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Anchor geotechnics for floating offshore wind: Current technologies and future innovations

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ABSTRACT

A rapid expansion of the anchor market is required to meet the increasing demand for floating offshore wind. This paper, which is aimed at a broad readership within and beyond geotechnical engineering, summarises the current state-of-the-art and discusses future developments of anchor types and geotechnical design methods.

Current anchor technologies are presented via comparative analytical assessments of performance across a range of practical scales and seabed conditions. This analysis demonstrates the relative merits and performance of different anchor types, using simplified cost-performance indicators for each anchor technology. An example outcome is the large differences in anchor efficiency (capacity per unit weight), that are linked to the different ways anchors achieve their holding capacity.

Potential improvements in the performance-cost response for each anchor type, through future enhancements, are then explored. These enhancements are categorised as (1) *unlocking* higher anchor performance through improved design methods with a better understanding of the geotechnical response, (2) *upscaling* or (3) *commoditising* of the anchor type, by making larger versions or enabling more efficient mass production and installation, or (4) *invention* of new anchor technologies. Finally, findings of the different sections are summarised within a single table to enable a quick selection of anchoring solutions.

1. Introduction

1.1. Decarbonisation, energy security and offshore renewable energy

The global growth of floating offshore wind is creating a huge new market for anchoring of floating structures. By the end of this decade, the number of floating wind turbines will far outstrip, by at least an order of magnitude, the number of installations to date for oil and gas facilities, (Gourvenec et al., 2022; GWEC, 2022; IRENA and GWEC, 2021). Three global imperatives are currently driving a growth in the expected offshore renewable energy (ORE) capacity to be installed in the next few decades: (i) increasing demand for energy due to growing global population with increasing wealth, (ii) decarbonisation of the economy to mitigate the climate emergency and (iii) increasing need for energy security by increasing local energy production, to reduce reliance on global supply chains that are vulnerable to geopolitical events.

A primary action to alleviate future climate change is to reduce the reliance on fossil fuels for energy production through the adoption of renewable energy sources (IPCC, 2021; UNFCCC, 2021). The Global Offshore Wind Energy Compact (IRENA and GWEC, 2021) proposes a global ambition of 380 GW of offshore wind by 2030 and 2000 GW by 2050 to meet the aims of the Paris Agreement. To meet these global targets will require installation of 80 GW of offshore wind annually to 2030 and 70 GW per year thereafter to 2050, compared to a current maximum of ≈20 GW installed in 2021, 3 times the capacity installed the previous year.

In this study, the UK is adopted as a illustrative example of offshore wind growth. It had the greatest installed offshore wind capacity globally until the end of 2021, when overtaken by China. In the UK, the operational capacity increased by an average of 1.2 GW/year over the 5 years 2017–2021, to a total of 11.3 GW (Coles et al., 2021), as shown on Fig. 1. However, to meet the UK's 2030 target of 50 GW requires a growth rate of 4.3 GW/year. The UK's Sixth Carbon Budget (The Climate Change Committee, 2020) predicts that 65–140 GW of offshore wind

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(OW) capacity will be required to meet net zero by 2050, with variations depending on societal and innovation effects. However, if the projected growth of the domestic (UK) hydrogen economy is included, with production via electrolysis from OW, this range grows to 110–226 GW and to 350–466 GW (ORE CATAPULT, 2020) if hydrogen export is considered (Fig. 1). These scenarios would require an OW growth rate of >5 GW/year and >15 GW/year respectively, which represents a 10–15 times increase in the rate of OW capacity installation, sustained over the next 27 years.

Growth plans similar to the UK exist in the EU, with the aim of achieving at least 340 GW of offshore renewable energy by 2050, which is an increase in capacity by a factor of almost 30 (European Commission, 2020). The recent Esbjerg Declaration of the continental North Sea nations has set out ambitions of 150 GW by 2050 (Frederiksen et al., 2022). Meanwhile, the ambitions of newcomers to the offshore wind market, the US, increased by nearly 30% to 50 GW within the last year and Brazil has over 100 GW of offshore wind projects registered for environmental impact assessment (GWEC, 2022). China dominates the Asia market, with targets for an additional 40–50 GW of offshore wind over 2021–2025 set out in China's 14th 5-year plan (S&P Global Commodity Insights, 2022) and independent forecasts indicating close to 100 GW of installed capacity by 2030 (GWEC, 2022). Vietnam, Taiwan, South Korea, Japan and India all have ambitious targets totally more than 70 GW by 2030 (GWEC, 2022). In addition new markets are emerging in Ireland, Colombia, Australia and the Philippines (GWEC, 2022). Exact targets change from year to year with the political climate, but the exponential growth of offshore wind globally is unequivocal, and is essential to mitigate the climate emergency. The target capacities include fixed-bottom and floating wind turbines, but floating solutions have great potential in Europe (Wind Europe, 2017), the US west coast (Barter et al., 2020), Japan (Bento and Fontes, 2019) and Brazil (Vinhoza and Schaeffer, 2021).

In the following section (1.2), the geotechnical requirements to meet offshore wind demand is illustrated using the UK growth rate as an example, but the principles of the predictions could be applied to other regions. The assessment and conclusions of the review of anchor technology (section 1.3 onwards) are drawn from and are relevant to seabed conditions and floating offshore wind developments worldwide.

1.2. Anchoring requirements for net zero

To set the UK growth in offshore wind in terms of anchoring requirements, the following assumptions can be made: (i) a mean turbine size of 10 MW is assumed for future applications, reflecting the general rise from the average capacity of the current turbine fleet of 4.7 MW, and an average of 9.6 MW installed in 2021 (Crown Estate, 2022), (ii) 3 mooring lines/anchors being required per floating turbine as a lower limit on requirements in the absence of any anchor sharing, and (iii) floating systems representing 75% of future capacity. This latter hypothesis is an extrapolation of recent trends, where the 2022 Scotwind seabed leasing round has 60% floating capacity i.e. 15 GW of 25 GW total (Crown Estate Scotland, 2022), compared to zero farm-scale floating in previous UK leasing rounds.

These assumptions enable conversion of the targeted installed OW capacity into a number of turbines and anchors, as shown in Fig. 1, with an upper limit rate of installation of 3400–4500 anchors per year. All of these quantities could be multiplied by ~7 to represent the EU context, where ORE has similar potential within a net zero strategy for a population that is seven times larger than the UK. Those quantities are far beyond the current supply chain capacity, and create motivation for anchor optimisation, or anchor sharing (Fontana et al., 2018), to reduce the overall demand.

New developments will also increase the demand for geotechnical field investigations and surveying. The energy production per unit plan area of a wind farm is projected to remain ~4 MW/km^2, with minimal effect of growth in turbine size, as demonstrated by Putuhena et al. (2022). This represents tens of thousands of km^2 to survey, as shown in Fig. 1. Site characterisation will typically require 5 CPTs per turbine, when considering all survey phases as well as the additional CPTs associated with cable routes. This estimate is based on 1 CPT per anchor (3–4 depending on mooring array) plus the CPTs along cable routes and performed at different stages of investigation, which are assumed to be a further 1–2 per turbine. We derived this estimate based on our review of existing offshore wind survey databases e.g. MDE, 2022, and allowing for an increase associated with multiple anchor sites rather than a single fixed foundation.

These projections can be set in context by comparison with the oil and gas industry, which has been operating floating facilities in the UK sector of the North Sea for the past 40 years. There are currently 16 floating oil and gas facilities in the North Sea (22 including the Norwegian Sea Territory, and 25 if capturing the very east Atlantic offshore Scotland) (Gourvenec et al., 2022). The higher 2050 projections for UK offshore wind involve around 1000 times more floating facilities than this current fleet.

These targets will require massive supply chain growth that must overcome numerous constraints, such as survey and installation vessel availability, anchor and foundation fabrication capacity as well as the required human expertise in offshore geotechnics and marine

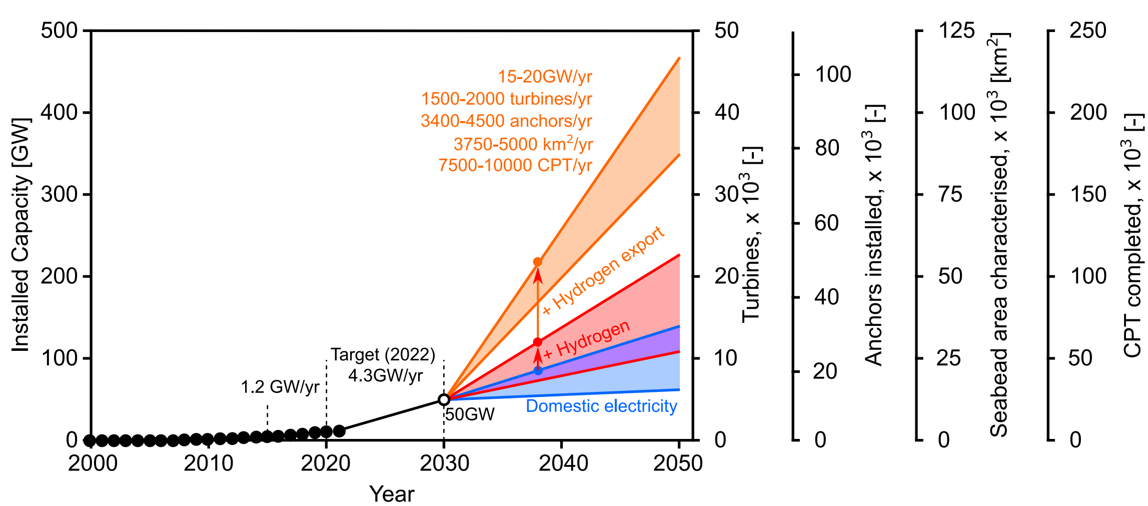

Fig. 1. Projected growth of offshore wind energy and implications for site survey and anchoring: the UK as a national example considering different scenarios of electricity demand.

engineering. This supply chain pressure strengthens the opportunities for innovation-driven advances in the design and installation of anchoring systems. For this reason, moorings and anchors rank as a high priority in technology and innovation roadmaps (e.g. (ETIP Wind et al., 2019)). The identification of optimal anchor types for different seabed conditions can help focus future investment in specific technologies. The huge growth of the market also creates conditions in which niche solutions, that suit only a particular set of project conditions, may still become commercially viable, due to the volume of production associated with only a small fraction of the overall market.

1.3. Typical anchor loading conditions

The magnitude and inclination of the load transferred to an anchor depends on the mooring type, which generally falls into three categories: (i) catenary, (ii) taut (or semi-taut) and (iii) tension leg. A summary of example loading conditions for these mooring systems in floating wind applications is provided on Fig. 2.

The most common mooring type currently is the catenary, in which the restoring station-keeping force is created primarily by lifting additional chain from the seabed. A catenary mooring line lies along the seabed, but often the pad-eye connection to the anchor will be embedded below the seabed surface. This creates an inclined load due to the shape of the inverse catenary in the soil, which is controlled by the chain-seabed interaction (Randolph and Gourvenec, 2011; Vivitrat et al., 1982). Taut mooring lines of synthetic rope provide restoring force through the non-linear stiffness of the line (Harrold et al., 2020), and are pretensioned to intercept the seabed at an angle and so deliver a more inclined load to the anchor than for a catenary mooring. They are of interest for floating wind as a means of reducing the length and footprint of the mooring system (Bach-Gansmo et al., 2020; Wise and Bachynski, 2020). Tension leg moorings are a vertical taut line with a large pretension.

Example cases of catenary and taut mooring systems show maximum loads for 5 MW floating turbines that are in the range 2–6 MN (Fontana et al., 2018; Pillai et al., 2022; Xu et al., 2021), but the load will increase for larger turbines, with load inclination at the anchor padeye between

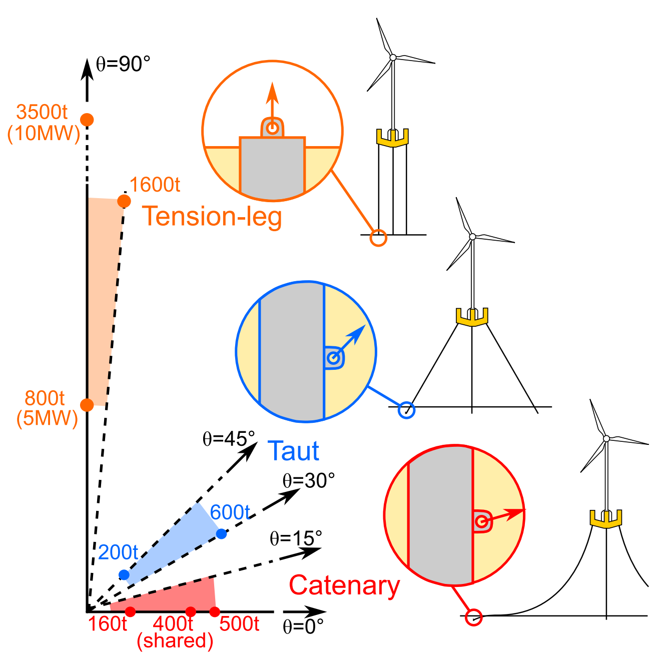

Fig. 2. Example of load vectors (metric tonnes) at the anchor padeye for different floating wind mooring designs. Loads obtained from (Fontana et al., 2018; Gao et al., 2021; Pillai et al., 2022; Wise and Bachynski, 2020; Xu et al., 2021).

0 and 15° for catenary moorings and 30–45° for taut line moorings (Randolph and Gourvenec, 2011). Tension-leg moorings apply a near-vertical, and larger load to the anchor compared to taut lines, with an example case for a 5 MW turbine indicating a maximum mooring load of 16 MN (1600t), but with an onerous constant pre-tension of 8 MN (800t) (Bachynski and Moan, 2014). A TLP case study for a larger 10 MW turbine indicated a 35 MN (3500t) maximum load (Wise and Bachynski, 2020). The design mooring load is assessed from simulations of the floating system in which the anchor is usually modelled as a fixed point, neglecting potential loss of pretension due to anchor displacement.

1.4. Anchor design specifications

An anchoring system for floating offshore wind has the following two primary performance requirements.

1. Capacity: the anchor design capacity must exceed the design value of the mooring load applied via the attached mooring line throughout its entire design life.
2. Installability: the anchor must be reliably installable in the local seabed conditions, to the embedment depth at which the required capacity is available.

An optimised design meets the capacity and installability requirements whilst minimising the relevant costs and risks, which span economic, environmental and end-of-life considerations. The design capacity may be influenced by cyclic and other effects that depend on time and the applied loading history and may also include an additional component from the seabed resistance ('friction') against the attached embedded mooring chain. Load and resistance factors are applied to the design loads and capacity according to the relevant design codes (e.g. DNV, 2012, 2002; ISO, 2019, 2016, 2015).

The design of OW turbines favours floating support over fixed-bottom beyond a water depth of around 60–80 m, in contrast with oil and gas platforms, which can use jacket or gravity-based structures in up to several hundred metres water depth. This contrast is because of the high cost and size of the fixed-bottom foundations that are required to support the tall but relatively light wind turbine structures in deep water. While fixed-bottom foundations for OW are dominated by monopiles (81%) and jackets (10%) (Wind Europe, 2021), many more options exist for floating wind structures, and these are detailed in the next section.

1.5. Aims and scope of the paper

The aims of this paper are.

- To highlight how the goal of net zero translates into demand for geotechnical anchoring solutions to provide station-keeping for floating wind turbines, of increasing size – as set out earlier in Section 1.
- To provide an overview of anchoring technologies, building on previously-published literature reviews and adding a classification system for anchor types.
- To perform a systematic comparison of performance, scalability and the additional challenges presented by particular seabed conditions.
- To scan the horizon for enhancements of geotechnical anchor technology, and classify the potential routes for innovation and technology development.

This paper is intended to be read beyond the geotechnical engineering community, given the identified need for a holistic design approach, considering the full station-keeping system response, including mooring-anchor interaction. It therefore includes some basic aspects of anchor behaviour, but includes comprehensive referencing to further publications.

Previous literature reviews of geotechnical anchoring systems, primarily focussed on oil and gas applications, include Gaudin et al. (2017), Knappett et al. (2015), O'Loughlin et al. (2015) and Randolph et al. (2011). More extensive treatments of the background literature are found in Randolph and Gourvenec (2011) and Aubeny (2017). This present paper builds on these earlier studies by (i) adding the recent context of net zero and floating offshore wind, (ii) reporting more recent advances, (iii) quantifying the relative performance of different anchor types, and finally by (iv) exploring potential future innovations.

2. Technical overview

2.1. Introduction

Many anchor types, which differ in shape and installation method, exist for offshore applications (Aubeny, 2017; Knappett et al., 2015; Randolph, 2020). Despite their differences, they share some similarities and can broadly be classified into three families as a function of the volume of soil they mobilise to resist loading from the mooring line (Fig. 3): (a) gravity-type, (b) pile-type or (c) plate-type anchors.

The resistance of gravity anchors, which rest on the seafloor, is governed by the submerged weight of the anchor (with any ballast) and the resulting sliding resistance under lateral load, which only mobilises a small volume of soil close to the surface. Other anchor classes are embedded, relying on the strength and weight of the surrounding soil to provide additional holding capacity. Pile-type anchors are embedded into the seabed but extend to the surface. They resist axial load via interface shear mobilisation and lateral load by soil bearing mobilisation. Plate-type anchors are totally buried, and mobilise soil bearing resistance against the face of the plate. Composite-type anchors combine features of these types, depending on the loading direction. Anchor types within a family may feature different installation methods. For example, piles may be driven, pushed-in, drilled, vibrated or installed using suction.

2.2. Gravity-type anchors

Gravity or surface anchors are a heavy weight laid onto the seabed, have zero or minimal penetration into the ground due to their self-weight and are relatively quickly operational. Under vertical uplift, the holding capacity of a gravity anchor is equal to the buoyant weight of the foundation and any ballast, which is material intensive and has a low efficiency by tonne of material used compared to other anchor options. Under horizontal loading, failure occurs due to the bearing capacity of the anchor being reached under the combination of the buoyant self-weight acting vertically and the horizontal action applied from the mooring line. This resistance may be limited for lighter anchors by sliding at the anchor-soil interface, which may be enhanced by providing short ribs or grilles underneath the anchor to ensure soil-soil shearing (see Fig. 4b).

The main types of gravity anchors consist of large precast concrete or steel elements, ballasted boxes or grillages. Large precast elements (Fig. 4a) are quicker to install than alternative anchor types, but are heavy as they are pre-cast onshore. Box anchors (Fig. 4b) comprise an empty box that is filled with a heavy ballast (e.g. rock fill or heavier, iron ore if available) once the box has been lowered to the seafloor. The two stage process minimises the lift capacity of the crane required to install the gravity anchor.

An alternative to the box anchor is the grillage and berm or ballast gravity anchor (Fig. 4c), comprising a flat grillage that is placed on the seafloor and buried by a rock-fill or iron ore berm. The grillage is placed towards the back of the berm such that the complete berm must be moved if the grillage starts to fail (Erbrich and Neubecker, 1999). Grillages use less steel than a mudmat or box anchor and their slight embedment enables the mobilisation of soil-soil friction at failure (Bransby et al., 2011; Knappett et al., 2012).

2.3. Pile-type anchors

Anchor piles are hollow, cylindrical, open-ended steel tubes that can be driven, pushed-in, drilled and grouted, or suction installed into the seabed. Driven piles are the most common offshore foundations and are usually hammered (i.e. 'driven') into the ground (Fleming et al., 2009; Jardine et al., 2005), even in weak rock (Buckley et al., 2021; Kay et al., 2021). The diameter, D, wall thickness, t, and length, L, of a pile are selected to provide the required capacity, within limits on D/t related to buckling of the cross-section and limits on D of around 10 m, limited by steel fabrication and transport. The ground conditions and planned installation method influence the required dimensions. For the smaller piles (e.g. 2–3 m), aspect ratios, L/D of greater than 40, and pile lengths of >100 m have been reported (Gavin et al., 2011; Iskander et al., 2002; Jardine et al., 1998; Senders et al., 2013), with the higher aspect ratio and longer piles being for axial rather than lateral loads. The cost of the large installation vessels necessary to handle the largest hammers, the duration of operations and mitigation methods necessary to reduce environmental disturbance (e.g. underwater noise mitigation, Koschinski and Lüdemann, 2013) are often the primary limiting factors. The repetitive hammering of piles leads to a degradation of the shaft resistance, also termed friction fatigue (Heerema, 1978; White and Lehane, 2004), but the shaft resistance then usually recovers, through processes of consolidation and other aging-related effects (Jardine et al., 2006; Randolph, 2003). Changes in shaft friction during driving can lead to free falling of the pile during installation in some soils (Randolph, 1988), which must be mitigated (Dechiron et al., 2020; Frankenmolen et al., 2017). In rock materials, piles can be formed of a steel tube that is grouted into a drilled hole, and combinations of driving and drilling can be used in layered soil conditions, with and without grouting (Finnie et al., 2019; Kay et al., 2021; Randolph and Gourvenec, 2011; Senders et al., 2013). This construction process can be expensive due to the complexity but is often necessary in layered profiles featuring rock.

Dimensions of suction piles, alternatively called suction caissons, due to the suction assisted method of installation, are limited by the stability of the internal soil plug during installation. They have large diameters, up to 16 m in sand (Andersen et al., 2005; Madsen et al., 2013) and 8–13 m in clay, and have length to diameter aspect ratios which range up to

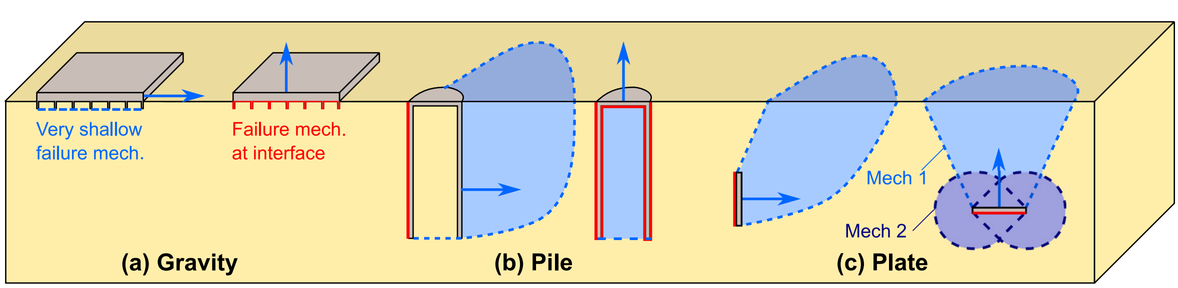

Fig. 3. Summary of the different types of anchors, as a function of the mobilisation of interface strength and the volume of soil they mobilise at failure.

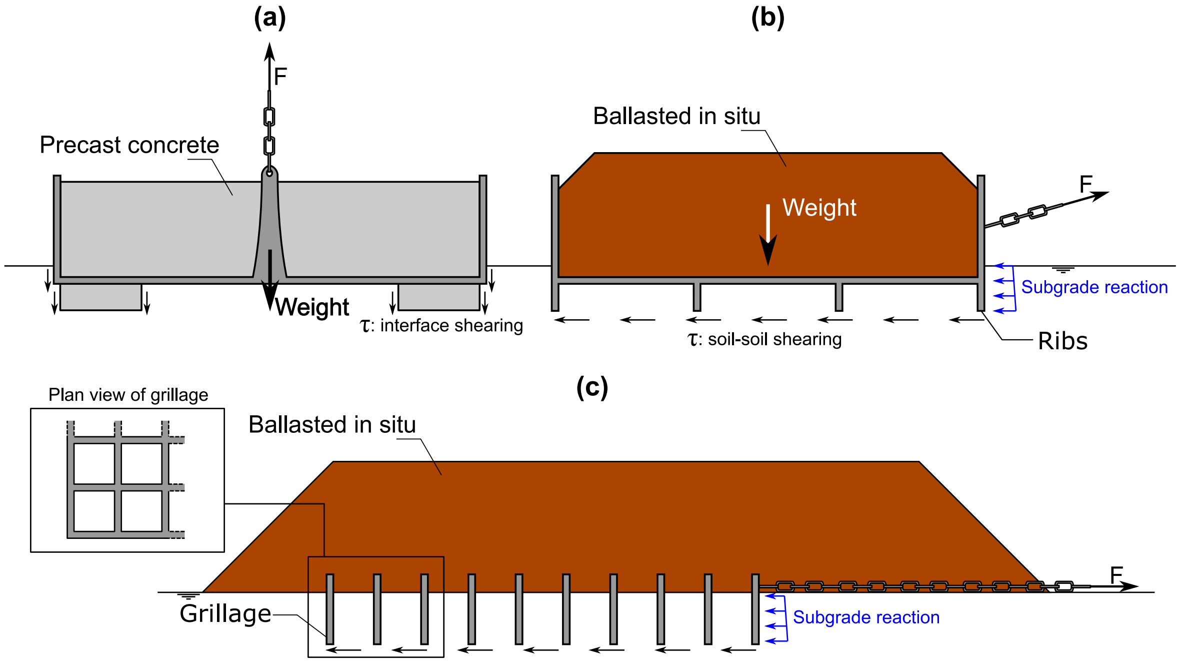

Fig. 4. Gravity anchors (a) Precast concrete anchor, (b) box anchor, and (c) grillage and berm anchor (after Randolph and Gourvenec, 2011).

typically 1 for sandy deposits (Erbrich and Tjelta, 1999; Klinkvort et al., 2019) and up to 8 for normally consolidated clay (Iskander et al., 2002; Randolph and Gourvenec, 2011). Suction piles are installed into the seabed by pumping water from inside the pile creating a difference of pressure (suction relative to ambient) across the underside of the caisson lid that relieves or overcomes the penetration resistance, depending on

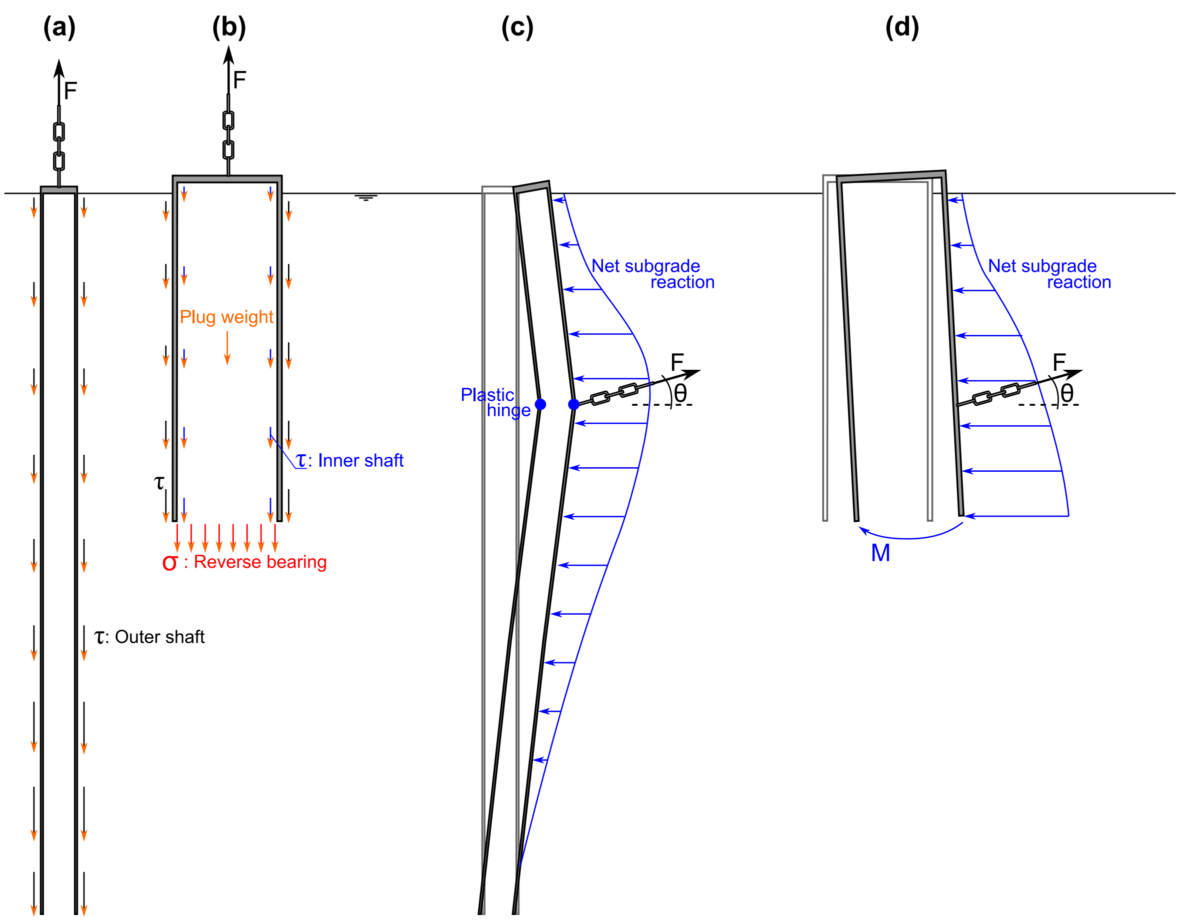

Fig. 5. Soil strength mobilised at failure for: (a,b) slender pile and caisson in tension (shear τ or normal σ stress) or (c,d) slender pile or caisson loaded laterally (M is base moment).

drainage conditions. Achieving sufficient penetration during installation is one of the main challenges for suction caissons, particularly in hard, over consolidated clays and in layered seabed profiles (Senders et al., 2007; Stapelfeldt et al., 2020).

In addition to their submerged weight, piles axially loaded in tension (Fig. 5a and b) mobilise the shear strength along the pile shaft interface. The volume of soil that contributes to the resistance is limited, but if the soil strength increases with depth, piles benefit from this additional capacity. The resistance mostly comes from the outer shaft for driven/drilled piles (Fig. 5a), while suction caissons (Fig. 5b) also rely on the weaker of (i) the resistance between the shaft strength on the inside of the shaft, or (ii) the plug weight and any available reverse end-bearing resistance (if passive suction underneath the skirt can be mobilised).

Piles loaded horizontally mobilise a large volume of soil towards the ground surface that opposes the pile lateral displacement. Longer, slender piles will tend to fail by a plastic hinge (or two), due to pile bending, forming at some depth below mudline (Fig. 5c). The soil tends to fail by forming a passive wedge close to the surface and/or by flowing around the pile (Murff and Hamilton, 1993). An active wedge may also be mobilised on the rear of the pile. Soil is displaced typically to a limited depth for piles loaded at the head, with a plastic hinge forming in the pile, or the lower part of the pile moving in the opposite direction. In contrast, for lateral loading of a suction caisson it is common for the pad-eye to be positioned at a depth that creates a rigid body translation for optimal capacity (Fig. 5d), or with a component of rotation depending on the depth of the padeye (Andersen et al., 2005; Tjelta, 2015). Caissons also mobilise a large wedge of soil close to the surface, and a flow around mechanism close to the base, creating a moment that opposes the rotation of the caisson (M in Fig. 5d).

The padeye depth can be chosen to maximise the pile or caisson resistance (e.g. 2/3 L in normally consolidated clay for pure lateral translation (Supachawarote et al., 2004)) with the mooring line cutting through the soil into an inverse catenary as the line is tensioned (Neubecker and Randolph, 1995). Consequently, the load applied to the pile is inclined (see section 1.4), leading to a component of tensile loading. Recent projects have identified a risk to anchor capacity from a trenching process, in which the anchor chain movement causes erosion of the soil in front of the pile above the pad-eye (Bhattacharjee et al., 2014; Sun et al., 2020), potentially reducing the anchor capacity.

2.4. Plate-type anchors

All plate-type anchors are embedded into the seabed and resist the applied load by mobilising a large volume of soil, which is loaded by the plate on its projected area. Anchors embedded close to the surface tend to mobilise a wedge of soil extending to the surface (shallow mechanism, Fig. 6c) (Al Hakeem and Aubeny, 2019; Cerfontaine et al., 2019; Meyerhof and Adams, 1968; Roy et al., 2021b). On the other hand, a flow around mechanism is mobilised if anchors are embedded below a certain depth, depending on the plate geometry (deep mechanism, Fig. 6d) (Meyerhof, 1951; Yu et al., 2011).

Drag embedment anchors (DEA, Fig. 6a) consist of a plate (the fluke) attached at an angle to a shank, to which the mooring line is attached, and are generally designed to be suitable for catenary moorings. They

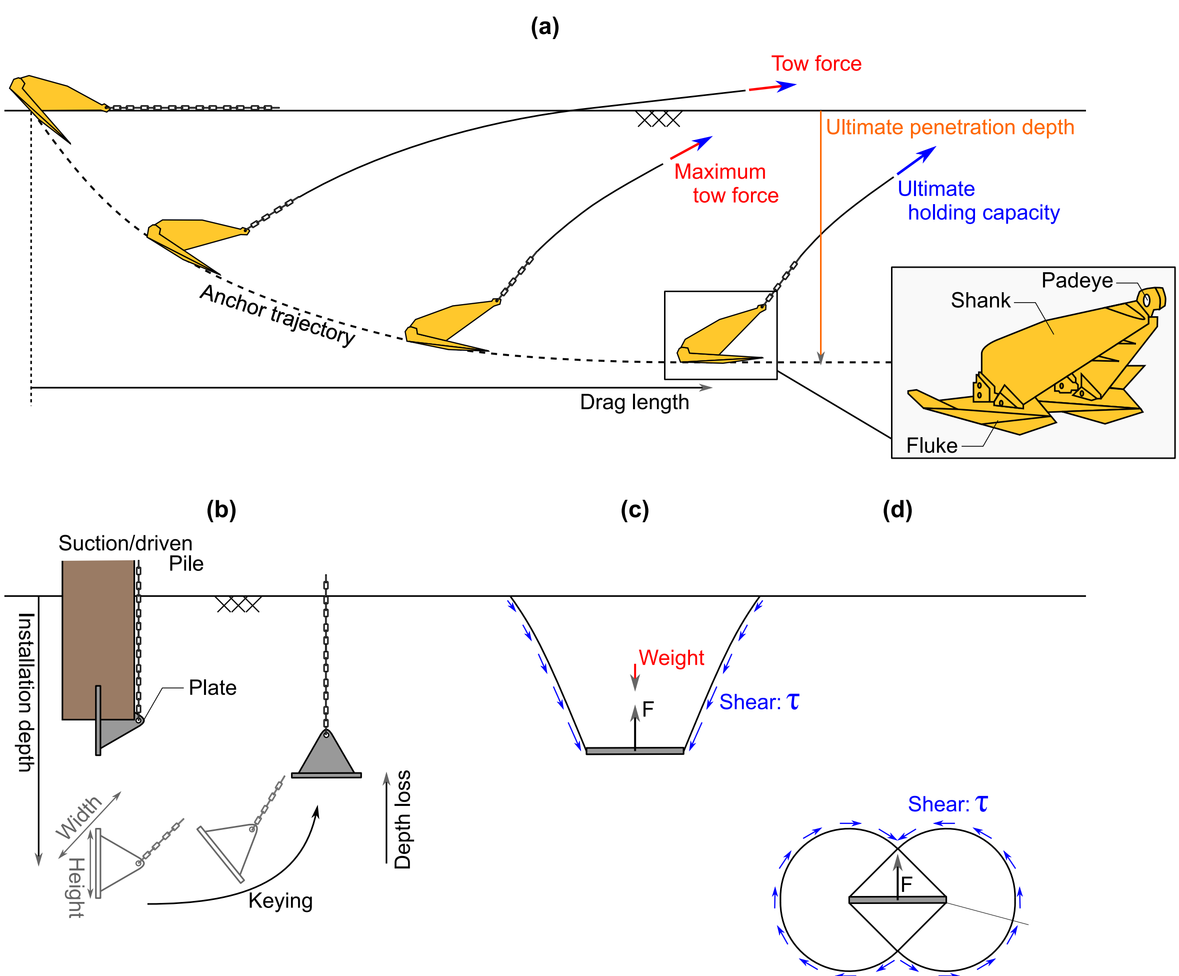

Fig. 6. (a) Drag embedment and (b) direct installation processes and keying (after Randolph and Gourvenec, 2011); (c) shallow failure mechanism; (d) deep failure mechanis.

are lowered to the seabed and then towed (dragged) such that their geometry forces the plate to cut into the seabed. The anchor trajectory eventually reaches an ultimate penetration depth governed by the anchor geometry and the kinematics of the anchor-line-soil interaction at which the ultimate holding capacity (UHC) is achieved (Neubecker and Randolph, 1996; O'Neill et al., 2003). An indication of capacity of such anchors is provided by the towing force that is applied during their installation. The final installation tension is usually sustained at a specified proof load for a period to demonstrate the anchor capacity. This proof load is often only a fraction of the UHC, and may also be less than the design ultimate mooring tension. This approach allows for some changes in anchor capacity, between the installation tension and the design load response, due to consolidation effects or from cyclic loading. It is also permitted for the installation tension to be lower than the design tension if the additional required drag distance is acceptable to the mooring arrangements, which can reduce the required vessel bollard pull during installation. The permitted design approaches depend on the soil conditions, and therefore the predictability of the drag anchor response (DNV, 2012).

Vertically loaded anchors (VLA) are similar to DEAs, but their shank can be reconfigured through a release mechanism, which allows the fluke to rotate under load such that it becomes perpendicular to the shank and mooring line and is therefore able to carry inclined or vertical loads. This makes the anchor suitable for taut or tension-leg applications (Aubeny and Chi, 2014; Zimmerman et al., 2009).

Directly embedded plate anchors (Fig. 6b) consist of a single rectangular or circular plate embedded at a certain depth, via a suction caisson (SEPLA) (Gaudin et al., 2006; Wilde et al., 2001), via a driven pile (Aubeny, 2017) or dynamically embedded after some free fall into the sea (Blake and O'Loughlin, 2015; Kim and Hossain, 2015; O'Loughlin et al., 2014). All plates are installed vertically and have to key, i.e. rotate to align perpendicular to the mooring line (Wang et al., 2011), which leads to some embedment loss before they are oriented in the direction that gives the maximum capacity.

The main challenge for plate anchors is to achieve sufficient embedment during installation (e.g. dynamic embedment) or to predict of embedment loss and remoulding resulting from keying (O'Loughlin et al., 2006; Peccin da Silva et al., 2021; Wang et al., 2011; Yang et al., 2012), which can all reduce the anchor resistance. The loss of embement depth can be significant and ranges between 0.5 and 2.0 times the plate height (Aubeny, 2017; Gaudin et al., 2006).

2.5. Composite-type anchors

A composite-type anchor comprises a combination of plate and pile-type elements. Screw (or helical) piles are composed of a steel circular shaft connected to one or more helices. Torque and compressive force are applied at the head to install them via a screwing action, with reduced underwater noise relative to hammering. Screw piles resist tensile loading by mobilising the soil bearing resistance above the topmost helix, similar to plate anchors (Cerfontaine et al., 2020a; Hao et al., 2019; Perko, 2009; Spagnoli and Tsuha, 2020). Screw anchors behave like a straight shafted pile when subjected to lateral loading (Al-Baghdadi et al., 2017; Ding et al., 2018) with some enhancement due to rotation of the helices, although the plate resistance can be fully mobilised if the pile rotation aligns the loading direction with the shaft. Upscaling from the relatively small dimensions from onshore applications to date is one of the main challenges for the use of screw piles offshore (Cerfontaine et al., 2020b; Davidson et al., 2022; Sharif et al., 2021), which will require installation tools capable of applying a large torque of several MNm, but this can be overcome by using groups of smaller screw piles (Bradshaw et al., 2022).

The dynamically embedded torpedo or fish-like anchors behave similarly, combining pile and plate type behaviours thanks to the addition of fins (Han and Liu, 2020; Kim et al., 2021).

2.6. Group-type anchors

A group-type anchor comprises of multiple plate or pile-type elements. Small groups of pile-type foundations offer the potential to provide high anchoring capacity without the need for the larger installation equipment associated with a single large pile of comparable capacity. In some soils, pin piles can be installed using dead weights ('clump weights'). A group of small 'pin' piles can be linked via a surface foundation, and connected via grouting or simply left within locating sleeves. Design methods have been established to estimate the combined capacity of this hybrid foundation, e.g. Dimmock et al. (2013) and Gourvenec et al. (2017).

The anchoring capacity offered by pile groups depends on the level of moment fixity that can be relied on at the pile top, as well as the group interaction effects between the piles (Fleming et al., 2009). This interaction can be positive (so the capacity of n piles is greater than n times the capacity of one pile), due to a mutual reinforcement in which neighbouring piles add to the strength and stiffness of the soil mobilised by other piles. Alternatively, the group effect can be negative, with overlapping of loaded soil zones, or the mobilisation of group-type block failure mechanisms. Small-scale pile group tests provide evidence of these different types of group interaction, during installation and loading, and allow optimisation of group arrangements (e.g. Bradshaw et al., 2022; Yetginer et al., 2006).

Group-type plate anchors have also been conceived. The use of multiple drag anchors attached in series along a mooring line was explored in early model tests by (Walker and Taylor, 1984). The second drag anchor is attached to the trailing edge of the fluke (plate) of the leading anchor, and is described by Vryhof (2018) as a piggyback approach. At a spacing of 2–5 anchor lengths, the efficiency can be above 100%: together, the capacity is more than double the single anchor capacity because of interaction effects (Lai et al., 2022).

3. Analysis of anchor performance

3.1. Introduction

Analyses presented in this part of the paper explore the relative performance of the different anchor types, and derive efficiency metrics for anchor performance and scalability. The aim is to compare the performance of various anchor types in a range of common soil conditions (described in section 3.2), considering different sizes of anchor with capacities assessed using simple current design methodologies (section 3.3), while accounting for installation constraints. The analysis is set out in section 3.4; to make it tractable, some more detailed aspects of anchor design are neglected, but are discussed in section 3.5.

3.2. Idealised ground profiles

A set of idealised ground profiles, representative of seabeds in many regions, are adopted to bound the anchor performance in a systematic way. Idealised uniform soil profiles of low strength (LS) and high strength (HS) clay, and loose and dense sand have been used, with parameters given in Table 1. The use of sand and clay mirrors the drained and undrained idealisations in capacity calculations that form the theoretical basis of standard geotechnical design methods.

In practice, seabed conditions can be complex with layering of different soil units, reflecting the past geological history of a given site. In addition, the simple clay-undrained and sand-drained linkages are not applicable to all loading scenarios, and the seabed can also feature rock, sometimes covered by a thin layer of sediment, or be composed of a transitional – silt-sized – soil, with behaviour different to either sand or clay. Key consequences of these complex challenges on anchor performance are discussed in Section 3.5.3.

Table 1
Synthetic ground profiles considered for the analysis of anchor performance. Sand properties are representative of the uniformly rounded silica HST95 sand (Al-Defae et al., 2013); clay profiles are representative of spanning data from Jardine and Potts (1988), Le et al. (2014), Yang et al. (2019), He et al. (2021), Yetginer-Tjelta et al. (2022). Symbols: adhesion factor (α), undrained shear strength (s_u), unit weight (γ), depth (z), soil sensitivity (S_t), initial vertical effective stress (σ'_{v0}), critical state friction angle (φ_{crit}), interface critical state friction angle (δ_{crit}), coefficient of initial earth pressure at rest (K_0), density index (I_D), cone penetration resistance (q_c), atmospheric pressure (p_{atm}).

Clay	
Low strength (LS)	High strength (HS)
$\gamma = 16$ kN/m^3, $s_u(z) = 5kPa + 1.5z$, $S_t = 3$,	$\gamma = 18$ kN/m^3, $s_u(z) = 10 + 240z \leq 250kPa$, $S_t = 3$
$\alpha(z) = 0.5\left(\frac{s_u}{\sigma'_{v0}}\right)^m$ with $m = -0.5$ if $s_u < \sigma'_{v0}$ and $m = -0.25$ otherwise	
Sand	
$\varphi_{crit} = 32°$, $\delta_{crit} = 24°$, $K_0 = 0.47$, $q_c(z) = 19\exp(3.2I_d)(\sigma'_{v0})^{0.7}p_{atm}^{0.3}$	
Loose	Dense
$\gamma = 19.3$ kN/m^3, $I_d = 0.3$	$\gamma = 20.4$ kN/m^3, $I_d = 0.9$

3.3. Analyses of anchor capacity

The capacity of the most common anchor types under lateral and vertical loading were calculated for each appropriate soil profile. Suction, driven and screw piles were investigated, as well as drag anchors, suction embedded plates and gravity anchors. The design anchor capacities were calculated for a range of practical dimensions using published design methodologies, as summarised in Table 2. The calculations are limited to monotonic resistance for simplicity, but cyclic loading is addressed in Section 3.5.1.

For each combination of anchor type and soil profile, the outcome of the analysis is the monotonic vertical capacity, $F_{90°}$ (for tension-leg or taut applications) and the monotonic horizontal capacity, $F_{0°}$ (for catenary applications) for a range of anchor sizes. The resistance to inclined loads is addressed in Section 3.5.1. The anchor dry mass, M, is also calculated as a useful proxy for crane lifting, logistical (e.g. dockside lay down area) and material requirements as well as for cost.

Where applicable, aspects of an anchor are optimised, such that the anchor providing a given resistance is the lightest possible, for instance by selecting the optimum padeye depth for suction piles. Secondary dimensions such as wall thickness are optimised within certain limits or typical ranges, with details provided in Table 2. Installation constraints are also considered, such as the maximum installation torque for screw piles (Cerfontaine et al., 2020b) or geometric limits to avoid plug failure for suction caissons (Klinkvort et al., 2019). No safety factors are imposed for simplicity.

3.4. Comparative anchor capacity

Results of optimised anchor resistance as a function of the dry mass are presented in Fig. 7. For some anchor types, the analyses are supplemented by available field test data (circular makers), which show general consistency with the calculated performance. For each anchor type, the performance line in Fig. 7 shows the variation in anchor capacity with size – indicated by the anchor mass. The higher the line, the greater the anchor efficiency (resistance to mass ratio, F/M), and the steeper the line, the greater the improvement in pile capacity as it is upscaled in mass. These characteristics are summarised further in Fig. 8, which shows the anchor efficiency at a reference mass of $M = 10t$ and the efficiency enhancement from anchor upscaling indicated by the slope, $d(logF)/d(logM)$ (see insert in Fig. 8b).

The following observations can be made from Figs. 7 and 8.

Table 2
Methods and assumptions adopted in illustrative anchor capacity calculations and constraints on installation or geometry.

	Anchor performance	Constraints
Gravity	Ballast material is concrete (dry unit weight 24 kN/m^3). **Vertical:** anchor resistance is limited to buoyant weight. **Lateral:** in clay, horizontal load is maximum for $V \leq 0.5\ V_{ult}$ (Gourvenec, 2007). In sand, design of grillages according to (Bransby et al., 2011; Knappett et al., 2012).	Foundation remains at the surface with low or no embedment. Ribs or grilles are used to ensure mobilisation of a soil-soil failure. Weight of the foundation is limited to 0.25 times the ultimate bearing capacity (V_{ult}) of the foundation.
Driven piles	**Vertical:** UWA05 CPT method (Lehane et al., 2007) in sand and (Randolph and Murphy, 1985) in clay.	Wall thickness based on API recommendation or calibrated based on case studies. Maximum pile length 60 m. Pile diameter ranging from 1.0 to 2.0 m (Schneider et al., 2007b). Unsupported span and buckling not checked during installation
	Lateral: Calculated by solving non-linear pile displacement with p-y curves. Capacity defined at maximum padeye displacement of 0.1D or plastic hinge. CPT-based p-y curves in sand (Suryasentana and Lehane, 2014) and API in clay (API, 2007).	**Lateral:** Padeye depth limited to 2D in sand and HS clay to avoid pile uplift failure due to steep angle of embedded chain (Frankenmolen et al., 2016). Maximum padeye depth in LS clay is 20 m.
Screw piles	**Sand:** Optimised design as per (Cerfontaine et al., 2020b; Davidson et al., 2022; Giampa et al., 2017)	Max. installation torque 5MNm, assuming upscaling of current largest torque available (Giken Gyropiler, 3MNm), although further upscaling may be technically feasible.
	Clay: Same algorithm as sand for optimisation, clay design as per (Spagnoli and Tsuha, 2020)	Max. shaft thickness to diameter ratio t/D = 0.1 In sand, one helix and depth limited to H/D = 7, multiple helices in clay.
Suction piles	**Vertical:** bearing capacity (Andersen et al., 2008; Aubeny, 2017) and shaft friction according to (API RP 2 A WSD, 2000) in sand; in clay considering reverse end bearing and plug pullout (Aubeny, 2017; Randolph and Gourvenec, 2011) **Lateral:** (Randolph and Gourvenec, 2011) in sand and N_p based on (Randolph et al., 1988) in clay	**Sand:** L/D ≤ 1 (Klinkvort et al., 2019) for soil plug stability. Wall thickness to diameter ratio t/D = 0.006 (for vertical capacity) (Bienen et al., 2018a, 2018b; Klinkvort et al., 2019). **Clay:** L/D ≤ 8 soil plug stability (Andersen, 2004; Randolph and Gourvenec, 2011); t/D = 0.006 (vertical capacity); t/D = 0.01 (horizontal capacity), D ≤ 8 m in sand and D ≤ 4.5 m in clay
Drag anchors	**Sand:** Empirical design charts for Stevpris anchor from API RP 2SK (2005) based on $F_0 = AM^b$ where A and b are provided; M dry mass	**Sand:** Predictions are conservative compared to manufacturer data for Stevpris Mk 6. Design chart assumed to relate to loose sand; dense sand applies 0.75 reduction factor to account for lower embedment as per API RP 2SK (2005)
	Clay: Empirical line from Manufacturer data for Stevpris Mk 6 anchor validated against Neubecker and Randolph (1995) model in matching soil profile ($s_u = 4 + 1.5z$); For HS clay, these calibrated line and anchor parameters are applied to alternative seabed strength profile in Neubecker and Randolph model to calibrate A parameter	**Clay:** Calibration based on 15 t Stevpris anchor with 0.16 m effective diameter chain and anchor properties from Neubecker and Randolph (1995).
Plates	**Clay** (SEPLA): plate resistance (Yang et al., 2012), keying for vertical loading (Wang et al., 2011).	Clay (**SEPLA**): suction caisson length to diameter ratio L/D = 6; plate length to suction pile diameter ratio L/D = 2. Padeye eccentricity to plate length ratio e/L = 0.5. Plate thickness to plate length ratio t/L ranging from 0.01 to 0.1.

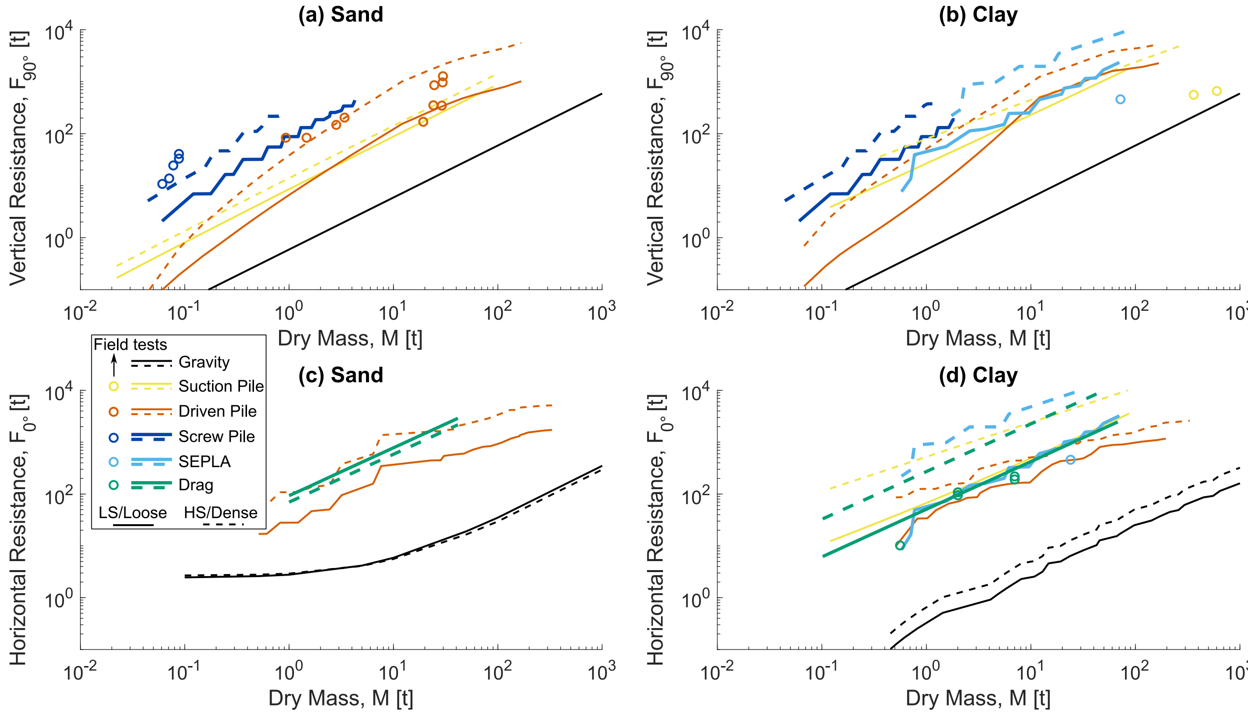

Fig. 7. Comparison of optimum performance analysis for different types of anchors (tensile or lateral resistance as a function of the dry mass of the anchor): (a) tensile in sand, (b) tensile in clay, (c) lateral in sand, (d) lateral in clay. The solid lines represents a loose sand or low strength (LS) clay profile, while the dashed lines represent a dense sand or high strength (HS) clay profile. Dicsrete markers represent field test data. Field tests data from (Brown et al., 2010; Colliat and Colliard, 2011; Gavin et al., 2014, 2011).

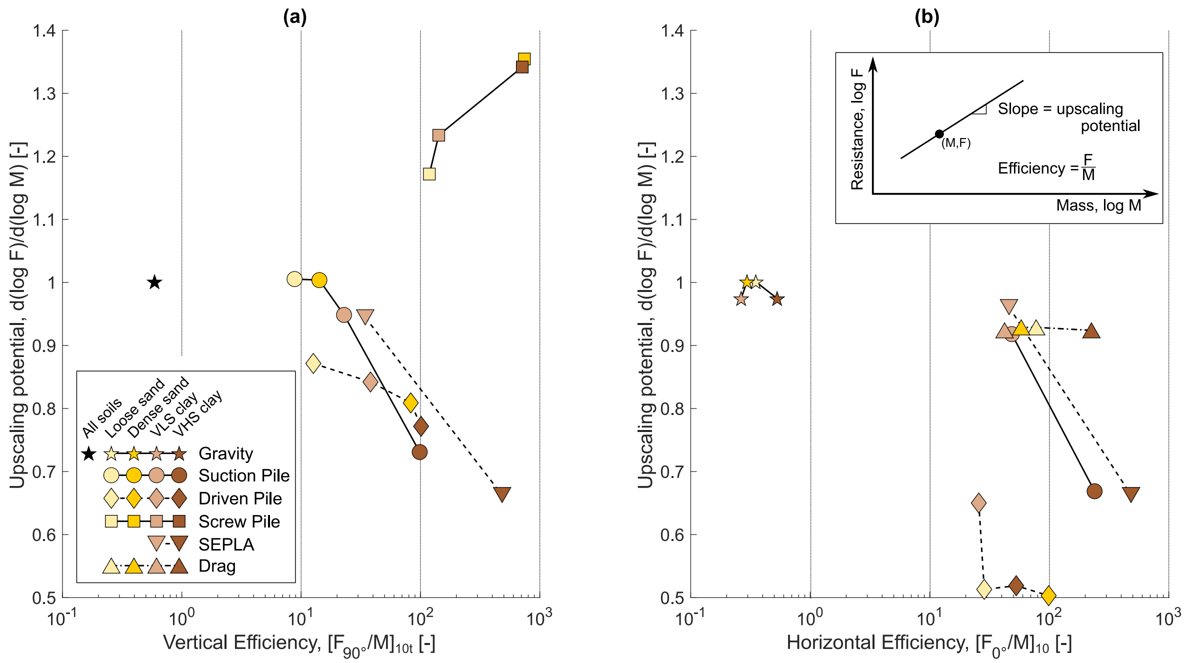

Fig. 8. Comparison of efficiency, calculated as the resistance to mass ratio (F/M) for an anchor mass of 10t, and upscaling potential, defined as the slope in the log-log space (resistance vs. dry mass, see Fig. 7), for all anchors considered in this study. Analysis for (a) vertical performance and (b) horizontal performance.

- Gravity anchors are the least efficient type, reflecting that minimal soil resistance is mobilised and capacity is generally proportional to anchor weight. This leads to efficiencies with F/M slightly below unity.
- Suction piles and driven piles are typically 1-2 orders of magnitude more efficient than gravity anchors, reflecting the mobilisation of soil resistance for vertical capacity and particularly for horizontal capacity. The capacity varies roughly in proportion to soil strength or penetration resistance with the vertical efficiency, F_{90}/M, ranging from 10 to 100 and the horizontal efficiency, F_0/M, ranging from 20 to 200 for the soil conditions considered.

- The upscaling potential for piles is around unity for vertical loading, reflecting that additional length or size adds proportionally greater shaft area. However, under horizontal loading the upscaling potential is lower, due to the structural capacity required to mobilise deeper soil resistance.
- Plate and composite anchors (e.g. screw piles) offer some of the highest efficiencies – ranging from 30 to 500, in both directions – reflecting the highest volume of soil mobilised per unit of anchor weight – although their applicability can be limited by installation restrictions or lack of current proven instatallion plant (e.g in the case of screw piles).
- Screw piles also offer the highest upscaling potential – greater than unity. This is because the optimum screw pile geometry calculated here is limited by the maximum torque available for installation (5MNm in this paper). The use of more powerful installation tools would unlock a greater anchor capacity for a marginal increase in anchor weight, hence the higher potential. The use of groups of screw piles could also provide sufficient capacity, while lowering installation requirements.

Constraints on the installation of suction piles in sand (L/D = 1, although some slightly longer piles are sometimes installed, e.g. (Tjelta, 1994)) limit their use against lateral loading (excessive rotation, Fig. 7c) and also limit the depth achievable by SEPLA technology (Fig. 7c). The maximum depth and resistance achievable by SEPLA in clay is also limited by the maximum embedment depth of suction piles (Fig. 7b,d). There is no geotechnical limit on driven pile dimensions, due to the large capacity and diameter of offshore hammers that have been developed for installing monopiles (fixed-bottom wind). However, the mobilisation of the biggest installation vessels comes at a cost that could rule this choice out, limiting *de facto* the absolute values available for driven piles.

There are only a few available solutions to sustain lateral loading in sand (Fig. 7c), although there are options for innovation in this case. For instance, screw piles were not considered, due to their relatively narrow shaft, but they could be inclined or be built with a depth-dependent shaft diameter, as per Cerfontaine et al. (2022) to enable this solution.

These analyses provide a quick tool to assess and rank the best technical anchoring solutions, before factoring in extra constraints such as cost of transport, supply chain capabilities, environmental constraints, and so forth. This simple analysis does not replace a thorough geotechnical design and some less favourable solutions could be redesigned for a bespoke application to provide enhanced performance.

This simple analysis does, however, provide a basis to increase the detail of techno-economic analyses of floating offshore wind systems (e.g. Castro-Santos et al., 2018; Ioannou et al., 2020; Maienza et al., 2022), by adding detail related to the anchoring system, and capturing the influence of differing regional ground conditions.

3.5. Challenges of complex conditions

3.5.1. Complex loading conditions

Taut mooring lines and to some extent, catenary lines induce inclined loading (meaning there is an upwards vertical load component, as well as a horizontal component) at the anchor loading point. Shared moorings or mooring misalignment during installation can lead to torsion or two-way cyclic loading (Fontana et al., 2018; Pillai et al., 2022), and keying of plate anchors that have the mooring line connected out of the plane of the plate introduces a moment component of loading at the anchor. Most anchor types, except deep piles, exhibit a coupling of the available capacity, i.e. the horizontal or moment load affects the vertical capacity and vice versa.

The mobilisable resistance under combined (or 'multidirectional') loading is described by a continuous surface, named an interaction diagram or failure envelope/surface, defining the combinations of loads that would cause failure. Therefore, permissible load states, from a geotechnical design point of view, fall within the failure envelope. Early use of interaction diagrams in geotechnics focussed on V–H interaction, building on the original solution from metal plasticity of the normal and shear force at cold welded connections (e.g. Green, 1954). The principle has been extended to capture effects of a range of foundation geometries, soil conditions and load paths including (e.g. Butterfield and Gottardi, 1994; Feng et al., 2015; Suryasentana et al., 2020; Ukritchon et al., 1998; Xiao et al., 2016). The principle has also been applied to suction caissons (e.g. Kay and Palix, 2010) and plate anchors (e.g. O'Neill et al., 2003; Peccin da Silva et al., 2021). Interaction diagrams have immense value as a design tool, and particularly when described as a single function, as the foundation geometry to meet the required factor of safety can be determined directly for given soil and loading conditions (Gourvenec et al., 2017).

Examples of V–H (inclined load) interaction diagrams for plates in sand and piles in clay are illustrated in Fig. 9a showing the increasing effect of load interaction with increasing relative embedment depth (H/B) for plates. The effect of an additional load, e.g. torsion or moment, can be represented by scaling the VH surface as a function of the mobilised additional load – such as illustrated in Fig. 9b for plate anchors under VHM loading (after O'Loughlin et al., 2006), due to keying of a SEPLA for a high excentricity padeye. The associated plate displacement is shown in Fig. 9c.

3.5.2. Variations in design soil strength

The capacities calculated in section 3.4 correspond to monotonic static loading in either drained (for sand) or undrained (for clay) conditions. However, Fig. 10a, uses the example of a plate anchor (width 5 m) to illustrate that the drainage mode depends on the load duration and soil properties (coefficient of consolidation, c_v). For instance, the continuous tension (for TLP mooring) applied to an anchor in clay can be drained at the design life scale, meaning that no or low excess pore pressures will remain in the surrounding soil by the end of the design life. In contrast, the response of a large anchor in sand can be undrained at the time scale of a wave period (meaning that no pore fluid flow nor volume change can occur). In contrast, the period of a whole storm, i.e. typically 1000–10,000 wave periods, is sufficient for full drainage to occur in the same sand, as shown for suction caissons by Cerfontaine et al. (2016). However, the cyclic period of the variable component of anchor loading for spar buoy and catenary mooring systems can be of the order 80–100s, and so the response to a single loading cycle could involve partial drainage in sand.

The effect of the loading rate on the anchor resistance is depicted in Fig. 10b and c, as a function of the dimensionless velocity (vD/c_v, with v the loading rate). An undrained response can lead to higher (e.g. in dense sand) or lower (e.g. in loose sand) capacity relative to the drained case. For instance, a resistance enhancement of 5 was reported by Roy et al. (2021a) for rectangular plates in dense sand. Finally, inertial effects for very rapid loading also have the potential to further increase the anchor resistance (Kwa et al., 2021).

Cyclic loading is often considered to lead to increasing displacement (ratcheting) or anchor resistance degradation, with respect to the monotonic resistance (Andersen, 2015; Herduin, 2019; Jardine and Standing, 2012; LeBlanc et al., 2010). Fig. 10e illustrates a stability diagram (after Jardine and Standing, 2012), which shows the effect of different combinations of average and cyclic loads (F_{av}, F_{cy}) applied to a pile loaded in tension. The pile behaviour can be stable (low accumulated displacement over many cycles) or unstable (failure – defined as an excessive displacement – within few cycles) after the definition of Poulos (1988). Such a diagram can be used to quickly assess acceptable cyclic design loads.

Finally, Fig. 10f and g illustrate the phenomenon of anchor setup, or ageing, resulting from the progressive dissipation of anchor installation effects, such as excess pore water pressure or stress relaxation (Huang et al., 2022; Jardine et al., 2006). This effect has been observed for piles and it has been shown that the shaft resistance of piles tested 100 days

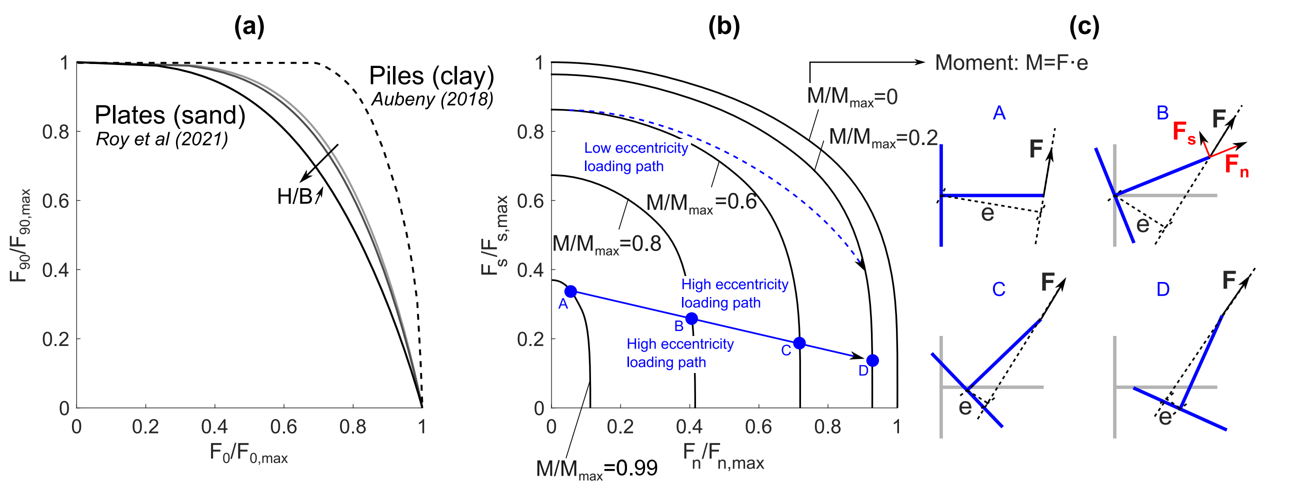

Fig. 9. Interaction diagrams to describe ultimate limit states under combined loads (a) comparison of anchors types based on (Roy et al., 2021b) for horizontal plates in sand and (Aubeny, 2017) for piles in clay; (b) effect of moment component on VH failure envelope – example for moment loading on a plate anchor during keying; (c) keying displacement of a plate with large eccentricity. F_n and F_s are the components of the applied force normal and parallel to the anchor plate respectively.

after installation had twice the resistance of piles tested directly after their installation (Jardine and Standing, 2012). Similar time effects exist for plate-type anchors, and can be enhanced by intervening cyclic loading, if this leads to densification. For example, Zhou et al. (2020b) showed a doubling of plate anchor capacity in soft clay as a result of sustained and cyclic loading.

In summary, the capacity of all anchors depends on the rate of loading relative to the rate of drainage, since this affects the soil strength that can be mobilised. In addition, the history of previous loading may lead to progressive changes in the stress condition and density of the soil around the anchor, which has a further influence on the available strength. Together, these effects can lead to both increases and decreases in anchor capacity relative to the initial monotonic capacity (drained in sand, undrained in clay), by factors typically in the range 2–5.

3.5.3. Non-uniform seabed conditions

The anchor capacity results presented in Section 3.4 were calculated based on idealised uniform soil profiles. However, real seabed conditions comprise layered soil profiles and heterogeneities. This introduces additional challenges such as premature refusal or insufficient embedment of anchors during installation, which can result in decreased anchor efficiencies (i.e. ratio of static capacity to weight), and of course requires modified design methods. For example, in the North Sea, layered soil profiles with clay or low permeability silt and sand have resulted in an increased the risk of insufficient penetration of suction caissons during installation (Stapelfeldt et al., 2020; Tjelta, 2015).

Early refusal of piles driven into hard layers of cemented carbonate material or very dense sand has also occurred during installation in the North Sea as well as in the North West Shelf of Australia (Erbrich et al., 2010; Watson et al., 2019). The presence of heterogeneities in sediments, such as boulders that are common in seabeds along the Atlantic East Coast (Stevens et al., 2019) can also cause pile tip distortion, damage and premature pile refusal. Furthermore, reduced installation embedment of drag anchors has been observed in layered seabed profiles where localised shallow harder areas or seabed areas with variable drainage characteristics prevent the anchor fluke tips from embedding sufficiently (Watson et al., 2019).

3.5.4. Rock seabed conditions

Rocky seabeds are found frequently in energetic sea sites were strong currents have eroded soft sediments. Pile driving is feasible in weak rocks such as chalk (Buckley et al., 2021; Palix and Lovera, 2020) although grouting is often used to ensure sufficient transfer of shear stress along the shaft (Lehane, 2011). Most rocks are too resistant to use other anchor installation techniques such as suction or static pushing – although gravity anchors are feasible. Drilling is the only option to install pile-type anchors in harder rocks (Bosco et al., 2016). One option is the drilled and grouted pile, which is formed by a steel tube that is lowered and grouted into position after the hole is drilled and cleared. If a surficial sediment layer is present, a drilled and grouted pile may also require a primary steel tubular pile to be driven through the sediment to keep the main hole open (Senders et al., 2013; Zehzouh et al., 2021). Alternatively, a drive-drill-drive strategy may be used, with the pile driven until relief drilling is performed through hard or rocky layers to a diameter slightly less than the pile, after which the pile is driven to the final depth, without the need for grouting (e.g. Finnie et al., 2019).

Guidance and recommendations are less well-established for the design of rock anchors compared to anchors in uncemented soils. Specialised types of lateral p-y soil reaction models have been proposed for rock, allowing for the brittle development of wedges (or chips) forming near the surface for laterally loaded piles installed in cemented soils (Erbrich, 2004). Cerfontaine et al. (2021) have simulated the behaviour of groutless rock anchors by limit equilibrium, establishing the variation in capacity across shallow and deep failure mechanisms. Ziogos et al. (2021) have shown that high rock-steel friction angles can be mobilised at low normal stress, relevant for gravity-based anchors (Yang, 2006).

Offshore rock anchor design and modelling can also draw on the extensive onshore practice, developed for rock anchors, mining and onshore piles (Brown, 2015; Seidel and Collingwood, 2001). However, failure of onshore rock anchors almost always occurs in the grout layer, and design guidance for failure mechanism in the rock mass may not be considered reliable (Littlejohn and Bruce, 1977). In addition, concepts developed for the mining industry, such as the Geology Strength Index (GSI) (Hoek and Brown, 2019), should be transferred to offshore conditions with caution. For instance, the Hoek and Brown models assume a frictional failure and were validated against field results (e.g. mine pillars). The underlying assumption is that the rock mass behaves as a continuum, which might not be true for anchors which may be relatively small with respect to the rock discontinuity spacing. In all cases, relying only on the intact rock strength is insufficient and an accurate description of the main discontinuities and joints (To et al., 2003) and site specific design is key in the prediction of any rock anchor capacity.

4. Innovations to enhance anchor technology

4.1. Introduction

This section looks to the future, to examine potential enhancements

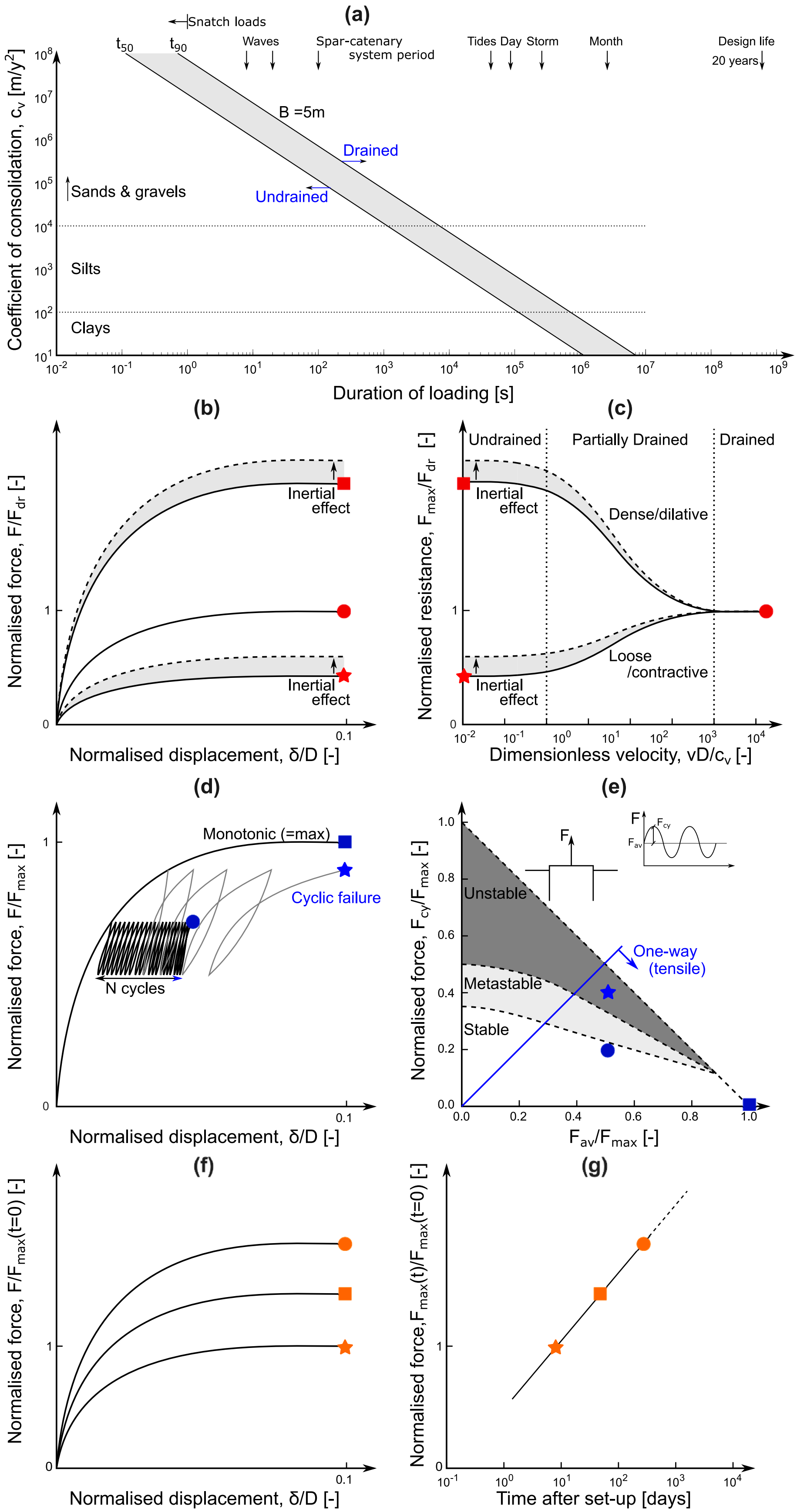

Fig. 10. Effect of complex loading on soil load-displacement relationships and anchor resistance, as included in the current practice: (a) relationship between load duration and soil coefficient of consolidation (c_v) and drainage mode (drained/undrained), based on data from (Singh and Chatterjee, 2018), for a strip anchor of 5 m width; (b,c) Rate effect on anchor resistance in sand (F_{max}), normalised by drained resistance (F_{dr}), after (Kwa et al., 2021; Roy et al., 2021a; Schneider et al., 2007a); (d,e) Cyclic loading effect on pile tensile resistance, normalised by the maximum monotonic resistance (F_{max}), after (Jardine et al., 2006); (e, f) Set-up effect on a pile resistance, normalised by the pile load just after installation ($F_{max}(t = 0)$) (Huang et al., 2022; Jardine and Standing, 2012).

of anchor technology for floating wind through different types of innovation, research and other developments. These enhancements are examined in a similar framework to the performance-cost ratios set out in Section 3. However, whereas the earlier analysis used ultimate monotonic capacity as a measure of performance, and weight as a basis for cost, it is recognised that a wider range of definitions of performance and cost can apply. Performance could include resilience under cyclic loading, as well as being expanded to include longevity and sustainability – e.g. resistance to fatigue or corrosion and ability to re-use.

A wider cost definition encompasses the full economic and environmental impacts (e.g. installation noise, material use, carbon emissions) as well as the duration and availability of design, fabrication and installation processes. These last aspects link to the supply chain and project programme, with a long duration for development meaning a risk of delayed startup, and loss or delay to power production and revenue generation. These programme constraints linked to supply chains and technology availability also threaten the likelihood of achieving net zero and mitigating climate change. Consequently, it can be argued that a supply chain bottleneck for offshore wind growth is a greater challenge than the direct cost of building offshore wind, given that the indirect costs if climate change is not mitigated will ultimately be much higher (The Climate Change Committee, 2020).

Research and innovation enhancements of anchor technology can be classified into four types, which each creates a different modification to the performance characteristic of an anchor, idealised in Fig. 11, as follows.

1. Unlocking: assuring a higher level of anchor performance than is assumed in current design practice, for example by identifying 'hidden' or overlooked aspects of anchor capacity or installability that are not allowed for in existing design practice. Unlocking leads to higher performance for the current cost – shifting the anchor characteristic upwards (to higher performance).
2. Upscaling: creating enlarged versions of current anchors, to extend their characteristic to higher levels of performance and cost, for example by increasing the diameter of monopiles, which is a current trend for fixed wind foundations. Upscaling adds a dotted extension to the anchor characteristic in Fig. 11.
3. Commoditising: improving the design, production or installation process of a current anchor, to allow the same anchor to be fabricated and installed with lower cost. Commoditisation shifts the anchor characteristic to the left (lower cost).
4. Inventing: creating new anchor concepts, for example by combining existing design features or introducing new ones, via composite- or group-type systems. Anchor invention adds a new anchor characteristic to the available options.

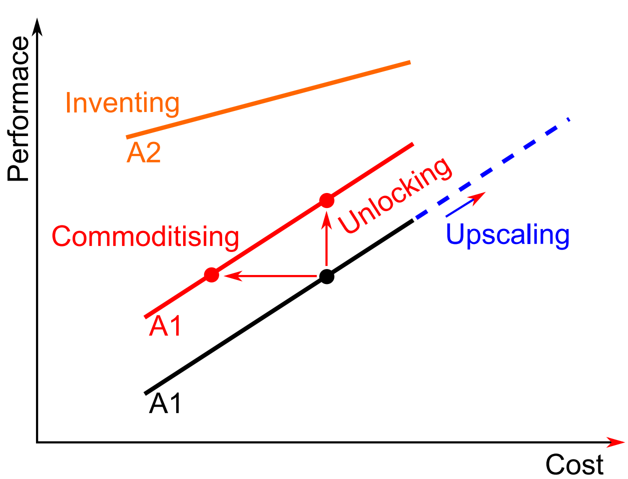

Fig. 11. Mechanisms to enhance the performance/cost ratio of anchor technology (A1 = anchor technology 1, A2 = anchor technology 2).

This taxonomy of enhancement types is useful because the same enhancement approaches can be applied to many anchor types. Each type of enhancement is discussed in sequence, in the following subsections.

4.2. Unlocking anchor performance

4.2.1. Introduction

The offshore industry has a long track record of progressively unlocking better geotechnical performance by refining the empiricism in design methods and/or improving understanding of the underlying mechanisms of the soil response. As knowledge increases, uncertainty reduces. For instance, recent decades have seen progressive increases in the design axial and lateral capacity and lateral stiffness of piles, result from improved prediction models supported by new understandings of the theoretical mechanisms from physical and numerical modelling, and validated by field experience (Byrne et al., 2020; Jardine et al., 2005). Such advances typically enter practice in parallel with adoption in international design codes (e.g. ISO, 2016). A similar path can be followed for anchor technology, that may lead to better performance than is captured by current design methods.

4.2.2. Whole-life changes in capacity

Conventional geotechnical design methods, as applied in Section 3.4, generally assume that the in situ soil properties control the ultimate capacity of the system, or they apply a reduction factor to allow for a damaging cumulative influence of cyclic loading. In many situations the opposite effect can occur: cyclic loading in combination with consolidation can lead to a gain in the strength of soft clays, and can lead to densification of sand. In both cases, the anchor or foundation can have higher long term strength and stiffness, as demonstrated through studies involving piles (Zhang et al., 2011), plate anchors (Zhou et al., 2020a) and suction caissons (Luo et al., 2020), which showed changes in strength and stiffness by a factor of 2–10.

Similarly, design of piled foundations has long recognised that axial capacity in clay progressively increases as the surrounding soil consolidates following driving (Dutt and Ehlers, 2009). More recently, database studies have established that the axial capacity of piles in sand can also rise, due to additional effects which have been linked to corrosion and creep. Medium scale (~0.5 m diameter) piles have shown gains in capacity by factors of two or more (Busch et al., 2022; Chow et al., 1998; Lim and Lehane, 2014). This data illustrates the potential to unlock significantly greater capacity from such effects, once they are properly understood and potentially then accelerated or enhanced.

In summary, long term changes in soil properties and stress conditions surrounding different types of anchor may lead to increases in capacity but are often overlooked in design. To support the adoption of this concept it is useful to redefine the requirement of limit state design as 'the design resistance *at any instant* must exceed the design action *at that instant*', so that changes in design resistance with time can be incorporated (Gourvenec, 2020). Using this approach, simulations of whole-life loading and geotechnical capacity evolution can be performed (e.g. Kwa et al., 2022), allowing the system reliability over the lifetime to be assessed, incorporating beneficial whole-life geotechnical effects.

To fully capitalise on these gains in anchor capacity, a more holistic approach to anchor reliability is useful, in order to accommodate the changing reliability of the anchor with time. Similar approaches to adopt time-dependent effects have been explored for structural reliability (e.g. Bai and Jin (2016)). A failure of a floating wind facility will not lead to a major pollution spill or loss of life, so reliability can be assessed based primarily on the economic cost.

On this basis, the cost risk to an owner depends on the reliability aggregated across a population of floating turbines and potentially across multiple wind farms of differing ages. If the owner uses smaller anchors that have a lower reliability in their early life, but gain in capacity over their operating life, the population will comprise anchors with a range of individual reliabilities, varying around the target. Therefore, the reliability of the population – i.e. the annual probability of an anchor failure within the population, per turbine in the population – may meet the conventional targets used currently for a single anchor and turbine, and therefore present the same cost risk to the owner as if larger anchors were used, and whole life capacity gains were disregarded. This concept is standard among commoditised industries, where systems follow a 'bathtub' profile of changing reliability through their life. Initial teething troubles cause low reliability, but are followed by a higher reliability throughout the operating life, until components deteriorate and reliability falls as the system reaches the end of the design life.

4.2.3. Mooring-anchor interaction effects: geotechnical inertia and ductility

A system modelling approach, considering the anchor as part of the entire mooring system, unlocks two sources of potential additional performance. In this case, the extreme loading events that govern the design can be treated as a time history of load at the anchor, rather than by the maximum instantaneous load. The simplest additional source of performance is the extra capacity available from inertial or 'added mass' effects, as well as from damping for cyclic dynamic loads. Inertial added mass effects relate to the required acceleration of the soil surrounding the anchor in order for failure to occur – where failure is now defined as the anchor moving either to cause a loss of station-keeping or such that it no longer has the same capacity, due to a loss of embedment or other change in geometry. Since extreme mooring loads apply only very briefly – often for much less time than a wave period (Hann et al., 2015) – the inertial effect can provide useful additional design capacity. Plate-type anchors are particularly efficient at mobilising added mass effects (Kwa et al., 2021).

The mechanical design of the moorings can also have a significant impact on anchor design, when a system approach is used in design. This can include (i) identifying where a change in mooring arrangement (e.g. from catenary to taut) reduces overall project cost; (ii) identifying an optimal angle in a taut arrangement that will optimise the capacity of the anchor; or (iii) the inclusion of in-line elements that provide mechanical damping to the floating mooring-platform system, reducing induced line tensions under a given set of external actions (with a tolerable increase in platform excursion) (Festa et al., 2022; Harrold et al., 2020). By lowering the required capacity at the anchor padeye, a smaller anchor can be used, unlocking amore efficient design.

The second related source of additional performance arises from any ductility that the anchor has. Since extreme loads are transient, and floating platforms can tolerate a limited change in offset, some irrecoverable movement of the anchor under a short term extreme design load may be tolerable. Some anchor types – such as piles – have minimal ductility and lose their capacity by yielding or being pulled from the ground if taken beyond their peak capacity. However, drag anchors and some plate-type anchors offer a higher ductility and can even show progressively higher resistance if pulled beyond their installed position (Aubeny, 2017), as they are typically installed by loading to only a fraction of their ultimate capacity. In this case, the inclusion of the anchor within the mooring system modelling may allow acceptable system performance to be demonstrated even if the anchor static design capacity is briefly exceeded during an extreme loading event and the anchor displaces.

4.3. Upscaling anchors

Monopiles for fixed wind turbine foundations have undergone continuous upscaling to reach diameters of more than 12 m in current designs, raising their capacity and stiffness to meet the requirements of greater water depths. This is being achieved by advancing capabilities for fabrication, lifting and transport of monopiles that now exceed 2000 tonnes in weight. In contrast, the capacity of anchors already used for oil and gas applications exceeds the current capacities required for floating wind, as illustrated in Fig. 2. In addition, as floating wind systems grow, most of the anchor types reviewed in this paper can be upscaled, without facing the fabrication and lifting challenges that constrain the larger monopiles.

However, some aspects of the installation process face barriers when considering upscaling of current anchor designs. Noise disturbance legislation in certain regions precludes pile hammer use, and so 'quiet' installation systems are preferred – including novel water-based hammers, vibration driving (van Dorp et al., 2022), or rotational jacking – particularly of screw piles (Cerfontaine et al., 2022). As these installation technologies are proven at larger scales, the capacity of anchors that can be installed using these low impact methods will increase.

4.4. Commoditising anchors

4.4.1. Manufacture, transport and installation

Previous applications of anchoring for oil and gas typically involve bespoke anchors in small quantities, to moor a single floating facility. The total number of anchors as well as the length of mooring line required for floating wind far exceeds the production for oil and gas applications, so anchoring requires commoditisation – i.e. transformation towards a rapid, mass production approach – to meet the type of global demand implied by the UK case study shown in Fig. 1.

Techniques that have supported acceleration of manufacture and assembly of foundation systems include the use of bolted connections and simple forms of steel unit, instead of welding in suction bucket design (Koteras and Ibsen, 2021). Other supply chain barriers include the available dockside area and the availability of suitable transport and lifting vessels, particularly around new regions of offshore wind development (e.g. the Celtic Sea, as described by ORE CATAPULT, 2020).

For transport, drag embedment and other plate-type anchors are more compact and stackable on deck, compared to tubular piles, which provides cost and installation time advantages (e.g. O'Loughlin et al., 2015). The installation duration and complexity is highly variable between anchor types. In approximate order of increasing duration: (i) gravity anchors are simply lowered to the seabed; (ii) dynamically-embedded anchors are lowered close to the seabed then released and self-install; (iii) drag-embedded anchors are lowered to the seabed then pulled to a specified pre-tension, which is held for a period (iii) suction installation schemes involve lowering followed by controlled embedment by pumping; (iv) hammering or vibration systems typically involve lowering then installation, with the complexity of attachment and support of the driving equipment; (v) drilled piles – which may involve lowering of the pile during drilling, or pre-drilling of the hole followed by pile lowering.

Acceleration of the anchor installation process is more feasible for options (i) – (iii) which involve lower lifting requirements and smaller vessels, which have higher availability. In hard rock conditions, drilling may be unavoidable, but subsea drilling systems for micropile groups have been proposed (Meggitt et al., 2013), as an efficient alternative to large single piles, and have less onerous support requirements.

4.4.2. Site survey and geotechnical characterisation

Commoditisation or streamlining of the anchoring element of offshore wind can extend to the geotechnical site charactersation. For instance, data can be gathered during drilling of micropiles to assess their resistance and adjust the pile length or the pile group size. For instance, this approach has been used to verify the capacity of small grouted piles installed as pipeline stabilisation and has two advantages. It reduces the geotechnical survey effort, and it lowers uncertainty on the pile capacity. However, it depends upon the ability for pile length to be adjusted easily on site, where not all anchor types have this possibility.

General steamlining of site geotechnical characterisation is also being targeted through greater interpretation of geophysical data, including the development of synthetic CPT profiles from seismic survey data in advance of (and to inform) the gathering of physical geotechnical data. Also, using seismic data for spatial interpolation between sparse geotechnical boreholes or in situ tests (Sauvin et al., 2019).

4.5. Inventing new anchor concepts

The final approach to advance anchor performance is through new types or variants of anchor concept. A key concept in this category is the shared anchor concept, in which multiple mooring lines from different turbines are attached to the same anchor, thus reducing the total number of anchors required (Fontana et al., 2018; Pillai et al., 2022). This approach has been used for Equinor's Tampen floating wind project in the North Sea, in which 19 anchors are used to secure 11 floating wind turbines in place (Equinor, 2022).

The embedded ring foundation has recently been proposed as a variation on the suction caisson, which suits shared anchor applications (Lee and Aubeny, 2021, 2020). The ring is created by removing (via pumping) the upper part of the caisson after installation, leaving the disconnectable lower section embedded at depth. Multiple padeyes with anchor line stubs are attached around the circumference of the ring, which by symmetry can resist omnidirectional loads. This is a typical composite-type anchor, which resists lateral loading in a plate manner and vertical loading as a pile.

Variants of drag embedment anchors have been developed to improve suitability in challenging soils: for areas with hard or cemented layers close to the surface, anchors with a serrated front to the shank such as the 'Stevshark Rex' have been developed (Vryhof, 2018).

Micropiles – which comprise a high strength steel rod grouted into a drilled shaft – are widely used onshore, and are being evaluated for offshore use, in the form of groups, connected by a pile cap. In rock seabeds, micropiles are attractive thanks to the inverse relationship between diameter and unit shaft resistance, due to the dilatant interface behaviour, making small piles highly efficient (Seidel and Collingwood, 2001; Thusyanthan et al., 2021).

On rocky seabeds, there is also potential for gravity foundations to be enhanced by similar dilatant interface behaviour. Gravity-based foundations are being used for fixed wind turbines on rocky seabeds, and underbase grouting enhances the sliding capacity of these structures. Cables on rocky seabeds have enhanced stability due to the ruggedness of the seafloor (Griffiths et al., 2019), and a similar behaviour could be harnessed for gravity-based anchors (Coles et al., 2021).

A range of other anchor types have been examined previously, without widespread commercial take-up, although in the emergent market for offshore renewables a renaissance is possible. These technologies include inflatable anchors (Newson et al., 2003), mechanically expandable anchors (Jalali Moghadam et al., 2022; Pisano and di Prisco, 2014), active suction-enhanced foundations (Allersma et al., 2003) and anchors that are shaped like fish (Chang et al., 2019).

Table 3
Comparison of the different anchor types with respect to the technology specificiations (section 2), anchor efficiency (section 3) and innovation potential (section 4). Dimensions after (Intermoor, 2022; Vryhof, 2018). Installation time is relative between 0 (very fast) and 10 (very slow). Ductility can vary between horizontal (H) and vertical (V) loading.

Anchor type	Gravity	Piles			Plates			Composite
Installation method		Driven	Drilled	Suction	Drag	SEPLA	VLA	Screw
Max Dimensions	e.g. 20 × 10 m grillage, but up to 50 m diameter concrete	D = 2–12 m L/D up to 60		D ≤ 16 m, L/D ≤ 1 or 8 (sand or clay)	e.g. 11 × 6 × 6m	e.g. 2.5 × 6m	e.g. 2 × 4m	NA
Efficiency (Fig. 8)	0.3–0.6	12–100	NA	9–240	40–225	46–483	NA	120–740
Installation time (on scale of 0–10)	3–6	3–5	8–9	3–4	3–4	3–4	NA	NA
Restricted to …			Hard ground	Tension mooring if in sand	Catenary mooring	Clayey soil	Taut mooring	
Ductility of response to loading	None	Low (V), moderate (H)			High	Low (V), Moderate (H)		Low (V) High (H)
Environmental considerations	Potential artificial reef	Noisy installation, Grouting discharge **(drilled)**			Large footprint – potential benthic damage			
Decommissioning	Recoverable	Non recoverable		Recoverable	Recoverable			Recoverable
Positioning	Accurate	Accurate			Uncertain embedment due to keying or drag processes; Uncertain position in plane due to anchor drag			Accurate
Suitable for shared anchors	Yes	Yes	Yes	Yes	No	No	No	Yes
Strengths	Silent installation and simple design	All solutions are well-established. **Driven:** robust and appropriate for layered grounds **Drilled:** only solution for rocky seabed **Suction:** silent installation, accurate positioning			**Plates** have the highest efficiency **Drag:** very well established and limited craneage requirements **SEPLA:** reusable installer, accurate positioning in plane			Silent installation and accurate positioning
Weaknesses	Craneage limitations, Seabed bearing capacity/ tilt.	**Driven:** refusal in hard ground, obstruction **Drilled:** complex process, grout discharge **Suction:** installation in layered soils, obstructions, needs good data for flow rates			**Drag/VLA**: uncertain embedment in hard or layered soils, each anchor is specific, require large bollard pull			Require demonstration at scale
Enhancement potential	Inclusion of whole-life, ductility and inertial/rate effects in design methodologies	Groups of micropiles			Upscaling of anchors, design methods improvements, prediction of final embedment			Groups, installation kit, design methods

Finally, new installation methods of existing anchor types can be used to clear some of the constraints previously identified. For instance, new techniques aim at reducing or suppressing underwater noise during pile installation, by using a cluster of sequentially installed piles (Huisman et al., 2022), or a combination of axial and torsional vibration (Kementzetzidis et al., 2022), or axial and rotary jacking (Deeks et al., 2010). Self-drilling and groutless anchors can be develop in rock (Cresswell et al., 2016) to reduce the environmental impact.

5. Summary

This section of the paper provides a summary of the earlier analysis and also provides a condensed comparative summary of the project considerations associated with each anchor type (see Table 3). From a purely geotechnical point of view, it is clear that plate-type anchors are the most efficient, as per section 3 definition. However, from a project perspective, the optimal anchoring solution will depend on many non-geotechnical factors, from the capabilities of the supply chain to the type of mooring configuration selected. Table 3 offers a wider picture of technical specificities, anchor efficiency and innovation potential of the different anchor types covered in this paper. This table can be used to quickly assess the location-specific suitability of anchor and mooring solutions in parallel with the design of the floating structure.

From a research perspective, anchor technologies with the highest enhancement potential are also those which require the most research to improve predictive methods (e.g. drag process or screw pile capacity) or installation equipment development (e.g. screw piles). While the trend for fixed-bottom foundations has been to continuously increase the dimensions of a single foundation type (e.g. monopile), using groups of smaller anchors could reduce the pressure on the supply chain (e.g. reducing demand for the limited fleet of larger transport and installation vessels), but requires much more research to quantify group interaction during loading and installation. Finally, the cost and complexity of installation of drilled piles, and the lack of suitable alternatives signpost anchoring in hard ground as in great need of research investments.

6. Conclusions

The expected growth of the floating wind market in the future will put significant pressure on the industry as a whole to design, manufacture and install a large number of cost-effective and reliable anchors. To meet these goals, it is imperative to optimise anchor design and innovate, either by enhancing design practice or inventing new technologies. Anchors are important components of the mooring system which should be considered and included from the start in a holistic design of the floating structure, as the seabed soil properties can rule out some anchoring technologies, and hence can constrain the mooring solution. This paper provides a state-of-the-art review of the current practice, a systematic comparison of anchor performance in representative soil conditions and a mapping of potential for innovations, which can be used by developers and designers as a quick decision tool at the early stages of design.

State-of-the-art anchor technologies have been classified into three families (gravity-type, pile-type and plate-type), based on the way in which they mobilise the surrounding ground to resist mooring loading. The monotonic resistance of the most common anchor technologies was compared accross a range of common soil conditions, allowing for the different sizes of anchor that can be produced by using simple design methodologies while accounting for installation constraints to show their relative merits and cost-performance trends.

The analysis shows that plate-type anchors are the most efficient (highest resistance to anchor mass ratio), and have good potential for upscaling, i.e. to increase in dimension and mass for more demanding future applications. The analysis also highlights how current installation constraints (e.g. aspect ratio, installation tool power) cap the performance of some anchor types, and sheds light on soil conditions and technologies that require innovation. A summary of additional challenges (e.g. cyclic loading, rate effects) and how they are tackled in practice is also provided. The outcome of this analysis is summarised via simple analytical expressions that provide a tool to compare the efficiency and upscaling potential of different anchor technologies in a techno-economic analysis of a floating offshore wind system.

The potential future enhancements of anchor technology developments were examined by exploring emerging innovation and research ideas that can advance anchor performance-cost response. Firstly, a better understanding of geotechnical mechanisms and a systems-based approach to design can *unlock* overlooked components of anchor resistance, for instance by considering whole-life enhancements in seabed resistance, by including installation effects or constraints on anchor performance, or by taking into account rate or inertial effects induced by the mooring line. Secondly, anchors can be *upscaled* in size, thus increasing their capacity, although this can have a trade off with installation considerations and limitations of the supply chain. These latter can be overcome by *commoditising* anchors to enable their rapid mass production. Finally, inventing new anchor types or variants can enhance advances in anchor technology, leading to new concepts including, shared anchors, where multiple mooring lines from different turbines are attached to the same anchor, or grours of smaller proven anchor technology (e.g. micropiles, screw piles).

CRediT authorship contribution statement

Benjamin Cerfontaine: Conceptualization, Formal analysis, Writing – original draft, Visualization, Supervision. **David White:** Conceptualization, Writing – original draft. **Katherine Kwa:** Conceptualization, Formal analysis, Writing – original draft. **Susan Gourvenec:** Conceptualization, Writing – review & editing. **Jonathan Knappett:** Writing – original draft. **Michael Brown:** Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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