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Design Recommendations for Monopiles Installed in Rock using an Insert Pile Concept

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ABSTRACT: The most common foundation concept for offshore wind turbine generators is the monopile, which is typically driven into a seabed consisting of layers of sand, silt and clay. However, expansion of offshore wind into new areas with rock near seabed requires innovative solutions to use the monopile concept. This paper presents recommendations for design of an insert pile solution, which is a novel solution for the use of monopiles in rock. The presented work stems from an offshore wind project with monopile foundations in Southeast Asia, where the site conditions required the monopiles to be installed into a shallow rock formation. For this project, an insert pile foundation concept was selected. This paper cover both the geotechnical in-place verifications, the drivability assessment, and the geotechnical interface to the rock through the grouted connection. The insert pile concept requires, beside the verification of the permanent phase, a verification of a temporary phases where the monopile is still not fixed to the rock. The paper concludes that the insert pile concept is a viable solution when rock is met at depths which require the monopile to go into the rock, but at the same time have sufficient soils above rock to ensure the temporary stability.

Keywords: Offshore wind; Monopile in rock; insert pile;

1 INTRODUCTION

Monopile (MP) foundations are the most used foundation concept for supporting offshore wind turbines. Monopiles are typically used where the site conditions are dominated by granular clastic soils, i.e. sand, silt and clay. For these conditions a vast experience in design methods has been collected over the past 20 years, with well-known and well proven design methods and codes, such as DNV-ST-0126 (2021), DNV-RP-C212 (2021) and API 2GEO (2021). Also, the installation process is based on the experience obtained over the past 20 years, see for instance Alm & Hamre (2001), Maynard et al. (2019) and Jones et al. (2020).

Nevertheless, some windfarms are located at sites where rock is present near the seabed. Such conditions often lead to selection of innovative foundation concepts, some of them requiring the monopile to be installed into the rock. The concept of choice will depend on the local soil conditions, depth to rock and any project specific constraints.

Sub-soil grouted connections have been used on offshore jacket projects, such as the Scottish wind farm Neart na Gaoithe, where piles up to 3.5 m in outer diameter was installed in a rock socket, cf. EDF renewables (2021). The combination of MP foundations and sub-soil grouted connections have been used for offshore wind farms in France. An example is the St. Nazaire offshore wind farm. At this site, rock was found near seabed. Hence, a solution with rock sockets was selected. For this concept, a drill was used to drill out a rock socket in the rock. As the rock was near seabed, a casing was not required to ensure a stable drilled hole. The MP were hereafter placed inside the rock socket, and the gap between rock and monopile was grouted. Similarly, the windfarms near Noirmoutier and Courseulles-sur-Mer in France have monopiles in rock.

This paper will present the learnings from the foundation design of a MP supported offshore wind farm in Southeast Asia, which is now in full operation. Due to varying depth to rock some of the monopile foundations could be installed as traditional impact driven piles, whilst others required installation into rock. During the early phases of the project several solutions for MP in rock was screened, with the conclusion that an insert pile concept would be a viable solution for the given site. This paper will present learnings related to design considerations for the insert-pile foundation concept.

2 SITE CONDITIONS

The soil conditions at the site consists of a mix of silty sand, silt and lean to high plastic clays. Typically, the top 5 meters are dominated by sandy sediments, whereas the soil from 10-20 m bsb are dominated by clayey soil units. Below the clastic soils, bedrock is found from ~13 m to deeper than 50 m below seabed. The rock is a Tuff, with an unconfined compression strength above 100 MPa. For most WTG locations, a layer of less than 2 meters of weathered rock forms a transition from clastic soils to the rock. The Geological Strength Index (GSI) is determined to 29.

The water depth ranges from 10 to 22 meters. Though significant seabed mobility is expected at the site, leading to a possible future larger variation in water depths. The seabed mobility is estimated to range from up to 13 m additional sedimentation (due toa migrating sandwave) to an additional errosion of the seabed of up to 7 m (though not at the same WTG location).

3 FOUNDATION CONCEPT

A monopile type of foundation with a bolted transition piece connecting the monopile to the WTG tower was considered as the most viable solution to support the WTG‘s at the site. This is because pin-pile jackets were considered infeasible due to the low water depth, and suction bucket jackets, were additionally not feasible due to relatively soft sediments below expected skirt tip level. Furthermore, the monopile foundation type is simple to manufacture and is often adopted in similar water depth ranges.

The use of sub-soil grouted connections for a MP foundation induce certain restrictions, which are not expected for pin-pile jacket piles. As the WTG is installed on top of the MP and transition piece, the tolerances for placement of boatlanding, interface level and hub height, also apply to the MP as installation tolerances.

Compared to traditional pin piles, the pile diameter of monopiles is significantly larger, and also the dominating loading conditions differ as MPs are dominated by lateral loading and overturning moment loading, whilst traditional pin piles are governed predominantly by axial loading.

4 THE INSERT PILE-SOLUTION

An illustration on the insert pile concept and the installation process is depicted in Figure 1. The installation sequence is shown in five steps, from a) to e). a) depicts the phase where the MP is installed to target depth just above the top of rock. How close the MP can be installed to the bedrock will depend on the uncertainty of the bedrock elevation including any change in elevation across the MP footprint. In addition, the distance may be limited by allowable tolerances for precision of the elevation for the MP top. b) shows the phase after MP installation, where the soil inside the MP is drilled out, and the rock socket (hole) is drilled out beneath the MP tip. In this regard it is worth to notice, that the diameter of the drill will be smaller than the inner MP diameter. Hence, the rock socket will also have a smaller diameter than the MP. c) shows the phase where the drilling equipment is removed and if possible, the rock socket is cleaned from any soil that may have entered. d) shows the phase where the insert pile is placed in the rock socket, and e) shows the final phase where the gap between insert pile and MP/rock is grouted and a grout plug is used to ensure no grout leakage into the insert pile.

4.1 Selection of the insert pile solution

Selecting an insert pile concept, requires additional considerations, and may eventually put constraints on the design. For the presented concept the MP is used as casing for the drilling equipment which is a significant advantage over a sacrificial casing. Using an insert-pile concept requires drilling equipment for making the rock socket, and limitations hereof will depend on available drill diameter. This may also induce limitations to the possible diameter of the insert pile. Depending on the selected grout material, the diameter of the rock socket, may then also influence the possible diameter of the MP. This is due to limitations imposed by the maximum allowable grout thickness, as demonstrated by the material supplier and documented in the grout material’s type approval certificate, typically up to 1000 mm.

As the insert pile need to be able to pass through the MP, the dimensions of the insert pile will put constraints on the minimum required inner MP diameter, and hence it results in limitations to allowable pile diameter change for conical MP section.

5 DESIGN PRINCIPLES

For the insert pile concept, design of temporary phases is vital regarding the feasibility of the foundation concept. Hence, the temporary phases need to be investigated early in design. For the investigation of the temporary phases involvement of installation contractor is advisable such that input from both installation contractor and foundation designer can be considered. Input from installation contractor is important as the insert pile is a novel concept. Hence, in contrast to piles that are installed by impact driving only, then standardized installation procedures for the foundation concept do not exist. Therefore, there may be a need to design innovative solutions to ensure required stability in temporary stages.

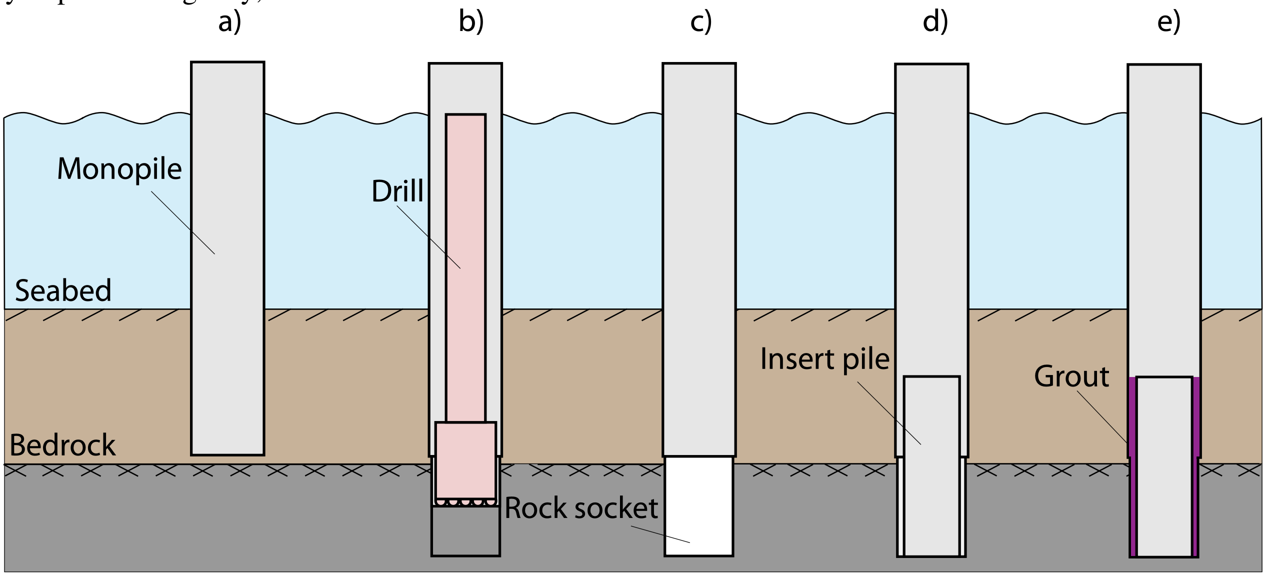

Figure 1. Installation process for the insert pile solution. a) the monopile is driven (or vibrated) until target depth above bedrock. b) The soil inside the monopile is drilled out, and a rock socket is drilled in the rock below the monopile. c) The drilling equipment is removed, and an empty rock socket is left beneath the monopile. d) an insert pile is installed into the rock socket. e) the gap between monopile-insert pile and rock-insert pile is grouted.

5.1 Temporary phase design

Chronologically, the temporary phase is of interest from the end of driving (Figure 1a)) until the foundation is appropriately connected to the rock via the grout (Figure 1e)). In that timeframe, the following must be ensured:

- (a) Ultimate Limit State (ULS) - the lateral and axial stability of the foundation against temporary loads must be ensured.
- (b) Serviceability Limit State (SLS) - limited movement of the monopile must be ensured.

Regarding the axial stability of the MP, traditional pile capacity methods may be used with careful considerations. Traditional methods used by the industry may very well be challenged or not be applicable as they are empirical and derived from pile load tests in different conditions. The most significant difference in the insert-pile concept is the drill-out of the inner soil volume during the temporary phase. Technically, this means the axial resistance is only provided by the outer shaft resistance and the end-bearing, this is further discussed in section 5.2.

Other noteworthy differences are the loading conditions during temporary phase. The weight of the drill rig must sit on top of the pile with a mass of a few hundred tons for large-diameter MP. The torque load during drilling must be taken by the MP. Lateral loads are mostly wave-dominated with some wind loads acting on the temporary sub-structure‘s surface (MP and drill rig).

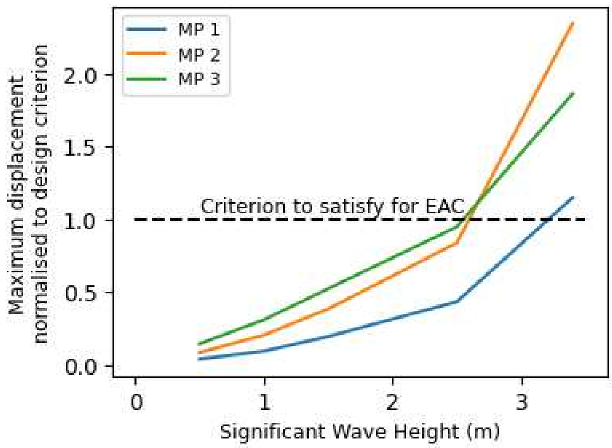

Figure 2. Example figure for three MP locations showing maximum MP displacement along grouted connection with respect to significant wave height occurring in temporary stage.

The lateral pile stability can be proven with the assistance of typical 1D Winkler beam software. However, the seabed conditions during installations may differ from the permanent design basis. For instance, this could be related to the state of the scour protection installation or to a different level of erosion or sedimentation around the MP.

Finally MP movements during installation must fulfill a strict criterion to not alter the grout curing process. In practice, it is seen beneficial to calculate pile displacements under various environmental conditions, such as sea states, cf. Figure 2, for a risk-based decision to install the piles in time periods where the grouted connection design is not endangered due to early-age cycling (EAC).

5.2 Bore hole stability

For the foundation concept it is vital to ensure borehole stability when drilling below the main pile. At the site in question, the slope of the bedrock was flat at all positions, and the monopile was driven till bedrock to close any spaces where the soil could fall into the future borehole. Uneven bedrock elevations may challenge the installation procedure. In such case, a thorough stability assessment of the soils overlying the bedrock need be carried out.

Due to the risk of rock breakage below the MP during drilling, the end-bearing may also be ignored in axial stability calculations for temporary case.

5.3 Driveability

Driveability assessment was performed to assess the installation process using impact hammer. The target penetration depth of the main pile was defined such that the pile was driven to refusal (allowing for a tolerance on embedment depth covering the uncertainty in bedrock elevation), on top of the bedrock. When driving a pile into bedrock the stresses near the pile toe will increase (as per wave equation theory stresses will double at a fixed end, Holloway (1975)). To reduce the risk for pile tip buckling, the hammer energy was reduced for the last meters above target depth (bedrock elevation). Though, this may not be possible for other projects.

Figure 3 presents the maximum compressive forces in the pile for the last penetration step with reduced hammer energy. The results show that even with reduced hammer efficiency then the modelled high end bearing from rock impact can cause stress concentrations at the pile toe.

For the insert pile concept limited ovalisation can be accepted as this may be a hindrance for the drilling equipment when drilling the hole for the insert pile.

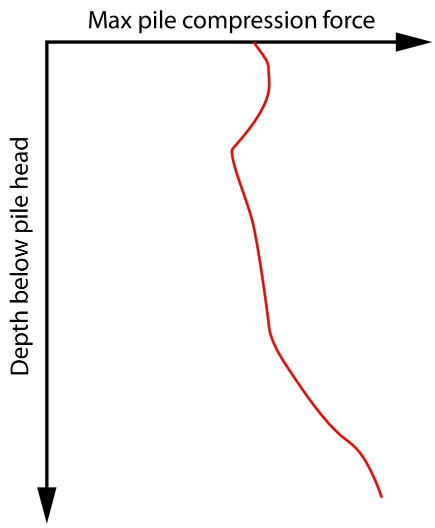

Figure 3.Representation of maximum compression forces in the pile for the last meter of driving. Stresses at pile toe increased due to impact of bedrock.

5.4 In-place design

For the in-place design for an insert pile foundation solution, the grouted connection between insert pile and main pile, and between insert pile and rock need to be assessed. Design recommendations provide analytical solutions for the design of the connection between main pile and insert pile, cf. DNV-ST-0126 (2021), whilst such are not available for the connection between insert pile and rock. Therefore, the grouted connection was assessed by means of 3D FE modelling. The 3D FE modelling for the grouted connection design need a very fine mesh to accurately model the grout material and the steel material of main pile and insert pile. Hence, it is not practical to use the same 3D FE model for both calibration of soil reaction springs and verification of grouted connection as the model size for the 3D FE model for grouted connection need to be relatively small, and further a simple linear elastic model with Mohr-Coulomb failure criterion was adopted for the modelling of soil and rock. As the soil and rock is modelled by a simplified model and as the model size of the 3D FE model for grouted connection verification are small, then the properties of the soil constitutive model need to be calibrated against the 1D model with calibrated soil springs. This calibration aims at ensuring similar pile response in terms of both deflections and distribution of cross-sectional forces. This is illustrated on Figure 4.

Besides being adopted for the verification of the grouted connection, the 3D FE model also was adopted for determining equivalent cross-section properties of the connection between main pile, grout and insert pile. These equivalent cross-section properties are important to consider in dynamic analyses (integrated load analyses) and for natural frequency assessment, as it has a significant contribution to the overall response of the structure.

5.5 Pile-insert pile-grout connection interface

The design of subsoil grouted connections must account for both the temporary and in-service phases throughout the structure's design life. In this context, the temporary phase encompasses the installation period of MP, IP, and the grout while it remains in a liquid or semi-rigid state. Conversely, the in-service phase commences once the grout has achieved its long-term strength and stiffness, allowing it to contribute effectively to the load transfer mechanism. Each phase presents unique challenges that must be addressed to ensure the structural integrity and reliability of the connection.

During the temporary phase, critical challenges specific to subsoil grouted connections arise, particularly regarding grout integrity between the IP and the rock socket. Key risks that must be mitigated include soil ingress within the grout annulus, especially in cases of uneven rock head surfaces where the MP may only partially contact the rock head around its circumference. In such cases, unsealed regions could permit soil ingress, compromising the grout annulus. To account for this, a dummy soil layer is introduced below the MP tip, see Figure 4. Additionally, over breakage of the rock during drilling or drill retrieval can lead to debris accumulation in the rock socket, and potentially enlarging the grout annulus. These factors can significantly impact the consistency and stability of the grout.

Once grout is introduced into the annulus, it is critical to control any movement induced by environmental loading on the MP during the grout's initial curing phase. Early-age cycling (EAC) of cementitious materials can lead to degradation in the mechanical properties of the grout, impacting its load carrying capacity. If the potential for EAC to exceed recommended thresholds is detected, extensive testing using a design-replicative setup may be necessary. Alternatively, the implementation of temporary supports can help mitigating the movement, thus preserving the developing strength and stiffness of the grout during this phase.

In the in-service phase, once the grout has matured and developed its intended mechanical properties, understanding the load transfer mechanism from the monopile to the surrounding rock layers is important. Load transfer within subsoil grouted connections that include an insert pile can be more complex than in other grouted configurations. Generally, the load transfer path begins at the MP, moves through the upper portion of the grout body, transitions to the insert pile, returns to the grout body at the lower end of the connection, and finally disperses into the rock layers. Careful mapping and evaluation of this load path for all straining actions help ensure that each component meets the relevant limit states within the load sequence.

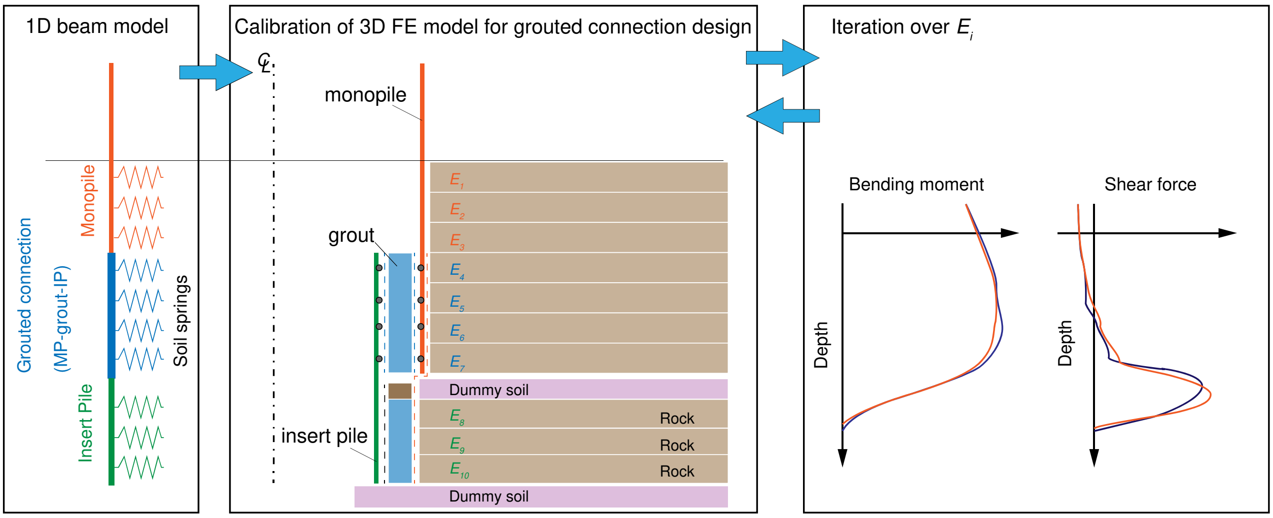

Figure 4. Calibration process for 3D FE model for grouted connection verification. Red curve represents target response from reference calculation, and black line represent the model specific response. Additionally, dummy soil layers are included in the FE modelling to conservatively discount the end-bearing capacity of both the monopile (MP) and insert pile (IP). This approach accounts for potential contamination of grout at the IP tip with soil debris, and uncertainty regarding the integrity of the rock ledge beneath the MP.

Two critical but less conventional factors in this load path are the interface condition between the grout and rock surfaces and the assumptions that can be reasonably and safely made about this interaction. It is advisable, where feasible, to document the surface roughness of the rock socket after drilling and drill retrieval. Another key consideration is the end-bearing condition and whether it is feasible to rely on it, given the likelihood of some debris remaining in the rock socket. Similarly, a dummy soil layer is introduced below the IP tip, see Figure 4.

6 CONCLUSION

This paper presents the insert pile concept, which for monopile foundations is a novel foundation concept that combines the monopile foundation concept with a sub-soil grouted connection. The paper describes the concept, and the installation phases for reaching to an in-place design. The paper presents considerations that needs to be taken before and during the design of an insert-pile foundation solution. This covers both aspects related to the temporary phase and aspects for the in-place design and provides guidelines hereto.

The aspects related to the temporary phase covers the temporary stability of the monopile, whereas aspects related to the in-place design covers topics, that are additional to normal design checks for a standard monopile foundation. This includes a description of the interface between the models needed to design the sub-soil grouted connection.

AUTHOR CONTRIBUTION STATEMENT

First author: Writing – original draft. Visualization, Formal analysis. **Second author**: Writing – review & editing, Methodology. **Third author**: Writing – original draft, Visualization. **Fourth author**: Writing – original draft, Formal analysis. **Last author**: Writing – original draft, Formal analysis.

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