Moorings and Foundations Catalogue, Deliverable 5.1

December 2016

Project Information

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Project Lead	EMEC Old Academy Business Centre Stromness, Orkney, KW16 3AW

Project Partners

EMEC ORKNEY THE EUROPEAN MARINE ENERGY CENTRE LTD	The European Marine Energy Centre Old Academy Business Centre Stromness, Orkney, KW16 3AW, UK http://www.emec.org.uk
CATAPULT Offshore Renewable Energy Development Services Ltd	Offshore Renewable Energy Catapult National Renewable Energy Centre Offshore House, Albert Street, Blyth, Northumberland, NE24 1LZ, UK https://ore.catapult.org.uk
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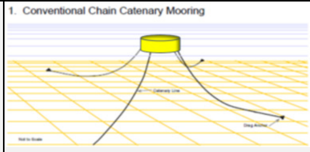
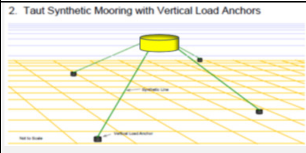
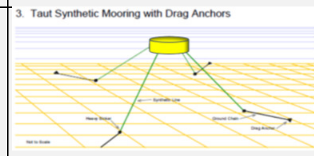
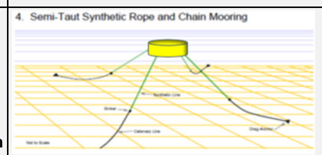
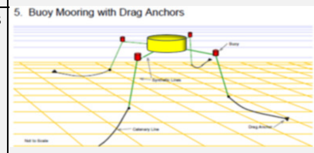
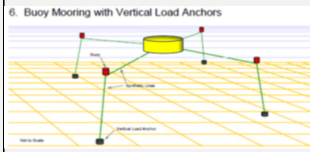
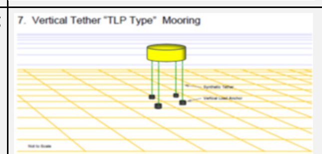
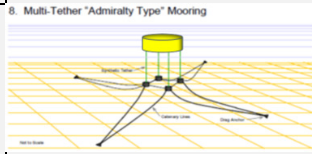
Executive Summary

EMEC completed a catalogue of mooring and foundation types, noting their applicability to different water depths and seabed types, their strengths and weaknesses and their common failure modes. This is intended as an initial source of information for developers within the marine energy industry, and is not a definitive or exhaustive list.

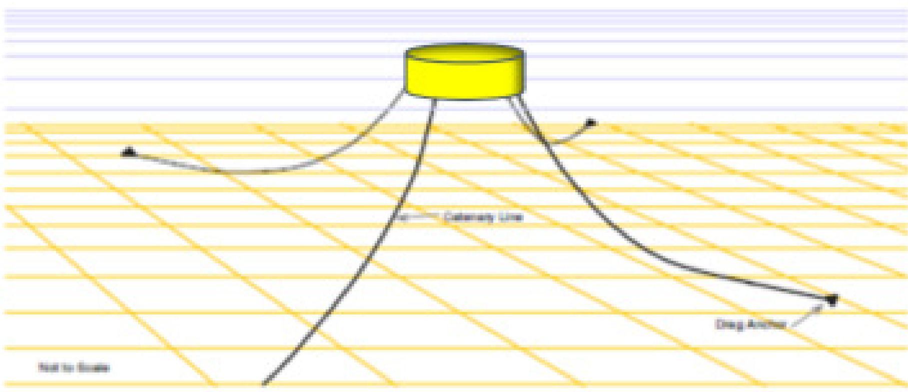
There were significant contributions from Tension Technology International, who have been instrumental in the design and pre-deployment testing of several existing and forthcoming marine energy converter mooring systems.

Updated 20161217 **Rev 2**

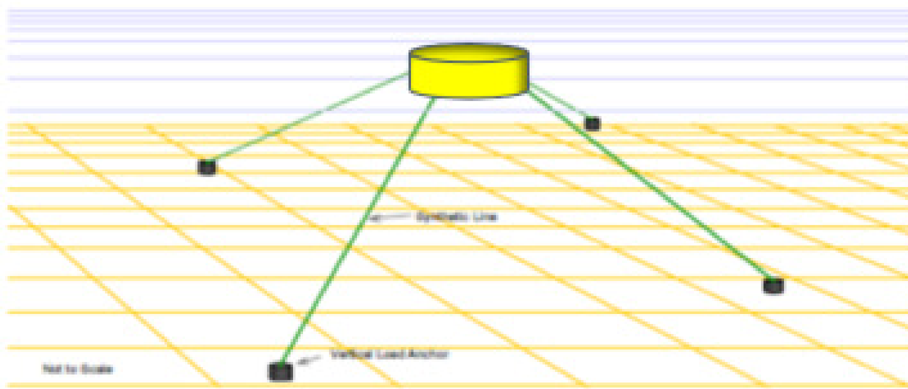
No	Mooring Class	Mooring Class Diagram	Descriptions	Target Regime	Advantages	Disadvantages	Technical Suitability in +100m water depth (for utility scale WEC)	Technical Suitability in <70m water depth (for utility scale WEC)	Possible component/system failure	Suitability for weather vaning	Scale considerations
#1	**Conventional Chain Mooring**		The chain catenary mooring is the most conventional system and can be considered as a benchmark against which other concepts are compared.	For exposed wave sites, better suited to deeper water. For large structures with design conditions Hs>10m, sub 70m water depth can be challenging, tending to unfeasible in shallower water.	• Conventional materials and mooring components readily available "off the shelf". • Characteristics and design issues well understood and standards published.	• Highly non-linear stiffness attracts large loads from wave induced surge motions hence high strength and/or large size chain needed. • Heavy chain lines have to be supported by the buoyancy of the WEC device. • Large footprint due to line scopes of 8 or more needed to avoid uplift at anchors. • Likely to be the costliest of all systems because of the heavy all-steel components.	Good	Poor	•Significant number of chain and associated connector failures. •Majority of failures at connector or discontinuity. •Out of plane bending caused by constrained link. •Corrosion and wear on chain links and shackles. •Insufficient compliance in system causing excessive snatch loads. • When combine with wire - failure at wire socket termination.	Could be adapted for attenuator, with all moorings connecting at bow.	Can be used on large scale systems if water is sufficiently deep. Handling of large chain (e.g. >3inch) can become prohibitively heavy and expensive. For smaller scale systems will depend on ratios of displacement, extreme wave height and water depth rather than scale limitation. For instance a small buoy at a proportionally scaled site may be feasible, but if smaller buoy is installed at full Atlantic site, chain may become unfeasible.
#2	**Taught synthetic mooring with VLAs**		The synthetic rope taut mooring concept has been pioneered in deep water moorings for offshore drilling and production platforms. Using synthetic lines – typically polyester – provides the system compliance, which is more linear in behaviour, to allow taut lines. The lower axial stiffness of nylon is particularly attractive for wave energy sites, where hydrodynamic loading on the mooring system tends to be dominated by first order motions (e.g. in surge). Further, in order to minimise peak line loads it often pays to increase the line length rather than line diameter. Line stiffness is equal to the rope modulus by cross-section area over length of line (k = EA/l) so having longer ropes for the same EA gives a 'softer' line. Note that permanent fibre rope moorings in the O&G industry have not utilised Nylon as this is developed for the marine renewables market (the shallower water of WEC sites means shorter lines so lower modulus is required for given line stiffness). Pre-tension requirements and line angles normally result in vertical load component at anchor (requiring VLA).	Particularly suitable for shallower water with exposed wave regime (less than 70m water depth). Nylon more suited to shallow sites than polyester, due to axial compliance. The shallower water sites may not require VLA, depending on the mooring spread to water depth ratio (i.e. angle of lift at anchor). Some drag anchors can accept vertical component of <20degrees, although may not be accepted by guidelines.	• Synthetic rope materials considerably cheaper than steel wire rope or chain. • Nearly linear system stiffness characteristics better control mean offsets and loads deriving from wave induced surge motions. • Has the potential to achieve a relatively compact footprint (anchor radius). • Relatively low horizontal offset with respect to electrical umbilical design limitations.	• Synthetic rope lines less robust than chain against abrasion wear and cuts. • Careful fibre selection and rope design expertise needed to achieve a good mooring. •This system clearly requires anchors capable of resisting vertical loading. Vertical load anchors as an option if sediment depths permits. Conventional drag embedment anchors may be suitable depending on the line inclination. Otherwise gravity base or piled anchors are required.	Good	Excellent	•Damage to line during handling during installation and recovery (e.g. abrasion, cuts, creep, heating, rope and sleeve wear and splicer). •Lack of experience of operator with synthetic moorings for permanent applications•RAMS not being followed correctly. •Design loads underestimated due to lack of experience in modelling lines. • Line pretensions not maintained. •Minimum operation pre-tensions not maintained.	Could be adapted for attenuator, with all moorings connecting at bow and also suitable for turret style mooring.	Mooring system can be scaled from 10T MBL to 1000T MBL and the option (end sentence?)
#3	**Taught synthetic mooring with Drag anchors**		#3 is a development of the taut synthetic mooring #2. Clump weight 'sinkers' are attached to the end of the synthetic segment and then chains extend horizontally to conventional drag embedment anchors. The sinkers can slide or lift-off in extreme sea states and are therefore not required to be as massive as gravity anchors for a taut system. This system allows the use of conventional anchors at the detriment of mooring footprint and cost but depending on site conditions may be more cost effective than #2.Guidelines do not normally allow for synthetic elements to touch the seabed.	Similar to #2, but suitable for sites with sediment.	Can combine chain (for ground conditions) with synthetics while satisfying minimum line tension requirements.	• Aspects of #1, #2	Good	Excellent	•Vertical loads and anchor causing pull-out• Zero tension loading caused by clumpweight hitting seabed, followed by sudden repeated pull, could put unnecessary load on mooring components and connectors.	Could be adapted for attenuator, with all moorings connecting at bow and also suitable for turret style mooring.	Clumpweight size could be prohibitive for large scale systems.
#4	**Semi-taut synthetic rope & chain mooring**		The semi-taut synthetic rope and chain mooring may be considered a hybrid system with characteristics of both a catenary and taut mooring. Like the fully taut concept, it has been used by the offshore industry for deep water moorings where all steel mooring lines would put too much weight on the vessel. The key benefit over #2 would be that this system allows the use of conventional drag embedment anchors due to the near horizontal force at the anchor. This may be important if an anchor capable of vertical loading is impracticable or too expensive for the given site.	Similar to #2, but suitable for sites with sediment.	• Better system stiffness characteristics than the all chain catenary system can give a workable design with lower strength components. • Cheaper than the all chain catenary as synthetic ropes (of same strength) cheaper and easier to handle during installation.	• Similar overall footprint (anchor radius) to the all chain catenary system. • Synthetic rope lines are less robust than chain against abrasion wear and cuts. • Careful fibre selection and rope design expertise needed to achieve a good mooring.	Good	Excellent	• As hybrid synthetic/chain system causes of failure similar to both #1 and #2. • May be more susceptible to minimum tension cycles than more highly pre-tensions #2.	Could be adapted for attenuator, with all moorings connecting at bow.	
#5	**Buoy mooring with drag anchors**		Mid-line Buoys are introduced in order to add compliance to the system in survival seas, and buoyancy station-keeping stiffness to the system in operating seas. The buoyancy can provide easier hook-up and un-hook of system. Steel chain and wire can be used for the risers to buoy, although lightweight, floating synthetics are preferred for between the buoy and vessel. Midwater buoys can be used instead.	Suitable for sites with sediment.	• Easy to hook, unhook mooring. Good station keeping in operating conditions. Heave motions are decoupled from mooring so may suit the operating mode of some wave energy systems.	• Buoys attract hydrodynamic loads in waves and strong surface currents. • Can lead to a design spiral of requiring bigger and bigger buoys, so as to avoid snatch loads, which ultimately leads to bigger anchor loads. • More components and connections which can break or become fatigued.	Fair	Fair	• Greater number of connections and components present risk of failure. • Mid line buoy can result in additional dynamic loads being imposed on lines and connectors, particularly in high wave regime site.	Could be adapted for attenuator, with all moorings connecting at bow.	For large scale systems, buoy can attract significant wave loads by themselves, which may be prohibitive.
#6	**Buoy mooring with VLA**		Is a variation on #5, whereby there is a requirement to reduce the mooring system footprint, or seabed conditions don't exist for drag embedment anchors.	Suitable for sites with no sediment	• Easy to hook, unhook mooring. Good station keeping in operating conditions. Heave motions are decoupled from mooring so may suit the operating mode of some wave energy systems.	• As per #5. • Anchoring requirements and loads can be significant compared to #5.	Fair	Fair	Similar to #5, with greater relative loads due to limited compliance in system.		As per #5
#7	**Vertical tether TLP type mooring**		This concept is analogous with offshore O&G TLP type moorings. It offers by far the smallest mooring footprint and utilises the device buoyancy to provide the mooring restraint and restoring forces. It is a laterally compliant system. The system clearly requires vertically loaded anchors of significant capacity which are likely to be the key cost driver for this system and may not be technically or economically viable depending on the site conditions. The mooring lines (tethers) must have sufficient compliance to accommodate tidal variation. For WEC devices in particular the effect of this mooring on performance must be determined as it supresses heave and pitch motions. The effect of mooring stiffness' on device performance has been examined in numerous papers. The effect of the supressed motion may be either positive or negative (or neither) depending on the device wave power absorption characteristics and will need to be assessed on a device basis. TLP type moorings tend not to be adopted for utility scale (1 MW – 2 MW rated capacity) wave energy devices. The ratio of extreme wave height to water depth for shallower wave sites, makes TLP type mooring challenging due to snatch loading. While the footprint is small the benefits may be outweighed by anchoring considerations and costs. While TLP type moorings allows devices to be tightly packed there may be diminishing returns as the high density arrays may become wave resource constrained. It is recommended that reference is made to experiences in offshore wind technology as some developers are adopting TLP technology (e.g. ETI and Gloston associates Pelastar system). TLP technology may be more viable for offshore floating wind as the sub-structure can have a smaller displacement or more transparent shape as they are designed for load shedding rather than wave energy absorption.	For exposed wave regimes sites, where the risk of snatch loads then there must be sufficiently deep water. Normally >100m water depth. For smaller devices, where PTO is integrated with line, technologies are able to target shallower water depths.	• A laterally compliant system that mobilises the buoyancy of the moored vessel to provide the mooring restraint.• Minimal seabed footprint - best of any concept by a considerable margin.• Tethers can be steel (deeper waters) or synthetic ropes in shallow waters.• Potentially low mooring cost – predominantly dependent on the anchoring cost.	• Requires sufficient vessel buoyancy to pre-tension tethers, but large water-plane area increases tether loads. • Needs sufficient water depth and tether axial elasticity to accommodate tidal range. • Careful fibre selection and rope design expertise needed to achieve a good mooring. • Significant risk and cost is transferred to VLA anchor design (e.g. piling). • Could impact on operating mode of any wave energy device (e.g. no heave compliance).	Fair	Poor	• Zero load cycles (snatch) leading to tension compression fatigue in mooring line. • High frequency resonance.	Not really suited to weather vaning (e.g. turret mooring would be under very high tensions).	Larger system are likely to lead to challenging design spiral in sub 100m water depths. Vessel buoyancy required to provide pre-tension over short line length. Increased buoyancy required to avoid snatch loads, which could lead to greater hydrodynamic loads and greater likelihood of snatch - all driving up anchor costs. Better suited to small scale, single leg WECs.
#8	**Multi-tether "Admiralty" type mooring**		This system is an adaption of the commonly used Admiralty mooring for buoys in coastal waters. Its popularity is thanks to excellent compliance characteristics which mean it is functional in shallow waters with high tidal range and gives good survivability in aggressive sea states. The footprint is relatively small and the use of drag embedment anchors is allowed owing to the clump weights and chains to anchors. The compliance also means MBL of components is minimised thus improving the cost basis. This may be an attractive solution allowing the use of drag embedment anchors in shallower waters where sufficient stable sediment exists. However, it is a complex system with many connections and since failures commonly occur at discontinuities in mooring systems this is likely to be an unreliable system. The original mooring system for the Pelamis device was essentially based on an Admiralty type mooring. Despite having an acceptable footprint Pelamis recognised the need to move towards an all nylon based system to reduce the anchor design loads and associated costs.	Good compromise for water depths less than 100m, with stable sediment (>6m sediment depth).	• A very compliant mooring system that should achieve a workable design with lower strength components. • Very compact footprint (anchor radius) much less than a multi-leg chain mooring. • Uses drag embedment anchors which have lower cost than vertical load anchors. • Synthetic ropes can be used for vertical tether lines (either polyester or nylon) to increase compliance and reduce overall cost.•Has the benefits of TLP, but able to provide some heave compliance in survival conditions.	• Requires sinker weight(s) to pre-tension the vertical tethers, which has to be supported by the buoyancy of the WEC device. • Requires additional tie lines or rigid structure to keep the multiple tethers parallel. • Large excursions may be an issue (e.g. in respect of power export cables etc.). • Large length of chain may be required on seabed to avoid lift-up at anchor. • Struggle to compete with #2 synthetic mooring in shallower wave exposed environments.	Good	Good	• Sinker can bounce off of seabed and swing about causing risk of failure to associated components. • Lots of lines and connections with associated risk of failure.	Could be adapted to weather vaning system, similar to Pelamis attenuator with single or double synthetic risers. This variation may have better reliability.	Clumpweight size could be prohibitive for large scale systems. Large chain lengths required when large scale buoys deployed in relatively shallow waters.
	Alternative type mooring system										
A	**Sheave based Technology**	e.g.: Laminaria, Nemos	A number of technology developers have adopted sheave based technology (e.g. mooring line running through pulleys). The sheave(s) may be located at anchor point and in some cases on structure or both. The purpose of the sheave can be to provide a continuous mooring system with power take-off integrated. Alternatively it can be used to redirect the forcing action into linear motions at power take off located separately.	Shallow to intermediate water depths	•Allows for continuous lines, with flexibility for PTO integration with line	• Sheaves are unproven and ropes will suffer from bend over sheave (fatigue), which is likely to require new flat rope designs to reduce the fatigue issues.			• Bend over sheave fatigue failure of rope. • Debris jamming sheave. • Sediment ingress with rope when in proximity to seabed (sheave may need to be supported off of seabed).		Not been developed for large scale systems as yet. Still developmental.
B	**Alternative mooring load absorbers**	e.g. TFI system, Seaflex, Exeter Tether	There is a class of mooring components, being developed, which provide compliance over a short length, whereas synthetic lines provide compliance over the full mooring line length. Could be used in conjunction with nylon mooring based technology for additional shock absorption. Some of this technology is rubber based, such as Seaflex and TFI. Other technologies include hose pump type compliance.	Shallow water moorings with high wave exposure	•Compliance can be provided over short mooring element length •Some of the technology has already been proven for smaller scale applications.	•Unproven and untested for large scale applications requires further development.			• Rubber fatigue and any associated mechanical components.	Depends on application.	It is understood that this technology has not be tested at significant scale, although deployed on small scale (e.g. seaflex used on fish cages).
C	**Storm Submergence**	e.g. Laminaria, Marine Power Systems	A number of wave technologies adjust their height in the water column depending on the seastate (e.g. winch down in survival conditions so as to reduce loads on the mooring system). Note - winch and fairlead sub-systems have not been considered as part of this study.	Need to be sufficiently deep, so that water particles velocities and acceleration are not significant at position lowered to in the water column.	•Avoidance of largest wave loads and impact waves.	•May require "failsafe" mode to ensure system is not stuck at surface in survival conditions. Winching mechanisms could be more vulnerable and will need to be properly qualified and tested at intermediate scale.		(Not?) Note likely to be a water depth shallower than 70m at which point operation mode becomes less attractive, due to water particle motion near seabed.	• Winching mechanisms may be vulnerable.	Not relevant to current technologies.	Not been developed for large scale systems as yet. Still developmental.
D	**Single leg point absorbers**	e.g. CorPower, Seabased, AWS II (waveswing), Carnegie	There is a class of surface and submerged point absorbers which operate using a single tether with integrated in-line power take-off, which is ground referenced. The PTO and any tidal compensation equipment could be housed at buoy end , anchor end or possibly mid-line. Some devices may adopt rigid leg or jacket which can accept compression loads, although could still be classed as a compliant mooring if they have a universal joint (for instance at seabed to allow pitch compliance and possible load reduction, compared to fixed device).	Normally suited to intermediate water depths in the range of 40m to 50m. It may be possible to go shallower or deeper, depending on technology, scale and wave regime.	•PTO and mooring system integrated.	• Susceptible to snatch loads in shallower water. • Limited redundancy should a mooring component fail. • May have requirement for tidal compensation.		See comment under target regime.	•Component fatigue and snatch loads.	Not relevant as point absorber.	Mooring loads and scale will be limited by the maximum size of buoy, which will be limited by point absorber theory.

No	Foundation Class	Descriptions	Target Regime	Advantages	Disadvantages	Technical Suitability in +100m water depth (for utility scale MEC)	Technical Suitability in <70m water depth (for utility scale WEC)	Possible component/ system failure	Suitability for weather vaning	Scale considerations
1	Gravity	A gravity foundation resists the shear and lift forces of a MEC through application of mass. Heavy structures are set onto the seabed and provide a solid connection point for a device. This approach has been used previously in tidal energy devices, but has potential applications for wave energy devices in certain situations.	Deployment sites that do not offer suitable drilling or piling options, or for devices with lower forces that do not require overly massive foundations.	Simple technique, with easily calculated and engineered forces involved.	Usually very heavy (upwards of 1000Te for a 1MW tidal energy device). Requires very heavy lift equipment and vessels which can be exceedingly expensive.	No particular upper limit to water depth.	No particular minimum depth for technology. Very shallow devices will need to add interaction with waves into structural calculations.	Design life is usually limited by the welds holding the structure together, and associated corrosion. Structural failures of gravity foundations have not been documented in the industry.	The base concept imparts no restriction upon weather vaning of a device, although the design and fabrication of the metalwork will need to take this into account.	A 1 MW tidal energy device held at a roor (moor?) hub height of approx 20m requires a gravity foundation of approx 1,200,000kg of steel. A tidal device of negligible generating output, but max loads of 3Te requires a gravity foundation of approx 40,000kg of high density concrete (seeded with scrap metal). For certain scales and environments, gravity foundations can be cost effective, compared to the surveying, design and extra marine operations required for piled or pinned foundations.
2	Piled	A piled foundation is based round the attachment of a steel (standard material) frame to the seabed using hollow piles, usually between 0.5m and 1m. This approach requires either the drilling of holes slightly wider than the pile into a rocky seabed, or the hammering of the pile into a sediment based seabed, In the rocky seabed situation, a cement or grout is used between the rock and the pile to fix the pile in place, and then again between the pile and the frame to connect those two together. Other methods of creating the pile to frame connection exist, such as swaging, bolting, and screwed shear pins. For sediment piling, the depth of burial required to provide the required reaction to applied forces will depend on the scale of forces, and the type of sediment. A defining feature of a piled foundation is there is no pre-tension on any of the metalwork.	This foundation approach can be used in multiple distinct seabed type and for many applications. Difficulties arise however when there are two seabed types concurrently, such as 2 metres of sediment over a hard bedrock, as the marine operations surrounding the use of the drilled piled approach become hampered by the sediment, or "Overburden".	Proven technology, that requires a frame sized only to resist the operational loads rather than to provide ballast to react the forces. Light frame (approx 100 tonnes for a 1MW tidal energy device) means smaller cheaper installation vessels.	Choosing a suitable piling approach will require a minimum level of survey to determine the type of seabed. This may involve subsurface drill surveys for rocky seabeds, and piercing sonar surveys and grab samples for sediment based seabeds.	No particular upper limit to water depth.	No particular minimum depth for technology. Very shallow devices will need to add interaction with waves into structural calculations.	Design life is usually limited by the welds holding the structure together, and associated corrosion. The connections between pile and seabed/pile and frame are additional points of failure, but usually easy to avoid through detailed engineering works. Structural failures of piled foundations have not been documented in the industry.	The base concept imparts no restriction upon weather vaning of a device, although the design and fabrication of the metalwork will need to take this into account.	There is a limit to both the size of piles that can be used, and to the loads that any one pile can resist. Therefore larger devices will require greater numbers of piles, with associated installation time and design requirements.
3	Pinned	A pinned foundation is based round the attachment of a steel (standard material) frame to the seabed using solid rock anchors. These differ from a pile in that the outer diameter is much smaller, they are generally only suited to rocky seabed. A hole is drilled and a rock anchor inserted/left in place. The anchor is activated by either being pulled upwards, or an internal screw mechanism utilised to create a spreading, or horizontal force that locks the anchor in place. It is this pre-tensioned and locked position that will allow the anchor to hold the frame securely to the seabed.	Rocky seabeds. Bedrock needs to meet minimum standards of integrity and strength. Heavily fractured bedrock will be difficult to work with, as it will break under either the pre-tension or operating forces.	Rock anchors are a proven technology on shore, and are being used more widely subsea. The size of drilling equipment needed for rock anchors is generally smaller than for piles, so smaller vessels can be used.	This approach requires competent rocky seabed, which will need confirmed through drill sampling and survey. There may also be requirements for load testing sample rock anchors to determine their capacity during the frame design stage.	No particular upper limit to water depth.	No particular minimum depth for technology. Very shallow devices will need to add interaction with waves into structural calculations.	Design life is usually limited by the welds holding the structure together, and associated corrosion. The connections between pin and frame are additional points of failure, but usually easy to avoid through detailed engineering works. Structural failures of pinned foundations have not been documented in the industry.	The base concept imparts no restriction upon weather vaning of a device, although the design and fabrication of the metalwork will need to take this into account.	There is a limit to both the size of pins that can be used, and to the loads that any one pin can resist. Therefore larger devices will require greater numbers of pins, with associated installation time and design requirements.

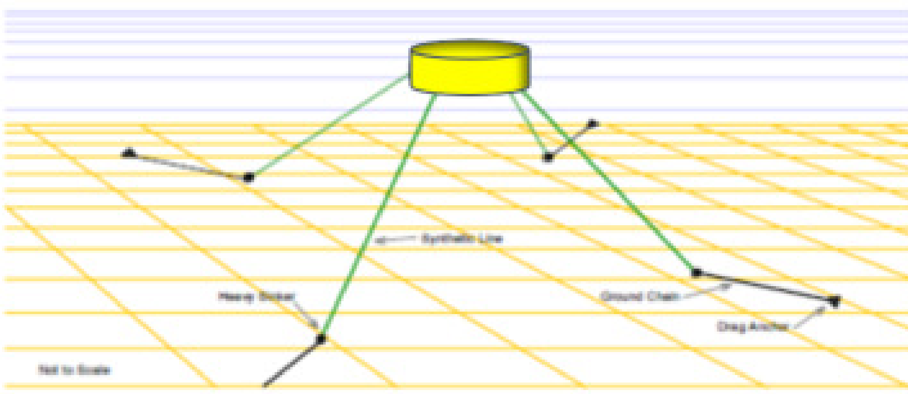
1. Conventional Chain Catenary Mooring



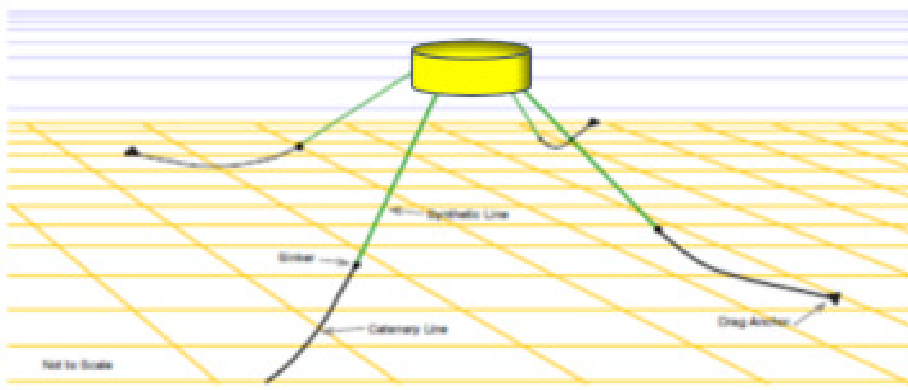
2. Taut Synthetic Mooring with Vertical Load Anchors



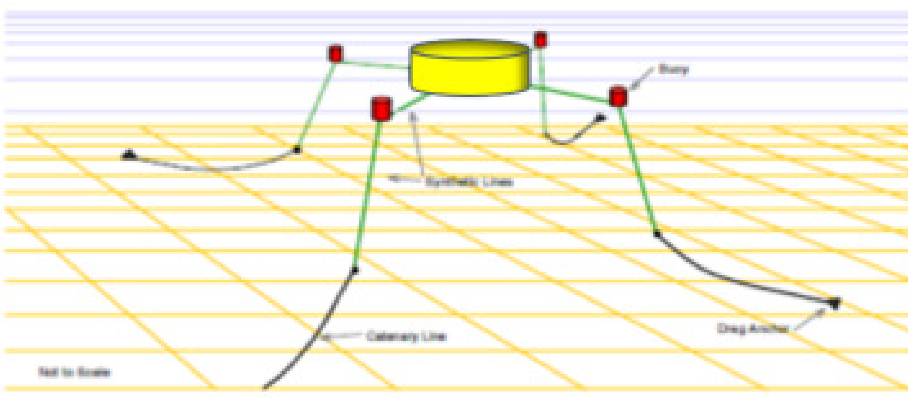
3. Taut Synthetic Mooring with Drag Anchors



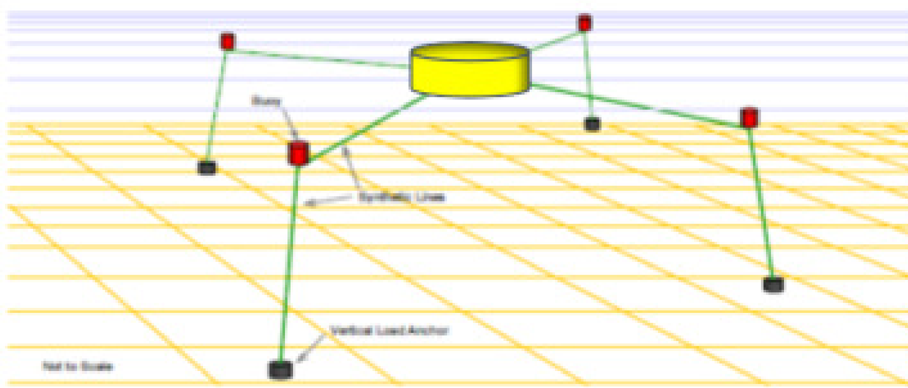
4. Semi-Taut Synthetic Rope and Chain Mooring



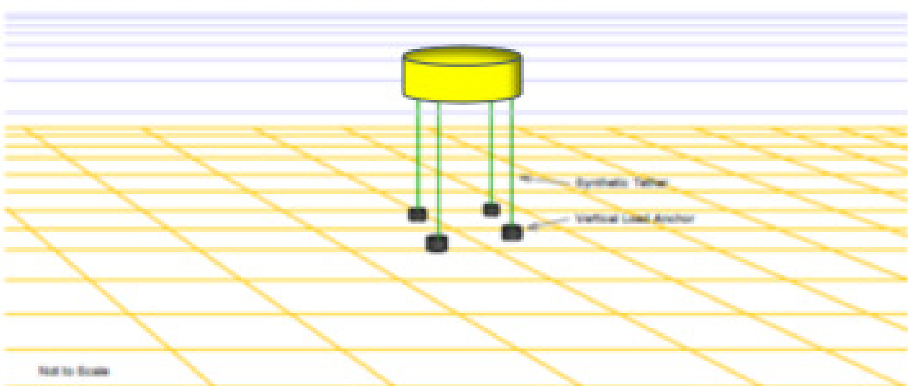
5. Buoy Mooring with Drag Anchors



6. Buoy Mooring with Vertical Load Anchors



7. Vertical Tether "TLP Type" Mooring



8. Multi-Tether "Admiralty Type" Mooring