Deliverable 4.2: Specific requirements for MRE foundation analysis

Lead partners:	Sandia National Laboratories and The University of Exeter
Contributing partners:	Tecnalia, DEME Blue Energy (DBE), WavEC Offshore Renewables
Authors:	Jason Heath, Richard Jensen, Jose Arguello Jr., Jesse Roberts, Diana Bull, Sandia National Laboratories; Sam Weller, Jon Hardwick, Lars Johanning, The University of Exeter

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Executive Summary

Marine Renewable Energy (MRE) systems involve single or arrays of devices that are secured to the seafloor via foundations and/or anchors. These MRE devices will transmit long-term cyclic loads to the seafloor sediment or rock, which may affect seafloor material properties and hence the overall physical performance of the MRE system. The response of seafloor sediments or rock formations is uncertain for the novel MRE systems and especially large arrays of 10s to >1000s of devices. This report summarizes critical inputs and tools for the design and analysis of foundations, anchors, and the response of the seafloor materials. Followed by an introduction in Section 1, Section 2 reviews the offshore structure and MRE literature to highlight current approaches and needed inputs for assessing interactions between foundations or anchors and seafloor materials, including potential environmental impacts. Section 3 addresses relevant marine geological settings that control key geotechnical engineering properties. Data collection activities are described, including *in-situ* site surveys and laboratory testing. Section 4 considers the unique interactions between MRE systems and seafloor materials, particularly cyclic loading and sediment response. Section 5 describes analytical and numerical tools and associated inputs for the design process of MRE foundations and anchors. Constitutive models are key to simulating sediment response and thus are discussed in detail. Important summary tables relate key variables of geology, geotechnical parameters, foundation or anchor type, and quantitative assessment tools including numerical analysis. Section 5 also addresses the incorporation of the geotechnical analysis into system-level tools to support decision making for MRE arrays. Section 6 presents conclusions and recommendations for future work.

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1. INTRODUCTION

Marine Renewable Energy (MRE) systems will transmit long-term cyclic and less-frequent relatively extreme loads to foundations and anchors that connect them to the seafloor. MRE arrays may involve 10s to >1000s of devices over areas up to several square kilometres [1]. Deployment capacity by 2050, for the United Kingdom as an example, is estimated to be 27 GW for wave and tidal energy devices [2]. Many devices may be tethered to a single anchor, thus creating fully three-dimensional, static and dynamic loading scenarios. The response of seafloor sediments or rock formations is uncertain and poses risks to performance [3]. As foundations and anchors represent a primary cost to construction and maintenance of MRE systems [4, 5], success of this new industry depends on interactions between seafloor materials and foundations and anchors.

This report presents critical inputs and tools for the design of foundations and anchors for MRE arrays and systems. Section 2 reviews the offshore structure and MRE literature to highlight current approaches and needed inputs for assessing interactions between foundations or anchors and seafloor materials, including potential environmental impacts. Section 3 addresses relevant marine geological settings that control key geotechnical engineering properties. Data collection activities are described, including *in-situ* site surveys and laboratory testing. Section 4 considers the unique interactions between MRE systems and seafloor materials, particularly cyclic loading and sediment response. Section 5 describes analytical and numerical tools and associated inputs for the design process of MRE foundations and anchors. Constitutive models are key to simulating sediment response and thus are discussed in detail. Important summary tables relate key variables of geology, geotechnical parameters, foundation or anchor type, and quantitative assessment tools including numerical analysis. Section 5 also addresses the incorporation of the geotechnical analysis into system-level tools to support decision making for MRE arrays. Section 6 presents conclusions and recommendations for future work.

2. LITERATURE REVIEW ON MRE FOUNDATIONS AND ANCHORS

2.1 Special Foundation-Anchor Design Needs

MRE devices are a unique application for foundations and anchors, especially for full-scale arrays [1]. It is necessary that several criteria specific to these devices are satisfied for design, installation, and maintenance. A brief overview of these criteria is provided in this section. For further information, the reader is directed to the report DTOcean *Deliverable 4.1 – A comprehensive assessment of the applicability of available and proposed offshore mooring and foundation technologies and design tools for array applications* [6] as well as more general reference documents [7].

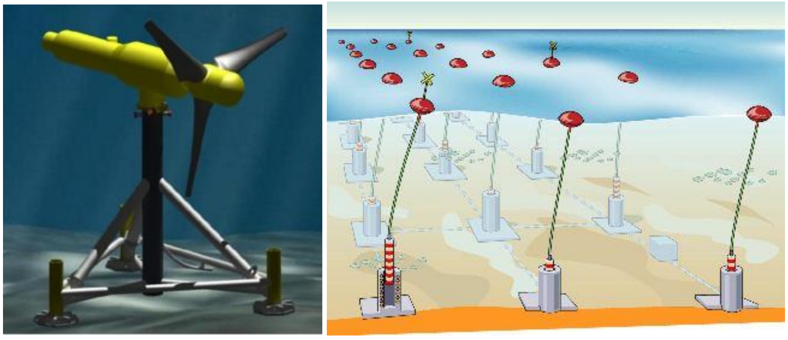

Figure 1. (*left*) Alstom/TGL 1-MW turbine (image source: [8]) and (*right*) Uppsala University wave power plant (image source and copyright: Karl Astrand and Division for Electricity, Uppsala University; [9]).

The operational requirements of an MRE device will dictate the way in which a durable connection with the seabed must be provided. The primary requirement of the connection is to maintain the position of the device either rigidly (i.e., tidal turbines on fixed support structures [10]) or allow device motions to occur which are within acceptable limits (e.g., the compliant mooring system of the wave energy converters shown in Figure 1). In the latter case, the support structure and foundation are an integral part of the power take-off system, illustrating the unique requirements of the foundation in this application. The design of the support structure may preclude incompatible anchor and foundation types (e.g., Table 1). As will be

		Foundation			Anchor			
		Piled	**GBS[1]**	**Suction piles or caissons**	**Fluke**	**Plate/ VLA[2]**	**Pile**	**Gravity**
Support Structure	Pile	✓	✓					
	Moored				✓	✓	✓	✓
	Tethered					✓	✓	✓
	Sheath system	✓	✓					
	Guyed tower					✓	✓	✓
	Telescopic	✓	✓					
	Shroud	✓	✓	✓				
	Jacket	✓	✓	✓				

[1] Gravity-based structures

[2] Vertical-load anchor

Table 1. Compatibility matrix for tidal turbine foundations and anchors.

discussed in this report, initial design selections such as these will determine which analysis techniques are used to determine the seafloor material response (see Section 5).

Guidance produced by certification agencies such as Det Norske Veritas is used to ensure that the designed and specified components are adequately durable and reliable for the application (e.g., [11]). Component durability incorporates the capacity to withstand infrequent peak loads as well as the effects of load cycling, environmental exposure, and changes in material properties over time. Reliability requirements are likely to be specified over different time-scales (i.e., over the entire deployment lifetime or between maintenance and/or replacement intervals). Guidance on these aspects exists for MRE devices, such as DNV-OSS-312 [12], the DNV/Carbon Trust *Guidelines on design and operation of wave energy converters* [13], and forthcoming International Electrotechnical Commission/TC 114 guidelines [14]. These documents largely refer back to existing offshore guidance for foundations and anchors (e.g. DNV-OS-C101 [15] for steel structures and DNV-OS-

E301 Position Mooring [16]) with consequence criteria modified for this new application. Whilst insight into MRE foundation and anchor durability and analysis is provided by a few studies (e.g., [17]), in the absence of deployment examples lessons can be learnt from similar foundations used in different applications, such as offshore wind turbines [18] and offshore platforms [19].

The economics of foundations and moorings will have a significant influence on which technology is selected. With the exception of off-the-shelf components (such as anchors and connecting hardware), costs are design dependent and highly variable (i.e., the commodity cost of steel [20]). Indicative capital costs for monopile installations can be drawn from the offshore wind industry, such as the UK Energy Research Centre's *Great Expectations* report [21]. Installation, maintenance, and decommissioning costs bring added complexity due to the variability of vessel and equipment day rates and accessibility (e.g., weather windows [22]). In addition to the cost-scalability of arrays, shared mooring, and foundation infrastructure for arrays of devices is a possible way of achieving capital cost savings as well as a way of reducing the number and difficulty of installation, maintenance, and/or decommissioning operations [23, 24].

The seafloor geotechnical response of full-scale arrays of 10s to >1000s of devices is of major importance to the physical performance of MRE systems. Previous MRE-specific work mainly focuses on hydrodynamics of the MRE system and not foundation and/or anchor response for devices in an array [1, 25-27]. More general offshore foundation and anchor literature focuses on the design and response of single foundations and anchors (for example, see [28]). Recent work such as [29] indicate that geological heterogeneity of seafloor sediments and bedforms may impact array layouts, design, and performance. Future research is needed to determine if arrays designed for maximum power output or other factors also satisfy geological limitations on foundation and anchor design. Of concern is the possibility of free drifting devices from failures of anchoring systems (e.g., due to unexpected dynamic loading to anchors), which then may affect neighbouring devices.

The assessment of anchoring and foundation systems will include determining environmental impact during the lifetime of the project. Installation operations have been identified as a potential source of noise, which could have negative environmental impacts [30], particularly noise during the installation of large piles (e.g., [31]). Monitoring and assessment of impact is not a trivial issue, particularly when background noise levels are significant and thus make noise source identification difficult [32]. The presence of the mooring or foundation system may be a migratory barrier or collision risk to marine species, but also provide habitat [33]. MRE arrays, such as tidal-stream turbines, may impact water level, tidal currents, sediment transport, and bacteria levels at great distances (e.g., in the tens of kilometres, see [1]). Further research is required to determine potential environmental impacts of anchors and foundations in this new application.

2.2 Relevant Literature for Sediment-Foundation Interactions

Detailed guidelines, best practices, handbooks, and textbooks exist for the general design, installation, and maintenance of offshore structures and associated foundations and anchors, including regional and site specific surveys and laboratory testing [28, 34, 35]. Much of this information is highly relevant for arrays of MRE devices, although the information is not directly targeted at array design. MRE-specific guidance is rapidly developing (e.g., see [36, 37]). Recent work highlights MRE-specific concerns. Barrie and Conway [29] present seabed characterization results for potential tidal, wave, and wind-energy MRE resources for the Pacific offshore of Canada. Their results indicate that subaqueous dune fields, mobile gravel lag, and boulder pavements, a result of a combination of climatic and eustatic sea level change and tectonic processes, can greatly impact local site development for MRE. Geological environments thus control geotechnical properties of seafloor materials, and foundation or anchor types are appropriate for certain sediment or rock types (see Section 5 for more detail; also see [28] for a summary of foundation-anchor types and performance for marine sediment types). Recent work investigating the effect of tidal- or current-turbine MRE systems on sediment transport indicates turbines can alter flow patterns and lead to local scour around seafloor structures [38], and sediment transport can be affected far (i.e., 15 km) from turbine arrays [1]. Altered patterns of flow within an array may lead to different loads on foundations and/or anchors that are placed at the margins or within an array of MRE devices. Thus, loading may be in part a function of the location of a foundation or anchor in a full-scale array of many devices. Foundation and anchor design may therefore need to address array size, impacts on local loads within an array, and the potential for cascading failure caused by an initial single failure within an array, and impact due to the location where a failure of a single device first occurs. The wind power industry may offer analogous examples of how to cope with different loads and foundation response due to placement of a device within a large array.

Literature on cyclic behaviour on marine sediment interaction with foundations and anchors is extremely important, as MRE systems will transmit cyclic loads (see Section 4 for information on MRE loading cases). Le et al. [39] study offshore wind farms and cyclic loading and failure of a marine clay with laboratory cyclic triaxial and shear testing, as a function of the total number of cycles and the average shear stress. A variety of cyclic-loading related studies, not specifically for tidal, current, or wave MRE, are still relevant and provide important background information for future work [3, 40-44]. The cyclic studies indicate potential failure processes due to strength and stiffness degradation, as a function of the magnitude and total number of the cyclic loads; a variety of laboratory and *in-situ* testing attempts to capture sediment response through initial, reloading, and unloading cycles. The constitutive behaviour of the sediments is key to performance of offshore support structures under cyclic loading [3]. Cyclic constitutive behaviour is thus discussed in detail with examples in Section 5, which address tools and inputs for quantitative analysis of foundations and anchors for MRE. Pertaining to MRE arrays of devices, excess pore pressure near to the foundation or anchor of a single device may possibly interact with adjacent foundations or anchors, depending on sediment permeability, anchor spacing, and the magnitude of the of excess pore pressure. (For more detail on excess pore pressure, see Section 4.)

3. SEAFLOOR GEOLOGY AND MATERIAL PROPERTIES

3.1 Seafloor Geologic Environments and Materials

In the DTOcean project, the primary seafloor geologic environments for MRE arrays are those of the continental shelves, for water depths of approximately 0–200 m. These include relatively high-energy tidal and ocean current environments of nearshore regions and the open shelf, as defined in the DTOcean deliverable *D1.1: Detailed deployment scenarios for wave and tidal energy converters* [45]. Relatively lower-energy, weak wave action, sediment-choked nearshore environments are excluded, such as lagoons, tidal flats, and deltas.

A continental shelf is the portion of the seafloor immediately adjacent to the continent, which slopes seaward at an average value of ~1° [46]. Its boundary is defined by an increase in slope to ~4°, which divides it from the deeper seafloor regions of the continental slope, the continental rise, and the abyssal plain. Continental shelves vary in width depending on whether the margins of the continents are passive or active in terms of plate tectonics. The width of continental shelves average only a few kilometres at the Pacific coast of North and South America, and are greater than 1000 km in the Arctic Ocean [46]. Topography of continental shelves range from smooth to irregular, depending on tectonic history, sediment transport and deposition, and sea level change over geologic timescales [29, 46, 47].

The relevant environments are typically dominated by terrigenous sediments [28, 48], which are derived by erosion of the adjacent continents. Typical composition of these sediments includes quartz, feldspar, and clay minerals. Sediment grain size can vary greatly (i.e., clay-sized at <4 μm to silt, sand, and up to boulder), depending on the sediment source and particular marine environment. The seafloor may also include pre-existing sediment or rock formations onto which the ocean may transgressed (due to changes in sea level over geologic time), or volcanic rock associated with islands or seamounts. Biogenous (i.e., derived from carbonate or siliceous hard parts of marine organisms) and hydrogenous (i.e., precipitated chemically from seawater) sediments [48] will probably be a minor component of seafloor materials for the desired environments for MRE; the deep, open ocean away from the continental margins is typically dominated by siliceous and carbonate biogenous sediments (see [48] for further information).

The distribution of sediments of different grain sizes and their style of layering or internal structure depends on the sediment source, transport, and depositional processes. The tidal-, wave-, and/or storm-dominated nearshore and open shelf environments exhibit a great range of sediment types, bedforms (e.g., subaqueous dunes), and heterogeneity [47, 49]. The marine geology thus plays a major role in controlling the distinct material geotechnical engineering properties of the sediments. Since certain foundation and anchors perform better in some sediments or rock types than others, knowledge of the marine geological environment and sediment distribution is key (Section 5 introduces the explicit constitutive relationships between seafloor materials and foundation and anchor performance).

Site surveys for geological and geotechnical properties for MRE systems include gathering information from previous studies, the so-called “Desk Top Study” and site-specific investigations. The Marine Geotechnical Engineering Handbook [28] lists several sources on seafloor material properties, including universities and government organizations (mainly in the U.S.), journal, and conference proceedings. The handbook also gives details on several types of recommended regional to site-specific surveys that apply to foundations and anchor types that can be used for MRE. The EU-funded MESH (Mapping European Seabed Habitats) project has been collating a large amount of mapping data (some of it dating back as far as 1870), which document seabed habitats and landscapes. An example of the mapping data is shown in Figure 2.

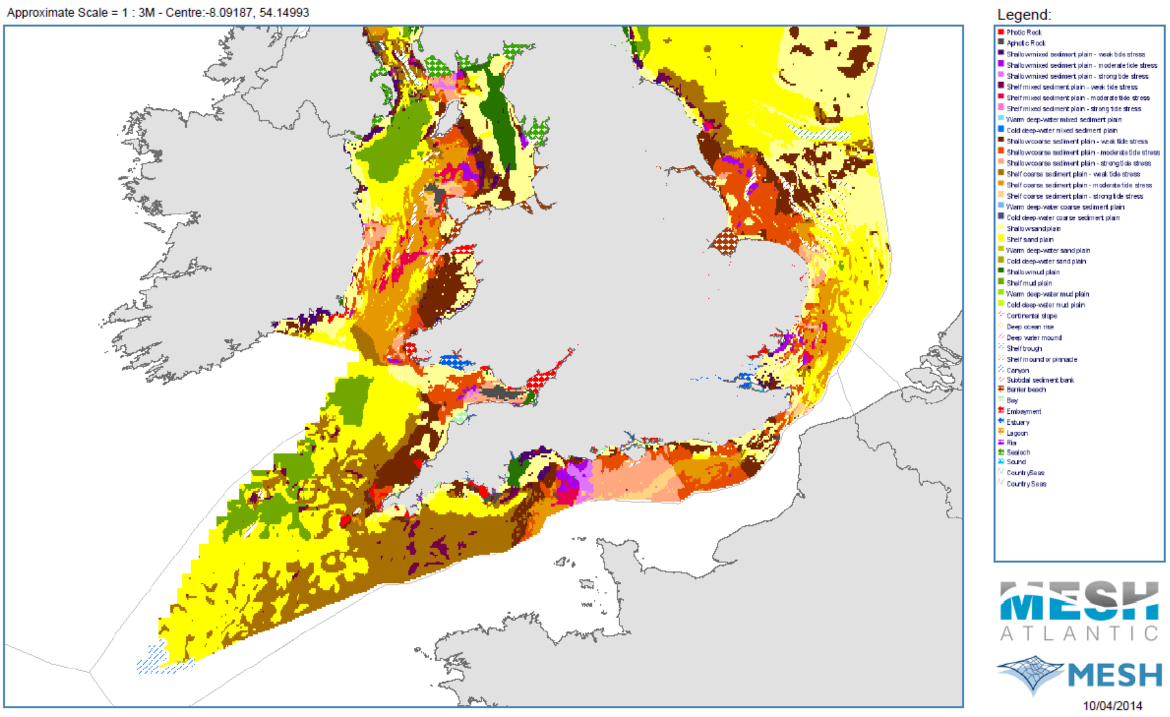

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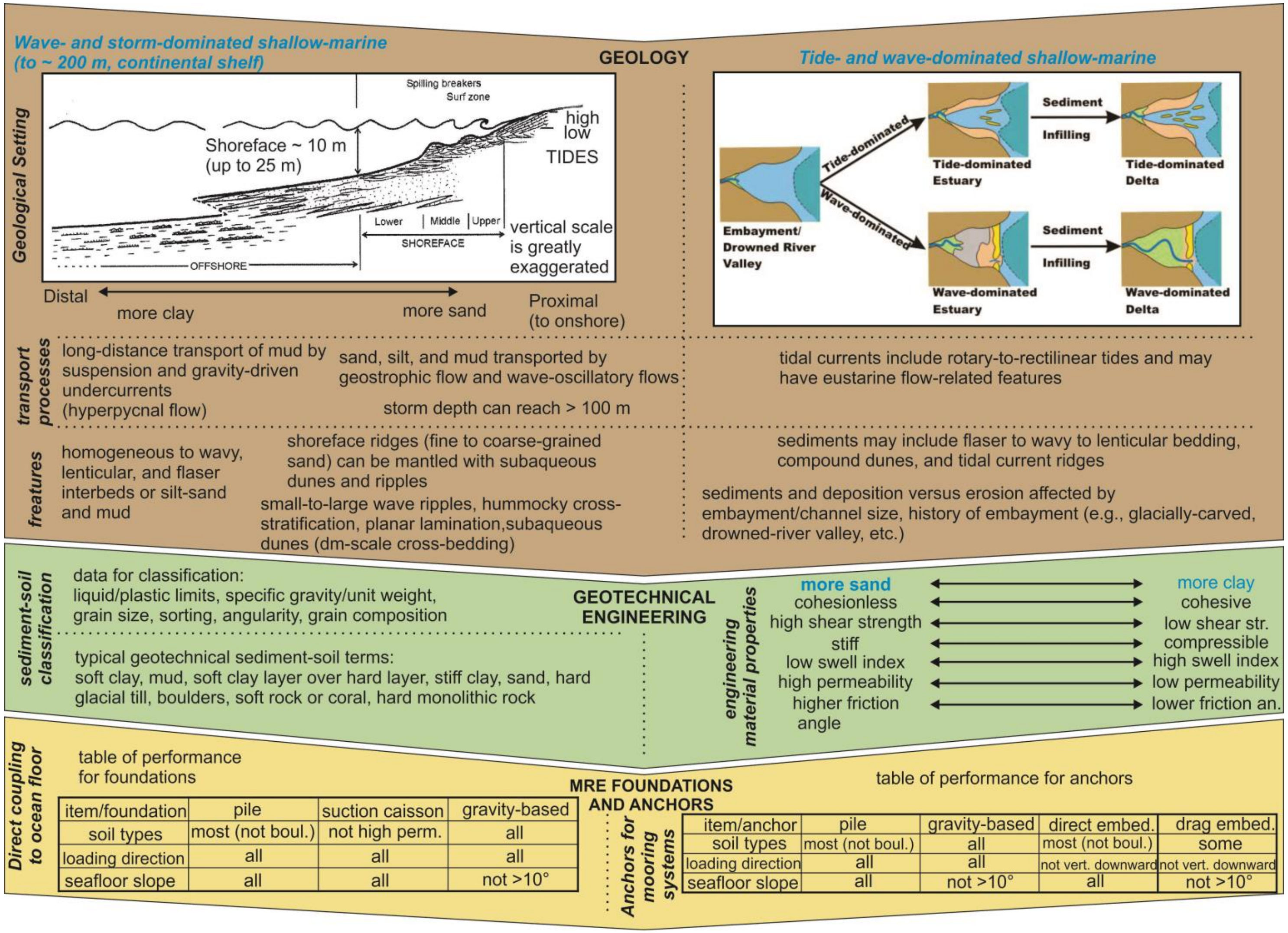
Figure 2. Example of a seabed landscape map of the seas around the southern UK.

Regional surveys can include acoustic reconnaissance for seafloor bathymetry and subbottom layering (e.g., sidescan sonar), limited seafloor material sampling (e.g., grab or dredge samplers, gravity corers, and vibracorers), and direct visual observation (e.g., underwater video camera; see for more detail [28, 29] on such data collection techniques). Site-specific surveys can include additional geophysical data collection at close survey line sampling for higher resolution seafloor and subbottom profiling. Sampling for laboratory testing should include relatively undisturbed samples for certain geotechnical tests (e.g., triaxial testing) that depend on original sediment structure. *In-situ* cone penetrometer, dynamic penetrometer, pressuremeter (based on expansion of an *in-situ* membrane within a borehole), and vane shear tests are also recommended for strength testing and sediment or soil classification (see the Marine Geotechnical Handbook [28], Chapter 2). Geophysical borehole logging techniques are also available, the techniques of which can characterize geological (e.g., layering), mechanical, and flow properties, but at relatively higher cost. It may be possible for site planners to use existing data to minimize costs. There are some open source data available on the seafloor landscape (e.g., such as the MESH project). Within the oil and gas arena, data from surveys are considered to be valid for certain time windows [50]; it could therefore follow that any previous survey data could be used when deciding what surveys need to be conducted. The full suite of sampling may be dictated by risks of failure (e.g., due to specific sediment and foundation/anchor types, such as anchor pullout versus foundation overturning), the specific geological environment, and regulatory requirements.

The UK has not produced any legislation regarding the regulation of surveying the seabed. There are some non-mandatory guidelines available when using seismic equipment [51], produced by the Joint Nature Conservation Committee (JNCC), which is part of the Department of Environment, Food and Rural Affairs (DEFRA). The use of Marine Mammal Observers are recommended and is also mentioned in the 2007 Code of Practice for the Protection of Marine Mammals during Acoustic Seafloor Surveys in Irish Waters [52]. A requirement of the Food and Environmental Protection Act is that surveys have to be carried out to determine levels of scour around wind turbine foundations and cables, as well as sediment contamination, sediment suspension, and impacts due to marine life [53]. This may also therefore be necessary for MRE devices and arrays.

3.2 Seafloor Geotechnical Parameters

Figure 3 presents a qualitative summary diagram on the progression from marine geological environment, to sediment type, to geotechnical engineering properties, and finally to foundation and anchor selection and performance. Prediction of foundation and anchor performance, in general, requires knowledge of sediment type and geotechnical or so-called engineering properties. Figure 3 summarizes sediment type data, including Atterberg limits, grain size, and texture (e.g., sorting and angularity); engineering properties include metrics for the degree of cohesion, shear strength (under drained or undrained conditions for sands or lower



item/foundation	pile	suction caisson	gravity-based
soil types	most (not boul.)	not high perm.	all
loading direction	all	all	all
seafloor slope	all	all	not >10°

item/anchor	pile	gravity-based	direct embed.	drag embed.
soil types	most (not boul.)	all	most (not boul.)	some
loading direction	all	all	not vert. downward	not vert. downward
seafloor slope	all	not >10°	all	not >10°

Figure 3. Schematic of the influence of geological and geotechnical properties of seafloor materials and performance of MRE foundations and anchors. Upper left image is adapted from [47]. Upper right image is from [49].

permeability materials), stiffness, swell index, and friction angle, all of which are affected by the amount of sand versus clay. The bottom portion of Figure 3 presents information on the relative physical performance of different foundations or anchors, given a sediment type (based on information from [28]). See the Handbook for Marine Geotechnical Engineering [28] for detailed descriptions of these parameters and their use in general foundation and anchor design. In Section 5, we present further information on more sophisticated numerical modelling analyses and associated parameterization of constitutive models from laboratory or field testing, which includes cyclic triaxial testing, and cyclic shear testing, centrifuge, and other testing. Section 5 also includes a flow chart for foundation and anchor design and assessing seafloor sediment response, which uses information from the major sections of Figure 3.

4. INTERACTIONS BETWEEN MRE SYSTEMS AND SEAFLOOR MATERIALS

Specific performance requirements for MRE foundations and anchors arise from the loads applied to and the response of the seafloor materials. Of particular interest is the long-term “fair weather” cyclic loading with less frequent higher magnitude loading due to storm conditions, rogue waves, or highly dynamic device motions. MRE systems are novel and thus previous foundation and anchor designs from other applications may not have considered the specific MRE loading cases for single devices to large-scale arrays with possible multiple devices connected to shared foundation or anchor points. Previous work has considered some interactions from the wake of arrays of tidal turbines for determining spacing and power, but not any impacts on foundations or anchors (e.g., see [25]).

Seelig [54] describes the following three categories of cyclic loading for direct-embedment anchors [54]:

1) cyclic line loadings and subsequent loss in strength of seafloor sediment immediately surrounding the anchor;

2) cyclic line loadings that cause accumulated movement or creep of anchors into shallower sediments, resulting in loss of short-term static holding capacity; and
3) earthquake-induced loading that causes loss in sediment strength and anchor failure.

In general, the impact on sediment strength due to cyclic loading is dependent on the time-scale of pore fluid flow in the sediments and the dissipation of excess pore pressure. If pore water drainage cannot occur quickly enough under the cycles of loading, the undrained shear strength will control sediment failure. Stiffness and strength degradation can also occur as deformation accumulates due to repeated loading and unloading [3, 40]. Interaction of excess pore pressure between devices in an MRE array may be a possible concern, which will depend on device spacing, the magnitude of excess pore pressure, and sediment permeability. Seelig [54] describes loss in strength due to anchor creep as dependent on sediment type, state, and the type of cyclic loading. Another major concern for cyclic loading in general is liquefaction or the condition of excess pore pressure under which sediments lose strength and behave like a liquid [3, 40, 55], which may need to be considered during foundation or anchor emplacement and during cyclic loading without sufficient dissipation of excess pore pressure in relatively low permeability sediments. Sediment characteristics that mitigate cyclic-induced strength loss include [54]:

- denser sediment (i.e., relatively higher unit weight);
- higher yield strength and strain-hardening behaviour;
- lower magnitude of cyclic loading; and
- lower frequency of total load cycles over the device lifetime.

Possible loading cases for floating and fixed MRE devices are given in Table 2, including information for devices tethered or attached to single or multiple foundation

		Wave Energy Arrays		**Tidal Stream Arrays**	
		Fixed	**Floating**	**Fixed**	**Floating**
	Example Device	*Oyster*	*Pelamis*	*AR-1000*	*SR250kW*
Frequent	Turbine rotation and blade passing frequencies			✓	✓
	Power Take-off and gearbox harmonics	✓	✓	✓	✓
	Wave / Tidal loading	✓	✓	✓	✓
	Wind loading	✓	✓	✓*	✓*
	Ice loading (location dependent)	✓	✓	✓	✓
	Anchor line pick-up and drop		✓		✓
	Irregular loading at shared connection points / foundations / anchors	✓	✓	✓	✓
Infrequent	Turbulence (eddies and surges)	✓	✓	✓	✓
	Steep waves / storms	✓	✓	✓*	✓*
	Tidal velocity extremes	✓	✓	✓	✓
	Wave slamming	✓	✓	✓*	✓*
	Seismic activity	✓		✓	
	Wind gusts	✓	✓	✓*	✓*
	Impact from vessels / marine life / ice flows	✓	✓	✓	✓
	Effect of anchor displacement and re-embedment (drag anchors only)		✓		✓
	Snatch loading at shared connection points		✓		✓
	Load and device response amplification due to hydrodynamic interactions between devices	✓	✓	✓	✓

Table 2. Possible loading cases for wave and tidal energy devices. Loads relevant for surface piercing structures or devices are indicated with an asterisk.

or anchor points. Based on expected peak cyclic loads and the total number of load cycles for the desired lifetime of the MRE devices, the capacity to withstand static and dynamic loading as well as liquefaction and creep movement should be carefully assessed with modelling tools (see Section 5). An example of loading during both calm and mild storm conditions was recorded by the South West Mooring Test Facility (Figure 4). These measurements were taken in the semi-sheltered Falmouth Bay, Cornwall, UK. The loads during the calm conditions show that each mooring limb experience gentle oscillations with no large spikes or anomalies. During the storm conditions, it can be seen that, in addition to the cyclic loads being significantly larger, there are also cases of much larger load spikes.

5. ANALYSIS OF MRE FOUNDATIONS AND ANCHORS

5.1 Design Process

Tools for the analysis of interactions between foundations, anchors, and seafloor materials need to be evaluated for their suitability for design, installation, estimation of maintenance timeframe, and full life-time performance assessment as a component of a MRE system. Design of foundation and anchors depends on seafloor material behaviour, and thus Figure 5 presents a flowchart that ties the geological setting of a proposed MRE site to required geotechnical parameters, seafloor foundation-anchor type, seafloor material analytical or numerical analysis, and ultimately installation.

The design of single foundations and anchors, taking into account seafloor material response, is an iterative process (see [28] for a general workflow, which is summarized here). The structural configuration of an MRE device and its loads affect the seafloor response. The geology of the site dictates the geotechnical engineering properties. Those properties are obtained through both review of previous studies and site-specific regional and local surveys and engineering judgement when data are not available [28]. Key controlling factors on seafloor response include the degree of cohesion, sediment texture (e.g., grain-size distribution, grain angularity,

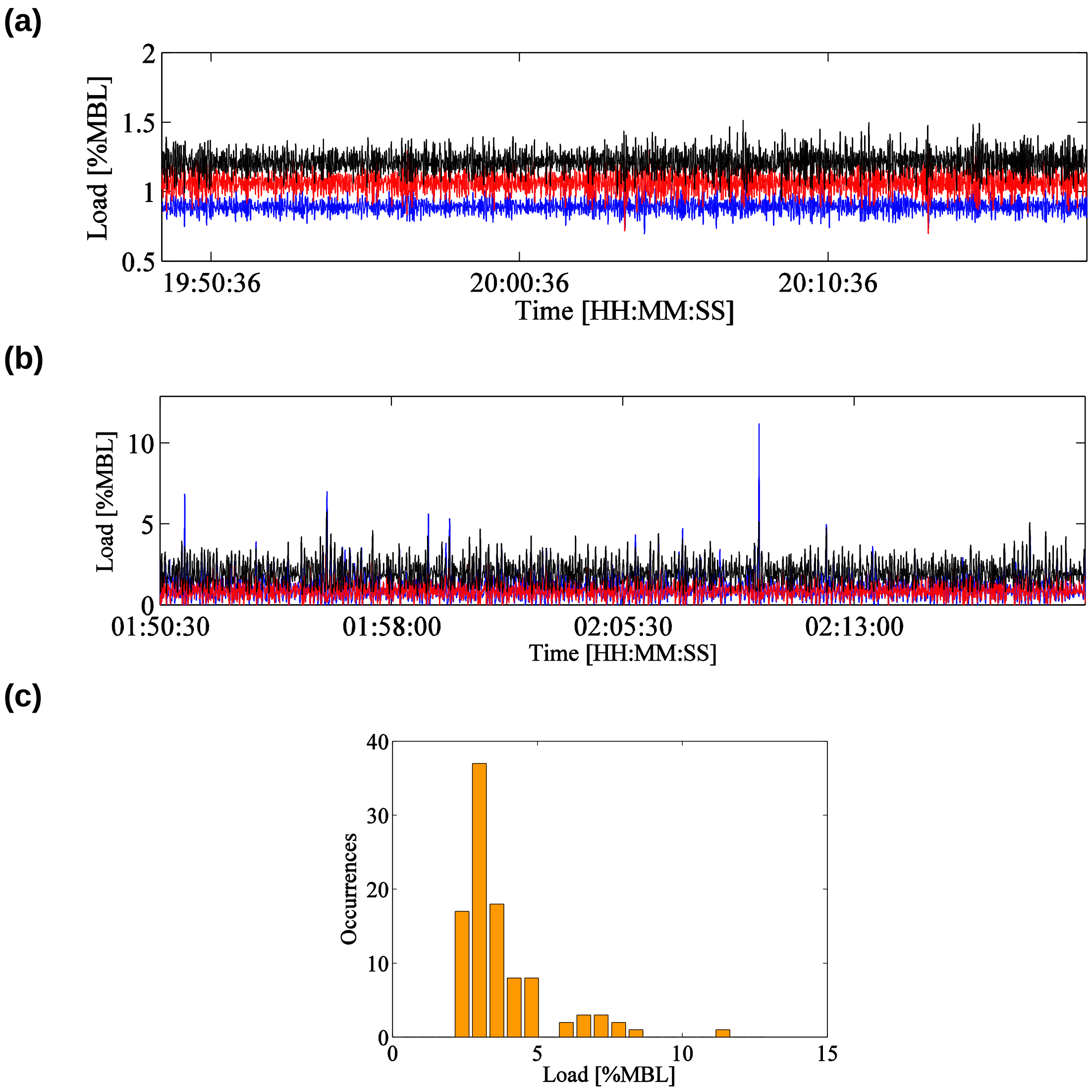


Figure 4. Tension time-series measured for the three mooring lines of the South West Mooring Test Facility (SWMTF) during a) calm and b) mild storm conditions in Falmouth Bay. c) Number of occurrences of significant axial mooring loads identified from tension measurements for all three lines recorded during the first deployment. Tensions are expressed in terms of the minimum break load specified by the rope manufacturer (MBL=466kN). Further details can be found in [56].

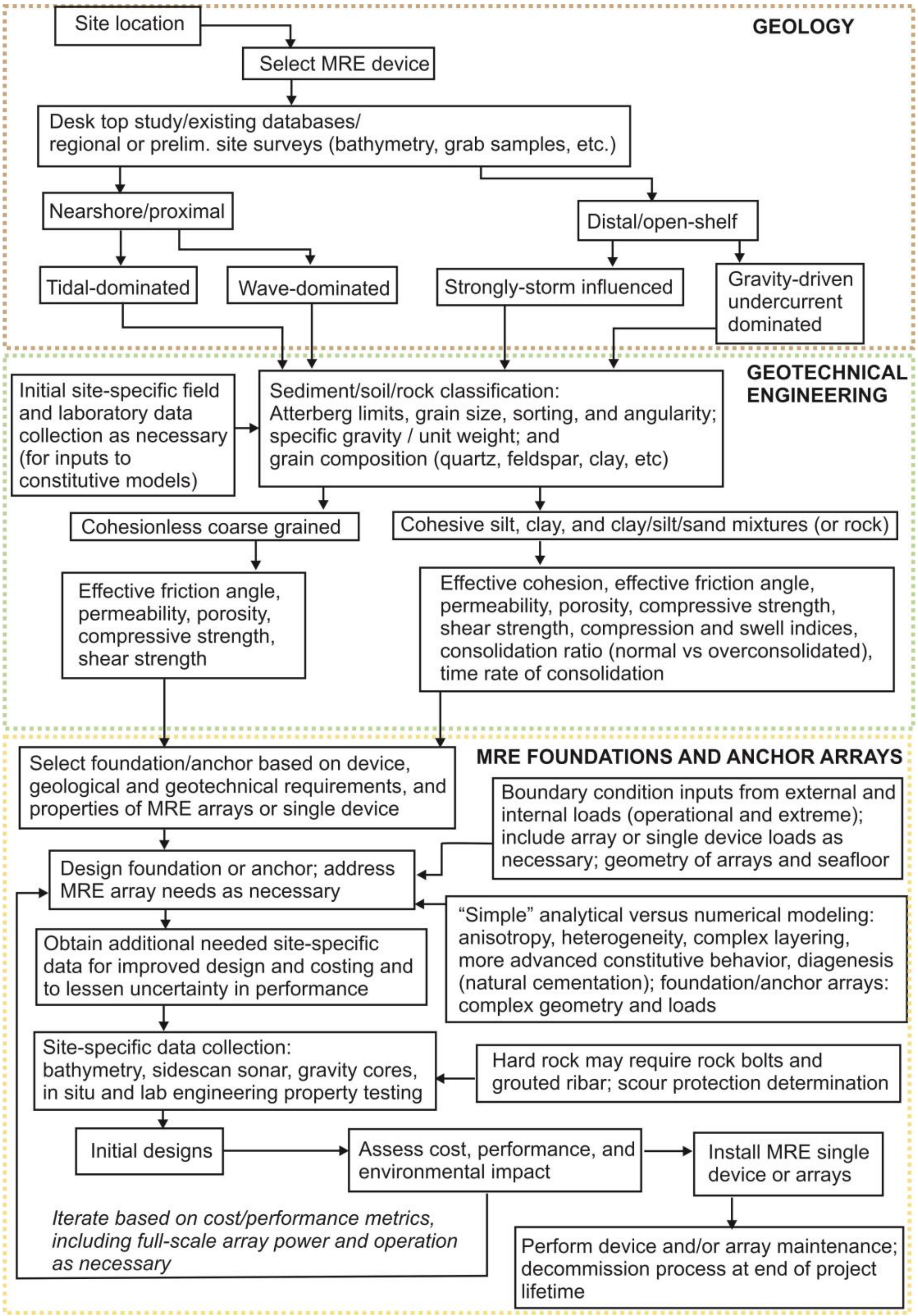
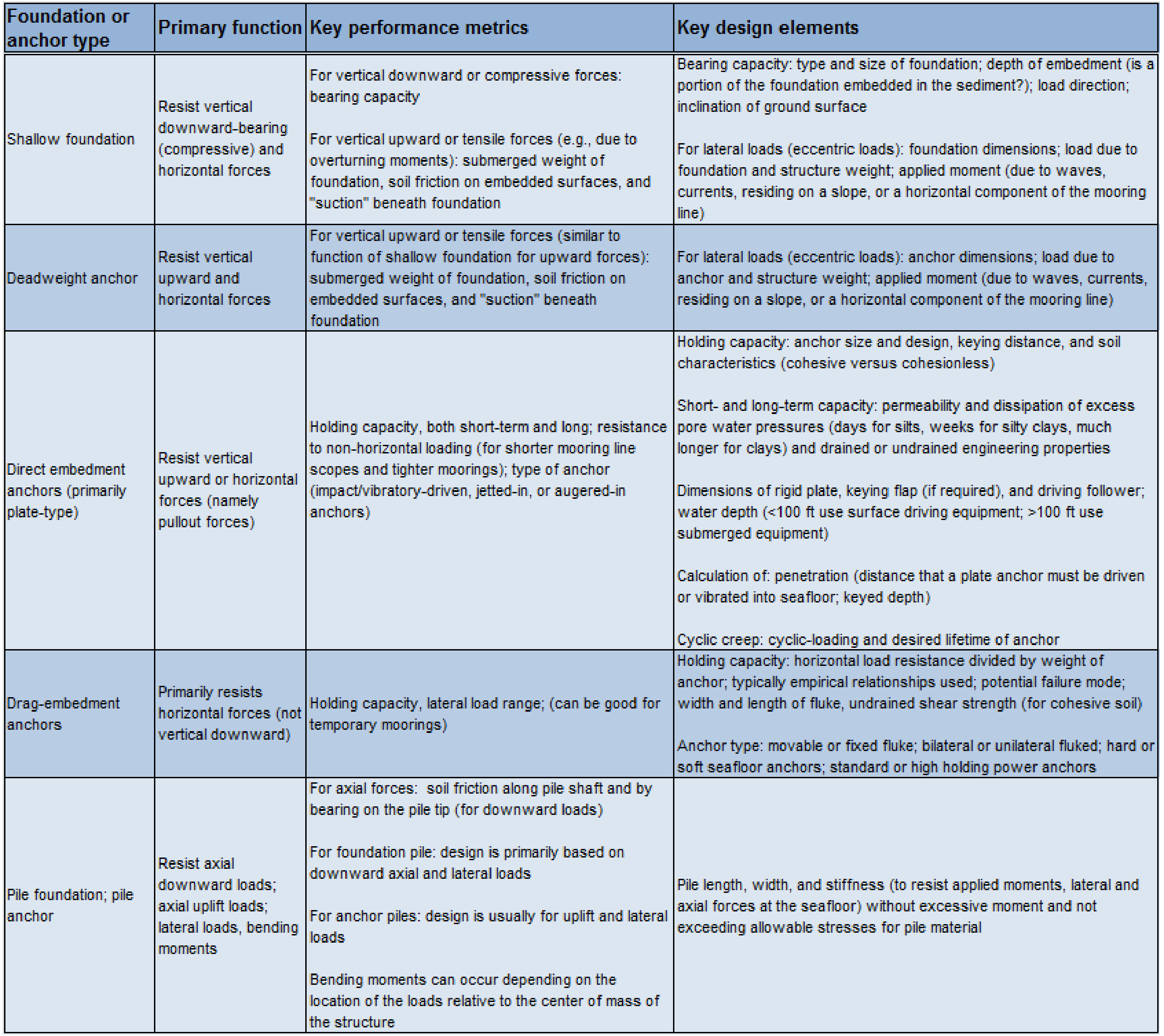


Figure 5. Flow chart for the selection, design, and installation of foundations and anchors, given geological and geotechnical properties.

and sorting), and strength parameters. Based on knowledge of the site and geological seafloor setting and materials, a preliminary foundation or anchor type is selected. This foundation or anchor must generally be commensurate with the designed function of the MRE device. Reasonable dimensions of key foundation/anchor components are first selected. The analysis for physical performance metrics then follows, including bearing capacity, resistance to horizontal or vertical forces (where applicable, see Table 3), holding capacity, predilection for creep movement of anchor, consolidation, and settlement. Several analytical solutions are available in the literature for the foundations and anchor types given in Table 3 (e.g., see Chapters 4-7 in the Handbook for Marine Geotechnical Engineering, [28]). At this point, the performance must be checked against desired function: will the performance be adequate or has the foundation/anchor been overdesigned; is the foundation/anchor too costly in terms of materials, installation, or maintenance? If so, it will be necessary to select more reasonable dimensions of the foundation/anchor and continue again through the subsequent steps. The design process will also need to include attention on potential interactions of devices in an array, such as: tethering of multiple devices in single anchors or foundations; excess pore pressure build-up due to overly closely spaced foundations or anchors; and potential cascading failure through an array started by failure of a single device (see Section 4).

Due to the complexity of the seafloor materials (e.g., layering or interbedding of sediment types like mixtures of sand and clay, spatial heterogeneity, and anisotropy of mechanical and hydrological properties) and MRE device and/or array loading cases (see Table 2), most performance assessment requires commensurate sophisticated analysis. Thus, numerical methods are warranted that can handle scenarios that are intractable for analytical methods, as discussed in Section 5.2.

Assessment of failure mode is part of the step that addresses adequate function design. Depending on the foundation/anchor type (and in addition to structural failure mechanisms), failure modes may include: bearing capacity failure (e.g., leading to rotation of the foundation), overturning (perhaps due to eccentric loads), uplifting,



Foundation or anchor type	Primary function	Key performance metrics	Key design elements
Shallow foundation	Resist vertical downward-bearing (compressive) and horizontal forces	For vertical downward or compressive forces: bearing capacity For vertical upward or tensile forces (e.g., due to overturning moments): submerged weight of foundation, soil friction on embedded surfaces, and "suction" beneath foundation	Bearing capacity: type and size of foundation; depth of embedment (is a portion of the foundation embedded in the sediment?); load direction; inclination of ground surface For lateral loads (eccentric loads): foundation dimensions; load due to foundation and structure weight; applied moment (due to waves, currents, residing on a slope, or a horizontal component of the mooring line)
Deadweight anchor	Resist vertical upward and horizontal forces	For vertical upward or tensile forces (similar to function of shallow foundation for upward forces): submerged weight of foundation, soil friction on embedded surfaces, and "suction" beneath foundation	For lateral loads (eccentric loads): anchor dimensions; load due to anchor and structure weight; applied moment (due to waves, currents, residing on a slope, or a horizontal component of the mooring line)
Direct embedment anchors (primarily plate-type)	Resist vertical upward or horizontal forces (namely pullout forces)	Holding capacity, both short-term and long; resistance to non-horizontal loading (for shorter mooring line scopes and tighter moorings); type of anchor (impact/vibratory-driven, jetted-in, or augered-in anchors)	Holding capacity: anchor size and design, keying distance, and soil characteristics (cohesive versus cohesionless) Short- and long-term capacity: permeability and dissipation of excess pore water pressures (days for silts, weeks for silty clays, much longer for clays) and drained or undrained engineering properties Dimensions of rigid plate, keying flap (if required), and driving follower; water depth (<100 ft use surface driving equipment; >100 ft use submerged equipment) Calculation of: penetration (distance that a plate anchor must be driven or vibrated into seafloor; keyed depth) Cyclic creep: cyclic-loading and desired lifetime of anchor
Drag-embedment anchors	Primarily resists horizontal forces (not vertical downward)	Holding capacity, lateral load range; (can be good for temporary moorings)	Holding capacity: horizontal load resistance divided by weight of anchor; typically empirical relationships used; potential failure mode; width and length of fluke, undrained shear strength (for cohesive soil) Anchor type: movable or fixed fluke; bilateral or unilateral fluked; hard or soft seafloor anchors; standard or high holding power anchors
Pile foundation; pile anchor	Resist axial downward loads; axial uplift loads; lateral loads, bending moments	For axial forces: soil friction along pile shaft and by bearing on the pile tip (for downward loads) For foundation pile: design is primarily based on downward axial and lateral loads For anchor piles: design is usually for uplift and lateral loads Bending moments can occur depending on the location of the loads relative to the center of mass of the structure	Pile length, width, and stiffness (to resist applied moments, lateral and axial forces at the seafloor) without excessive moment and not exceeding allowable stresses for pile material

Table 3. Relationship between foundation and anchor types and their primary function, performance metrics, and key design elements. The companion Table 4 further ties foundation and anchors to geological settings and engineering properties. Much information in this table is summarized from [28].

Seafloor material (Geology)	Geotech index properties	Geotech engineering props	Appropriate foundation or anchor type	Relative function	Relative installation costs	Motivation for numerical analysis
Soft clay, mud	Water content, unit weight, specific gravity, liquid limit, plastic limit, plasticity index, grain size	Undrained shear strength, sensitivity, soil cohesion, friction angle, compression index, coefficient of compressibility, permeability	Shallow foundation	good	low	differential consolidation, anisotropy
			Deadweight anchor	good	low	differential consolidation, anisotropy
			Direct embedment anchors (primarily plate-type)	good	intermediate	"soaking" process, sensitive sediments
			Drag-embedment anchors	good	intermediate	"soaking" process
			Pile foundation; pile anchor	ok	high	consolidation, large strains
Soft clay (0-6 m) over hard layer	Water content, unit weight, specific gravity, liquid limit, plastic limit, plasticity index, grain size	Undrained shear strength, sensitivity, soil cohesion, friction angle, compression index, coefficient of compressibility, permeability	Shallow foundation	good	low	heterogeneous consolidation
			Deadweight anchor	good	low	heterogeneous consolidation
			Pile foundation; pile anchor	good	high	heterogeneous consolidation
			Drag-embedment anchors	ok	intermediate	penetration into hard layer
Stiff clay	Water content, unit weight, specific gravity, liquid limit, plastic limit, plasticity index, grain size	Undrained shear strength, sensitivity, soil cohesion, friction angle, compression index, coefficient of compressibility, permeability	Shallow foundation	good	low	anisotr., low perm., excess pore press.
			Deadweight anchor	good	low	anisotr., low perm., excess pore press.
			Direct embedment anchors (primarily plate-type)	good	intermediate	anisotr., low perm., excess pore press.
			Pile foundation; pile anchor	good	high	anisotr., low perm., excess pore press.
			Drag-embedment anchors	good	intermediate	anisotr., low perm., excess pore press.
Sand	Water content, unit weight, specific gravity, grain size	Undrained shear strength, soil cohesion, friction angle, compression index, coefficient of compressibility, permeability	Shallow foundation	good	low	bedforms and overturning
			Deadweight anchor	good	low	bedforms and overturning
			Direct embedment anchors (primarily plate-type)	good	intermediate	bedforms and penetration
			Pile foundation; pile anchor	good	high	vibration and liquefaction
			Drag-embedment anchors	good	low	bedforms and penetration
Hard glacial till	Water content, unit weight, specific gravity, liquid limit, plastic limit, plasticity index, grain size	Undrained shear strength, sensitivity, soil cohesion, friction angle, compression index, coefficient of compressibility, permeability	Shallow foundation	good	low	extremely heterogeneous
			Deadweight anchor	good	low	extremely heterogeneous
			Direct embedment anchors (primarily plate-type)	good	intermediate	extremely heterogeneous
			Pile foundation; pile anchor	good	high	extremely heterogeneous
			Drag-embedment anchors	ok	low	deflection of anchor and poor embed.
Boulders	Water content, unit weight, specific gravity, porosity	Boulder-size distribution; nature of packing or pavement	Shallow foundation	good	low	stability and topography
			Deadweight anchor	good	low	stability and topography
Soft rock or coral	Water content, unit weight, specific gravity, porosity	Unconfined compressive strength, tensile strength, Poisson's ratio, bulk modulus, residual shear strength, friction angle	Shallow foundation	good	low	pre-existing fractures/weaknesses
			Deadweight anchor	good	low	pre-existing fractures/weaknesses
			Direct embedment anchors (primarily plate-type)	good	high	pre-existing fractures/weaknesses
			Pile foundation; pile anchor	good	high	pre-existing fractures/weaknesses
Hard, monolithic rock	Water content, unit weight, specific gravity, porosity	Unconfined compressive strength, tensile strength, Poisson's ratio, bulk modulus, residual shear strength, friction angle	Shallow foundation	good	low	pre-existing fractures/weaknesses
			Deadweight anchor	good	low	pre-existing fractures/weaknesses
			Direct embedment anchors (primarily plate-type)	ok	high	strength and damage during installation
			Pile foundation; pile anchor	ok	high	strength and damage during installation

Table 4. Relationship between geologic setting and seafloor material properties to foundation type and motivation for numerical analysis. See Table 3 for further details on foundation and anchor types. Much information in this table is summarized from [28].

pullout, horizontal sliding or combinations of these; slow foundation displacements (excessive consolidation settlement) including non-uniform displacement; installation problems; and recovery problems with high resistance to breakout; and finally scour and undermining (see [28] for further discussion, which has been summarized here).

The companion Tables 3 and 4 are capstone tables of this report. They show the relationships between many key factors in the design of MRE foundations and anchors, including: the geologic setting, geotechnical engineering, the relative function (or preferred foundation or anchor type given a particular seafloor material, where "good" means it functions well, "ok" is typically not preferred, and no listing for a particular foundation/anchor means poor performance), relative costs for installation, and motivating factors for sophisticated numerical modelling.

5.2 Applicable Tools and Inputs

Analytical solutions and empirical equations for general foundation and anchor design are presented in the literature (see [28, 34]); however, the unique loading cases and long lifetimes of MRE systems may necessitate sophisticated analyses that relax many of the strict assumptions of the analytical solutions and provide predictive results that empirical equations cannot. If a particular design has unique features or is one that is judged close to some failure limit from a performance perspective, numerical modelling may elucidate additional details of its performance permitting a detailed assessment of its adequacy for the intended purpose instead of only relying on the application of a larger factor of safety. Furthermore, numerical analysis may also facilitate deeper understanding of foundation-anchor behaviour where greater understanding is sought, not just for design, but also for the foundation's performance relative to other pieces of the overall system (e.g., changes in stiffness to the overall system as a result of the response of the foundation). Numerical analysis an important method to address behaviour of the nonlinear coupled nature of fluid saturated porous media.

Numerical analysis methods may be needed that can address:

- transversely isotropic (e.g., properties are uniform in horizontal directions but different in the vertical direction) or fully anisotropic (e.g., properties vary with direction) mechanical and fluid flow properties;
- coupled fluid flow, excess (relative to hydrostatic) pore pressure increase and dissipation, and sediment deformation;
- complex geometries for the interfaces between seafloor materials and foundation and anchors;
- simultaneous mechanical and flow modelling of the seafloor material response and the entire foundation or anchor itself;
- appropriate constitutive (or material) models that capture the range of stress-strain, yield, and failure behaviour of the relevant seafloor materials, including dynamic, large strains, non-linear, plastic deformation, and cyclic degradation of strength and stiffness;
- failure planes, disaggregation, or liquefaction;
- complex time-series for boundary conditions, which capture cyclic loading and loads changing direction, possibly due to multiple tethering to single anchors;
- aging effects due to “soaking” or re-consolidation of sediments surrounding a drag embedment anchor after placement (see [28]);
- spatially heterogeneous mechanical and fluid flow properties, including the ability to input geostatistical realizations of property fields; and
- large-scale simulations for evaluation of entire arrays in realistic tidal channels or other heterogeneous environments to determine, for example, whether pre-designed regular rectangular MRE device array spacing conflicts with heterogeneity of seafloor sediments.

Commercially-available numerical modelling software has been used successfully for over 30 years in offshore geotechnical engineering of foundations and other related applications (e.g., for discussion of the historic use of Abaqus finite element analysis (FEA) on consolidation, gravity-based structures, driven piles, suction piles, and other applications, see [57]; for an example of modelling of cone penetrometer testing, see [58]). A variety of commercial codes applicable to marine geotechnical engineering are available (e.g., Abaqus, Plaxis, COMSOL, ANSYS, etc.); however, code comparison and validation has not yet been performed to determine the relative suitably of the codes for the MRE single device or array design. Commercial codes can offer a vast arsenal of material constitutive relations or models that can range from elastic, hypo- to hyper-elastic, viscoelastic, to a variety of plastic behaviour. Commercial codes also typically have an Applications Program Interface (API), which allows a user-defined constitutive model to be incorporated into the code. The API typically has access to the entire variety of solver options available in the code, so that the user can thereby incorporate whatever phenomena is deemed appropriate in the user-defined constitutive model. This capability is extremely useful when the user does not want to be limited to the constitutive models built into the code. Commercial codes can also incorporate separate constitutive models for the device itself and the surrounding sediment (e.g., see [59] for an Abaqus FEA study using linear elastic behaviour of a suction bucket foundation and elastoplastic behaviour of the sediment). The literature has examples of incorporating sophisticated generalized plasticity models into commercial codes for modelling cyclic forces and complex interactions between offshore structures and marine sediment, including non-linear behaviour with cyclic-loading-induced strength and stiffness degradation [42].

When using numerical methods to model offshore structure/seafloor interactions, the constitutive relations (or models) of marine sediment response are of prime importance—even more so than the particular modelling software used, as poor results will be obtained if an inappropriate constitutive model is used, regardless of the modelling code. To constrain the summary of information from the literature, we focus mainly on constitutive models that can accommodate MRE-related phenomena, including the following: cyclic loading and associated changes in material properties, large-strain (e.g., for structure embedment or in situ cone penetration testing), liquefaction, and/or layered sediments, and/or cohesive and cohesionless sediments (Table 5). Sophisticated numerical analysis, at the

Constitutive models	Material	Features	Comments on cyclic loading	Ref. example(s)
Bounding surface plasticity model by Hu et al. (see [42])	Marine clay, over to underconsolidated	Bounding surface models (isotropic and kinematic hardening rules; applied in ABAQUS (see [41])	Captures cyclic behaviors: cyclic shakedown and strength degradation; initial anisotropy; 8 material property parameters, obtainable from lab tests	[41, 42]
BWGG	Cohesive soil	1D, static/dynamic response; reproduces complex non-linear behaviors: cyclic mobility; liquefaction; stress-strain loops; pore-water pressure buildup; example not found for modern MRE systems	Reproduces stiffness and strength degrading behavior due to cyclic loading; may require in situ or lab cyclic triaxial and cyclic simple shear tests for parameterization; 3 parameters to capture experimental modulus decline and damping growth versus shear strain curve	[40]
Disturbed-state concept (DSC)	Saturated cohesive (clay-bearing) soils	Inelastic response during loading (virgin) and unloading-reloading (non-virgin) behavior; drained and undrained behavior and pore water pressure	Accommodates cyclic loading; 15 parameters, (intact state, critical state, disturbance parameters, nonvirgin parameters); parameterization may include cyclic cylindrical triaxial and truly triaxial devices	[43]
Drucker-Prager	Sand, clay	Plastic deformation; cone penetration examples include von Mises yield criterion with associated flow rule; implemented in ABAQUS; large displacement	Our literature search has not yet found direct examples for cyclic loading; cone penetration examples are relevant	[60, 61]
Elastoplastic	Soft cohesive marine soils	Literature includes von Mises plastic or Tresca yield criterion for marine applications; can incorporate depth dependent shear strength; solved with ABAQUS and Arbitrary Lagrangian-Eulerian	Can be applied to cyclic loading (see [59]); number of cycles very important on ultimate bearing capacity; some applications, e.g., cone penetration test, not applicable to cyclic loading and more for large-strain problems	[58, 59, 62, 63]
Elasto-viscoplastic based on Cam-Clay model	Clay/sand, layered material	Elasto-viscoplastic for normally consolidated clay, based on Cam-Clay model and the extension of an overstress-type viscoplasticity; previously used for earthquake applications; low to high level strain; IQCA-2D, effective stress-based liquefaction code	Obtains cyclic loading and possible liquefaction for sand/clay layering	[55]
Generalized plasticity framework	Sand (presented by [3])	Isotropic material response for granular soil behavior under monotonic and cyclic loading, non-linear elastic soil response; captures critical state condition, dilative response after peak, liquefaction in loose sands, memory of previous stress path, plastic modulus	Handles cyclic loadings and complex foundation-structure interaction; SandPZ suited for water-soil and water-structure and structure-soil interfaces; 13 material parameters requiring definition; need monotonic and cyclic triaxial tests in general	[3]

Table 5. Constitutive relations applicable to marine sediments.

minimum, may need these types of material models. Stickle et al. [3] strongly emphasize the need of an appropriate constitutive model to capture sediment or soil response for marine foundations or structures. They identify cyclic loading as the principle feature of an appropriate constitutive model. They state that classical plasticity models, such as Von Mises, Drucker-Prager [60, 61], and Cam-Clay, do not capture plastic deformation due to repetitive loading as the reloading-unloading cycles are placed within the yield surface interior and thus, elastic deformations are represented, but not plastic sediment or soil degradation with repetitive loading. The constitutive model should capture the non-associative plasticity of the geomaterials. Stickle et al. [3] list a variety of approaches to improve upon classical plasticity theory models, including the re-modified Cam-Clay model, isotropic-kinematic hardening plasticity models, bounding surface models, bubble models, and generalized plasticity models. They prefer generalized plasticity models because yield or potential surfaces are not explicitly defined, but rather gradients in those functions, and furthermore, because of the combination of simplicity and accuracy of these models. Table 5 presents several constitutive models of sediment response to loads from offshore structures, with literature sources for cyclic loading and large strain examples [3, 40-43, 55, 58-63].

The constitutive models require parameterization or material parameters to properly represent the sediment or rock response. This is a primary input for the numerical modelling, in addition to boundary conditions and geometrical considerations. Such parameterization typically requires data to be collected from *in-situ* field testing or, probably most commonly, from laboratory testing of sophisticated sediment response behaviour. The initial stress state may also be required. The number of parameters depends on the particular constitutive model (see Table 5, showing that some require 8 and as many as 15, for the examples given). For example, the Hu et al. [42] bounding surface plasticity model requires four parameters related to critical state soil mechanics and four for the hardening modulus. Table 6 summarizes a subset of the constitutive models of Table 5 that capture cyclic sediment response,

Example reference	Constitutive model	Constitutive model parameters[1]	Obtaining parameters
[42]	Bounding surface plasticity	8 parameters Critical state soil mechanics (λ, κ, M, G, or ν) Hardening modulus (γ, ζ_r, η, β)	Critical state parameters from in situ or lab tests; tests may include isotropic consolidation including critical state lines in extension and compression; monotonic element tests Hardening from trial and error modeling of lab results of undrained monotonic shearing and undrained cyclic triaxial tests; reloading and unloading cycles needed for ζ_r and η,
[40]	BWGG	Parameters for shear modulus and damping curves Shear modulus, undrained shear strength, parameters for hysteretic nonlinear response of sediment, and others (see reference as the parameters are not presented in the reference for ready enumeration here)[2]	Lab tests including cyclic triaxial and cyclic simple shear; reloading and unloading curves needed In situ tests including standard penetration (SPT) and the crosshole Centrifuge or shaking table sediment response
[43]	Disturbed-state concept	15 parameters two for elasticity (E, ν) five for δ_0 model (γ, β, n, h_1, h_2) two for critical state (m', λ), two for disturbance function (A, Z) four for non-virgin loading (K_1,K_2,β^{UL},β^{RL})	Lab testing includes loading-unloading-reloading; stress paths include conventional triaxial compression, reduced triaxial compression, and cyclic; shear tests include consolidated undrained with pore-water-pressure measurements; reference discusses cylindrical and cubical samples (for truly triaxial testing)
[3]	General plasticity framework	13 parameters Dimensionless parameters involving initial bulk modulus, initial mean effective stress, initial shear modulus, the exponent for non-linear elastic stiffness, fitting shape of stress path in undrained triaxial test, fitting for number of cycles in a series of loading-reloading, and others (see reference for full details)	Generally obtained from lab tests, including monotonic and cyclic triaxial tests

[1] See reference for definition of parameters, especially for those given here with symbols

[2] Note that full methodology for parameter identification not included in the reference for this constitutive model

Table 6. Constitutive models with information on parameters and in situ or laboratory testing.

with listing of the parameters needed and the types of laboratory or field testing required.

Geotechnical laboratory testing can be labor intensive, involving many samples and stress paths. Testing may involve the following (also see Table 6): cyclic simple shear and cyclic triaxial (or truly triaxial) with loading-unloading-reloading paths; reduced triaxial compression; measurement of pore-water-pressure; or centrifuge or shaking table sediment response measurements. A complete discussion of specific parameters and associated tests is beyond the scope of this report; we simply note that sophisticated numerical modelling may involve commensurate sophisticated laboratory or field testing. We also note that geological materials can be very spatially heterogeneous, depending on the geologic environment. A very involved (and potentially expensive) field sampling and laboratory testing plan may be required to capture heterogeneous properties necessary for numerical modelling that incorporates spatially varying properties.

Future research needs to determine what specific constitutive models are relevant for novel MRE systems, for the MRE cyclic and other loading cases (see Table 2), and what laboratory or field testing will give the required parameters. The peer-reviewed literature does not yet seem (as far as we can tell) to have a study on what constitutive models are most appropriate for sophisticated numerical modelling MRE analyses, which tackle the complex examples given in the bulleted list above.

Commercial numerical codes are mainly suited for running on desktop computers and/or typical engineering workstations. Simulations with commercial codes are by design limited to problem sizes on the order of hundreds of million degrees of freedom, or so. This allows for simulating the sediment and the structure. However, MRE studies may require very sophisticated simulations, such as those tackling some of the problems listed above, including: full spatial (and temporal) heterogeneity in fluid flow and mechanical properties; complex geometries of a variety of interfaces (e.g., device-sediment, device-seafloor); and full-scale, entire MRE device arrays of up to 1000s of devices. Only massively parallel architecture and software specifically designed for such architectures can handle such problems with complex heterogeneous multiphysics. These massively parallel systems may accommodate more degrees of freedom than can be handled by the commercial codes by several orders of magnitude. Systems such as these are generally only available at some governmental institutions and large companies in the oil and gas industry. Although commercial software may have certain specific coupling capabilities (e.g., Abaqus/Aqua capabilities in Abaqus/Standard to model wave, buoyancy, current and wind loading), full coupling of computational fluid dynamics of open ocean water interaction with mooring systems, the device operation, and the sediment-foundation/anchor interaction is probably beyond current computational abilities. Thus, loads for seafloor material-foundation/anchor interaction require boundary conditions from other sources, such as separate simulations by other methods for the loads or measurements from the field. While not ideal, this may be advantageous for the foundation and/or anchor designer in that it permits the focus to remain on the foundation and/or anchor analysis and design.

It needs to be emphasized that there are a number of numerical software solutions, both commercial codes as well as academic codes that can adequately model offshore sediments under a cyclic loading regime that would be applied as a result of the interaction between an MRE foundation or mooring. However, it is of the utmost importance that appropriate constitutive models be utilized in the numerical simulation.

5.3 Systems-level Decision Tool for MRE Arrays Design

The DTOcean project [6] is developing a system-level tool for MRE array design that will take input criteria about a site and devices and undertake analysis of several interlinked aspects of MRE array design, including the following: array layout, moorings and foundations, power systems, system control, and operation. The tool may include several submodules to analyse the numerous assessment criteria, including: reliability, economics, environmental impact, lifecycle logistics (including installation, operations, maintenance and decommissioning) as well as physical performance (e.g., power generation) of the particular type of array configuration.

This report supports the development of a foundation/anchor and sediment response submodule of Work Package 4 of the DTOcean project's future system-level tool on mooring and foundations by assembling information that may become part of the submodule. The submodule should probably include the major processes or phenomena detailed in the flow chart of Figure 5, from site selection, surveys, to analysis and design of foundations and anchors and predicting sediment response. Equations in the submodule will need to capture the relevant physics of single to full-scale arrays of multiple devices. Interactions of multiple devices may need to capture excess pore development, local loads due to location in an array, and varying seafloor material properties due to heterogeneity and time-dependent processes, and potential impacts of cascading failure for different anchor types (e.g., overturning of foundations versus pullout of anchors). As detailed in Sections 2 and 5, a variety of inputs and analytical or numerical techniques exist to design the foundations and anchors and predict physical performance. The system-level tool, however, will probably not be able to run numerical models directly due to long run times: response surfaces or reduced-order models will probably be necessary so that run times of the system-level tool will be reasonable (for an example of developing reduced order models for sensitivity and uncertainty analysis from the field of geologic CO_2 storage, see [64]). Rapid run times of the system-level tool could incorporate probability density functions of parameters and examination of system performance (e.g., physical or economic) and sensitivity to model inputs, thus determining what parameters have the greatest control on desired system-level behaviour.

6. CONCLUSIONS AND RECOMMENDATIONS

The hydrodynamic performance of MRE device arrays is probably easiest to optimize using regular spacing, which may not be commensurate with seafloor complexity. The marine geological environment can be very heterogeneous in terms of seafloor topography (e.g., due to bedforms), distribution of material mechanical and flow fluid properties of sediments, and sediment types. Thus, numerical analysis may be necessary to understand and predict foundation/anchor and sediment interactions and hence the performance of the MRE devices in an array configuration. The state of the art for geotechnical commercial codes for numerical analysis is able to incorporate sophisticated constitutive models (e.g., involving general plasticity models) of sediment response, even including stiffness and strength degradation due to cyclic loading. However, commercial codes, typically run on engineering workstation computers, do not have the degrees of freedom necessary to simulate full-scale MRE device arrays for 100s to 1000s of devices in heterogeneous geologic environments. Massively parallel architecture and software specifically designed for such architectures could handle full-scale simulation of foundation/anchor and sediment response for 1000s of MRE devices with heterogeneous multi-physics involving the geomechanics of the sediments, fluid flow, and the mechanics of the devices themselves. Future work for sophisticated analysis of MRE foundations, anchors, and sediment response thus requires sophisticated field and/or laboratory testing to parameterize constitutive models, and to possibly utilize massively parallel simulations if the behavior of full scale arrays in complex geologic environments, like tidal channels, is desired. Laboratory testing for cyclic sediment response needs to reflect the particular loading conditions of MRE systems, including possibly stochastic or spectral oscillations to represent realistic loading [3]. Massively parallel computers are not readily available; governmental institutions or large oil and gas companies, which have such capabilities, may need to get involved if such studies are deemed necessary. With this being said, much can be learned about the behavior of individual devices and seafloor response using commercial software or even analytical solutions with factors of safety used to account for performance and/or reliability uncertainties. The choice for using sophisticated numerical analysis may derive from the need to avoid strict assumptions of analytical solutions and to facilitate deeper understanding of the performance of full-scale MRE arrays.

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