Repurposing Flexible Flowlines as Torpedo Anchors for Offshore Floating Renewable Energy Devices

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Abstract

Flexible flowlines are tubes made of layers of metal and polymers laid across the ocean floor to transport fluids in oil and gas production. There are thousands of kilometres of flexible flowlines in Australia that will be decommissioned from depleted oil and gas fields in the next thirty years. The design and composition of these pipes make recycling challenging. In an effort to find sustainable alternatives and promote a circular economy, this study will investigate the feasibility of repurposing flexible flowlines as torpedo anchors for mooring offshore floating renewable energy generators. The investigation is completed in two stages. The first stage is to generate designs for the anchors based on the specifications of a flexible flowline and features of infield torpedo anchors. The second stage is to test the efficacy of the designs by measuring their hydrodynamic and geotechnical performance. Six model anchors (3D printed) will be released to freefall through still water in the UWA Large O-Tube to measure the drag coefficient and freefall stability. The results will inform the three best designs (fabricated by workshop) to undergo dynamic installation in a centrifuge to measure embedment depth and holding capacity in preconsolidated kaolin clay. The results will be compared with the performance of torpedo anchors infield and literature.

1. Introduction

Flexible flowlines are tubes made of layers of corrosion resistant steel wires cocooned in a leakproof thermoplastic jacket. The flowlines are used to transport fluids in oil and gas production and are decommissioned at the end of field. The Australian oil and gas industry asset stock includes 1700 km of infield flowlines that will likely be removed from operation in the next thirty years (Advisian, 2020). This stockpile of material provides an opportunity for innovation to develop more sustainable equipment to support the energy transition. To this end, upcycling of decommissioned components into other functions will minimise the resources used to manufacture new materials, while diverting quality materials such as steel, copper, and polymers away from landfill.

One idea is to turn the flexible flowlines into torpedo anchors for mooring offshore floating structures, which is pertinent to meeting growing investment in offshore renewables. Flexible flowlines are heavy and fabricated in lengths of several hundred metres, so turning the flowlines into torpedo anchors has the advantage of reducing them to manageable lengths. For example, flowlines from the Enfield oil field weigh up to 200 kg/m unflooded in air (HeroX, 2021). On the other hand, torpedo anchors are rocket shaped, steel pipes filled with scrap metal or concrete and sealed with a cone nose. First developed in 1996, torpedo anchors have been used to anchor flexible risers and semi-submersible drilling rigs to the seafloor (Brandão et al. 2006; Lieng, Tjelta & Skaugset, 2010). Torpedo anchors are launched vertically into free fall from a designated height above seabed and drive into the soil by the kinetic energy gained during descent. Table 1 compares the specifications of infield torpedo anchors with that of flexible flowlines from the Enfield oil field (HeroX, 2021). No prior work has been completed to assess the feasibility of turning flexible flowlines into torpedo anchors, so the aim of this project is to prove the concept and determine whether further investigation is worthwhile.

	Torpedo Anchors	**Flexible Flowlines**
Length (m)	10 - 17	Hundreds of meters to be cut to design
Outer Diameter (inch)	30 - 42	< 15
Mass (kg per m)	2000 - 6500	< 200
Features	Three to four rectangular or trapezoid flukes, conical nose	Layers of steel cocooned in thermoplastic jacket
Release Height Above Seabed (m)	40 - 135	
Terminal Velocity (m/s)	~ 36	
Tilt on Impact (degrees)	2 - 9	
Tip Embedment Depth (m)	9 - 35	
Holding Capacity (kN)	~ 7500	

Table 1 Dimensions and installation parameters of infield torpedo anchors, compared with that of flexible flowlines from the Enfield oil field

1.1 Effective Torpedo Anchors

Torpedo anchors must freefall with accuracy and speed through water to reach the seabed in an upright position to embed deeply and maximize the resistance to extraction in all directions. Freefall stability; terminal velocity; embedment depth; and holding capacity are maximized by optimizing an anchor's geometry.

A higher impact velocity is implied by a higher terminal velocity, which in turn is achieved by minimizing the drag force on the anchor. For a given mass, drag force is minimized by minimizing the drag coefficient. For achieving freefall stability, Fernandes et al. (2011) proved it was necessary to move the apparent center of gravity below the hydrodynamic center.

Resistance to extraction is provided by the friction between the soil and anchor, as well as the weight of the soil bearing down. In general, resistance to extraction increases with tip embedment, which in turn increases with impact velocity and anchor mass. Richardson (2008) installed model torpedo anchors into soft clay and found that for an anchor of given mass and diameter, increasing length (aspect ratio) decreases tip embedment. However, deeper embedment was observed when keeping density constant and allowing mass to increase linearly with aspect ratio, which suggests that the greater mass overcomes the additional frictional resistance added by the increased surface area. Moreover, anchors with sharper tips were conducive to deeper embedment and greater resistance to extraction. Fins also influence the embedment depth. Longer, and wider fins decrease tip embedment but provide greater surface area over which friction can resist extraction. Ads et al. (2020) found that for torpedo anchors with the same aspect ratio and weight, longer fins decreased tip embedment but increased holding capacity by more than finless torpedo anchors.

2. Process

2.1 Design Generation

The body of the new torpedo anchors are based on the dimensions of an inner diameter 9-inch (production) flexible flowline from the Enfield oil field, which was selected for its large outer diameter (15 inch) and heavy specific mass (196 kg/m). The design will include a 30º cone nose, flukes and be ballasted with scrap material. Although the nose, flukes and ballast are unlikely to be fabricated from the flexible pipe itself, these features were deemed necessary to maximize the anchor's chance of embedment in soil and provide a starting point for further design. Truncating, cutting, and carving the surface of the flexible pipe were assumed possible.

Six designs were finalized for testing at model scale in water. Two were inspired by the geometry of torpedo anchors used in industry (T-98 and DPA) but sized to the body of a 15-inch flexible pipe. These incorporate the flexible pipe the least, however, provide a benchmark to assess whether features unique to the flexible pipe will aid or penalise performance. The two novel designs build on the DPA benchmark (L/D = 11) and each sport one change that is unique to the flexible pipe: semicircular fins created by cutting a flexible pipe in half lengthwise, and fish scales carved into the outer jacket of the flexible pipe (Figure 1). The ring fins and fish scales are hoped to increase the anchor's resistance to extraction from soil. Table 2 summarises the designs.

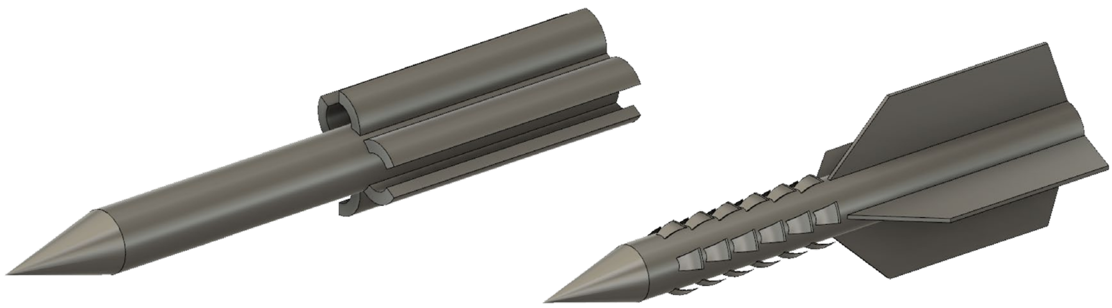

Figure 1 New designs: anchor with three semicylinders interlocking the flexible pipe as flukes (left) and with fish scales carved into the polymer jacket (right)

Anchor	Length (m)	Diameter (m)	Distinguishing Feature
(#1) T-98	6.0	0.38	Four rectangular fins 0.32 m x 3.6 m
(#2) DPA	4.2	0.38	Four trapezoidal fins
Ring Finned Anchors: (#3) 3R, (#4) 4R	4.2	0.38	1. Three 9-inch half cylinders 2. Four 6-inch half cylinders
Fish Scales: (#5) SS, (#6) LS	4.2	0.38	Fish scales carved into the upper shaft (arbitrary sizes: small, large)

Table 2 Prototype dimensions and features of the six torpedo anchors which were tested at 1/30 scale in the UWA Large O-Tube

2.2 Testing in Water

Six designs were 3D printed at 1/30 scale and ballasted with lead pellets, then released vertically to freefall through still water in the deepest section (1.4 m) of the UWA Large O-Tube. The trajectory of the freefall was filmed, and the displacement extracted using the free video analysis and modelling tool Tracker. The displacement was numerically differentiated for velocity and acceleration, which were used to find the drag coefficient based on the force balance of an object freefalling through water given by:

$$Accelerating\ Force\ on\ Submerged\ Body = Submerged\ Weight - Drag$$

$$(\rho_{anchor} - \rho_{water})\mathrm{V}a = (\rho_{anchor} - \rho_{water})\mathrm{V}g - \frac{1}{2}\rho_{water}v^2 C_D A$$

$$a = g - \frac{\rho_{water}v^2 C_D A}{2(\rho_{anchor} - \rho_{water})\mathrm{V}}$$

$$C_D = \frac{2(\rho_{anchor} - \rho_{water})V}{\rho_{water}A} * \nabla \qquad \text{Equation 1}$$

Where $C_D, \rho_{anchor}, \rho_{water}, A, V\ and\ \nabla$ are the drag coefficient, density of the anchor, density of the water, projected area of the anchor, volume of the anchor and the gradient of the line describing the relation between acceleration and velocity squared, respectively. The freefall stability of the designs was evaluated by the anchor's maximum tilt angle and the distance between release and impact locations. Each anchor was released at least ten times.

2.3 Testing in Soil

One benchmark and two new designs will be dynamically installed into preconsolidated kaolin clay to measure the embedment depth and holding capacity under vertical monotonic loading. Installation in the centrifuge will allow accurate replication of the body forces (weight) and stress conditions of the prototype at laboratory scale. The models are fabricated at 1/50 scale from steel, under the assumption that the prototype can be ballasted with material heavy enough to achieve a density close to steel (7800 kg/m^3).

3. Results and Discussion

A typical acceleration versus velocity squared plot is shown in Figure 2a for an anchor freefalling in water. The initial region shows the anchor accelerating downwards on entry into water before the drag coefficient becomes constant and Equation 1 holds. This observation is consistent with Fernandes et al. (2006), who find that there are two acceleration periods in an anchor's descent: an initial acceleration during which C_D is likely varying fast, followed by a second acceleration period during which C_D is well defined and constant. The last region describes the anchor's impact with the floor (acceleration upwards and decreasing velocity).

C_D values were calculated for the top, middle and bottom third of the descent for each track to assess how C_D was changing. Figure 2b shows the C_D values for each third averaged across the tracks for each anchor. The drag coefficients for the middle third were the most consistent (smallest standard deviation) for all anchors. This may be due to variations in the initial tilt angle or the difficulty in tracking the object at the edges of the camera frame.

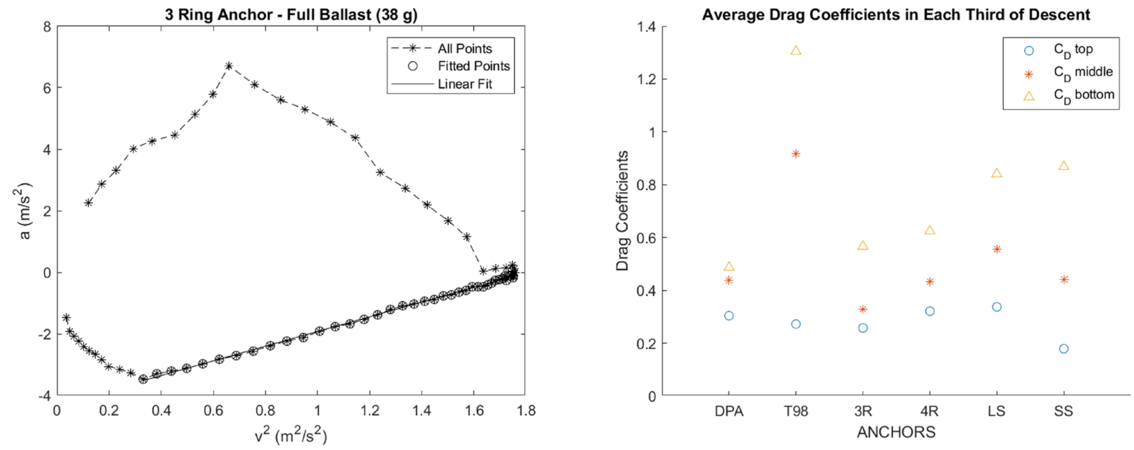

Figure 2 **(a)** Typical acceleration versus velocity squared plot for one track, and (b) drag coefficients for the six anchors

The drag coefficient for the DPA geometry was within the reported range (0.2 – 1.2 by Hasanloo et al., 2010). However, that for the T-98 geometry was higher than reported (0.5 by Fernandes et al., 2006). This may be because the tank was too shallow for the longer anchor to reach flow regimes with higher Reynolds numbers and truly stable drag coefficients ($Re > 10^6$ in the reported source compared to $< 3.4 \times 10^4$ in this study). For example, Hasanloo et al. (2010) released three finned, steel torpedo anchors through 4 m of still water and found that C_D decreased from 0.8 to 0.4 when Reynolds number increased from 1.1×10^5 to 1.3×10^5. Regardless, a comparison between the benchmark and new designs can still indicate relative performance. The drag coefficients of the three and four ringed anchors are similar to the DPA for all thirds. The same is observed for the fish scaled anchor but with greater range across the thirds.

Figure 3a shows the impact locations for one anchor and 3b shows the distance between the point of impact and release. The benchmark DPA is the most precise as expected of an infield anchor. All other anchors except for that with large fish scales had comparable dispersions.

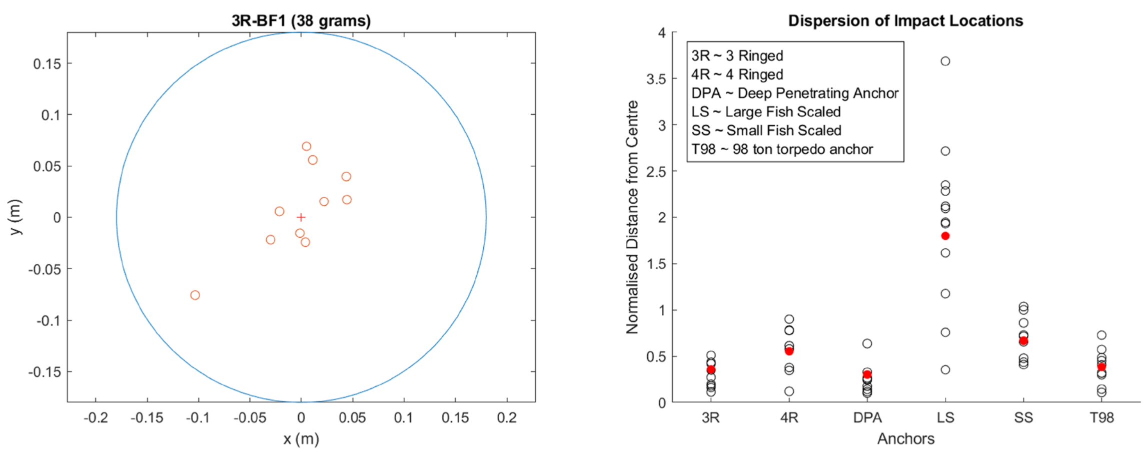

Figure 3 (a) impact locations of 3 ringed anchor, (b) distances from the center of each release, each hollow point denoting one track and solid points denoting averages

4. Conclusions and Future Work

The objective of this project is to investigate the performance of torpedo anchors constructed from flexible flowlines. The angle adopted by the project is to check whether the geometry of the new designs would penalize, if not enhance, the performance. The benchmark DPA had the greatest freefall stability as measured by the shortest distance from the point of release to landing (average 0.04 m). Moreover, changing the shape of the flukes did not penalize the drag coefficient greater than 20% even if considering the worst (largest) values from the bottom third: 0.57 and 0.49 for the three-ring finned anchor and DPA, respectively. The fish scaled anchors were perhaps expected to perform worse because the protrusions make the surface of the body rougher. The accuracy of the anchor with smaller fish scales, however, makes the design worthwhile testing in soil to assess whether the serrations increase holding capacity.

The remaining work is to test the performance of the new designs in soil. The DPA, three ring finned and fish scaled anchor will be dynamically installed at 1/50 scale into preconsolidated kaolin clay. The tip embedment will be measured, then the anchors will be pulled out at a constant loading rate to measure the resistance to extraction. Three installations per anchor are planned, each at a different release height (impact velocity). The performance of the new designs will be compared with the benchmark anchor and literature.

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