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The challenges of follower retrieval after anchor pile installation - a case study

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ABSTRACT: Anchor piles are widely used for mooring structures to the seabed and are also considered a viable solution for anchoring floating wind farms in deeper waters. Anchor piles need to be installed with the pile top at or below seafloor level, requiring a follower between the hammer and the pile to avoid embedment of the hammer in the soil. Plug heave during pile driving and penetration of the soil plug in the follower can make retrieval of the follower a very challenging task, especially when the topsoil layer consists of poorly permeable, cohesive soils. This was the case during the Shell Penguin project, with a stiff glacial till plug making follower retrieval a challenging exercise. In this paper, a detailed analysis of the retrieval process is presented, with analysis of the forces acting on the follower and their relation to the topsoil properties and site conditions. The case study is accompanied by a calculation model, including friction and the occurrence of a (partial) vacuum at the follower-soil interface. The model is generally applicable to assess the required follower retrieval forces of any project, allowing for better installation risk assessment and risk mitigation.

Keywords: Anchor pile installation; pile driving; pile plug; pile driving equipment; follower retrieval

1 INTRODUCTION

One of the risks of using a follower in offshore pile driving, with the aim to reach pile penetration with the pile top below the seabed, is the follower getting stuck upon retrieval (i.e. the required retrieval force exceeds the crane capacity). Dimmock et al. (2023) describe significant pile plug development during anchor pile installation at Shell Penguin. Despite precautionary measures (e.g. wire cutting and jetting of the pile plug during intermittent lifting of the follower for the last meters of driving or intermittent ‘dipping’ of the follower), the follower retrieval was often very challenging.

IQIP have witnessed multiple projects with similar challenges, however no calculation models, written accounts in the open literature or engineering rules relating to follower retrieval are known to the author. In this paper we aim to explore this subject in more detail, taking Shell Penguin as case study. The results will be useful in any mooring installation project using a follower, and become relevant as floating wind developments are maturing.

2 SHELL PENGUIN CASE

2.1 Project scope

The Penguin field is located in the UK sector of the North Sea, 240 km to the North-East of the Shetland Islands. 12 anchor piles were installed for an FPSO mooring (OD 2.438 m, length 30 m, average wall thickness 70 mm) with the piletop flush with the seabed (Dimmock et al., 2023). IQIP was contracted by an installation subcontractor to the project, and delivered a Hydrohammer S-1400, 2500 mm sleeve and 96“ follower to the project (Figure 1), which were operated by IQIP personnel.

The case study presented in this paper is conducted by reviewing the project documentation and service logs, interviewing former crew and mathematical modelling of the relevant physical processes.

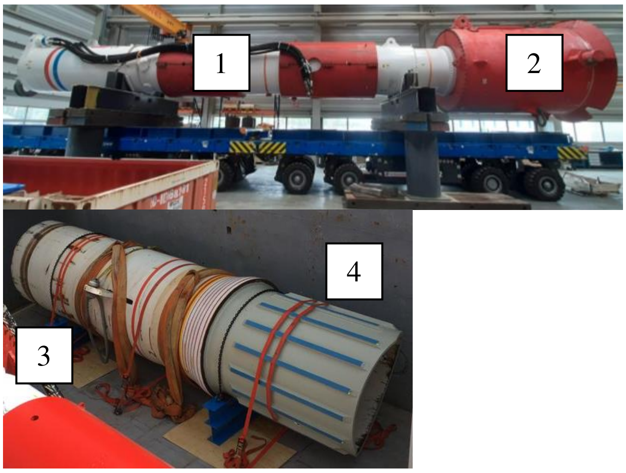


Figure 1. IQIP S-1400 hammer assembly (1) with pile sleeve (2) and 96" follower (bottom). The follower is inserted in the sleeve on the left end (3) and into the pile on the right end (4). (Pictures used with permission of IQIP).

2.2 Penguin site conditions

The Penguin site, with a water depth of ~164 m, consists of Holocene deposits (mainly silty and gravelly sands of various density in the top 0.5 mbsf, followed by high to very high strength clays, sometimes as deep as ~26 mbsf) overlying the Tampen, Sperus and Cape Shore Formations respectively.

The Tampen formation, a glacial till, starts with high to extremely high strength sandy clay, with high overconsolidation in the deeper layers, down to ~20 mbsf. Successive strata in the Tampen formation consist of sands, gravels, cobbles, silts and clays of various densities and strength.

The topsoil layer (order of magnitude meters thickness) is governing the follower retrieval as this determines the properties of the pile plug that protrudes in the follower. The geotechnical properties of the topsoil vary across the site. Out of the 12 anchor locations, we find only 3 to be fully governed by the Holocene deposits, with ~0.2 m of loose to medium dense sand followed by high strength clays. One location has ~4m of sand at the top followed by Tampen clays. The remaining 8 locations all show 0.2 – 0.75 m of sand followed by high strength Tampen clays for the next ~7 – 20 m. Overall, high strength clays dominate the first meters of topsoil. The undrained shear strength of these clays is plotted versus the depth for the first 8 m of seafloor in Figure 2.

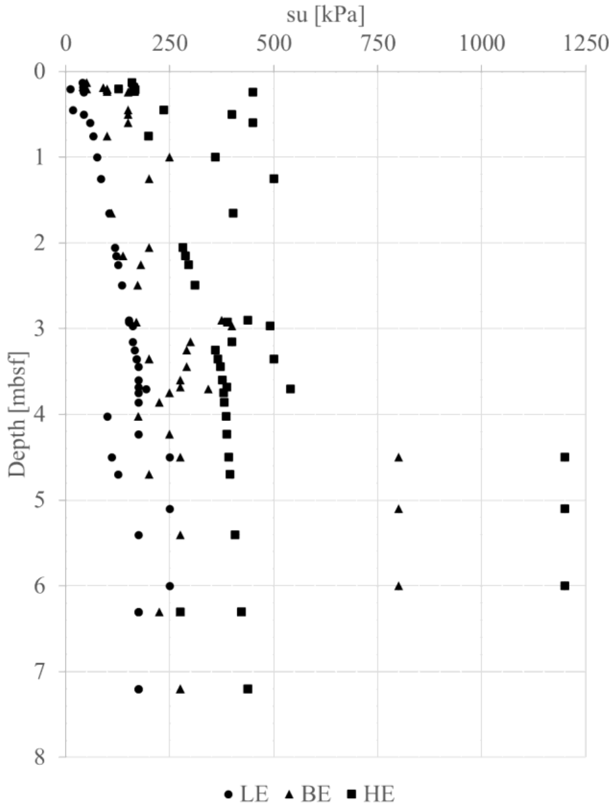


Figure 2. Undrained shear strength of the clays in the first 8 meters of topsoil at all anchor locations at Shell Penguin.

2.3 Follower retrieval

IQIP crew and Dimmock et al. (2023) both report on the difficulties of retrieving the follower from many locations. Different strategies were followed: application of a non-stick coating, 'dipping' (i.e. taking the follower off and re-stabbing it after small increments of driving, to clear the clay) and periodically removing the excess plug by jetting and wire cutting.

This resulted in varying lifting forces. Often, the reported crane load with hammer, sleeve and follower was in the range 220 – 275 tonnes, while the submerged assembly mass was roughly 240 tonnes. Considering the apparent inaccuracy of the crane load recording, the force is seen to be in line with the submerged assembly weight.

Three extreme lifts were reported. In these instances, the maximum crane capacity of 430 tonnes was insufficient, and the hammer and sleeve were removed and lifted on deck again, to be replaced by a 60"x96" internal lifting tool (ILT). The reported forces are 205 tonnes, 295 tonnes (service logs) and even peaks of 430 tonnes (personal communication by former crew) before the follower came loose. The follower and ILT had a combined submerged weight of 147 tonnes, indicating follower retrieval forces of

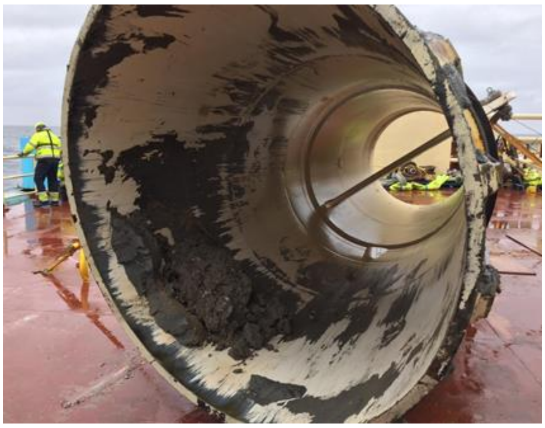
58, 148 and 283 tonnes (569, 1452 and 2776 kN) respectively.

The development of a pile plug played a crucial role. As the pile heads were driven flush with the seabed, the displaced soil volume was partially compensated by plug heave inside the pile. Figure 3 shows a plug as encountered during one of the first anchor pile installations. Dimmock et al. (2023) report on four other plugs, having lengths varying from 1 – 4 m, although after follower removal some of the plugs broke off, so actual lengths could have been larger.

Upon inspection of the follower on deck, as shown in Figure 4, clear remains of clayey material can be seen on both the inside up to the follower lifting bar, and outside of the follower between the ribs, suggesting significant plug heave (~4.5 m up to the lifting bar) and intrusion of soil in the annulus of the follower and pile. The crew reported being able to remould the clay with their thumbs, using large force. The significant excess plug length of ~4.5 m up to the lifting bar demonstrates that properties of first meters of seabed play a role in the soil-related forces that occur during retrieval.

The application of a non-stick coating could explain the clean patches on the surface, but as can be seen, the coating was insufficient to fully prohibit adhesion.

Figure 3. Pile plug sticking out of the pile as seen from the piling template after removal of the follower.



a. Clay traces inside the follower.

b. Clay traces between the ribs of the follower (exterior).

Figure 4. Clay traces on the interior (a) and exterior (b) point at significant plug heave and intrusion of the material in the annulus between pile and follower. (Photos used with permission of IQIP and Shell).

3 FOLLOWER RETRIEVAL FORCE ANALYSIS

3.1 Governing processes

During driving, the displaced soil volume V is partially taken by the development of a soil plug in the pile (Randolph and Gourvenec, 2011). Typically 50% of the volume is moving in the plug, although Luger and Thijssen (2020) advise a safety factor of 1.3, resulting in 65% of displaced volume absorbed in the plug. With the pile head flush with the seabed, the excess material then enters the follower.

Figure 5 schematically shows the pile-follower-plug system with the dominant physical processes occurring upon follower retrieval. Assuming intrusion of soil (clay) material in the annulus, the governing forces during retrieval (next to the crane force, gravity and buoyancy on the follower) are identified as friction/shearing of the clay between the follower and plug and within the annulus, and the development of a cavity at the toe of the follower.

This cavity needs to be filled with either surrounding material or water, and given the stiff nature of the Penguin clay, water is the only option. However, since the clay has a low to negligible permeability, and the annulus is filled as well, the flow of water is prohibited. This could lead to the occurrence of a (partial) vacuum at the toe of the follower.

The above process is informed by the Shell Penguin experience and evidence found on the follower. An alternative failure mechanism would be full tensile failure of the plug in the case of sufficient wall friction to hold the plug in place in the follower upon lifting. This mechanism is left outside of the current analysis.

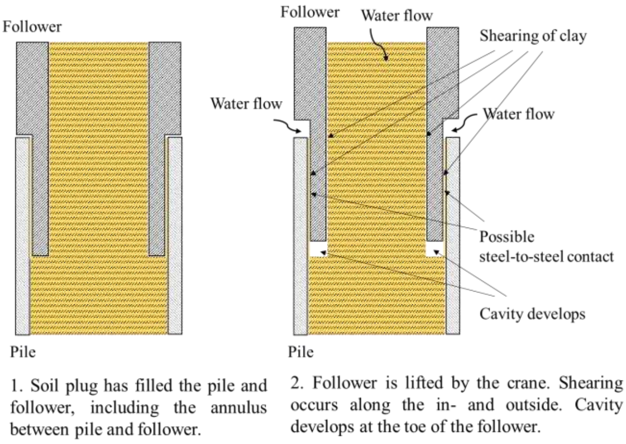


Figure 5. Pile-follower-plug system (left) and the governing processes upon retrieval (right).

3.2 Retrieval force model

A more detailed view on the stresses and pressures is given in Figure 6, including definitions of the plug length L_{plug}, follower stick-in L_f, follower internal diameter $D_{f,i}$, pile inner diameter $D_{p,i}$, pile outer diameter $D_{p,o}$, wall shear stresses (in Pa) $\tau_{w,i}$ acting on the inside surface of the follower, $\tau_{w,o}$ acting in the annulus, partial vacuum p_v (in Pa) and the vertical displacement of the follower during lifting h.

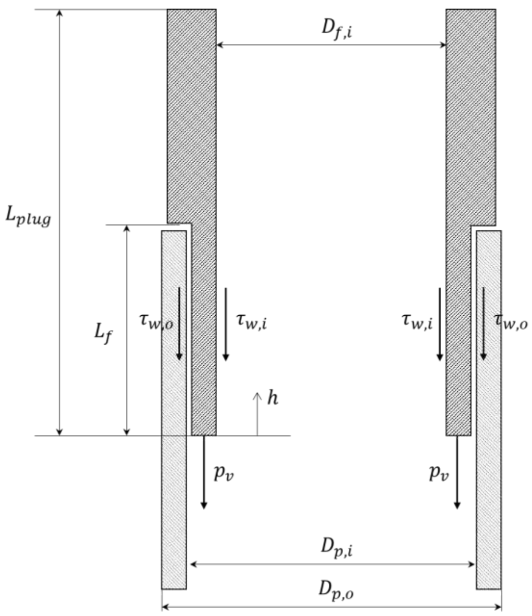


Figure 6. Definition of follower and pile dimensions and the stresses and pressures acting on the follower during retrieval.

The length of the plug inside the follower, for a pile-head flush with the seabed, is defined as $L_{plug} = H_{plug} + L_f$. The plug height above seabed H_{plug} follows from the volume balance for plug heave, corrected for the reduced follower internal diameter and including a safety factor on the volume distribution:

$$H_{plug} = \frac{0.65 \cdot \left(D_{p,o}^2 - D_{p,i}^2\right) \cdot Z_e}{D_{f,i}^2} \quad (1)$$

With Z_e the embedment depth of the pile in m.

If we assume a very slow lifting operation, the equation of motion of the follower reduces to a quasi-static force balance (i.e. $d^2h/dt^2 = 0$) and the crane needs to overcome the submerged weight F_{sw}, friction force and vacuum force.

Friction F_f can be modelled as the sum of internal and external shear stresses due to the plug and clay intrusion between pile and follower:

$$F_f = \int \tau_{w,i} \, dS_i + \int \tau_{w,o} \, dS_o \quad (2)$$

With S_i the inner surface area and S_o the outer surface area of the follower in the pile (Figure 5).

For a first assessment, we propose a simple formulation for clay-steel wall shear stresses (based on the uplift resistance formulation for piles in clay in Poulos and Davies, 1980):

$$\tau_w = \alpha \cdot su \quad (3)$$

With su the clay undrained shear strength, α=1.0 for soft to firm clay, α=0.75 for stiff to very stiff clay and α=0.25 for very stiff to hard clay.

Substitution of Equation 3 in Equation 2 and performing the integration, gives the friction force as a function of follower displacement during retrieval:

$$F_f(h) = \alpha \cdot su \cdot \pi \cdot \left[\left(L_{plug} - h\right) \cdot D_{f,i} + \left(L_f - h\right) \cdot D_{p,i}\right] \quad (4)$$

The vacuum force F_v is a result of a differential pressure at the toe of the follower with respect to the ambient pressure:

$$F_v = \int \ (p_c - p_a)\, dS_t \quad (5)$$

With p_c the pressure in the cavity, $p_a = \rho g H$ the ambient pressure, H the water depth and S_t the surface area of the toe.

Continuity demands the flowrate of water into the cavity Q to be in keeping with the cavity growrate:

$$Q = -S_t \cdot \frac{dh}{dt} \quad (6)$$

As the cavity grows, $p_c < p_a$ and the flowrate will be determined by the permeability of the clay in the pile plug, in the annulus and the available surface area, such that:

$$\frac{dp}{dz} = -\frac{Q \cdot \mu}{\kappa \cdot A} \quad (7)$$

With dp/dz the pressure gradient over the soil plug in Pa/m, z the vertical coordinate through the plug (positive upward), Q the flowrate of water through the plug in m^3/s, μ the seawater viscosity in Pa s, κ the soil permeability in m^2 and A the cross-section area of the plug in m^2 (neglecting the annulus).

From Equations 5 and 7 the relation between follower retrieval velocity and the vacuum force can be derived. For this, the assumption of the plug being dominant and the condition $p_{vap} \leq p_c \leq p_a$, with p_{vap} the water vapour pressure, is a constraint, and the lifting displacement h is included by the notion $dp/dz = (p_c - p_a)/\Delta z$, with $\Delta z = L_{plug} - h$:

$$F_v(h,t) = \min\left\{S_t \cdot (p_a - p_{vap}), \frac{1}{2} \cdot S_t^2 \cdot \left(L_{plug} - h\right) \cdot \frac{\mu}{\kappa \cdot A} \cdot \frac{dh}{dt}\right\} \quad (8)$$

Equations 4 and 8 show that the total follower retrieval force is depending on time and displacement, and as such the equation of motion of the follower itself needs to be solved.

We can however calculate the peak force required during lifting, as this will occur at the onset of lifting ($h = 0$ m, maximum contact) and at maximum vacuum, i.e. $\Delta p = p_a - p_{vap} \approx p_a$. This yields the maximum retrieval force that can be used in engineering practice:

$$F_{r,max} = \alpha \cdot su \cdot \pi \cdot \left(L_{plug} \cdot D_{f,i} + L_f \cdot D_{p,i}\right) + \left(\rho \cdot g \cdot H - p_{vap}\right) \cdot \frac{\pi}{4} \cdot \left(D_{f,o}^2 - D_{f,i}^2\right) + F_{SW} \quad (9)$$

3.3 Calculation results for Penguin and evaluation

During the retrieval at Penguin, the maximum crane capacity of 430 tonnes or 4218 kN was required to lift an ILT and the 96” follower with a combined submerged weight of F_{sw} = 1442 kN, resulting in a combined friction and vacuum force of 2776 kN.

We can use this number to verify Equation 9. The relevant model input is summarized in Table 1: follower and pile dimensions are based on the project specific equipment, and the range of undrained shear strengths is estimated from Figure 2 at a depth of 3 mbsf, which is deemed representative for the plug at the end of driving based on the follower stick-in length $L_f \approx 3$ m and the notion that the first 3 m of pile plug will enter the annulus between follower and pile. The factor α = 0.25 for very stiff to hard clay is chosen based on the associated su strength range.

Table 1. Model input for friction and vacuum force calculation.

Parameter	Value
$D_{p,i}$ [mm]	2298
L_{pile} [m]	30
Z_e [m]	30
$D_{f,i}$ [mm]	2128
L_f [mm]	2980
L_{plug} [m]	5.4
su [kPa]	{100, 200, 450} (LE, BE, HE)
α [-]	0.25
H [m]	164

With Equation 9, using the low, best and high estimate clay undrained shear strength scenarios (LE, BE, HE), we find the following numbers: F_{vac} = 982 kN, F_f = {1440, 2881, 6482} kN.

We see that vacuum by itself is not sufficient to explain the retrieval force, and at least 2776 – 982 = 1794 kN of friction force would be expected (ratio ~1:2 vacuum:friction). This falls in the range between the LE and BE su parameters, closer to LE. The factor α = 0.25 represents the soil resistance based on a range of clay strengths rather than a single number, hence the precision of the model is limited by its empirical nature. We have however demonstrated that the order of magnitude of the model is correct and the range is reasonably correct.

Clearly, more detailing of the model is required as it comes to its precision in calculating the friction component of the retrieval forces.

Model improvement can be found in i) a more detailed assessment of the effectively covered surface of the stick-in part of the follower, due to the presence of ribs (partial intrusion of the plug in the annulus), ii) a better understanding of the friction between the follower interior coating and the clay (friction is an interface property, not a soil property as such, and use of non-stick coatings in the Shell Penguin follower have played a role) which will directly influence the factor α, and iii) a non-conservative estimate of the excess plug length.

4 CONCLUSIONS

Installation of anchor piles flush or below the seabed requires a follower. Plug heave during installation poses the risk of a difficult to retrieve follower.

During installation of the mooring piles at the Shell Penguin site, multiple occasions of difficult retrieval were encountered. A closer look at the topsoil properties demonstrated the presence of hard clays of different origin. Pictures of a retrieved follower demonstrated the presence of clay remains on the exterior and interior of the follower, which was further supported by camera footage of a large clay plug above the anchor pile and written accounts of the crew.

By studying the pile-follower-soil plug system in more detail, the follower retrieval force was seen to be dominated by friction (based on the observed clay traces) and by the occurrence of a partial vacuum in the cavity under the pile toe. The latter was shown to be dependent on the permeability of the soil plug and the ambient pressure around the pile.

The full equation of motion, including the partial vacuum force, is introduced in this paper, and this equation was simplified to present an engineering formula for calculation of the follower retrieval force. The engineering formula is verified with data inferred from the Penguin case study.

The verification calculations show that both vacuum and friction forces have played a role at Penguin, in approximately a ratio of 1:2. It was furthermore demonstrated that under reasonable assumption of steel-clay interface friction for the specific Penguin clays, the total friction force could be conservatively estimated from the LE and BE soil properties.

The engineering formula is generally applicable to any anchor pile and follower configuration, and as such can be used for verification of crane capacity for installation works.

AUTHOR CONTRIBUTION STATEMENT

J.M. van Wijk: Conceptualization; Formal Analysis; Investigation; Methodology; Validation; Visualization; Writing – original draft.
C.J. Stokman: Validation; Writing – review.
P.C. Lachnit: Conceptualization; Resources.

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