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The Flexibly Embedded Plate Anchor: An efficient and adaptable anchoring system for floating wind

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ABSTRACT: A flexibly embedded plate anchor (FEPLA) is a new anchor type designed for floating offshore wind comprised of a removable central multi-function follower capable of embedding a plate anchor in a range of soil types. The FEPLA penetrates the plate to a target depth by several installation methods including vibro hammering and impact hammering. After plate installation, the central follower is retrieved and reused for the next installation, leaving the plate anchor vertically embedded in the soil which may be keyed, similarly to other vertically embedded plate anchors. This paper introduces the novel anchor, focusing on two of the installation methods: impact hammering and vibro hammering. Driveability is assessed for a range of soil profiles and plate anchor sizes using industry standard methods. The potential advantages of multi-function installation are discussed along with the next steps in the FEPLA development.

Keywords: anchor, vibro hammer, impact hammer, plate anchor

1 INTRODUCTION

The Flexibly Embedded PLate Anchor (FEPLA®) is a new update to the Suction Embedded PLate Anchor (SEPLA®) (Wilde et al., 2001) that has seen hundreds of installations worldwide since 1998. The FEPLA is unique in that it uses a removable multi-function follower to install a plate anchor to target depth.

The anchor combines the installation benefits of a vibro and impact hammer with the capacity benefits of a plate anchor. The multi-function follower, shown in Figure 1.1, comprises a vibro hammer clamped to the top of the follower and an impact hammer encased in the follower and secured at the lower end. The closed-ended follower is slotted to allow for the plate anchor to be held in place during installation with a hydraulic anchor clamp, similar to the vibro clamp, and stop cap at the base of the follower.

The FEPLA penetrates the plate to a target depth in the seabed by a combination of installation methods shown schematically in Figure 1.2 and described in the following stages:

1. Setup and Lowering. The FEPLA follower and plate anchor is assembled on the deck. The mooring line is attached to the plate anchor by means of twin plate steel shank. The plate anchor is mounted to the bottom of the follower. Followers are compatible with a range of plate sizes. The assembled follower with plate anchor slotted in the bottom is then lifted from the deck. The FEPLA is lowered vertically through the water column to the target position at the seabed.
2. Vibro Installation. The FEPLA is installed by vibro installation until stability depth is reached or until refusal. The stability depth is the depth where the pile is geotechnically and structurally stable when the winch is slack.
3. Impact Hammer Installation. Once the stability depth is reached or vibro refusal criteria is met, the winch is lowered further to introduce slack. The FEPLA is further penetrated to the target penetration depth by the impact hammer contained within the follower.
4. Follower Recovery. At target penetration, the plate anchor clamp is released and the winch cable line pulled vertically. To ensure upward movement of the follower and that the plate anchor remains stationary at the target penetration depth, the vibro can assist in the follower retrieval and be returned to the vessel

deck. The final step that may be considered is the plate anchor keying. However, this step is not considered in this study.

This paper introduces the novel anchor and provides an overview of an analytical study in a range of soil types. The vibro installation stage (2) is assessed with a CAPE vibratory hammer and the impact hammer installation stage (3) considers drivability using a MENCK hammer. The desk study represents the first performance data results of the FEPLA and provides insight into the feasibility of the new concept as well as identifying knowledge gaps for the anchor development.

Figure 1.1. Flexibly embedded plate anchor (Credit: Acteon)

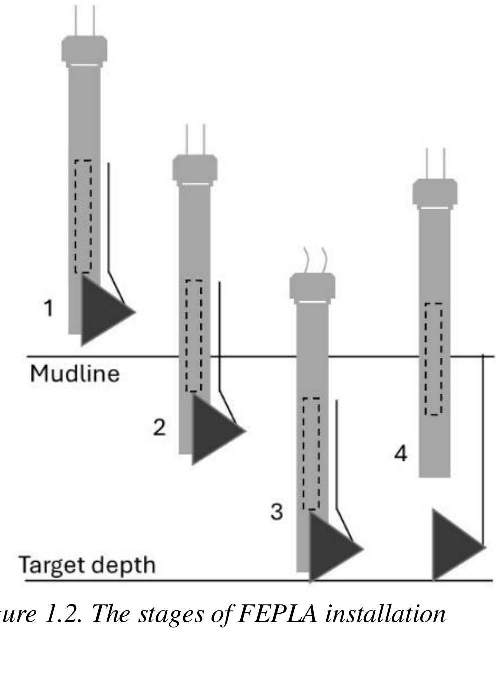

Figure 1.2. The stages of FEPLA installation

2 ANALYSIS MODEL

2.1 Soil Profiles

Four design profiles, representing a variety of site conditions including soft clay (*SC*), uniform clay (*UC*), medium sand (*MS*), and dense sand over clay (*SOC*) have been assumed for the study, with details provided in Table 2.1.

Table 2.1. Design soil profiles

Soil Profile	**Depth**	**Soil Type**	γ'	s_u	Φ'
-	m	-	kN/m^3	kPa	°
Soft Clay (*SC*)	0.0	Clay	7.0	1.0	-
	40.0	Clay	7.0	49.0	-
Uniform Clay (*UC*)	0.0	Clay	9.0	50.0	-
	40.0	Clay	9.0	50.0	-
Medium Sand (*MS*)	0.0	Sand	10.0	-	33.0
	40.0	Sand	10.0	-	33.0
Dense Sand Over Clay (*SOC*)	0.0	Sand	11.0	-	36.0
	10.0	Sand	11.0	-	36.0
	10.0	Clay	12.0	75.0	-
	40.0	Clay	12.0	75.0	-

2.2 Follower and Anchor Properties

Four plate anchor and follower sizes are given in Table 2.2 corresponding to the four soil profiles above. Note that a comprehensive plate anchor sizing or follower sizing has not been conducted for this preliminary scope. Instead, the plate anchor sizes provide a general range considered applicable to the floating wind industry with approximately 1,000Te maximum intact mooring tension at the seafloor.

The bottom of the FEPLA is shown in Figure 2.1. Plate thickness varies from 75mm for the shank to 120mm for the main plate. The follower OD is 1.22m with a wall thickness of 20mm and 25mm. The D/t ratio is ~60 and the follower L/D ratio varies ~15 to ~30. Inside the follower, the hammer cushion has been positioned 1m above the top of the plate anchor.

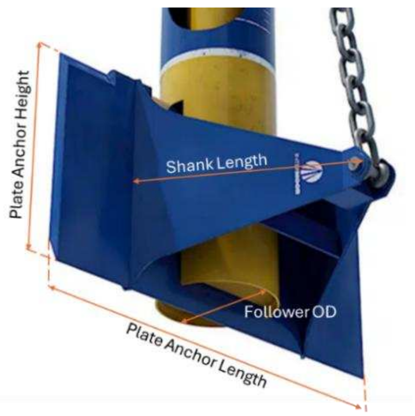

Figure 2.1. FEPLA dimensions

Table 2.2. FEPLA dimensions

Parameter	*SC*	*UC*	*MS*	*SOC*
Plate Anchor Height (m)	6.8	5.6	3.1	4.6
Plate Anchor Length (m)	8.8	7.3	4.0	6.0
Plate Anchor Shank Length (m)	3.4	2.8	1.6	2.3
Follower Penetration (m)	34.70	28.60	18.45	23.50
Hammer Ram Depth Inside Follower (m)	26.90	22.00	14.35	17.90

2.3 Hammer Selection

2.3.1 Impact Hammer

The MHU270T is a closed-loop hydraulic system hammer, powered by MENCK's MHU power pack. It is suitable for pile driving in water depths up to 3,000m (10,000ft). Impact hammer and cushion details are provided in Table 2.3.

Table 2.3. Impact hammer properties

Parameter	Value
Name	MENCK MHU270T
Maximum Energy Rating (kJ)	270
Hammer Efficiency* (%)	95
Stroke (m)	1.89
Hammer Weight (Te)	38.05
Anvil Weight (Te)	6.83
Cushion and Helmet Spring Stiffness (kN/mm)	10,000 (assumed)
Coefficient of Restitution (-)	0.8

* >95% energy transfer in air. Hammer efficiency decreases with water depth.

As defined in the MENCK operational manual, the recommended blowcount for suitability of a hammer size is 100 blows/0.25m. The refusal criteria for the continuous driving without any long interruption is reached when the blow count exceeds 250 blows/0.25m.

2.3.2 Vibro Hammer

The S-CV320 has the capabilities of a traditional vibro hammer, including a gearbox with eccentric gears to generate vibration, a suppressor to dampen vibrations to the crane, and clamps to fix the vibro tool to the pile. Details of the vibro hammer are provided in Table 2.4. The refusal criterion is met when the penetration rate is less than 0.002m/s (Trubshaw et al., 2022).

Table 2.4. Vibratory hammer properties

Parameter	Value
Name	CAPE S-CV320
Maximum Power (kW)	1,307
Hammer Weight (Te)	75.1
Frequency (Hz)	23.3
Hammer Efficiency (%)	100

3 METHODOLOGY

3.1 Soil Resistance to Driving, SRD

For the impact hammer installation stage, SRD are calculated for each FEPLA geometry and soil design profile. The unit skin friction and unit end bearing are calculated per Stevens et al. (1982). Since the follower is essentially closed-ended, SRD is assessed for plugged pile conditions. Given the generalized soil profiles, upper bound parameters given in Stevens et al. (1982) have been used.

3.2 Soil Resistance to Vibro Driving, SRV

For the vibro installation stage, the unit skin friction component of SRD is reduced to account for the reduction of contact pressures in granulated soil and the increase of excess pore pressure in cohesive soils. Jonker (1987) proposed a reduction factor, β whereby the SRV unit skin friction, $f_{s,vibro}$ (kPa) is calculated as:

$$f_{s,vibro} = \beta \cdot f_s \quad (1)$$

For this study, $\beta = 0.5$ has been selected, which is slightly higher than the range of 0.1 to 0.45 proposed by Jonker (1987), but similar to the back-calculated results of Robertson (2010) and Trubshaw et al. (2022).

No reduction factor has been applied for end bearing, due to uncertainty about the effects of the FEPLA geometry on vibratory driving, discussed later.

3.3 Dynamic Analysis

The drivability analyses for both the vibro and impact hammer installation stages are preformed using GRLWEAP, Offshore Version 14.1.20.1 (Pile Dynamics, Inc., 2021).

The dynamic resistance is represented by damping and quake values that account for the inertia and viscosity effect of the soil. For the vibro analysis, there is considerable uncertainty regarding suitable dynamic parameters. The quake and damping coefficients are taken from Alm and Hamre (1998), where toe and shaft quake are 2.5mm, toe damping is 0.5s/m and shaft damping is 0.25s/m. Similar dynamic parameters have been considered in vibro back-analyses described in Irvine et al. (2023).

3.3.1 Hammer Properties

The impact hammer is described in Table 2.3. The hammer was modelled 1.0m above the top of the plate anchor using the bottom driving mode in GRLWEAP. Although bottom driving is unusual offshore, it is frequently done onshore. Generally, the hammering point can be any part of the pile. In GRLWEAP, similar analyses are used for hammering at the top and bottom of the pile. In bottom driving mode, the hammer ram strikes a cushion and helmet. The cushion and helmet stiffness are currently not available for GRLWEAP for this novel anchor. Therefore, it has been assumed at 10,000kN/mm which is in line with cushions of similar diameter.

The vibro hammer used for analysis is the CAPE S-CV320, described in Table 2.4.

3.3.2 Pile Properties

The FEPLA follower and plate anchor have been modelled as a non-uniform hollow steel pile. The model is separated into two sections: the follower and the plate anchor. Cross-sectional area and perimeter have been selected to reflect the FEPLA skin friction area and bearing area. Specific weight is calculated by dividing the total weight of the section by the modelled solid volume of the section. For the follower section, the weight of the inactive hammer is also included in the total weight of the section (i.e., in impact analysis, the vibro hammer weight is considered; in vibro analysis, the impact hammer weight is considered).

4 RESULTS

4.1 Soil Resistance to Driving and Vibro

Results of the upper bound soil resistance to driving and vibro are plotted in Figure 4.1. The SRD/SRV increases with depth for the clay profiles and medium sand, and it increases with depth until 10m and then reduces for the dense sand over clay profile.

Given the unique plate/pile geometry shown in Figure 2.1, the proportion of bearing resistance is very high, particularly in sand where it accounts for ~90% of the SRD. This is expected given that the total bearing area of the plate anchor, including the main plate, shank, and padeye block, is typically over twice the bearing area of the essentially closed-ended follower.

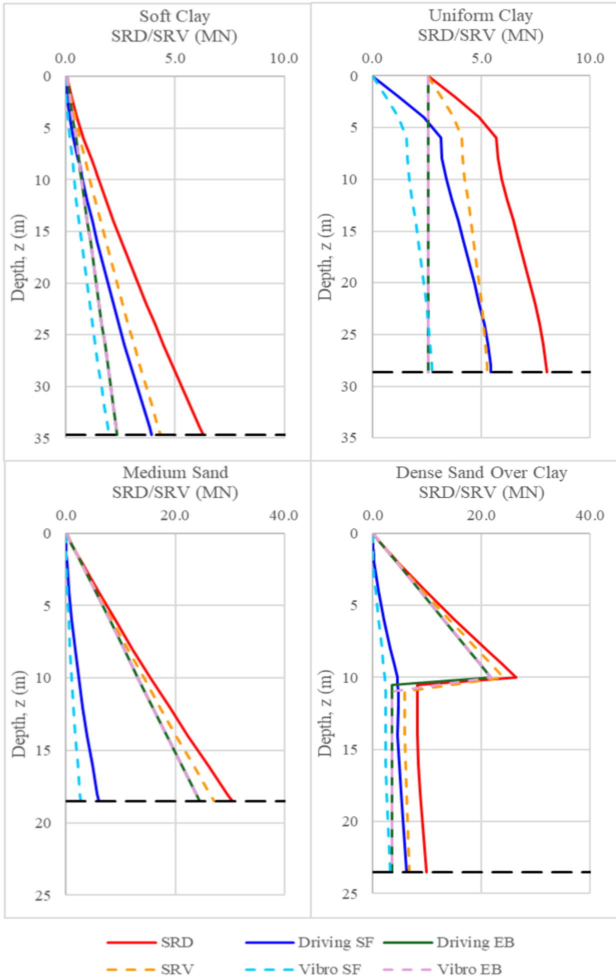

Figure 4.1. Soil resistance to driving/vibro

The SRD results shown in Figure 4.1 are likely conservative, particularly at deeper penetration depth where the Stevens approach tends to overpredict SRD, as it does not apply any frictional degradation. In addition, upper bound values have been used in the estimation of SRD and no reduction of soil resistance from the vibro installation stage has considered.

The greatest uncertainty in the results shown in Figure 4.1 is the SRV. The four soils have been assumed to be moderately sensitive, i.e. a 50% cyclic reduction has been applied to the skin resistance. In reality, the static (weight) and cyclic components (vibro) of the load can be compared with cyclic laboratory tests at similar stress levels to estimate the number of cycles to failure and hence the SRV. It is understood that the approach of using beta factors is limited when considering vibro driving. In addition, the SRV is calculated directly from the SRD at shallow penetration depth where the Stevens (1982) approach tends to underpredict SRD.

There is also uncertainty regarding the bearing component of the follower. There is little to no information on vibro installation of closed ended piles in the geotechnical literature. It is expected that very large small-strain moduli would be required to propagate the relatively modest stress waves sufficiently through the soil to influence the bearing resistance of a closed ended pile.

4.2 Installation Results

4.2.1 Vibro Hammer

Vibro hammer driveability results are detailed in Table 4.1 and shown in Figure 4.2 (a.) through (d.). In the clay soils, the vibro alone can quickly penetrate the FEPLA to target penetration. The minimum installation times given in Table 4.1 are unrealistic as they correspond to full vibro energy at 23.3Hz. In practice, the vibro frequency would be reduced and the vibro hook speed would control the penetration rate. It is expected that penetration rates of 1-3m/minute could be achieved. These installation rates are encouraging and a considerable improvement to the SEPLA in clay soils, that typically require several hours to reach target penetration depth.

In the sandy soils, the vibro hammer refuses before target penetration depth, which is expected. This occurs at 6m below seabed in the MS profile, and ~7.5m in the SOC profile. These penetrations are equivalent to ~32% of the total follower length. Potential measures to increase the vibro refusal depth in sand could be to incorporate vibrojetting (Konstadinou et al. 2023). For these harder driving conditions, the impact hammer is required to reach target penetration depth.

Table 4.1. Vibro hammer driveability results

Parameter	*SC*	*UC*	*MS*	*SOC*
Refusal Depth (m)	N/A	N/A	6.0	8.0
Max. Penetration Rate (m/s)	0.67	0.28	0.10	0.09
Min. Installation Time (min)	1.00	3.00	Refusal	Refusal
Max. Power (kW)	1,168	1,324	1,327	1,285

4.2.2 Impact Hammer

Impact hammer driveability results are detailed in Table 4.2 and shown in Figure 4.2 (e.) through (h.). Results indicate the FEPLA can be driven to target penetration depth before reaching the refusal criteria with the MENCK MHU270T for all soil profiles.

The bottom driving effect reduces the blow counts per 0.25m because hammer impact energy is delivered to the point where soil resistance is highest, which is the bearing resistance for the FEPLA. The reduced blow counts per 0.25m could also be attributed to the shaft resistance reduction caused by a reduction in pile diameter due to Poisson's ratio effects (Choe and Juvkam-Wold, 2002) and the unloading of the effective stress (Fellenius, 1991).

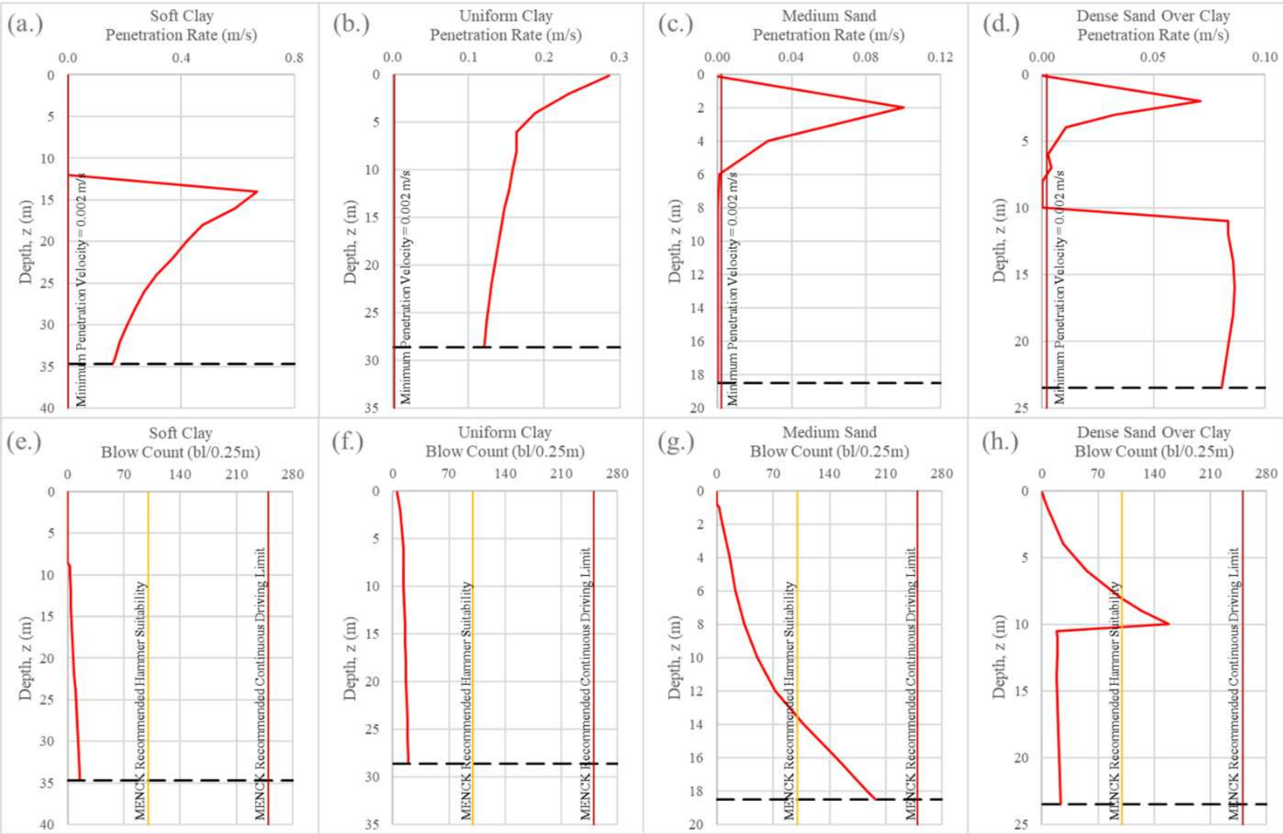

Figure 4.2. Vibro hammer penetration rate (a. - d.)/ Impact hammer blow count (e. - h.) versus depth results

Table 4.2. Impact hammer driveability results

Parameter	*SC*	*UC*	*MS*	*SOC*
Max. Blow/0.25m	15	19	198	158
Min. Installation Time (min)	23	46	145	99

5 CONCLUSIONS

The objective of this paper was to introduce a new anchor designed for floating offshore wind. The FEPLA is considered an update to the SEPLA that has been in use for over twenty years. The discussion on the new anchor concept is supported by results from dual installation studies (vibro and impact driving) in a range of soil types varying from soft clay to layered dense sand. The preliminary study has highlighted knowledge gaps and challenges to be considered in future anchor development. The following conclusions can be drawn:

- Through impact driving, the FEPLA can install plate anchors in sand, layered profiles, and harder sediments;
- The multi-function follower provides flexibility when encountering varying or unexpected soil layers with reduced risk of refusal. For example, there is no need to recover equipment to change embedment modes;
- The FEPLA can achieve faster installation time compared to other plate anchor installation methods. Results indicate FEPLA may reach target penetration depth within minutes of vibro hammering in soft and uniform clay. In comparison, suction installation typically takes several hours to reach penetration depth as the penetration rate is limited by the allowable underpressure to prevent heave inside the skirts or cavitation in the water (DNV, 2021), and by local soil features such as layered or varied soils (Sturm, 2017);
- The FEPLA may be less sensitive to verticality than driven piles, as the plate anchor will be keyed upon line tensioning;
- There remains uncertainty in regards the vibro installation in sand primarily due to the large component of bearing resistance. Although results positively indicated the follower penetrated ~32% of the total follower length in sandy soils, further studies are required.

Overall, it is hoped that this paper has demonstrated the FEPLA could be a viable option for floating offshore wind and has highlighted further areas of research required to progress the technology towards adoption.

Experimental 1g testing is currently being performed at the University of Dundee to investigate the FEPLA performance in sand. This ongoing testing seeks to address uncertainty in vibro installation in sands and vibro installation of close-ended piles.

AUTHOR CONTRIBUTION STATEMENT

John Morton: Supervision, methodology, writing – review & editing, project administration, validation. **Rose Walker**: Methodology, writing – original draft, formal analysis, visualization, software. **Karen Khreiss**: Methodology, formal analysis, software. **Tom Bauer** and **Tom Fulton**: Conceptualization, data curation, funding acquisition.

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