HyPE-ST

Hydraulic pile extraction scale tests for testing the removal of piles from the soil at the end of their operational life

Public report

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1. Summary

Decommissioning of offshore wind farms at the end of their operational life requires full or partial removal of foundation structures such as monopiles. Removing entire piles is more sustainable, economical, and less hazardous in terms of health and safety than partial removal. This is because e.g. underwater cutting can be avoided, and no steel remains in the seabed. A promising method for full pile removal is hydraulic extraction. This method involves sealing the pile after removal of the top structure, and pressurizing water inside its void, thus forcing the pile to move upwards. Before applying this method offshore at full scale using expensive vessels and equipment, a better understanding of the pile-fluid-soil interaction in different soil types is needed. To accomplish this, an extensive hydraulic extraction testing campaign has taken place as part of a Joint Industry Project. Tests are performed at scales of 1:20 and 1:30 for a prototype monopile with a diameter of 8 m. Four different soil conditions were used: medium dense sand, dense sand, medium stiff clay, and layered soil. The piles were installed by impact driving. During the extraction process, several parameters have been monitored including pressure, flow, pile displacement and plug displacement. This report summarizes the test program and shares some insights from the results.

2. Introduction

Thousands of offshore wind turbines are already installed and operating in the North Sea and much more are planned in the next decades as part of the energy transition to low or zero carbon emission and the climate change actions (Figure 1).

Offshore wind farm developers are legally required to decommission their offshore wind farms (or parts thereof) at the end of their operational life. Foundation and sub-structures of wind turbines, offshore high-voltage substations, AC/DC converter stations, meteorological masts, accommodation platforms, etc. typically have to be removed all the way down to the seabed level or a couple of meters below. The exact requirements differ from country to country. The offshore wind industry has gained very little practical experience with the removal of bottom-fixed foundations until now. Recent experiences from the limited number of decommissioning of offshore wind turbines have demonstrated that the difficulties of underwater cutting and cutting below the seabed tend to be underestimated. External cuts require customized equipment (clamped frames/guide-rails) in order to support the cutting tool. As for internal cuts, off-the-shelf cutting tools from the oil and gas industry can be used only to a limited extent because the diameters of monopiles for wind turbines keep increasing. More importantly, any cut below the level of the local seabed requires an excavation in order to make the level of the cut accessible for the cutting tool. Removing the scour protection as well as the soil can be considerably time-consuming and hence costly.

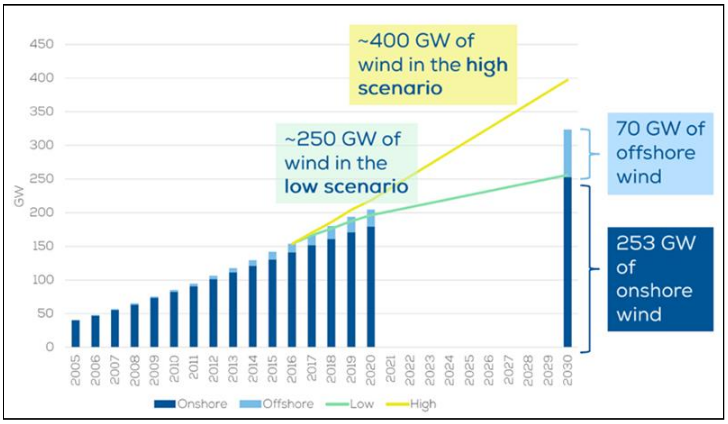


Figure 1: Forecasted cumulative installed capacity until 2030 under WindEurope's low and high scenario (Source: WindEurope.org)

A removal method that requires neither an excavation nor any cuts of the foundation structure could be substantially less expensive than a partial pile removal. No part of the pile would be left behind on site, making such a method environmentally more sustainable than a partial removal of piles. One method for full pile removal is hydraulic extraction. This method involves sealing the pile and pressurizing a fluid inside its void, thus pushing the pile upward.

Before applying this method offshore at full scale using expensive vessels and equipment, a better understanding of the pile-soil interaction, leakage of fluids and the residual mechanical force required under different circumstances is needed. This has been researched in the project HyPE-ST (Hydraulic Pile Extraction - Scale Tests), which is the subject of this report. This method is not completely new but there is hardly any (recent) literature found on such an application in the field or research. For example, a patent was granted in 1957 in Germany (DE 1,014,036 B), which refers to the fundamental principle of pushing an embedded steel pile upward by filling its void with water followed by pressurization. In 2006, a patent in the US (US 7,090,434 B1) was granted for a caisson removal process that effectively describes the removal of a pile by means of pressurization in an offshore environment. Some aspects of decommissioning of suction caissons are given in OWA (2019) and Lorenti, L.S.D.et al. (2017) presented numerical back analysis of installation and extraction of a caisson in layered soil. In the Netherlands, the BLUE Piling Offshore Test Project, an offshore demonstration test took place in 2018 of a new pile driving technology, which involves the use of a large water column to drive a pile in the soil. After the installation, the pile was extracted using water pressure. This gave confidence to the applicability of the concept, but it did not (publicly) answer fundamental questions regarding soil-pile interaction and the possible wider applicability/limitations of such a technology.

In this Join Industry Project (JIP) HyPE-ST, tests are performed at a scale of 1:20 and 1:30 for a prototype monopile with a diameter of 8 m. Four different soil conditions were used: medium dense sand, dense sand, medium stiff clay, and layered soil. The piles were installed by impact driving. The tests have been instrumented and during the extraction process, several parameters have been monitored including pressure, flow, pile displacement and plug displacement. This report describes the analytical model that was developed for the experimental design, the test-setup, and first insights from the tests.

3. Project objective and structure

The HyPE-ST project is an R&D project that aims at the fundamental understanding and demonstrating the feasibility of hydraulically extracting monopiles for decommissioning. Before this extraction technique can be applied safely and efficiently at full scale, better understanding must be gained of the interaction between the pile and the soil before and during the extraction process. Possible leakage of pressurised fluids must be minimized and understanding of how much force is required while extracting the pile must be gained. Scale tests are therefore a prerequisite for the application of this hydraulic pile extraction at full scale, which are the main objective of this project.

The project is led by Innogy and includes 6 partners as illustrated in Figure 2. The partners are research institutes, offshore contractors, offshore wind project developer, monopile manufacturer, and a wind turbine developer. This one-year project started on 1 December 2018 and consists of four main work packages. The first work package, a desk study, has focused on laying the groundwork for the subsequent experimental work. A thorough understanding of certain effects was required in order to design the scale tests in an appropriate way. The effects are, among others, scalability aspects, set-up and aging effects, effect of pile installation method, and legal and regulatory requirements.

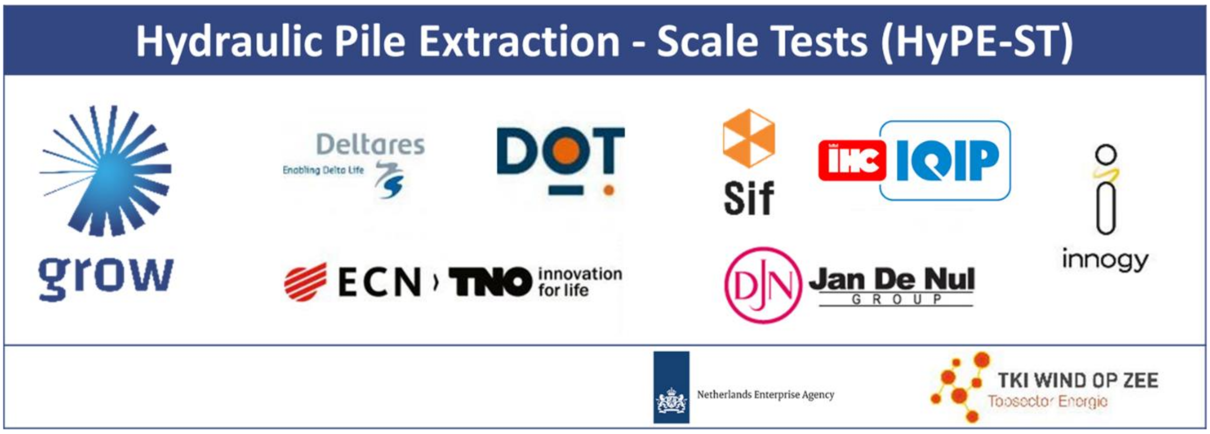


Figure 2: The HyPE-ST project consortium

The other three work packages have focused on the experimental campaign: experimental design and writing of test specifications (work package 2), testing phase (work package 3), and analysis and reporting (work package 4). The distribution of work during the project can be seen in Figure 3.

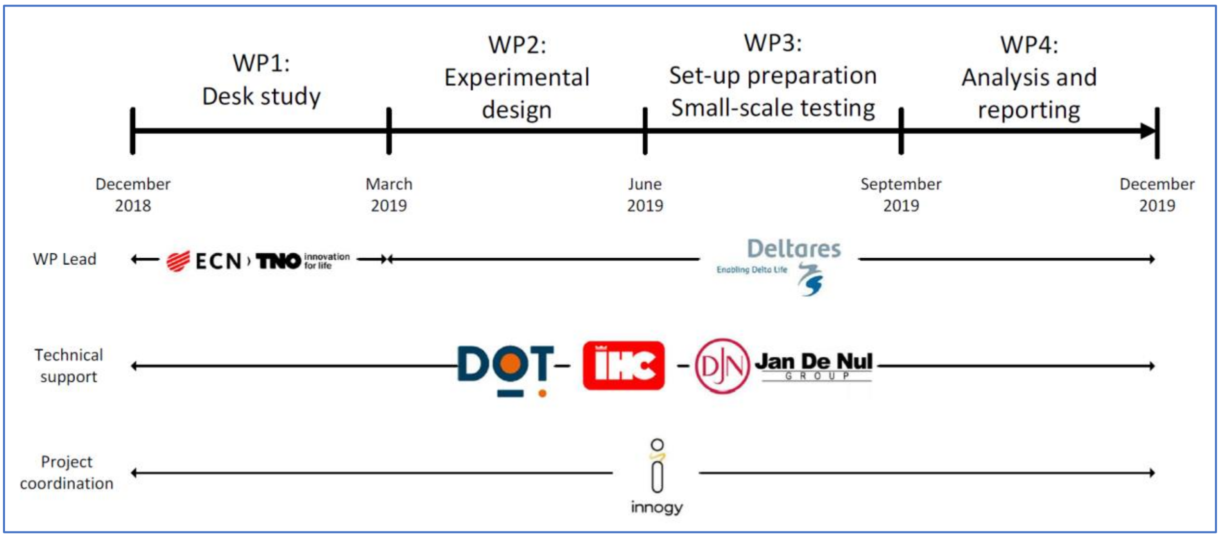


Figure 3: HyPE-ST project stages

4. Work package 1 (WP1): Desk study and analytical prediction model

The purpose of the desktop study [P1] was to lay the groundwork for the subsequent experimental design. A thorough understanding of technical aspects and legal and regulatory requirements is necessary to design the scale tests in an appropriate way. The technical aspects covered include the effect of pile installation method, constructive design and manufacturing monopile features, set-up effects, environmental impact of extraction, and scalability, among others.

4.1 Inventory of relevant factors and processes related to hydraulic pile extraction

4.1.1 Legal and regulatory framework

The proposed method of hydraulic extraction requires applying overpressure inside the pile. Several laws prescribe the conditions to be met before pressure equipment is used. The international regulations for offshore decommissioning states that Dutch requirements for decommissioning of platforms and other facilities are driven by OSPAR Decision 98/3. A short description of the requirements laid down in this legislation is shown in Table 1.

Table 1: Netherlands Summary Decommissioning Requirements

Item	Nominal requirement	Legislation driving requirement
Platforms and other facilities	Removal but derogations possible.	OSPAR Decision 98/3.
	Under Decision 98/3 the dumping and leaving wholly or partly in place of offshore installations is prohibited.	
	Decision 98/3 recognises it may be difficult to remove the 'footings' of large steel jackets weighing more than 10,000 tonnes and concrete installations. As a result, there are derogations for these categories of installations if the internationally agreed assessment and consultation process shows leaving them in place is justifiable.	
	Removal includes the installation itself and scrap/ other materials in the immediate vicinity. May limit the obligation to a specified depth.	Dutch Mining Act, 2003.
Pipelines	Removal but exceptions can be made based on cost benefit analysis.	Beleidsnota Noordzee 2016-2021
	Removal on case by case basis may be ordered by MEA.	Dutch Mining Act, 2003.
Drill cuttings piles	Case by case.	OSPAR 2006/5 and OSPAR 2009.
		OSPAR currently developing sampling and monitoring guidelines in relation to cuttings piles.
Decommissioning Plan needed	Yes, a Closure or Decommissioning Plan has to be submitted to the Ministry of Economic Affairs (MEA) for approval before a mining location is actually closed or an offshore installation is decommissioned.	Dutch Mining Act, 2003.

4.1.2 Technical aspects

4.1.2.1 Applying pressure to monopiles

The risk involved in pressurizing monopiles is assessed by a force balance between the hydraulic pressure and the strength of the material. Barlow's equation is the result of this balance, and gives an estimate at which critical pressure, P, the stress in the material exceeds an allowable limit. This allowable stress limit depends on the processes within the material that are allowed, and this can be related to a defined stress level, S (e.g. the yield strength or the ultimate tensile strength), with a safety factor, F. When the material stress increases, the strain will change from an elastic deformation at small stresses (< yield strength) to plastic deformation and even fracture/failure at high stresses, see Figure 4. The safety factor, F, considers uncertainties in the material stress properties (usually small for steels having material certificate) and in the interpretation of lab test results to the prototype scale. Note that it is assumed here that the applied pressures can be controlled accurately.

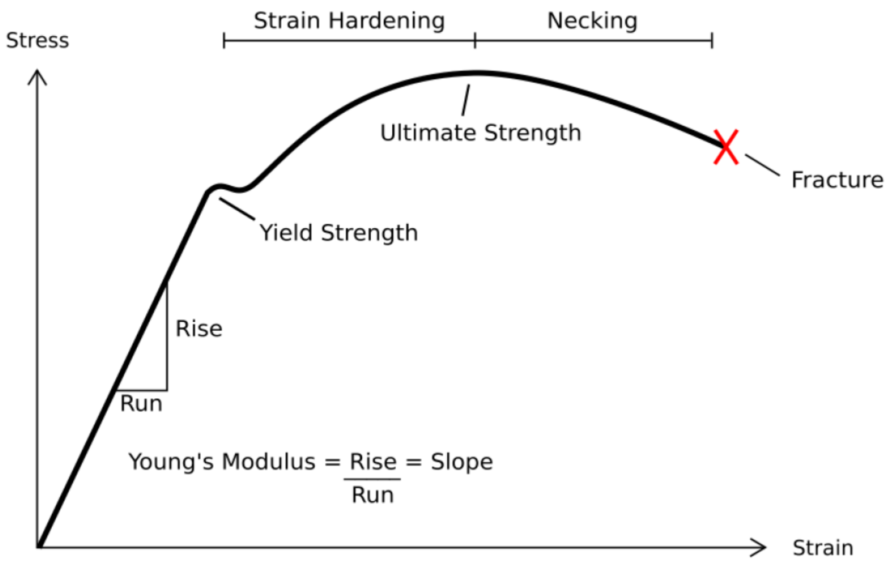


Figure 4: Typical strain-stress behaviour of a material

The critical pressure is estimated by:

$$P = \frac{2S \cdot d_w}{D_o \cdot F}$$

where d_w is the wall thickness and D_o is the outer diameter. To estimate the onset of deformation the yield strength is used for S, in combination with F = 1.5. To estimate the bursting pressure the ultimate tensile strength (UTS) should be used for S, in combination with F = 1 [R32]. Eurocode 3 (EN 1993-1-1 and EN 1993-1-5, design of steel structures) does not describe the process of hydraulic extraction of monopiles and which combination of S and F should be taken to estimate the maximum allowable pressure level.

As a preliminary estimate it seems to be suitable to use the yield strength together with F = 1.5 [R30]. Then the maximum allowable pressure is estimated at 31bar (S_{Yield} = ~235MPa, F = 1.5, d_w/D_o = 1%). It is recommended to assess the effective remaining wall thickness of the monopiles prior to extraction.

4.1.2.2 Installation method

There are several methods available for installing an open steel pile offshore, including vibratory driving, jetting and impact driving. The installation process changes the original soil stress state, soil density and pore water pressure and influences not only the pile performance during loading but also the pressure required to extract the pile.

The most adopted method to install a monopile is impact driving. The method is well understood and predictable, allowing an accurate and robust installation of the support structure. An advantage of this method is that it allows an estimation of the axial load bearing capacity at the end of driving. However, there are some disadvantages of using this installation method offshore, including considerable noise levels caused by repetitive hammering and fatigue damage due to hammer impact onto the pile, which could possibly cause damage to secondary steel.

With pile jetting a carefully directed and pressurized flow of water is used to assist in pile placement. The application of a concentrated jet of water at the pile tip liquefies the soil at the pile tip during pile placement. This reduces the friction and interlocking between adjacent sub-grade soil particles around the water jet, and thus decreases the bearing capacity of the soil below the pile tip. This causes the pile to descend toward its final tip elevation with much less soil resistance, largely under its own weight.

Because of the disruption of the soil, the lateral strength (and history effects) of the piles can be reduced significantly (notably in soils with significant cohesion), and often may not be specifically determined [R33].

When installing a monopile through vibration, the pile is moved up and down quickly. The vertical action of the pile is achieved by a series of paired eccentric weights that exert a certain (vertical) moment onto the assembly whilst rotating. An advantage of opting for vibratory technique over impact driven installation include high rates of penetration and reduced noise levels during the installation process [R12]. Especially in marine environments where serviceability is of concern and stringent noise emission limitations are enforced, opting for vibratory driven installation appears a positive choice. However, in order to ensure the installation process, being well-controlled (accurate) and producing a robust load bearing structure, it is important to understand the soil-structure interaction during and after the installation process in order to ensure the structure can adequately support (dynamic) loads. This is still a topic of on-going research. Certifying bodies therefore recommend impact driving over the last part of the installation process

For offshore applications, piles are commonly impact driven [R11]. Therefore, this project focusses solely on impact driven monopiles.

4.1.2.3 Corrosion

The corrosion state of a monopile at the end of its lifetime must be considered when planning for decommissioning by means of hydraulic extraction. The presence of corroded surfaces, inside and outside of a monopile, must be taken into account when evaluating structural strength and hydraulic extraction risks.

The following paragraph is quoted from Buck (2017) [R3].

“The most critical corrosion zones of offshore wind structures are the splash/tidal zone and closed compartments filled with seawater (e.g. the internal of a monopile or jacket foundation structure)”.

“Local corrosion attack by microbial corrosion (MIC) has been noticed on the internal surface of different monopile foundations on different locations in the North Sea. With grouting failure

repair of several monopile foundations, local corrosion attack was detected on the internal surface area of the unprotected monopile. Until then the internal area had been a black box: the hedge was sealed to reduce and stop the internal corrosion process. Nowadays, MIC processes inside monopile foundations are still not known in very much detail and require further investigation to find optimal control measures".

"In existing wind farms, no anti-fouling techniques are currently applied on the foundations. In this situation, the uncoated steel subsea zone and the coating system on the transition piece are both susceptible to biofouling." "Biofouling creates micro-environments encouraging MIC",

Corrosion leads to a loss of wall material, hence a decrease of monopile strength. Consequently, corrosion inhibition is often attempted (e.g. by using cathodic protection or coatings).

The use of cathodic protection (e.g. by using alloys of zinc, magnesium and aluminium) can have some unwanted side-effects such as: 1) increase in acidity, 2) formation of H_2 (possible hydrogen embrittlement) and/or H_2S (poisonous), and 3) pollution of water and soil with heavy metals (in case zinc has been used). Deltares has developed a methodology in which water replenishment holes in the monopile cause refreshment of the monopile interior water such that this water quality is similar as the surrounding sea water [R29] [R31]. H_2S formation and pollution of the soil should still be considered.

Since not all corrosion processes seem to be controlled well yet, and since corrosion inhibition measures are reported to have failed, [R3], one should consider inspecting the monopile on corrosion and assess its remaining mechanical strength prior to extraction. Also soil pollution and presence of H2S should be assessed.

4.1.2.4 Environmental impacts

At the end of the lifetime of offshore wind turbines must be decommissioned, which is also stated in the permits (e.g. for the Dutch offshore sector this is within two years after end of exploitation and within the duration of the permit ([R5] to [R10]). This reduces the risk of corrosive pollution in the long term. The recycling of materials and components is also a positive impact of the decommissioning.

During the process of hydraulic pile extraction there are several aspects on the environmental impact that need to be considered:

- Noise emission
- Spill of monopile interior water to the surroundings
- Pollution of soil in the monopile interior.
- Damage to sea life in surroundings of monopile

These items are further detailed in the following sub-sections.

4.1.2.4.1 Noise emission

Operations at sea in general cause noise emissions higher than the natural surroundings (e.g. sailing, offshore construction (pile driving, deposit scour protection), and wind parks). Sea life may be affected by this, depending on the noise sound level and/or frequencies of the sound. However, it is yet not fully understood, how each species is affected by noise (sound) and how it differs between species. Both the noise sound level and the duration of the noise seem to be of relevance.

With respect to hydraulic extraction of monopiles, it is expected that the noise emission will remain within the acceptable limits. Also, the operation itself is targeted to be within about 1 or 2 days per monopile. Even though the noise level is expected to be low, and that the scaling of noise to prototype dimensions is unknown, it is recommended to measure the noise level during some scale tests. In a later stage, during the hydraulic extraction of an actual monopile at sea this again should be measured, to rule out any unwanted side effects [R28] [R34].

Offshore personnel can be exposed to noise during working hours and is protected against its effects by imposing maximum noise levels. Noise is also produced during installation, normal operation and decommissioning of a subsea system. There are national laws in place that aim to protect flora and fauna from harmful effects from the generated noise. The most important one is the ‘Nationale Wet Natuurbescherming’ (2017), which has replaced the ‘Natuurbeschermingswet’ (1998), ‘Boswet’ and the ‘Flora- en Faunawet’.

4.1.2.4.2 Spill of monopile interior water to the surroundings

The monopiles may be (partially) filled with sea water during their lifetime at sea, and this water may be of less quality than that of the surrounding sea water (e.g. due to corrosion products and/or corrosion inhibitors injected herein to prevent corrosion).

For a 6m and 8m diameter monopile filled internally with a 20 m high water column, this amounts to 565 m^3 and 1005 m^3, respectively. It may be required to get a permit for such spillage, e.g. Denmark has amended their Law on Environmental Protection of the Sea in December 2014: *“all spills over 5000L should be reported immediately to the Danish Environmental Protection Agency (DEPA)”* [R2] . For the Netherlands a permit is required (due to the International OSPAR-agreement and the London Dumping Convention protocol). However, it may be that the monopile has water replenishment holes *“to prevent acidification of stagnant water, which can cause damage to sensitive cables and other fitting inside the monopile”* [R31]. With these water replenishment holes, it is expected that the water quality of the monopile interior is similar as the ambient sea water. Then, a permit for spill seems not relevant.

This topic is of relevance for all methods on monopile removal, and not specific for hydraulic extraction.

4.1.2.4.3 Pollution of soil in the monopile interior

When using cathodic protection with zinc, the top layer of the soil inside the monopile may become polluted with zinc (this is less problematic when using magnesium or aluminium). When the monopile interior has stagnant water (i.e. no water replenishment holes are present) this should be assessed. This volume of soil may need to be removed and cleaned [R4].

4.1.2.4.4 Damage to sea life in surroundings of monopile

“Large offshore structures have unique effects on the marine ecosystem. They induce changes in biodiversity, with repercussions on local as well as regional ecosystem functioning” [R15] [R17]. It has been found that wind farms can be more efficient in conservation of marine life, than marine protected areas. Removing such offshore structures (by any method) will thus also change the ecosystem again and may therefore be restricted.

4.1.2.5 Scalability

The scalability refers to the similarity in behaviour between the prototype and model scale. The challenge in physical modelling using soil material is to prepare soil samples with known and controlled properties (the dimensions of the scale model and the properties of the materials other than soil are commonly well known and controllable).

Using scaled grain sizes in a scale model may result in stress-strain behaviour of the soil that is much different from the prototype, hence it is common to use similar particle sizes to have realistic stress-strain behaviour. However, then also other phenomena (e.g. dilatancy, wall roughness effects, etc.) may become dominant in the scale model compared to the prototype, and extrapolation of the results small-scale test to full-scale conditions should be done with care.

Therefore, physical modelling is suitable for understanding relevant mechanisms, performing parametric studies and validation of numerical models/methods, rather than using physical modelling to obtain a precise quantitative number for a future prototype situation in the field. Therefore, it may be advisable to perform tests at various scale factors using the same soil samples. A detailed description of the scalability of soil conditions and potential consequences for the extraction process of monopiles is described in report [P2].

4.1.2.6 Setup effect

The set-up effect refers to the increase of bearing capacity of an installed monopile often observed over time, not only after reduction of the initial excess pore pressures (related to installation) but also after typical pore pressure reduction times. A detailed description of the set-up effect and potential consequences for the extraction process of monopiles is described in report [P2].

4.1.2.7 Relevance of specific monopile design features

This section addresses the relevance and impact of certain design features of the monopile, which differ from the design considered in the tests, on the extraction process. The geometry of the monopile to be tested concerns a constant diameter pile, with a cap on top that ensures the internal volume of the pile can be pressurized.

A transition piece with air-tight platform is installed on top of the monopile foundation. The transition pieces can be installed by means of a grouted connection with an overlap of approximately 1.5·D with the monopile foundation (see Figure 5), but most transition pieces nowadays are commonly bolted to the monopile foundation.

Small changes in shape in the monopile near the connection to the transition piece are not uncommon, e.g. from cylindrical to a conical shape. These are not believed to affect the extraction process or introduce such different shapes and volumes that the simple cylindrical piles in the small-scale tests no longer qualify as representative.

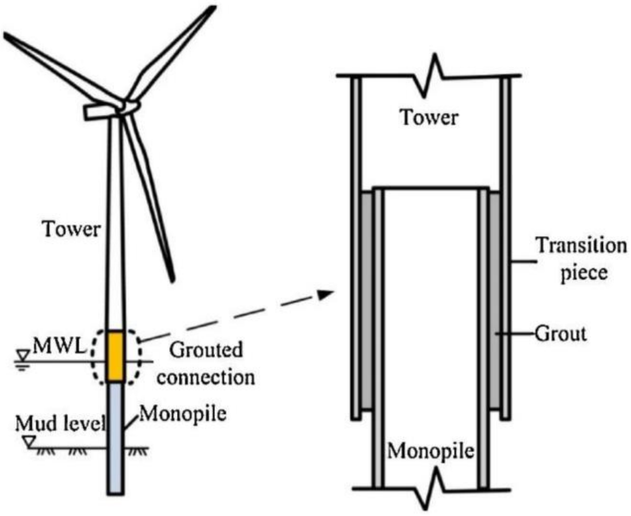


Figure 5: Schematic representation of an offshore wind turbine and its grouted connection to the monopile foundation.

To hydraulically extract the monopile foundation from the soil, it is advantageous to decommission the transition piece and internal (air-tight) platform: they introduce additional weight and benefit only partially from the buoyancy forces. If one would opt to leave the transition piece and platform in place, this implies that

- The platform is already water tight, no additional measures need be taken topside. However, some actions on the monopile openings may still be required as described below,
- The platform will need to be reinforced so that it can sustain the required forces for hydraulic extraction.

If the transition piece is grouted, then the grout would possibly fail if extracting the pile with the transition piece in place (the grout is not designed for such high shear loads). Therefore, for a grouted connection, it is recommended to remove the transition piece before extraction. For a bolted transition piece, it could be left in place, but would introduce additional weight and benefit only partially from the buoyancy forces as mentioned previously.

If the internal platform and transition piece are removed (typically single piece of steel), a submerged monopile remains that is open to seawater. To pressurize the internal volume of the monopile, the top needs to be sealed. This can be achieved by either a) welding a seal onto the monopile in case of a grouted connection, b) installing a new seal by means of a bolted connection.
Welding a plate onto the monopile such that it is sealed off can be done subsurface but will require attention to detail. The internal stress during pressurization will be largest at the edges between monopile and seal. Another option could be to explore a (hydraulic) clamping solution or to consider a hemispherical shape of the seal.

Various cables and umbilicals can be either routed from the mudline to the tower internally, or externally by means of a so-called J-tube. Opting for internal routing of the cables will

- require a suitable opening in the monopile, through which the cables can be pulled up towards the platform after installation.
- require a suitable opening in the (water-tight) platform.
- imply that any potential damaging effects from wave loading on the structure are reduced.

In case of internal routing of the cables, the opening in the monopile needs to be sealed off before it can be pressurized. This opening can be sealed off by for example installing a suitable plate on the inside of the monopile over the hole. In case of an external routing, the J-tube can be decoupled along with the transition piece and platform.

4.2 Model for hydraulic pile extraction

As part of work package 1 [P1], an analytical model was developed by TNO in collaboration with the Joint Industry Partners. The analytical model was developed to be able to predict the pressure required to extract the piles in the experimental setup.

Five forces acting on the monopile during the extraction process can be identified, see Fig. 3 (left). The resultant force is given by:

$$F_R = F_H + F_{Fint} + F_{Fext} + F_A + F_W \qquad [1]$$

Where F_R = resultant force F_H = hydraulic upward force, F_{Fint} = internal friction force, F_{Fext} = external friction force, F_A = buoyant upward force and F_W = gravitational downward force, see Figure 6 (left).

For perfectly drained conditions in homogeneous soil, the effective soil stress in the soil inside the pile follows from solving the differential equation [2]:

$$-\frac{d\sigma'_v}{dz} + \frac{dH}{dz}\gamma_w + \gamma' - \sigma'_v K \frac{4}{D}\tan(\delta) = 0 \qquad [2]$$

Where σ'_v = effective vertical stress in the soil, z = vertical coordinate (taken 0 at the soil water interface and positive downwards), H = hydraulic head, γ_w = specific weight of (sea-) water, γ' = submerged soil weight, K = ratio between effective horizontal stress and effective vertical stress, D = inner diameter of the pile and δ = interface friction angle, see also Figure 6 (right). The solution of equation [2] is given by:

$$\sigma'_v(z) = \frac{\alpha}{\beta}\left(1 - e^{-\beta z}\right) \qquad [3]$$

Where $\alpha = \frac{dH}{dz}\gamma_w + \gamma'$ and $\beta = K\frac{4}{D}\tan(\delta)$. The total internal friction force is obtained by integrating the product of the effective stress and $\pi D\, K\tan(\delta)$ over the depth:

$$F_{Fint} = -\pi D K \tan(\delta) \int_0^d \sigma'_v(z)\, dz = -A\,\alpha\,(d + \frac{1}{\beta}\left(e^{-\beta d} - 1\right) \qquad [4]$$

The external friction force follows from:

$$F_{Fext} = -\pi(D + 2t)K\tan(\delta) \int_0^d \gamma' z\, dz = -\pi(D + 2t)\, K\tan(\delta)\, \gamma' \frac{1}{2} d^2 \qquad [5]$$

Where t = wall thickness of the pile.

Alternatively, the internal and external friction force can be estimated with a method based on Cone Penetration Test (CPT) data, such as the University of Western Australia (Lehane, B.M.

et al. 2005) or Imperial College Pile friction model (Jardine, R. et al. 2005). See also Houlsby, G.T. et al. (2005). The differential equation for the effective vertical stress σ'_v in the soil inside the pile is solved numerically when using a CPT based friction model as no simple analytical solution can be provided.

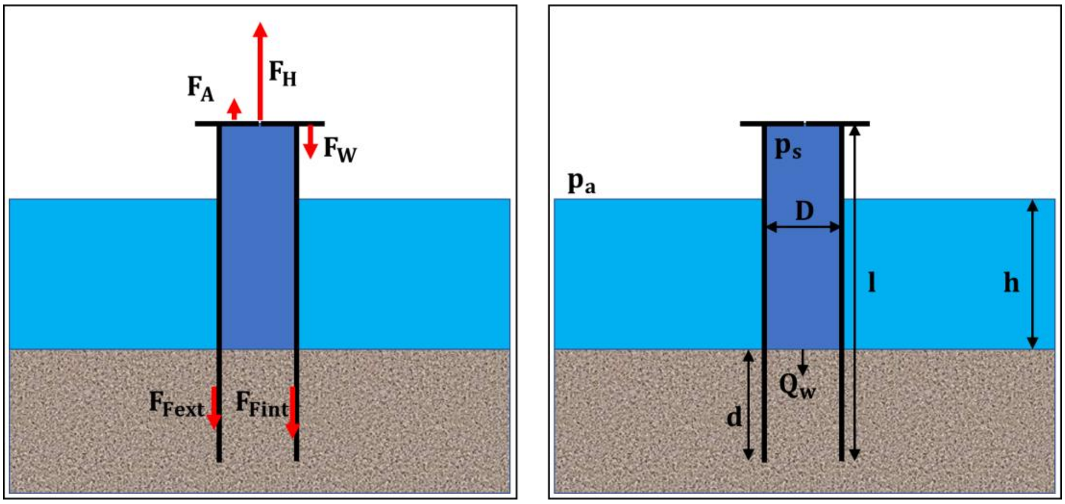


Figure 6: Illustration of the forces that act on the monopile during the extraction process (left) and parameters used in the analytical model (right).

The downward gravitational force F_W, the upward buoyance force F_A and the upward hydraulic force F_H are:

$$F_W = -M_{pile}\, g \tag{6}$$

$$F_A = \frac{h}{l}\, V_{pile}\, \gamma_w \tag{7}$$

$$F_H = A\,(p_s - p_a) \tag{8}$$

Where M_{pile} = mass of the pile, g = gravitational acceleration, h = water depth, l = length of the pile, V_{pile} = volume of the pile material, p_s = pressure at the top of the water column inside the pil and p_a = ambient pressure. See Figure 6 (right). A similar approach of evaluating a force balance was followed in Lehane et al. (2014) for extraction of a suction caisson in sand.

For undrained conditions in homogeneous soil, Eq. [4] is substituted by:

$$F_{Fint} = -\pi D \int_0^d \tau_w \, dz = -\pi D\, a\, s_u\, d \tag{9}$$

Where $\tau_w =$ undrained shear stress, $a =$ cohesions coefficient and $s_u =$ undrained shear strength. Similarly, the external friction force for undrained conditions equals:

$$F_{Fext} = -\pi(D + 2t) \int_0^d \tau_w dz = -\pi(D + 2t)\, a\, s_u\, d \qquad [10]$$

The break-out pressure is defined as the pressure p_s (at the top of the water column inside the pile) for which the resultant force $F_R = 0$. A larger pressure gives a positive (upward) resultant force $F_R > 0$. The analytical model was extended to include combinations of drained and undrained soil layers (not presented in this report). With the analytical model, predictions of the break-out pressures were made for different soil configurations and scales envisaged for the HyPE-ST experimental test program. The calculated break-out pressures are used as input for the experimental design.

5. Work packages 2&3 (WP 2&3): Experimental design and testing phase

The objective of the laboratory scale tests is a proof of concept of the hydraulic pile extraction method. A secondary objective is to gather data to help better understand the pile-soil interaction and the potential leakage of fluids during pile removal under different circumstances. Additional information on the works conducted in WP 2 & 3 can be found in [P3].

5.1 Experimental design

5.1.1 Test facility

The tests are performed in Deltares' Water-Soil Flume. The Water-Soil Flume comprises a large concrete research-flume of 50 m x 5.5 m x 2.5 m (length x width x depth) and settling basin of 50 m x 3.5 m x 2.5 m (length x width x depth) with a motorized carriage, travelling on top of the flume. The traveling carriage consists of a multipurpose installation platform complete with data-acquisition and data-processing systems and vibrating needles for compaction of sandy soils.

The flume can be divided into compartments of variable size. For the HyPE-ST project, two compartments were created, referred to as A and B, each of dimensions 7.2 m x 5.5 m x 2.5 m (length x width x depth), see Figure 7.

5.1.2 Test piles

The HyPE-ST tests are performed at two different scales: 1:20 and 1:30. A monopile with a diameter of 8 m and an embedded length of 40 m (5 times the diameter) is chosen as reference. For the scale 1:20 piles, the outer diameter equals 406.4 mm (16") and the embedded length equals 2.0 m. For the scale 1:30 piles, the outer diameter equals 273.0 mm (10.75") and the embedded length equals 1.33 m. The wall thickness is not to scale. A flange with a thickness of 30mm was welded to each pile to be able to seal the pile with a cap.

Figure 7: Left: test compartments A and B created for the HyPE-ST project in the Water-Soil Flume. Right: scale 1:20 piles (bottom) and scale 1:30 piles (top).

5.1.3 Soil types

Different (engineered) soil types are constructed in the compartments of the Water-Soil Flume: Dense sand, medium dense sand, clay and layered soil configurations (a combination of dense sand and clay).

Sibelco S90 sand is used for the preparation of the sand models where d_{50} is 180 $\mu\mathrm{m}$ and the coefficient of uniformity c_{u} is 1.5. Fresh water is used to saturate the sand. The sand is built-up in layers of 0.5 m thickness. After each new layer of sand is added, the traveling carriage inserts vibratory needles in the sand bed to compact it to the desired relative density. Cone penetration tests (CPTs) are performed to characterize the soil properties and to confirm the target relative density is achieved.

A clay factory – that is present in the vicinity of the flume - allows manufacturing of clay to desired specifications. In the clay factory, Abdichteton FT-S1 powder is mixed with fill sand and fresh water. The ratio of the clay powder, sand and water determines the strength of the end product. By extruding the mixture, clay bricks are manufactured with dimensions 1.5 m x 0.5 m x 0.2 m (length x width x height), see Figure 8 (left). The clay bricks are stacked in the flume to construct the clay soil profile, see Figure 8 (right). For the HyPE-ST project, more than 300 clay bricks with an undrained shear strength of 40 kPa were manufactured.


Figure 8: Left: Clay brick exiting the extrusion press. Right: stacking of the clay bricks in the flume.

5.1.4 Pile installation

In each soil profile, 6 piles are installed, see Figure 9. The installation is done by pile driving. Dragline beams are positioned on top of the flume to allow positioning of the IHC Fundex CP25D pile driver. The ram mass used for the HyPE-ST project is 1650 kg. For each pile installation the blow count and energy per blow is recorded. After installation in sand and layered soil configurations, in-situ falling head tests and CPTs are performed.


Figure 9: Left: IHC Fundex CP25D pile driver positioned on dragline beams on top of the flume. Right: 6 piles are installed in each soil model.

5.1.5 Test setup

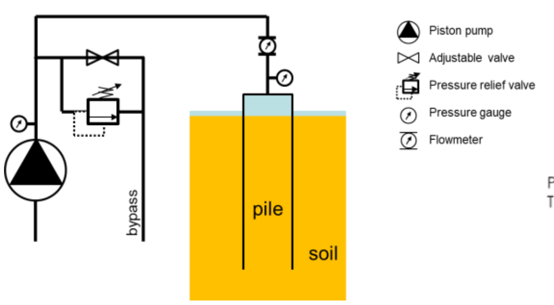
Figure 10 (left) shows a schematic overview of the pump layout. A piston pump with 5 pistons is used to pump fresh water into the pile. The flow delivered by the pump is controlled with a frequency controller. The pressure in the pile depends on the applied flow, the permeability of the soil inside the pile and the plug length.

A bypass with an adjustable valve is connected to the pump to control the flow. When the bypass valve is fully opened, all flow goes through the bypass and there is no build-up of pressure in the system. When the bypass valve is fully closed, all flow goes towards the pile and pressure will build up. By adjusting the bypass valve, the flow towards the pile - and thus the pressure in the pile – can be controlled. The vertical velocity of the pile is limited by the flow that is delivered by the pump. Furthermore, a pressure relief valve (PRV) ensures that the pressure in the system does not exceed a pre-set pressure.

Figure 10 (right) gives a schematic overview of the measurement layout. Measurement equipment that is used during the hydraulic extraction tests consists of:

- Wire displacement transducer to measure the displacement of the pile head;
- Flow meter to measure the water flow towards the pile;
- Pressure gauge at the pump to measure the pressure delivered by the pump;
- Pressure gauge at the pile cap to measure the pressure in the pile;
- Pore water pressure sensors at 0.2, 0.4 and 0.6 m from the bottom of the basin (-0.2, 0 and +0.2 m from the pile tip) to measure the pore water pressure;
- Temposonic to measure the distance between plug surface level and the pile cap;
- Cameras to record the pile movement and monitor the soil surrounding the pile.

All measured variables are processed by the data-acquisition system. The measurements are logged at 10 Hz in a single datafile.



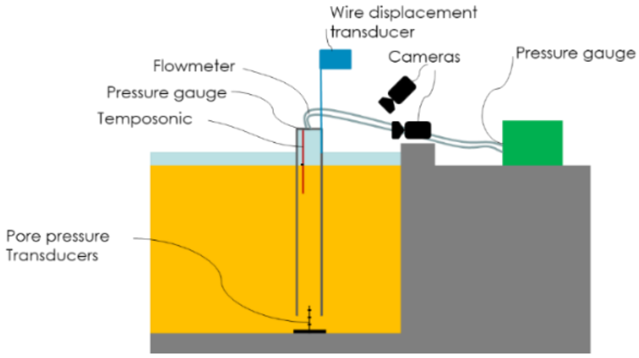


Figure 10: Left: Water pump layout. Right: Measurement layout.

5.1.6 Test procedure

Before the start of the hydraulic extraction tests, the cap - including the measurement devices - is lifted to the pile by the overhead crane and the cap is bolted to the flange. Next, the air vent valve on top of the cap is opened. Depending on the soil type, the by-pass valve is either partially opened (clay and layered soil configurations) or fully closed (sand). The pump is turned on to fill the pile with water. When water flows of the air vent, this indicates filling is complete. For safety reasons, the overhead crane remains connected to the pile during the test.

The hydraulic extraction test starts when the air vent valve on the cap is closed. As water flows towards the pile, the pressure in the pile builds up. The flow is kept constant for 5 minutes, while the pressure inside the pile and the vertical movement of the pile are monitored. When the pile has not moved, the flow is increased and held constant again for another 5 minutes while monitoring the pressure and vertical movement. This is repeated until vertical movement of the pile is detected.

When vertical movement of the pile is detected, the flow is kept constant so that the piles are extracted at a constant rate. The crane is hoisted, following the pile movement, while the slings are kept slack, so no mechanical force is applied by the crane during the extraction process. The pump is kept running at a constant flow until the pile gets unstable or until the pile stops moving upwards. When this occurs, the test is stopped. The pump is turned off, recordings are stopped, and the pile is lifted from the test area using the overhead crane.

5.1.7 Test scope

Four piles, two piles of both scale 1:20 and scale 1:30, are extracted from each uniform soil model. The uniform soil models are clay, medium dense sand and dense sand. For the dense sand, tests were also performed after a longer setup time. In addition to the uniform soil model tests, four piles of scale 1:20 are extracted from two different layered soil configurations: 1) dense sand with clay below and 2) dense sand with bentonite added on top. The effect of the presence of bentonite is quantified by comparing the extraction of a pile from sand with and without bentonite added, as well as comparing the extraction of a partially excavated pile with and without bentonite added. The test scope of the hydraulic extraction tests is schematically illustrated in Figure 11. In addition to the hydraulic extraction tests, mechanical pull tests were performed, as well as small-scale tests and a variety of lab tests. These tests are not included in this report.

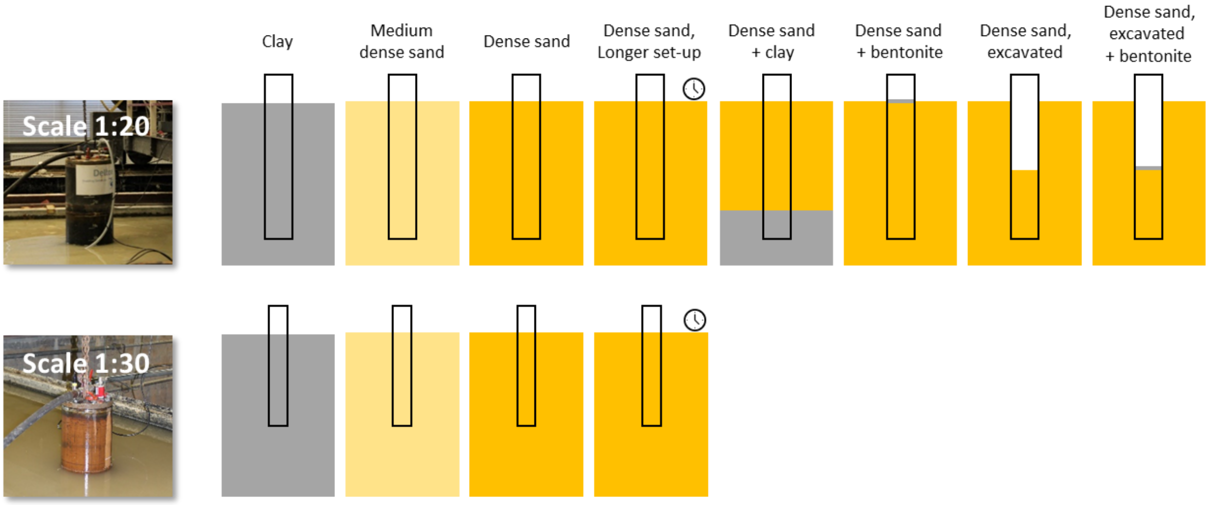


Figure 11: Schematic overview of hydraulic extraction test scope.

6. Work packages 4 (WP4): Interpretation of test results

This section presents the first insights from the test results as contained in [P4]. Because the HyPE-ST project is a confidential project, no values for the break-out pressure or other variables are presented in this report. The tests have shown that hydraulic extraction is a feasible concept at the tested scale. Figure 12 shows snapshots of the hydraulic extraction process of a scale 1:20 from dense sand.

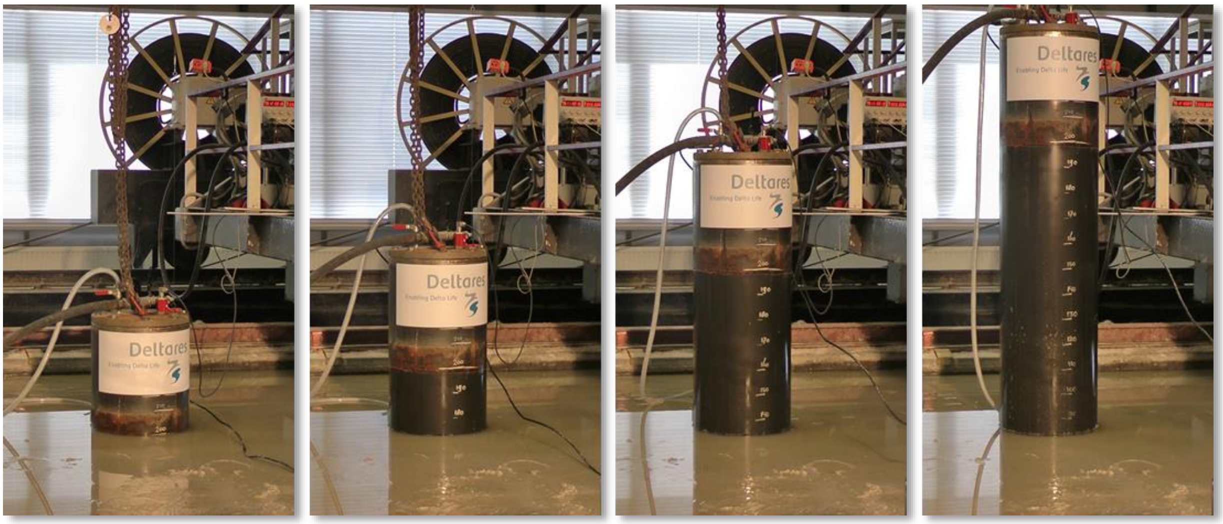


Figure 12: Scale 1:20 pile being hydraulically extracted.

A typical result of hydraulic extraction test is given in Figure 13, where the pressure in the pile is plotted against the vertical displacement of the pile. The highest pressure, at a displacement of the pile equal to 0, is referred to as the break-out pressure. When the pile moves upwards, the pressure decreases until it stops moving upwards after a certain distance.

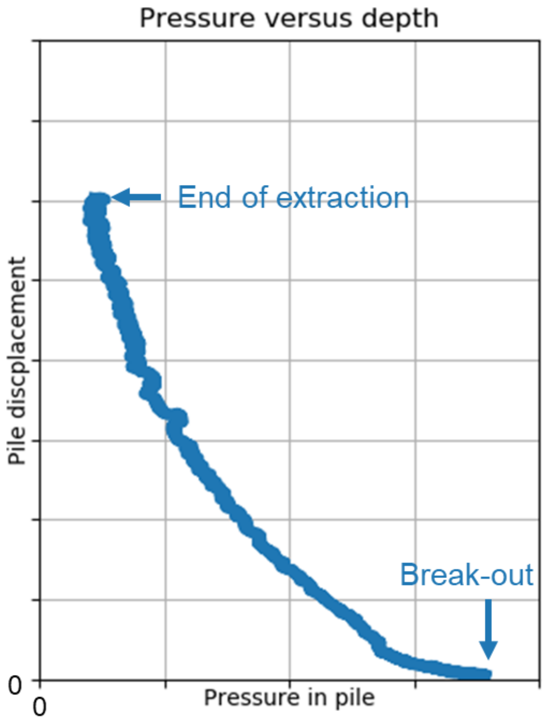


Figure 13: Scale 1:20 pile being hydraulically extracted.

The break-out pressure depends strongly on the scale and on the soil configuration. Particularly the presence of a soil layer with low permeability can strongly affect the break-out pressure. Figure 14 shows the relationship between the installation energy and break-out pressure for piles installed in sand. As expected, a higher installation energy generally results in a higher break-out pressure.

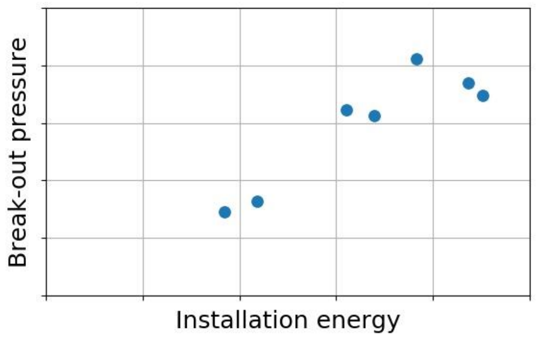


Figure 14: Break-out pressure versus installation energy in sand for scale 1:20 piles.

No significant difference in break-out pressures was found between tests where the set-up time was relatively short (extraction 1 week after installation) and tests where the set-up time was longer (extraction 6 weeks after installation).

7. Concluding remarks

The Hydraulic Pile Extraction Scale Tests have demonstrated the feasibility of the hydraulic extraction method at a scale 1:20 and 1:30 for a variety of soil configurations. At the tested scale, the break-out pressure was observed to strongly depend on the soil type and configuration. Particularly the presence of a soil layer with low permeability can have a large effect on the break-out pressure.

The method of hydraulic extraction becomes more efficient for less slender piles. Offshore foundation piles in the wind industry show a trend towards larger diameters and shallower installation depths. This makes the hydraulic extraction method very promising for future decommissioning of offshore wind turbine foundations.

To further develop the hydraulic pile extraction technology, a validation process of the proposed model must be conducted against full-scale measurements.

8. Acknowledgements

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