Proceedings of ISFOG 2025
5TH INTERNATIONAL SYMPOSIUM ON
FRONTIERS IN OFFSHORE GEOTECHNICS
Nantes, France | June 9-13 2025

ISBN 978-2-85782-758-0

Geological, geophysical and geotechnical aspects of boulders and their influence on offshore foundations

D. A. Kort*, B. Bellwald, M. Vanneste, P. Sparrevik
Norwegian Geotechnical Institute, Oslo, Norway

M. E. Vardy
Sand Geophysics, Southampton, UK

**Arjen.Kort@ngi.no (corresponding author)*

ABSTRACT: The presence and size of boulders are important drivers for the selection of offshore wind turbine foundations and cable routes. Inadequate understanding of the boulder issue can jeopardise the installation and performance of penetrating foundations and can involve significant delays and associated cost increases. For geotechnical design, this requires sufficient insight into where boulders come from, where they can be expected, how they can be detected, avoided and/or mitigated, and which boulders still can have an acceptable effect on the performance and integrity of the foundation. The paper briefly presents the geological, geophysical and geotechnical aspects of boulders from the perspective of foundation engineering. The first part explains that boulders can be expected in areas and stratigraphic levels affected during the Pleistocene glaciations. Deposits with potential boulders include glacial till, towards the bottom and along the slopes of tunnel valleys and its infill, or drop stones in glacial clays. The second part of the article discusses various geophysical techniques that can be used for boulder detection and the feasibility of selected methods, such as 3D UHR seismics, and acoustic coring. It shows that the costs of boulder detection increase significantly as the smaller boulders need to be detected. This raises the question of what boulder size should be detected. The third part of the article presents some simplified methods to assess the behaviour of a boulder during installation of intrusive foundations including downward/lateral pushing of the boulder and crushing boulders, and some installation experiences.

Keywords: Boulder; Penetration; Glacial deposit; Geology; Geophysical investigation

1 INTRODUCTION

Embedded boulders can damage foundations during installation of piled and/or skirted foundations or compromise the behaviour of such foundations. Examples related to offshore foundations are pile tip buckling of large diameter thin-walled monopiles (Nietiedt et al., 2023) and installation refusal of thin-walled skirted foundations. Foundations that cannot be penetrated to the desired installation depth and damaged foundations cause significant delays and associated cost increases. Geotechnical design requires sufficient insight into where boulders come from, where they can be expected, how they can be detected, avoided and/or mitigated, and which boulders can still have an acceptable effect on the performance and integrity of the foundation.

While the basis of piled and skirted foundation design typically includes information from site-specific offshore CPTs, other in situ testing and onshore laboratory testing of selected soil and rock samples, boulder detection relies primarily on geophysical site characterisation. Boulder risk assessment should therefore be subject to integrated ground modelling through combining geological, geophysical and geotechnical data.

This paper presents some geological and geophysical background of boulders and boulder detection, which could facilitate the geotechnical engineering in a boulder-rich area.

2 GEOLOGICAL ASPECTS

2.1 Quaternary geological time scale

Geological aspects of boulders relate to the origin and formation of boulders during the Quartenary. The Quaternary geological time scale extends from about 2580 kilo annum (ka) ago to present and is subdivided into the Pleistocene and the Holocene (last 11.65 ka). The Pleistocene is again subdivided into an Early, Middle and Late time period. In Northern Europe, the sediments that were deposited during the Middle and Upper Pleistocene typically cover the uppermost 100 metres of ground below seafloor and are therefore considered relevant for offshore geotechnics. During the Pleistocene, numerous glacial periods were accompanied by significant advances of ice sheets in Europe, Asia and North America, during which sealevels dropped to 80 to 120 metres below present sealevel due to ice accumulation near the poles. During a glacial period, the glacier experienced repeated advances and retreats of smaller extents. The long glacial periods were separated by shorter interglacial periods (Figure 1).

Marine isotopic stages (MIS) separate the Quaternary into glacial and interglacial periods. Variations in the 18O/16O isotope ratio (two isotopes of oxygen) by mass is used as a diagnostic of ancient ocean temperature change. The data are derived from pollen, foraminifera (plankton) and other organic remains that reflect climate history and are present in the soil samples.

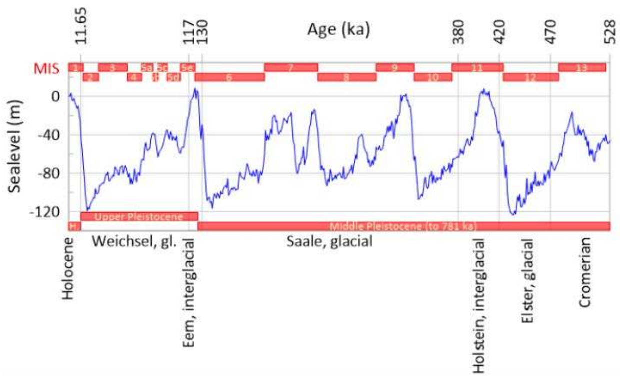

Figure 1. Quaternary time scale for Northern Europe. Age in thousands of years (ka)

2.2 Formation of boulders

During a glacial period, glaciers grow due to the excessive accumulation of precipiation in the form of snow and ice at freezing temperatures near the poles and in the mountains. The ice mass moves slowly down-slope driven by self weight, creating rivers of ice, also called ice streams. Boulders are formed when freeze-thaw weathering cycles occur in the rock, as a result of pore water thaws and refreezes. Each time the pore water freezes, it expands, causing the crack to widen slightly and eventually the rock to break off. The rock fragments are picked up by the ice and migrate gradually to the bottom of the glacier, where they join other debris. As the glacier flows, it grinds the rock on the sides and bottom of the ice stream, picking up more debris and forming more boulders. In addition, bedrock can also be plucked at the base of an ice stream. This process is enhanced in fractured and faulted bedrock due to the expansion of freezing pore water, especially with the presence of permafrost and gas hydrates. For geotechnical purposes, the glacial material can be thought of as a dispersed mixture of unsorted solid particles with ice in the pore space (Figure 2). This can also apply to the underlying ground over which the glacier flows further down-slope. This ground is compacted and frozen by the thickness and weight of the glacier.

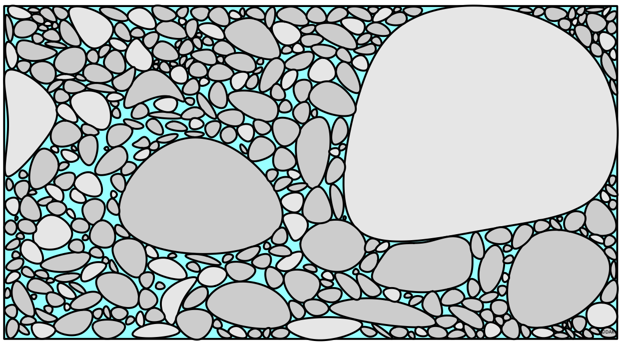

Figure 2. Glacial material, composed of solid particles and ice in the pores

When the glacier stops advancing and starts retreating, it deposits the mixture of pore ice and solid particles. Eventually, the pore ice melts, reducing the pore volume and – in case of a closed pore space – increasing the effective stresses in the ground. This ground is known as glacial till and the process may explain why glacial till is typically experienced as very compacted and with extremely high shear strength. It is therefore very likely that glacial till contains boulders, especially near the ends of the glaciers.

Alternatively, when the glacier reaches the open sea, large chunks of ice break off and form floating ice sheets or ice bergs. When a floating ice sheet eventually melts, cobbles and boulders fall to the seafloor. They can penetrate into soft clay deposits, which can be experienced as drop stones in clays. Such drop stones can also be experienced in stiffer clays if the clay deposit is compacted during a later glacial event. Cobbles and boulders may also roll or sink into tunnel valleys, that are deep valleys carved into the hard soils beneath the ice by the discharge of large volumes of meltwater (Bellwald et al., 2024). Cobbles and boulders may also remain on the seafloor and in later stages be covered by outwash and marine sediments, such as the remobilized Holocene sands.

3 GEOPHYSICAL ASPECTS

Geophysical aspects of boulders relate to the detection of their presence and size. Seafloor boulders can be detected by visual or camera inspection using ROVs, or by seismo-acoustic methods (e.g., multi-beam echo-sounding bathymetry and backscatter, side-scan sonar imagery). Detecting boulders buried within the sediment requires the use of ultra-high-resolution seismic data, ideally in 3D, in order to properly "position" their occurrence in the sub-surface. On such data, boulders would typically stand out as a high-amplitude reflection, accompanied by a diffraction hyperbola (on unmigrated data).

3D seismic reflection tools allow the thickness and shape of different soil units and objects (like boulders) to be determined, as well as the description of internal structures and the internal acoustic appearance. The main difference between the different seismic reflection tools is their resolution and penetration-ability, which depend on both the frequency of the seismic waves and the composition and density of the soil layers. Note that 2D seismic reflection data are more commonly used than 3D. Amplitude anomalies on 2D data may however be caused by out-of-plane objects, which would be incorrectly positioned along the line at the wrong depth.

Despite the wide range of geophysical sensors on the market and the equally wide experiences with their performance, which also strongly depends on the complexity of the site, Figure 3 provides an overview of commonly used geophysical tools and sensors used in offshore site characterisation and their capabilities in terms of frequency range, vertical resolution and maximum vertical penetration depth. These capabilities are derived from simplified and empirical 1-dimensional rules of thumb: $\lambda/4 = v_p/(4f)$ and $\delta = 75 v_p/f$ (Denham, 1981) using v_p = 500-1500 m/s to capture a typical range between very dense tills and very soft clays. In here, $\lambda/4$:= vertical resolution (λ := wavelength); v_p:= p-wave velocity; f := frequency; δ := penetration depth (2-way travel time).

Figure 3 shows a range of minimum required frequencies needed to detect a boulder of 2 m and 0.5 m in diameter. The ranges are derived based on the assumption that a) 2 pixels are needed to detect a boulder; b) the boulder is located directly below the survey line; c) that the wave field propagation allows boulder detection on seismic data by a 2-way travel time (e.g., by anomalies, diffractions). It shows that boulders smaller than 2 metre in diameter are hardly detectable using Pingers, Chirps and Boomers and that boulders smaller than 0.5 metre in diameter may not be detectable below 35 metre depth, i.e., potentially along a full (mono)pile length. A sparker source with a central frequency of 1,000 Hz seems capable to image objects larger than about 0.5 m and achieve high resolution and sufficient penetration. In practice this means that 3D seismic data is required for boulder detection.

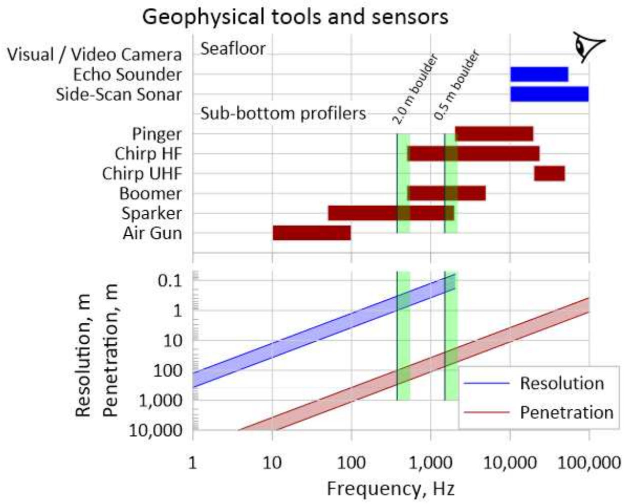

Figure 3. Potential of geophysical tools and sensors

Figure 4 presents the TNW case study of boulder detection based on 3D Ultra High Resolution Seismic (UHRS) data (RVO, 2022). A subset of the 3D UHRS data volume was interpreted to identify and map all discrete targets that potentially represent a boulder. Each target was then manually assessed, quantifying the location and burial depth of the potential boulders or removing erroneous targets. In this way, 2474 boulders were detected in a subset area of approximately 1 km x 2 km and 40 m deep, with diameters ranging from about 2 to 7 m. However, boulders smaller than 2 m in diameter are also important for foundation installation. The quantity of smaller boulders can be assessed, for example, using an empirical cumulative boulder size fraction curve (Sand Geophysics, 2020).

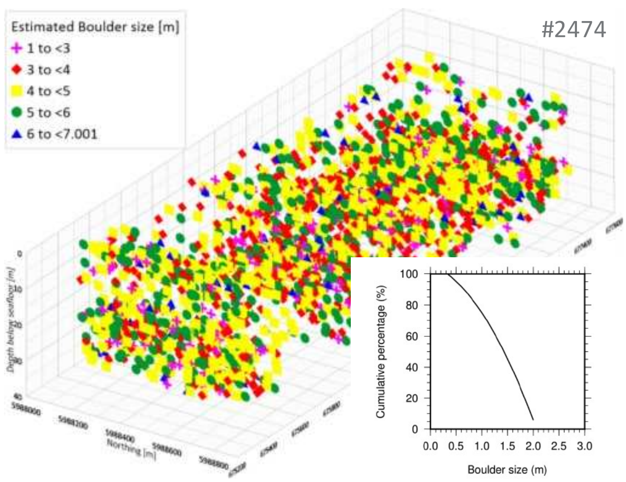

Figure 4. Example of boulder assessment from 3D UHRS data

3D UHR survey data are ideally suited for early detection studies of boulders to support further risk assessments related to concept selection, design, marine operations and offshore foundation fabrication, as they can cover large areas in relatively short offshore times. For detailed engineering and site-specific assessments, e.g., for foundation, pipeline and cable installation, more accurate information on the quantity, size and depth of smaller boulders may be required. HF to UHF seismic tools are more suitable for detecting boulders with diameter < 2 m. However, the penetration depth of such systems is typically less than 10 metres. The attractiveness of the different systems depends on the economic balance between the objective of the survey and the operation time. For example, the Sub-Bottom Imager (Dinn, 2012) and the diffraction imaging method (Römer-Stange et al., 2022) may be more suitable for surveys along cable routes whereas the Acoustic Corer (Noel and Griffiths, 2024) can be more appropriate for boulder mapping for installation of (mono)piles or thin-walled skirted foundations where boulders may be avoidable by minor repositioning (Figure 5).

In summary, the detection of smaller boulder sizes requires 3D High Frequency to Ultrahigh Frequency seismic tools. However, the use of higher frequency comes at the expense of the achievable penetration depth. For optimal planning of a 3D geophysical survey at an early stage of an OWF development, a good understanding of the minimum boulder size to be detected in the survey is useful.

Applying local detection methods such as those in Figure 5, implies that the cost of boulder detection increases significantly as smaller boulders are to be detected. This raises the question of what boulder size should be detected or what boulder size can be accepted.

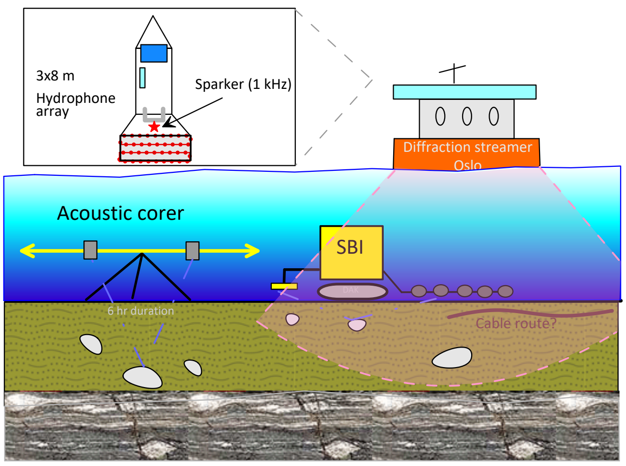

Figure 5. Acoustic corer, Sub-Bottom Imager and 3D diffraction imaging

4 GEOTECHNICAL ASPECTS

Geotechnical aspects of boulders concern the geomechanical behaviour of boulders and their interaction with structural foundation elements during installation and operation. For example, for a thin-walled (mono)pile or skirted foundation, interaction with a boulder can lead to local bucking at the pile tip, especially if the pile tip is already slightly damaged during fabrication, transport or installation (Nietiedt et al., 2023). For a suction foundation, pushing down a boulder can facilitate the formation of a piping channel between the suction chamber and open water, leading to suction penetration refusal. Both events lead to costly delays and should be avoided.

When a piled or skirted foundation encounters a boulder during installation, one of the following scenarios will occur; see also Gargarella (2018):

- The boulder will be pushed down or (eventually) to the side, leaving both the pile and the boulder intact
- The boulder will split and the skirt will pass through the split boulder
- The boulder will remain in place and the (steel) skirt will suffer local buckling at the tip
- The boulder will stay in place and the (steel) skirt will suffer virtually no damage at the tip

4.1 Boulder will be pushed down

The mechanism of a boulder being pushed down by a thin-walled skirt is very similar to a ball cone or a T-bar penetration test. The general experience from a ball cone penetration test is that the undrained shear strength of clay can be described by $s_u = q_{ball}/N_{kt,ball}$. A typical value in normally to slightly overconsolidated clay is $N_{kt,ball}$ = 10. The increase in penetration resistance ΔQ_{push} in clay is

$$\Delta Q_{push} = q_{ball} \cdot A_b = s_u \cdot A_b \cdot N_{kt,ball} \quad (1)$$

In sand,

$$\frac{\Delta Q_{push}}{A_b} = s_q \cdot q \cdot N_q + \tfrac{1}{2} \cdot B \cdot \gamma' \cdot s_\gamma \cdot N_\gamma \quad (2)$$

In here, $s_q = 1 + \sin\varphi'$; $q = \gamma' z$; $N_q = e^{\pi \tan\varphi'} \cdot \tan^2(45 + \varphi'/2)$; $s_\gamma = 1 - 0.3\, B/L$; $N_\gamma = 2 \cdot (N_q - 1) \cdot \tan\varphi'$; γ' := effective unit weight (8-11 kN/m^3, depending on the soil density); $A_b = L \cdot B$ is the projected base area of the boulder ($L \geq B$); φ' := effective drained friction angle; z := depth of boulder.

4.2 Boulder will split

Depending on the lithology and the internal structural damage or fracturing of the boulder, the boulder may split by the penetrating pile tip or skirt tip. The mechanism of this splitting is very similar to a point load test in rock. The increase in penetration resistance is

$$\Delta Q_{split} = \frac{I_{s(50)} \cdot {D_e}^2}{\left({}^{D_e}/_{50}\right)^{0.45}} \ll F_{push} \text{ in [N, mm]} \quad (3)$$

In here, $D_e = \sqrt{4A_s/\pi}$; $A_s = H \cdot B$ is the side area of the boulder; $I_{s(50)}$ is the point load strength corrected for a 50 mm boulder (ISRM, 1985).

4.3 Pile/skirt tip will fail

Pile tip buckling has been observed in field cases and has been extensively investigated by a.o. Kramer (1996), Gargarella (2018), Le et al. (2023) and Nietiedt et al. (2023). They all concluded that an initial distortion at the pile tip increases the probability of pile tip buckling during impact driving, even when the soil conditions consist of very dense tills without boulders.

A simplified analogy to assess the minimum lateral distortion load for possible skirt tip failure is the point load on the edge of a flat plate in Figure 6 (Kramer 1996). Using f_y := yield strength of steel, this yields for the allowable penetration force increase:

$$\Delta F_{yield} = f_y \cdot t^2 \cdot \sqrt{2} \quad (4)$$

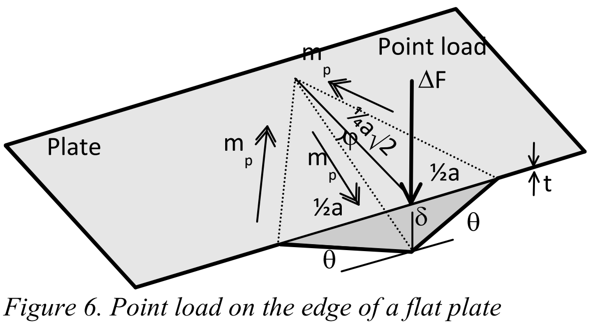

Figure 6. Point load on the edge of a flat plate

4.4 Penetration refusal

Penetration refusal will occur if the penetration load P cannot generate the penetration force increases needed to pass the boulder:

$$P \leq \Delta Q + Q_{tip} + Q_{shaft} \quad (5)$$

In here, Q_{tip}:= the pile/skirt tip resistance; Q_{shaft}:= the pile/skirt shaft resistance and $\Delta Q < \Delta F_{yield}$ follows from eqs (1-4) where applicable.

4.5 Example

Let's consider a steel pile/skirt with D = 6 m diameter (D/t = 100, f_y = 355 N/mm^2) penetrating in glacial till with s_u = 500 kPa. The tip hits a (spherical) boulder ($I_{s(50)}$ = 2 MPa) with D_e = 2 m at 10 metre depth.

- The tip resistance is $Q_{tip} = 9 \cdot s_u \cdot A_{tip}$ = 24.2 MN
- The required additional penetration resistance against boulder push is ΔQ_{push} = 15.7 MN (eq. 1)
- The additional required penetration resistance against boulder split is ΔQ_{split} = 1.52 MN (eq. 3). This is about 6% of the tip resistance.
- The minimum lateral distortion load is ΔF_{yield} = 1.81 MN (eq. 4).

In this example, the most likely scenario is that the boulder will split during penetration. No significant local damage to the tip is expected, also because, given the splitting of the boulder, the lateral load component is expected to be minor.

A more competent boulder with $I_{s(50)}$ = 20 MPa would require ΔQ_{split} = 15.2 MN, which is 63% of the tip resistance. In that case, the boulder can be split or pushed aside, provided that sufficient penetration force is available. There is also a potential for local damage to the tip that should be further investigated, as $\Delta Q_{split} \gg \Delta F_{yield}$. Since the boulder can be pushed aside, the lateral load component that initiates the buckling of the pile tip can be significant.

5 CONCLUSION

The presence and size of boulders are important drivers in the selection of offshore wind turbine foundations and cable routes. This paper provides insight into where boulders come from, where they can be expected, how they can be detected, avoided and/or mitigated, and which boulders can still have an acceptable effect on the performance and integrity of the foundation. Important aspects related to boulders affecting offshore foundations are the following:

- An integrated geological, geophysical and geotechnical ground model facilitates a risk assessment of boulders.
- Embedded boulders can be expected in areas that have been exposed to glacial processes in the past and in the immediate vicinity of these areas. This includes glacial tills but can also

include the edges of tunnel valley-infill or other clay infills with drop stones.

- Embedded boulders can be covered by Late Pleistocene deglacial and interglacial sediments, such as the mobilized sands of the Holocene or the deglacial outwash sequences.
- 3D UHRS seismic surveys are a useful tool to provide a design basis for boulder risk assessments in early project stages, when the exact layout of the OWF is not yet determined. This includes 3D diffraction imaging described by Römer-Stange et al. (2022).
- Detection of smaller boulder sizes requires specialised techniques, such as sub bottom imaging or acoustic coring. This can be initiated in a later project stage when the exact layout of the OWF has been determined, to evaluate how boulders can– preferably – be avoided or, if really necessary, mitigated.
- The impact of boulders on intrusive foundations is dependent on the lithology and size of the boulders as well as the soil strength in which the boulder is embedded. Therefore, larger boulders may be acceptable in soft to medium clays and at shallower depths then in very dense glacial tills.
- Inadequate understanding of the boulder issue can compromise the installation and performance of penetrating foundations and can cause significant delays and associated cost increases.

AUTHOR CONTRIBUTION STATEMENT

Arjen Kort: Conceptualization, Formal Analysis, Investigation, Methodology, Visualization, Writing- Original draft. **Benjamin Bellwald**.: Conceptualization, Methodology, Validation, Writing- Original draft. **Maarten Vanneste**: Conceptualization, Methodology, Validation, Writing- Original draft. **Per Sparrevik**: Conceptualization, Supervision. **Mark Vardy**: Investigation, Writing- Original draft.

REFERENCES

Bellwald, B., Hansen, R. C., Wood, G., Durot, B., Klinkvort, R., Collins, M., Kort, A., Janszen, A., Polonio, I., Piotrowski, J., Andresen, K.J., Carter, G., Stewart, M., and Vanneste, M. (2024). Geohazards and engineering challenges related to heterogeneous infill of tunnel valleys. In *Fifth EAGE Global Energy Transition Conference & Exhibition (GET 2024)* (Vol. 2024, No. 1, pp. 1-5). European Association of Geoscientists & Engineers.

Denham, L.R. (1981). Extending the resolution of seismic reflection exploration. *Journal of the Canadian Society of Exploration Geophysicists*, 17, pp. 43–54

Dinn, G. (2012). Field experience with a new sub-bottom investigation tool: Acoustic 3-D imaging of the sub-seabed. In *2012 Oceans* (pp. 1-9). IEEE

Gargarella, P. (2018). *Numerical study of flint/boulder behaviour during pile driving*. MSc thesis. Politecnico di Torino.

ISRM (1985). Suggested method for determining Point Load Strength. *International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts,* 22(2), pp. 51-60

Kramer, G. (1996). *Investigation of the collapse mechanism of open ended piles during installation*. MSc thesis. Geotechnical Report No. 404. TU Delft, Netherlands.

Le, V. H.; Akdag, C. T.; Aubram, D.; Daryaei, R.; Rackwitz, F. (2023). Experimental investigations on monopile tip buckling during impact driving. *Offshore Site Investigation Geotechnics 9th International Conference Proceeding*. pp. 792-798(7). Society for Underwater Technology. https://doi.org/10.3723/QKNH7776

Nietiedt, J.A., Randolph, M.F., Gaudin, C. and Doherty, J.P. (2023). Preliminary assessment of potential pile tip damage and extrusion buckling. *Ocean Engineering*, Volume 275, 114071. http://doi.org/10.1016/j.oceaneng.2023.114071

Noel, M. and Griffith, S. (2024). Defining the Buried Boulder Risk for an Offshore Wind Farm with 3D Acoustic Imaging. In Fifth EAGE Global Energy Transition Conference & Exhibition (GET 2024) (Vol. 2024, pp.1-5). European Association of Geoscientists & Engineers.

Römer-Stange, N., Wenau, S., Bihler, V., Keil, H., Ramos Córdova, C. A., & Spiess, V. (2022). Boulder detection in the shallow sub-seafloor by diffraction imaging with beamforming on Ultra-High Resolution seismic data—A feasibility study. Earth and Space Science, 9, e2021EA002156. https://doi.org/10.1029/2021EA002156

RVO (2022). Ten Noorden van de Waddeneilanden Wind Farm Zone Geological Ground Model. Report No. WOZ2200196 Rev. No. 3. Netherlands Enterprise Agency. https://offshorewind.rvo.nl/

Sand Geophysics (2020). Boulder size distribution from the North American Atlantic Seaboard. Unpublished data set.