WECs are often categorised into groups by *location* and *operating principles* (energy extraction method).

Location is closely linked to the historical development of WECs. Static installed units at the *shoreline* were the first commercial units to extract energy from sea waves, and are often regarded as *first generation* (WaveNet 2003). As a consequence of higher wave energy density at open sea it is more profitable to install devices in the open sea, even if installation costs rise. This initiated the development of a seabed anchored *second generation*, which were installed at the *nearshore* adopting experience gained from the first generation. The development of new energy extraction methods initiated the *third generation* associated with *offshore* units. The third generation devices are typically moored floating units that often rely on different design technologies, but also employing principles and ideas from the first and second generation devices. These devices were seen historically as not commercially viable due to the high installation costs. However, the prospect of high wave energy densities, the continuous development in offshore technologies and the political and social need for more energy from renewable sources have made the commercial development of third generation devices currently much more attractive. The distinction between nearshore and offshore devices is here associated with the station keeping method, limited by the installation depth: there are technical restrictions that apply to nearshore devices how deep water they may be deployed, and offshore devices have corresponding shallow water restrictions.

The energy extraction methods or *operating principles* can be categorised into three main groups:

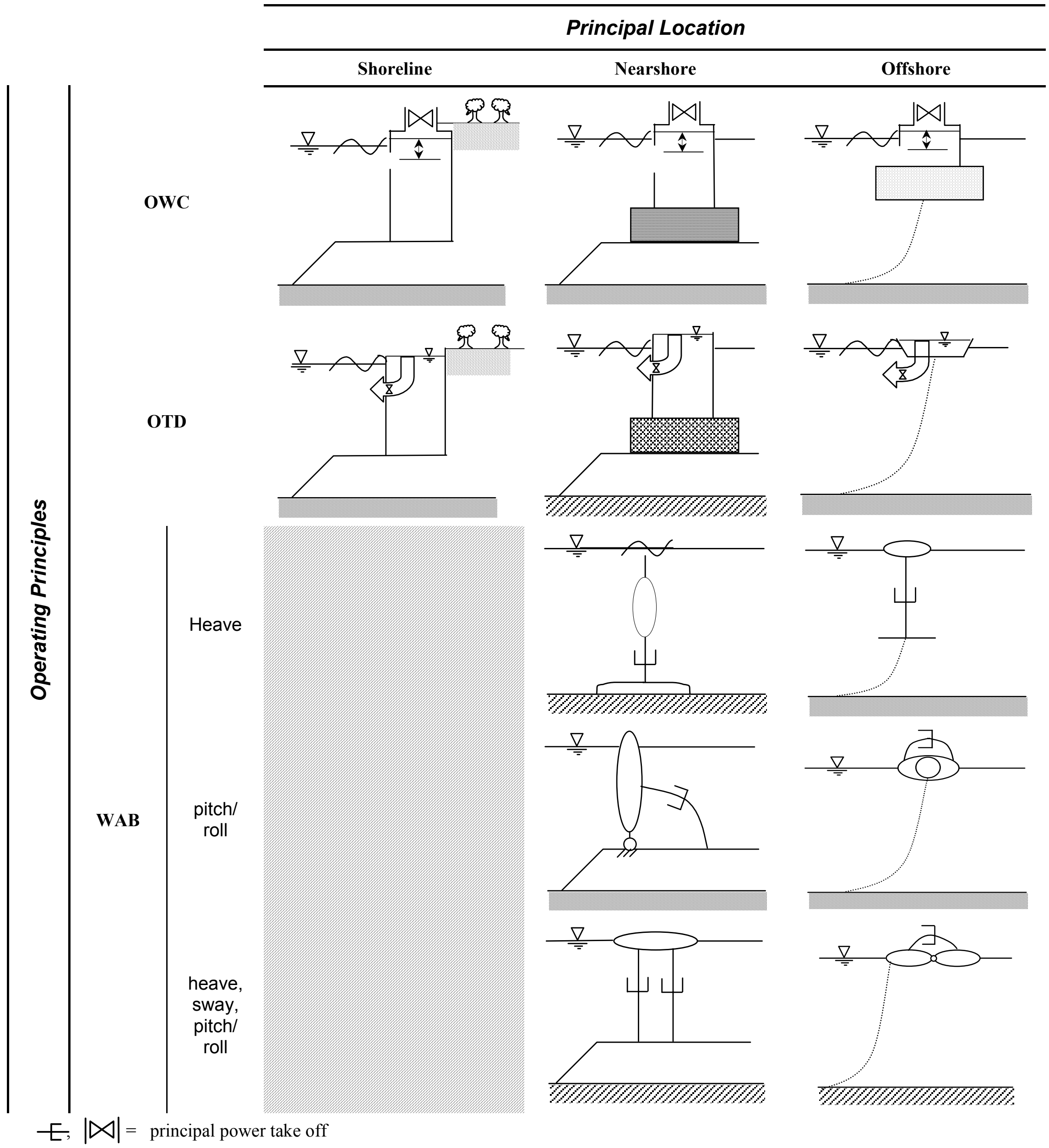
- **Oscillating Water Columns (OWC)**
  Waves cause the water column to rise and fall, which alternately compresses and depressurise an air column. The energy is extracted from the resulting oscillating air flow by using a Wells turbine
- **Overtopping Devices (OTD)**
  Ocean waves are elevated into a reservoir above the sea level, which store the water. The energy is extracted by using the difference in water level between the reservoir and the sea by using low head Kaplan turbines
- **Wave Activated Bodies (WAB)**
  Waves activate the oscillatory motions of body parts of a device relative to each other, or of one body part relative to a fixed reference. Primarily heave, pitch and roll motions can be identified as oscillating motions whereby the energy is extracted from the relative motion of the bodies or from the motion of one body relative to its fixed reference by using typically hydraulic systems to compress oil, which is then used to drive a generator.

The wave activated bodies (WABs) can be further categorised in sub-groups describing the energy extraction by the principle motion of the floating body (heave, pitch and roll). The motions of surge, sway and yaw requiring an external restoring force (mooring) in order to return to its original equilibrium position, and are of less interest (for energy extraction) at this stage for WECs than the purely oscillatory motions of heave, roll and pitch.

Shoreline installed devices are mostly made of concrete and use oscillating water columns, breakwater-OWCs or overtopping devices as the operating principle. Devices installed at nearshore will mostly be gravity anchored, resting directly on the seabed, or fixed to the seabed. Common energy extraction methods for nearshore devices are OWCs and OTDs, but wave activated bodies are also used. Whilst the techniques to anchor shoreline and some nearshore devices could follow established engineering procedures, each offshore device requires an independent design study to ascertain the extreme environmental loads that must be withstood, cost effectively. The moorings for offshore devices are more complex and interact strongly with the energy extraction method and the orientation of the device to the mean wave direction, for efficient power conversion. Table I provides an overview of possible operating principles at the three defined locations with schematic drawings of wave energy devices.

The ability of a device to capture energy related to the direction of the incoming wave front has a further important influence on the station keeping. These *directional characteristic* can be categorised in the groups:

Table I Schematic drawings of WEC devices for operating principles and principal locations



- **Point Absorber**
  A *Point Absorber* is relatively small compared to the wave length and is able to capture energy from a wave front greater than the physical dimension of the absorber
- **Terminator**
  A *Terminator* has its principal axis parallel to the incident wave crest and terminates the wave. The reflected and transmitted waves determine the efficiency of the device
- **Attenuator**
  An *Attenuator* has its principal axis placed parallel to the direction of the incoming wave and converts the energy due to the relative motion of the parts of the device as the wave passes along it.

The efficiency of a terminator or attenuator device is linked to their principal axis being, according, parallel or orthogonal to the incoming wave crest. The point absorber does not have a principal wave direction and is able to capture energy from waves arriving from any direction. As a consequence the station keeping for the terminator and attenuator has to allow the unit to weathervane into the predominant wave direction, but this is not necessary for the point absorber.

Table II Possible operating principles for the principal location and directional characteristic

Principal Location	*Directional Characteristic*		
	Point Absorber	**Terminator**	**Attenuator**
Shoreline		OWC, OTD	
Nearshore	WAB	OWC, OTD, WAB	WAB
Offshore	WAB	OWC, OTD, WAB	WAB

The relationship between the three main classifications

- Principal Location
- Operating Principle
- Directional Characteristic

are shown in Table II, presenting the possible operating principles for the location and the directional characteristics. At the shoreline the only feasible operating principles are oscillating water columns and overtopping devices, which are terminators. Table II shows that at nearshore and offshore, point absorber or attenuator devices can only be WABs, whilst for terminator devices all three categories of the operating principles are possible. OWCs and OTDs are 'static' energy converters of the terminator kind. As a result their mooring has to be stiff, restraining modes of motions but allowing for adjustment towards a parallel wave approach and for tidal ranges. The station keeping requirements for the mooring of wave activated bodies can be either static or dynamic. If the wave extracting body is operating within a reference frame, the mooring has to provide a nearby static station keeping ability for this frame. If the active body is directly moored, a dynamic station keeping system must provide sufficient freedom to the energy extracting motion(s) whilst restricting other motions for optimum energy extraction. A generic station keeping study for nearshore and offshore devices should focus on a static and dynamic mooring system with its associated stiffness and freedom requirements.

MOORING REQUIREMENTS FOR OFFSHORE WEC DEVICES

The two major requirements for a WEC mooring are to withstand the environmental and other loadings involved in keeping the device on station, and to be sufficiently cost effective so that the overall economics of the device remain viable. Rather than simply considering the mooring as an additional cost item in the overall economics of the device, the mooring system in many cases can, and it is argued, should be designed as an integral element of the overall system and contribute to its power extraction efficiency and thus to the income stream. Refined mooring systems should be designed to keep devices at optimum orientation relative to the waves and could also be part of an optimum control system for the specific power bandwidth of a WEC unit. A discussion on optimum control of WECs can be found in Falnes (1993). An active mooring system may increase installation costs, but an enhanced performance would mean higher amortisation and may justify the higher costs. However, individual devices require different design approaches and the overall economics of a mooring system is closely linked to the device design itself.

There are a range of rules, guidelines and regulations for mooring systems published by various authorities (e.g. DNV 2001, API 1969) around the world. The most stringent of these apply to the design, analysis and maintenance regulations for the floating structures of the offshore oil and gas industry. The reasons for this stringency is the risk of substantial loss of life and the danger of environmental pollution should failure occur. Floating wave energy devices will normally operate unmanned, and there is no danger of major environmental pollution; so regulation and guidance can be framed more in terms of the overall economics and the financial consequences of any mooring failures. Manning of devices will only occur during installation or maintenance, in low wave conditions when the chances of mooring failures are remote. At first sight to regulate WECs, similar rules to those of marine agriculture would seem appropriate. However WECs are deliberately placed in areas of high wave energy density, normally avoided by fish farms. So the 'Tentative rules for certification of floating fish farms' from Det norske Veritas - DnV (1988) in combination with the mooring rules for

mobile offshore units ‘Position Mooring’ (POSMOOR) from DnV (1989), as described by Berdahl and Martensson (1995), would be a possibility for first design guidelines for WEC mooring systems .
The economic case for WECs improves with the installation of many devices at a particular field as this reduces the grid connection cost per device, and so it is likely that in the near future offshore wave energy farms will be built. The optimum farm layout would be dominated by the array interaction between the devices which will be a function of their design. However, the risk of a device breaking free from its mooring needs to be considered. The initial danger would be damage to the neighbouring devices, in addition to the possibility of a loose device providing a hazard to shipping and other maritime systems.
The following list shows the requirements that need to be considered for WEC moorings systems:

- The primary purpose of the mooring system is to maintain the floating structure on station within specified tolerances under normal operating load and extreme storm load conditions.
- The excursion of the device must not permit tension loads in the electrical transmission cable(s) and should allow for suitable specified clearance distances between devices in multiple installations.
- The mooring system must be sufficiently compliant to the environmental loading to reduce the forces acting on anchors, mooring lines and the device itself to a minimum; unless the stiffness of the mooring itself is an active element in the wave energy conversion principle used.
- All components must have adequate strength, fatigue life and durability for the operational lifetime, and marine growth and corrosion need to be considered.
- A degree of redundancy is highly desirable for individual devices, and essential for schemes which link several devices together.
- The system as a whole should be capable of lasting for 30 years or more, with replacement of particular components at no less than 5 years.
- The mooring must be sufficient to accommodate the tidal range at the installation location.
- The mooring system should allow the removal of single devices without affecting the mooring of adjacent devices.
- Removal of mooring lines for inspection and maintenance must be possible.
- The mooring must be sufficiently stiff to allow berthing for inspection and maintenance purposes.
- Contact between mooring lines must be avoided.
- The mooring should not adversely affect the efficiency of the device, and if it is part of an active control system it must also be designed dynamically as part of the overall WEC system.

MOORING CONFIGURATIONS FOR FLOATING STRUCTURES AND THEIR SUITABILITY FOR WAVE ENERGY CONVERTERS

A variety of mooring configurations have been developed over time for the station keeping of floating vessels and a comprehensive guide can be found in Barltrop (1998). The simplest method is to use a gravity anchor on a single line mooring. However this provides, amongst other limitations, no redundancy and clearly multiple mooring lines are desirable for reliability. Increasingly specific requirements for the station keeping of floating vessels, in particular in the oil industry, have resulted in the evolution of sophisticated mooring designs. Spread moorings using *catenary* lines are common for semi-submersible platforms and vertical tethered moorings for TLP platforms. In some cases spread moorings are not suitable since they essentially fix the heading angle. To enable a vessel to weathervane into the incident waves a rotating *turret mooring* or a single point attachment from the vessel to a fixed or floating structure/buoy is utilised, hence the term *single point mooring* (SPM). Furthermore active mooring or dynamic positioning (propulsion) could be a station keeping option for WECs. The main types of mooring configurations are presented in Table III.

Floating wave energy converter units moored by free hanging catenary moorings may not be able to allow for sufficient extension without excessive loads when the tidal range is large. Another disadvantage of such a configuration could be the restraining stiffness affecting the modes of motion specific to the energy extraction mythology of the WEC, and the wear of the mooring lines at the seabed touch down point. The introduction of configurations used for floating systems with flexible risers such as *Lazy S*, *Steep S*, *Lazy Wave*, *Steep Wave* or *Pliant Wave* could decrease the system stiffness thereby reducing the mooring loads. The use of these *multi-catenary* mooring configurations could provide flexibility in particular modes of motion required to improve the energy extraction for wave activated WEC designs.

Revenues from WECs, in comparison to the offshore industry, are smaller and their economics more strongly linked to the location, installation costs and down time periods. The mooring system has an important impact on the economics and it is necessary to provide, at low installation cost, a reliable system that has little downtime and long intervals between maintenance. The suitability of design approaches from the offshore industry for WECs are ranked in Table III. The wording high, medium and low is mainly used to describe the suitability of these mooring configurations in relation to safe station keeping and moderate installation costs. Mooring systems with expensive installation costs but with the potential to improve energy extraction are identified as 'medium' suitability, since they could become economically viable.

Table III Possible mooring configurations and suitability for wave energy converter

Mooring Configuration	Characteristics	Suitability for WEC
Spread Moorings		
Catenary Mooring	The mooring lines of a free hanging Catenary Mooring arrive horizontal to the seabed so that the anchor point is only subject to horizontal forces. The restoring forces are mainly generated by the weight of the mooring lines returning the system to equilibrium.	High
Multi-Catenary Mooring	The catenary mooring lines incorporate weights and buoys to form S- or Wave type configurations. Steep and lazy touch down points are possible.	High
Taut Spread Mooring (Tethered Mooring)	The mooring lines of a Taut Spread Mooring arrive, typically at an angle to the seabed with the anchor point capable of resisting horizontal and vertical forces. The restoring forces are mainly generated by the elasticity of the mooring line. The mooring lines of a TLP are orthogonal to the seabed, with the restoring force mainly generated by the change in buoyancy of the topside structure.	Low
Single Point Mooring		
Turret Mooring	An internal or external catenary moored turret attached to a floating structure allows weathervaning around the turret.	Low
Catenary Anchor Leg Mooring (CALM)	The floating structure is moored to a catenary moored buoy and is able to weathervane around the moored buoy.	High
Single Anchor Leg Mooring (SALM)	The floating structure is moored to a single anchored taut buoy and is able to weathervane around the moored buoy.	High
Articulated Loading Column (ALC)	A moored floating structure can weathervane around a bottom hinged column, which has a swivel above the water line.	Medium
Single Point mooring And Reservoir (SPAR)	A catenary anchored SPAR buoy allows the storage of a medium (oil, hydrogen) and a floating structure to weathervane around a mooring point.	Medium
Fixed Tower Mooring	A fixed tower anchored into the seabed allows the moored floating structure to weathervane around the mooring point.	Medium
Dynamic Positioning		
Active Mooring	The technique for the Active Mooring consist of mooring lines which are spread around the floating structure, where the inboard end of each mooring line is held by a servo controlled winch. A central computer tensions or loosens the mooring lines in order to keep a fixed seabed position.	Low
Propulsion	The technique consists of positioning a floating structure above a fixed seabed point by the use of propellers or thrusters which are controlled from a central computer.	Low

Free hanging catenary or multi-catenary moorings and CALM or SALM single point moorings appear the most favourable options at present as they have well established design criteria and relatively moderate installation costs. However, the suitability of a free hanging catenary mooring, a multi-catenary mooring or a combination of both has to be carefully evaluated in the context of the stiffness requirements of a WEC. If a CALM or SALM single point mooring is a favourable system, allowing the WEC to weathervane, this may require a relatively large operational footprint and result in an unacceptably large spacing between devices, especially when there are several WECs in an 'energy farm'.

ALC, SPAR or fixed tower single point moorings are ranked as having 'medium' suitability for wave energy devices. Their installation costs would be relatively high and, in the first instance, would not appear to be suitable for WECs. However, the use of a SPAR configuration could provide a storage area for a medium like hydrogen, eliminating the expense of a power transmission cable. The ALC could be the active body itself for the power extraction and could therefore become a suitable arrangement.

The use of taut spread mooring, dynamic positioning and the turret single point mooring appear not be economical at this stage and hence are not considered suitable. Taut spread moorings require expensive seabed anchors and strongly restrict the alignment to the incident wave, and would provide insufficient response to tidal change at the typical installation depth for most locations around the UK. However, the motion characteristic of a TLP with relatively small dynamic responses would be suitable for OWCs or OTDs but may require the expense of an active mooring system to allow for tidal ranges.

MOORING SYSTEM COMPONENTS AND REQUIREMENTS

Primary mooring components are the mooring line and anchor. These are used along with other items such as connecting elements, floats, etc. These components must be chosen with consideration of the mooring configuration, location and the requirements of a long term mooring. Requirements for components of a long term mooring are discussed in the offshore standard DNV_OS_E301' *position mooring'* (2001), where long term mooring is defined for floating units positioned at the same location for five years or more. Table IV describes different characteristics of mooring line materials such as chain wire rope, synthetic rope and various anchor types.

Table IV Mooring components and relative costs

Mooring Components	Characteristics	Costs
Mooring line		
Chain	Depending on required proof strength Grade 3, 3S or 4 should be used for offshore moorings. Chains provide a good catenary stiffness effect and have good abrasion and bending properties. Suitable for long term moorings but require regular inspections.	Medium
Wire Rope	Spiral Strand, Six Strand and Multi-Strand wire ropes available but only the Spiral Strand is suitable for long term mooring. Due to the elasticity of wire ropes it can be used in tensioned mooring applications. Extreme bending must be avoided.	Low
Synthetic Rope	Typical fibre ropes are Polyester, Aramid, HMPE or Nylon ropes. The weight of the ropes in water is around zero allowing them to be close to neutrally buoyant or buoyant. The weight and elasticity properties make them more common for very deep water tether applications. Short term experience in real conditions results in a high safety factor being applied. Considerable change in axial stiffness after installation requires re-tensioning. Axial compression and hysteretic heating at extreme storm condition needs to be avoided and fishbites can be a problem.	High
Anchor		
Gravity Anchor	Horizontal holding capacity is generated by dead weight providing friction between seabed and anchor.	Medium
Drag-Embedment Anchor	Horizontal holding capacity is generated in the main instalment direction by the embedment of the anchor in the ground.	Medium
Driven Pile / Suction Anchor	Horizontal and vertical holding capacity is generated by forcing a pile mechanically or from a pressure difference into the ground, providing friction along the pile and the ground.	High
Vertical Load Anchor	Horizontal and vertical holding capacity is generated due to a specific embedment anchor allowing loads not only in the main instalment direction.	High
Drilled and Grouted Anchor	Horizontal and vertical holding capacity is generated by grouting a pile in a rock with a pre-drilled hole.	High

Mooring line material and anchors as shown in Table IV should be selected in the context of the seabed condition, mooring configuration, design specification of the WEC and the costs. As part of the ongoing SUPERGEN project, companies were asked to provide price information for chain, wire and fibre ropes. The information gathered from this request is shown in Figure 1, where the price per metre length is plotted against the minimum breaking load. The data gathered to date in this study is limited and cannot be considered completely representative of the whole picture. However, from the figure it can be seen that considerable cost differences can be identified between chain, wire ropes and synthetic ropes, but there are factors other than breaking load that must be considered in the overall system design. The choice for a mooring line material would be more likely to be based on physical attributes and technical issues rather than cost.

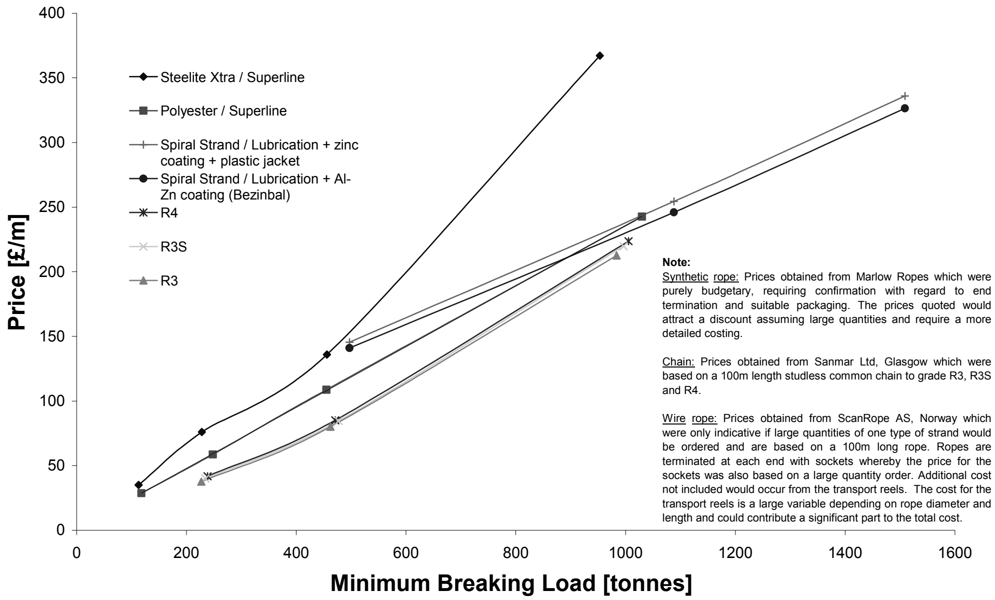


Fig 1 Comparison for costs of mooring line materials

The main technical considerations of a mooring line will be its performance in respect to its reliability and stiffness characteristics. Fibre ropes require high safety factors since long term experience is not available (DNV 2001), with the result of higher instalment costs. This increase in instalment costs needs to be considered, and is reflected in the high relative costs for the mooring lines in Table IV. The main advantage of a fibre rope in very deep water, its buoyancy property, would be secondary for moderate WEC instalment depths. However, if the WEC unit requires large motion response then the stiffness property of a fibre rope could contribute to it. Long term experience of chains and wire ropes contributes to smaller safety factors thereby reducing their instalment costs. However, the bending properties of the wire ropes require more consideration with regard to transport and instalment procedures. Plastic protected wire ropes would provide ideal long term mooring properties at predictable maintenance periods provided the curvature within the mooring line can be kept within prescribed limits. Chains have the advantage of ideal bending properties and good seabed abrasion qualities with predictable maintenance intervals.

The location and the use of a specific mooring configuration or mooring line material often requires a specific anchor type. A gravity anchor has low unit costs for its mass and in order to provide horizontal holding capacity it must be very large, as it relies on its dead weight to generate surface contact friction. Mooring configurations with requirements for the anchor to be able to withstand horizontal and vertical loads, which would for example be the case for fibre ropes that are not designed to allow for abrasion at the seabed, make gravity anchors an unsuitable choice. The seabed condition itself could dictated a specific anchor type or allow a choice of anchor type installations. This becomes obvious for a rocky seabed where embedment would not be an option. The cost of installing a particular anchor could be significant and could negatively influence the choice of a location and/or mooring configuration.

Other components such as connecting elements or winches would be required to be chosen to satisfy current regulations and requirements for insurance purposes. According to the DNV standard, connecting elements for a long time mooring requires purpose made shackles or triplates. Swivels, pear links, C-links, Kenter shackles and ordinary D-shackles are not permitted by current offshore regulations for long term moorings. Simple mooring configurations would typically not be in need of a fairlead or winch / winch equipment. However, if an active mooring were to be considered these components would be required and appropriate regulations would need to be considered.

DISCUSSION

Techniques used within the offshore industry are directly applicable to WECs though there are fundamental differences in the mooring system design requirements for WECs compared to those for conventional offshore moorings. At present most of the mooring standards for the offshore industry, as presented for example in DNV or API standards, can be employed to secure safe station keeping of such devices.
As a consequence of the response requirements for WEC units, engineers are faced with a degree of uncertainty as to the most suitable mooring configuration and the long term reliability of the mooring components; so the optimal design cannot at this stage be achieved without risk of failure. Mooring configuration designs for WECs need to evolve from experimental and theoretical studies, and through the experience which will be gained from the prototype wave energy devices currently being installed at sea. The basis for the mooring design and the development of a generic mooring system divides itself into two categories. The first relates to what can be termed *motion independent devices* such as OWCs, OTDs and stationary moored WABs, where such moorings act to provide a stable platform in all environmental conditions. The second relates to what can be termed *motion-dependent devices* such as active moored WABs, whereby the dynamics of the device and its primary modes of energy extraction would require the application of an interactive mooring system. The resonant behaviour and mooring loads of simple bodies in such configurations need to be studied for different load conditions, and the aspects of safety, economics and reliability need to be considered.

Although current methodologies employed in the design of offshore moorings can be applied to WEC moorings, it is the additional design requirements through which interactive moorings can improve the operational efficiency of the moored WEC device that will be addressed within the EPSRC SUPERGEN research programme, in which the authors are involved. In the authors opinion moorings have been of secondary concern to the WEC designer, but if through careful design the operational efficiency can be enhanced, their importance will be appreciated. In order to determine the possible improvements to the operational efficiency performance indicators are necessary, but as this is very much a fledgling industry little is either known or publicly available concerning the performance of WEC units related to their station keeping. The research group undertaking this study aim to investigate generic mooring systems applicable to typical WEC concepts, demonstrating efficiency improvements through mooring design.

CONCLUSION

At present no particular WEC design can be identified as the dominant commercially suitable device. Generic mooring configurations have to be developed in accordance with the operational performance and with consideration of safety, reliability and economics. It is considered by the authors that the industry is at such a stage in its development that an objective assessment will help in identifying requirements and engineering solutions to WEC mooring system design.

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