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# Drained monotonic and cyclic capacity of a dynamically installed plate anchor in sand

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ABSTRACT

The emergence of commercial offshore floating renewable energy devices that are expected to be deployed in large integrated arrays in relatively shallow water requires anchor types that are suited to sandy seabeds. This paper considers centrifuge test data that quantify the capacity of a novel dynamically installed plate anchor in sand under drained monotonic and cyclic loading. The monotonic tests investigated the role of the eccentricity of the load attachment point from the plate, the mooring line load inclination at the seabed and the plate embedment depth, whereas the cyclic tests examined the capacity mobilisation due to both regular and irregular drained cyclic loading for a fixed embedment depth and seabed load inclination. The test data indicate that an optimal anchor design would employ a load attachment point that is eccentric from the plate by at least 0.6 times the plate height, and that the anchor provides higher capacity when the seabed load inclination is horizontal (catenary mooring) than when it is vertical (vertical taut mooring). The centrifuge data show that drained cyclic loading does not degrade anchor capacity, and may be beneficial provided the cyclic loading involves a history of lower level cyclic loading that densifies the sand.

## 1. Introduction

Offshore renewable energy devices, including wind turbines, wave and tidal energy converters, offer significant potential to move towards clean, renewable energy. Floating wave energy convertor and wind turbines are maintained on station using mooring lines that terminate at anchors located on or embedded in the seabed. Knappett et al. (2015), Diaz et al. (2016) and Gaudin et al. (2017) review existing anchor technology in the context of the technical requirements and economic constraints associated with offshore floating renewable energy. These studies note that plate anchors are attractive due to their high holding capacity yet low size and weight, although difficulties in installing plate anchors in the sand dominated seabeds that floating energy devices are likely to be located may constrain their use. Plate anchors may be installed by drag embedment, although adequate penetration of drag anchors in sand is notoriously difficult and challenging to predict (Neubecker and Randolph, 1996; Heurlin et al., 2015; O'Loughlin et al., 2017). Other anchor types, such as driven piles may be used, although they are less efficient, and installation requirements and durations are considerable. This has the potential to seriously impact the economics of emerging marine renewable energy technologies, which will be deployed in large integrated arrays requiring a large number of accurately positioned anchors.

An alternative solution could be dynamically installed anchors, which require minimal installation time and can be deployed without the need for dedicated ancillary equipment such as pile hammers. Dynamically installed anchors are installed by allowing them to free-fall through the water column, such that the combination of their self-weight and the kinetic energy gained through free-fall embed them into the seabed. Various anchor designs have been proposed for deep water soft sediments (e.g. Lieng et al., 2000; Medeiros Jr. 2002; Shelton, 2007; O'Loughlin et al., 2014) and have been used or considered for offshore oil and gas floating facilities. Current dynamically installed anchors are generally perceived to be less suitable for sand due to the dilatant behaviour of sand and concerns regarding embedment potential. However, alternative dynamically installed anchor designs may achieve higher penetrations in sand, and prove to be a viable anchoring solution for granular seabed deposits (e.g. Gerkus et al., 2016).

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This paper considers one such dynamically installed anchor concept that has been designed primarily for sand, although may also prove to be feasible in other seabed sediments. The anchor and the installation process is conceptually shown in Fig. 1. The anchor adopts a thin ‘blade-like’ design which contrasts with the majority of existing dynamically installed anchor designs that typically utilise solid cylindrical shafts with conical or ellipsoidal tips (O'Loughlin et al., 2004). The anchor features a plate at its lower end that is attached to an upper removable follower that provides the additional mass to increase penetration potential. In cross-section the plate is comprised of two thin blades that project from a central core, and taper from a maximum width at the top of the plate to zero width at the bottom of the plate. Two additional fins at the trailing end of the upper follower (Fig. 1) are included to improve hydrodynamic stability during freefall in water. Following embedment, the follower is retrieved to the installation vessel for re-use in the next installation, leaving the plate anchor vertically embedded in the seabed.

The embedment potential of the anchor has been demonstrated through centrifuge tests in loose and dense silica sand (Chow et al., 2017). Anchor tip embedments were in the range 0.9–2.2 times the plate height in these centrifuge tests, and were strongly dependent on impact velocity, follower mass and sand density. This suggests that deeper anchor embedment could be achieved by geometrically optimising the follower. Subsequent centrifuge studies investigated the monotonic and cyclic capacity of the anchor in saturated dense silica sand to quantify the capacity potential of the anchor. The results from these studies are considered in this paper.

## 2. Centrifuge tests

### 2.1. Soil properties and sample preparation

The centrifuge tests were conducted in medium dense sand samples that were prepared using a commercially available fine sub-angular silica sand with properties as listed in Table 1. Seven sand samples were prepared at 1*g* in centrifuge sample containers with internal dimensions of 650 × 390 × 325 mm (length × width × depth) by air pluviation to give final sample heights of approximately 200 mm. Each sample was vacuum-levelled to create a level surface and then saturated with water from the base of the container. About 40 mm of free water was maintained above the sand surface during the centrifuge testing. The relative density was $D_r = 66 \pm 3\%$ (saturated densities, $\rho_{sat} = 2034–2043$ kg/cm$^3$), with the exception of one slightly looser sample for which $D_r = 53\%$ ($\rho_{sat} = 2017$ kg/cm$^3$). Each sample was spun to the testing acceleration of 50 g and two cone penetrometer tests (CPTs) were conducted to characterise the samples. The cone penetrometer tests were performed using a model cone penetrometer with a diameter of 10 mm penetrated at a velocity, $v = 1$ mm/s such that the response is expected to be drained (Silva and Bolton, 2004). As shown in Fig. 2, the cone tip resistance, $q_c$, increases with depth in all samples, which reflects the increasing vertical effective stress with depth. Variations in $q_c$ between samples are consistent with the measured range in $D_r$, and indicate that the profile of strength and density is relatively consistent across the seven samples.

**Table 1**
Properties of silica sand used in this study.

| Property | Value |
|---|---|
| Specific gravity, $G_s$ | 2.67 |
| Particle size, $d_{10}$, $d_{50}$, $d_{60}$ | 0.12, 0.18, 0.19 mm |
| Coefficient of uniformity, $C_u$ | 1.67 |
| Coefficient of curvature, $C_c$ | 1.02 |
| Minimum dry density, $\rho_{min}$ | 1497 kg/m$^3$ |
| Maximum dry density, $\rho_{max}$ | 1774 kg/m$^3$ |
| Critical state friction angle, $\phi'_{cs}$ | 31.6° (triaxial) |

### 2.2. Model anchors and mooring line

Four model anchors (A1, A2, A3, A4) were manufactured for the centrifuge tests as shown in Fig. 3. Each model anchor was wire-cut (electrical discharge machining) from a single block of stainless steel, followed by precision machining to achieve the detail around the anchor padeye and the taper on the plate. The models are at a 1:50 reduced scale and maintain the same material density as the field scale anchor, such that the centrifuge scaling laws (Garnier et al., 2007) apply. These imply that a practically sized full-scale anchor would have a plate height of 2.4 m, a follower length of 7.25 m (with a mass of 5134 kg) and an anchor mass of between 1290 and 1960 kg (depending on the anchor), although variations on this are to be expected based on the mooring requirements.

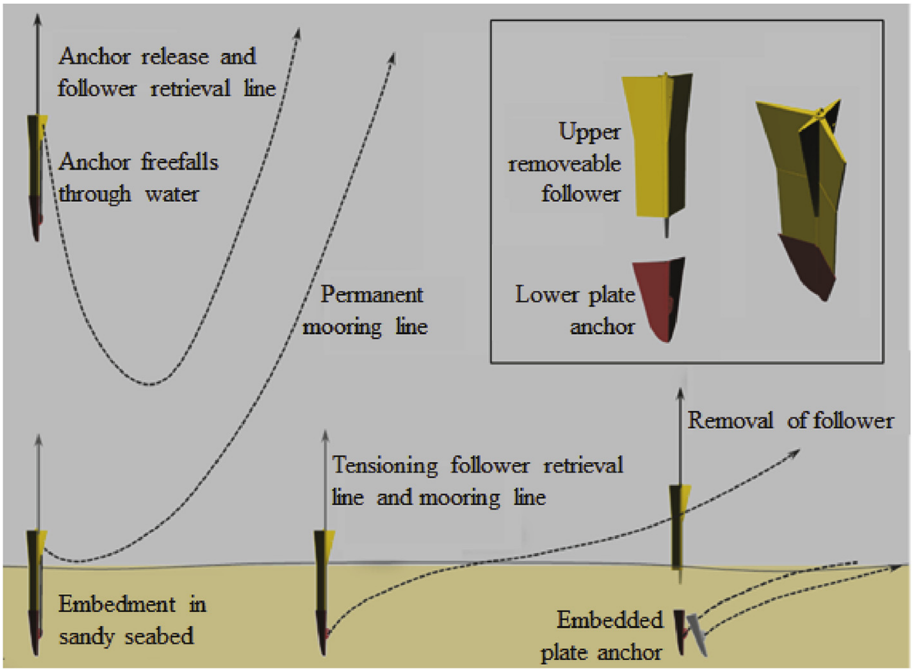

**Fig. 1.** Dynamically installed anchor concept.