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Insights On Suction Pile Offshore Installation in West African Deep-Water Field

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ABSTRACT: Suction piles have been widely used in oil & gas industry for several decades. The present paper provides feedback on the design and installation of six suction piles installed in West African deep-water field. Three suction piles were used as restraining piles for flexible risers and were submitted to a horizontal load reaching 50 T. The last three suction piles were used as Manifolds foundations and were submitted to high compressive loading reaching 350 T. For this field, piles outer diameter was standardized and fixed to 4.9 m for manufacturing issues, whereas penetration depths ranged between 11 m and 20 m below seabed. In this project, typical aspect ratios ranging from 2 to 4 were used. Water depth in the field ranges between 800 and 1300 m and soil conditions are soft to firm clay with some intermittent silt layers in specific locations. A specific challenge of the field is the high seabed slopes in certain locations near channel areas. Three restrain piles were installed where the seabed slope ranged between 7 and 9 degrees. This paper summarizes the methodologies followed for suction pile design in terms of stability, installation, extraction and settlement analyses based on API recommendations. It provides also a useful and considerable feedback of suction piles behaviour during offshore installation. Indeed, measured and predicted self-weight penetrations and required suction pressures are compared, analysed and discussed in order to check design assumptions and improve design methodologies for future projects in similar soil conditions.

Keywords: Suction pile, installation, self-weight penetration, suction pressure.

1 INTRODUCTION

Since 1982, the offshore industry has witnessed the emergence of an innovative foundation system based on suction piles (Andersen et al., 2005). They were initially developed for offshore floating platforms as anchoring system suitable for deep-water environments. Their use has since expanded to more various engineering offshore projects, including foundations of subsea structures subjected to high compressive loads such as Manifolds. Recently, suction piles have been used as foundations of offshore floating wind turbines in shallower water depths. Suction piles offer a viable alternative to conventional offshore foundations due to their significant cost savings in manufacturing and installation, reduced environmental impact, and durability, as they can be easily decommissioned.

Suction piles can be described as steel cylinder open at the bottom and sealed at the top with a top plate. These foundations are characterized generally by a large diameter and a high aspect ratio ($\frac{L}{OD}$) . Figure 1 illustrates the typical geometry of a suction caisson.

The installation process can be relatively simple especially in clayey soils. After lowering from vessel to a position near to the seabed, the suction pile is installed into two stages: i) it penetrates into the seabed under its own self-weight to a certain depth below mudline called "self-weight penetration depth", ii) water entrapped below top plate is pumped out through a top hatch, creating an under pressure inside the caisson. The resultant pressure differential

across the top plate induces a caisson embedment into the seabed until it reaches the required target depth.
Suction piles can have several offshore applications (Huang et al., 2003): it can sustain high compressive loads or combined loading from supported structures, or they can act as anchors connected to mooring lines or steel catenary risers or flexible risers. In this second case, suction anchors are mainly submitted to high static or dynamic tension loads.

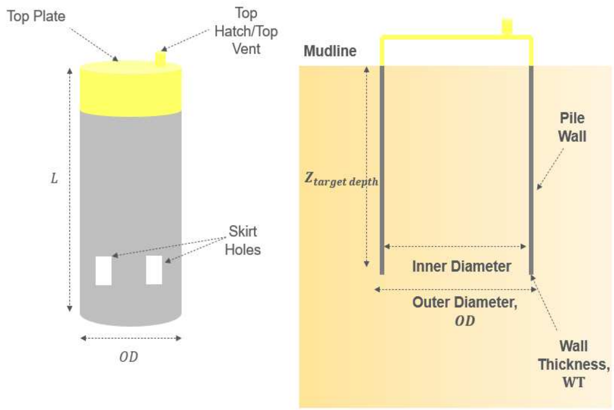

Figure 1. Suction caisson typical geometry

The safety philosophy of offshore suction piles is based on a Load Resistance Factor Design (LRFD) approach as recommended in ISO 19901-4 (2022), or on global safety factor approach as recommended in API RP 2SK (2008). In addition, these codes propose suction piles design principles required for stability, long-term settlement, installation and extraction analyses.
The present paper provides feedback from an installation campaign involving six suction piles in a deep-water field. It starts by a brief description of site and soil conditions encountered in the field, the pile properties used for the various structures and the loads applied on foundations. It then outlines the design principles adopted during engineering phase to select the appropriate pile geometry according to the different constraints. Finally, it compares the predicted and measured values of penetration depths and required suction pressures during installation phase. A back-analysis concludes this paper in order to assess adhesion factors during installation of suction piles.

2 GENERAL SITE CONDITIONS

2.1 Geotechnical design parameters

Suction piles studied in the present paper are located in a West African Offshore deep-water field, with water depths ranging between 900 and 1,700 meters. Several Cone Penetration Tests (CPTs) were conducted in the studied area to identify soil conditions and geotechnical design parameters. The results of the geotechnical investigation indicate a seabed composed predominantly of soft to firm clays and silts, resulting in a generally smooth seabed, except in canyons areas.
To offer a broad range of undrained shear strength, CPT data in the vicinity of the studied suction piles were interpreted (Figure 2). Based on this interpretation, low estimate (LE) and high estimate (HE) design profiles of undrained shear strength were established.

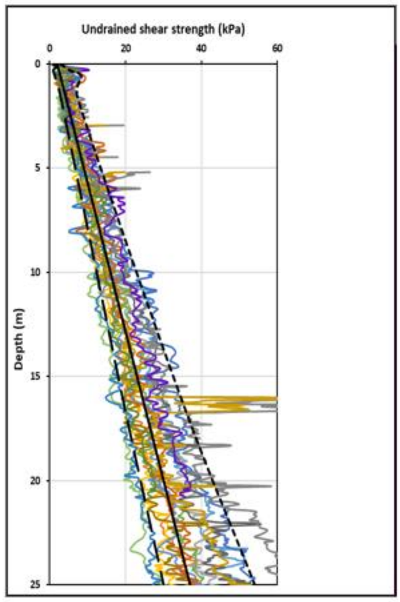

Figure 2. Undrained Shear Strength Profiles

Laboratory tests were also performed on soil samples extracted from the field and allowed to determine soil sensitivity S_t. The ranges of soil sensitivity S_t considered in suction piles design are presented in Table 1.

Table 1. Low Estimate (LE), Best Estimate (BE) and High Estimate (HE) soil sensitivity

Parameter	LE	BE	HE
S_t	2.9	3.8	5.0

2.2 Geohazards

The offshore field is characterized by the presence of channel areas especially in north and southern region. Channels are generally susceptible to various geohazards, including seabed slope instability,

significant scour, sediment transport, and the presence of hard soil layers.
Restraining piles studied in the present paper are installed in the north of the field, along the edge of a channel area, where the seabed slope is 8.3°. Manifold piles are located in the south of the field with a less seabed slope, not exceeding 3°.
No scouring was observed in the location of the studied structures.

3 STRUCTURAL PILE PROPERTIES

Six suction piles were installed during the offshore campaign across different vessel trips. Two types of suction piles were used during the specific project: i) three suction piles used as Manifolds foundations, ii) three suction piles functioning as anchoring systems for flexible risers.

3.1 Caisson geometries

Manifolds foundations geometries are described in Table 2 whereas restraining piles properties are summarized in Table 3 .

Table 2. Manifolds piles geometries

Pile	Property	Unit	Value
MF.1	Outer diameter	[m]	4.9
	Total length L	[m]	20
	Embedded length	[m]	20
	Wall thickness	[mm]	25
MF.2	Outer diameter	[m]	4.9
	Total length L	[m]	18
	Embedded length	[m]	18
	Wall thickness	[mm]	25
MF.3	Outer diameter	[m]	4.9
	Total length L	[m]	18
	Embedded length	[m]	18
	Wall thickness	[mm]	25

Table 3. Restraining piles geometries

Pile	Property	Unit	Value
RP.1	Outer diameter	[m]	4.877
	Total length L	[m]	13.0
	Embedded length	[m]	11.4
	Wall thickness	[mm]	25
RP.2	Outer diameter	[m]	4.877
	Total length L	[m]	13
	Embedded length	[m]	11.4
	Wall thickness	[mm]	25
RP.3	Outer diameter	[m]	4.877
	Total length L	[m]	14.5
	Embedded length	[m]	12.9
	Wall thickness	[mm]	25

Caisson geometries for both piles applications are decided based on in-place behaviour and manufacturing constraints. Indeed, a standardized outer diameter and a constant wall thickness equal to 4.9 m and 25 mm respectively were adopted for all piles to simplify the manufacturing process and vessel transport.

3.2 Weights and CoGs

The dry W_{dry} and submerged weight W'_{sub} of each suction pile considered in the design is presented in Table 4. A minimal net weight is considered for skirt penetration analyses whereas a budget maximal weight is considered for in-place stability analyses, long term settlement and extraction predictions. Net weights and budget weights are estimated based on the tolerance and values presented in Table 4.

Table 4. Caisson weights assumed

Pile	W_{dry} (T)	W'_{sub} (T)	Tolerance
MF.1	90.5	78.7	±3%
MF.2	78.2	68.0	
MF.3	78.2	68.0	
RP.1	62.4	54.3	
RP.2	62.4	54.3	
RP.3	67.7	58.9	

Suction piles present generally Center Of Gravity (CoG) lateral offsets, inducing additional moments about the centreline of the pile. Table 5 presents the lateral offset considered for in-place analysis for each pile.

Table 5. Centre of gravity offsets considered for in-place analysis

Pile	CoG_x (m)	CoG_y (m)
MF.1	-0.030	0.490
MF.2	-0.030	0.490
MF.3	-0.030	0.490
RP.1	0.008	-0.011
RP.2	0.008	-0.011
RP.3	0.027	-0.004

4 SAFETY PHILOSOPHY AND LOADING

4.1 Safety Factors

A global safety factor approach is adopted for in-place analysis for the six caissons. API RP 2SK recommends the safety factors provided in Table 6. Allowable pile capacities are computed by dividing lateral and axial ultimate capacities called $R_{ult,H}$ and $R_{ult,v}$ respectively by lateral and axial safety factors $\gamma_{r,H}$ and $\gamma_{r,v}$ respectively. Horizontal and vertical loads H_{max} and V_{max} should not exceed the allowable pile capacities as expressed in equations (1) and (2).

$$H_{max} \leq \frac{R_{ult,H}}{\gamma_{r,H}} \quad (1)$$

$$V_{max} \leq \frac{R_{ult,v}}{\gamma_{r,v}} \quad (2)$$

Table 6. Adopted safety factors for in-place analysis

Conditions	$\boldsymbol{\gamma_{r,H}}$ ***(-)***	$\boldsymbol{\gamma_{r,v}}$ ***(-)***
Intact (ULS)	1.6	2.0
Damaged (ALS)	1.2	1.5

For a combined loading, the adopted safety factor depends on the failure mechanism controlling the pile holding capacity.

4.2 Applied loads

To check the stability of the foundation and select the required embedded length, all the applied loads must be identified.
Therefore, the following loads are considered for all piles:

- Piles weights.
- Supported module weights for manifolds foundations.
- Additional moments due to pile and module CoGs offsets.
- Additional horizontal loads and moments due to pile tilt during installation.
- Additional horizontal loads and moments due seabed inclination.
- Additional torsional loads for restraining piles installed with misalignment.
- Operational loads.
- Extreme environmental loads especially for restraining piles.
- Loads due to vessel motions.

Table 7 summarizes the maximal loads applied on each suction pile.

5 DESIGN METHODOLOGY

5.1 General process

The general process of suction pile design adopted is illustrated on Figure 3. Four geotechnical analyses are performed during this process as detailed below:

Table 7. Maximal vertical loads, horizontal loads and moments applied on suction caissons

Pile	$\boldsymbol{F_{max}}$ **(T)**	**Direction**
MF.1	351	Vertical (Compression)
MF.2	134	Vertical (Compression)
MF.3	134	Vertical (Compression)
RP.1	47.2	Horizontal (Tension)
RP.2	47.2	Horizontal (Tension)
RP.3	51.3	Horizontal (Tension)

- **Stability analysis:** This study is based on the recommendations of API RP 2SK and was performed using Finite Element Method (FEM). It is considered as the most rigorous general method of analysis available for complex structural systems. The most critical failure mechanisms were identified for each suction pile.
- **Long-term settlement analysis**: this study was performed by developing a 2D finite element model and by adopting a Soft Soil constitutive model on Plaxis software.
- **Landing speed analysis**: recommendations of are adopted to reach a maximal landing speed equal to 0.5 m/s.
- **Installation and extraction analyses**: it is performed according to API RP 2SK expressions.

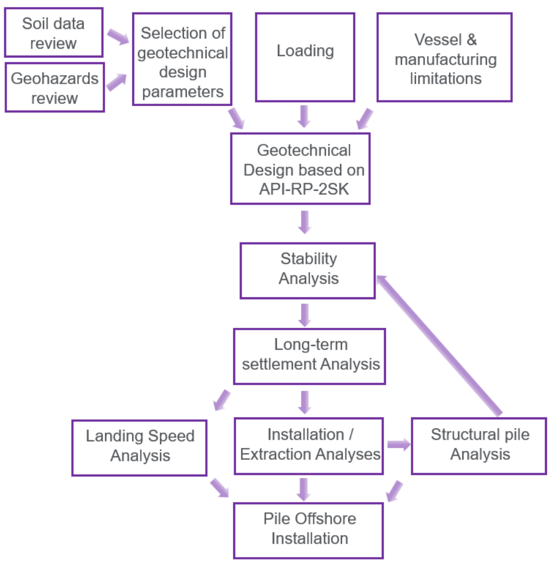

Figure 3. General process of suction pile design during detailed design phase

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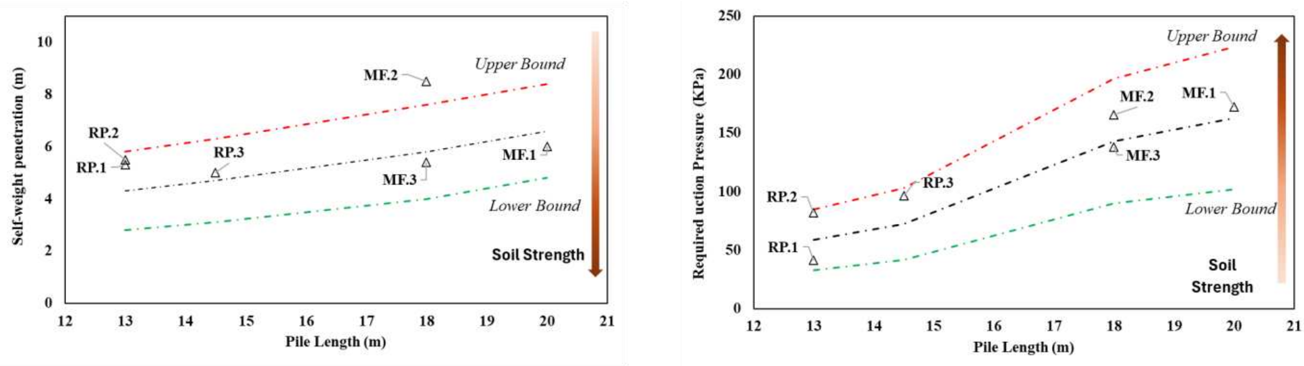

Figure 4. a) Predicted and measured self-weight penetration for piles MF.1, MF.2, MF.3, RP.1, RP.2 and RP.3, b) Recorded and predicted required suction pressures for piles MF.1, MF.2, MF.3, RP.1, RP.2 and RP.3.

5.2 Suction pile installation

According to API RP 2SK, a suction pile installation analysis (called also penetration analysis) includes the calculation of three quantities:

- The penetration resistance applied on the suction caisson by the soil.
- The required suction pressure allowing anchor embedment.
- The allowable suction pressure to avoid soil plug failure.

The penetration resistance Q_{tot} is calculated for each soil layer using expression (3):

$$Q_{tot} = Q_{side} + Q_{tip} \quad (3)$$
$$Q_{side} = A_{wall}.(\alpha_{ins} S_{u,DSS}) \quad (4)$$
$$Q_{tip} = A_{tip}.(N_c.S_{u,tip} + \gamma'.z) \quad (5)$$

Where Q_{side} is the resistance along pile sides, Q_{tip} is the resistance at pile tip, A_{wall} is the sum of inside and outside wall area embedded in soil, A_{tip} is the pile tip cross sectional area, α_{ins} is the adhesion factor during pile installation, $S_{u,DSS}$ is the direct simple shear strength, $S_{u,tip}$ is average soil strength at pile tip, N_c a bearing capacity factor and γ' soil unit weight.
The required under pressure ΔU_{req} is computed based on equation (6):

$$\Delta U_{req} = \frac{Q_{tot} - W\prime}{A_{in}} \quad (6)$$

Where W' is submerged pile weight during installation and A_{in} is plan view area where the underpressure is applied.
The allowable underpressure is given at specific soil layer according to equation (7):

$$\Delta U_{allow} = N_c.S_{u,tip} + \frac{A_{inside}.(\alpha_{ins} S_{u,DSS})}{A_{in}} \quad (7)$$

Where A_{inside} is internal area of the caisson at a specific soil layer.
A minimal safety factor of 1.5 is applied on ΔU_{allow} computed.

6 INSTALLATION FEEDBACK

Self-weight penetrations and required suction pressures of each suction pile were recorded during installation campaign. Figure 4 summarises the results of self-weight penetration and required suction pressures recorded. It plots also the lower and upper bounds predicted during design based on API RP 2SK method. For self-weight penetrations calculations, the lower bound limit corresponds to a combination of HE soil strength and an adhesion factor α equal to 0.26 (based on BE soil sensitivity), whereas upper bound limit corresponds to a combination of LE soil strength and $\alpha = 0.26$.
For required suction pressures calculations, the lower bound limit corresponds to a combination of LE soil strength and an adhesion factor $\alpha = 0.26$, whereas upper bound limit corresponds to a combination of HE soil strength and $\alpha = 0.26$.
Figure 4.a (left) shows that all measured self-weight penetrations are in the range predicted by the API RP 2SK method, except for MF.2 manifold suction pile. Indeed, the measured self-weight penetration exceeds by 0.9 m the upper bound limit predicted for MF.2. The recorded self-weight penetrations indicate that the soil conditions at the installation locations of MF.1 and MF.3 likely present higher soil strength compared to those at installation locations of MF.2 and restraining piles RP.1, RP.2 and RP.3.
Figure 4 (right) shows that all required suction pressures are in the range predicted by API RP 2SK method. For piles RP.1, MF.1 and MF.3, soil strength

trends concluded from Figure 4.a are confirmed by Figure 4.b. However, high suction pressures were required for installation of piles RP.2 and MF.2, even if measured self-penetrations were close to upper limit predicted. The reversal trend in suction phase can be explained by two parameters: i) suction duration ΔT and ii) average rate of pressure increase R_p.

Figure 5 shows that the highest values of R_p are recorded for RP.2 and MF.2 (29.1 and 37.4 KPa/h respectively). Measures show that for both piles, suction pressure was increased by almost 7 KPa each 15 min in average. This process is adopted offshore in order to accelerate pile full penetration to reduce vessel time. Indeed, suction phase of MF.2 and RP.2 lasted 3.8 and 3.0 hours respectively.

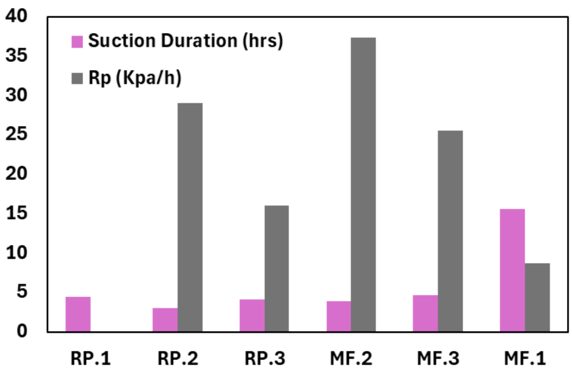

Figure 5. Recorded suction duration and average rate of pressure increase for piles MF.1, MF.2, MF.3, RP.1, RP.2 and RP.3.

Figure 5 shows that suction phase for MF.1 suction pile lasted more than 15 hours, with a limited value of R_p equal to 8.7 KPa/h. The high value of ΔT and reduced R_p can be explained by:

- High soil strength at MF.1 location.
- Hard soil layer expected between 11 and 12 m penetration depth (more than 3 hours required to overcome soil resistance at this depth level).
- Limited values of structural maximal pressure allowable to avoid lateral buckling of pile MF.1.

Due to the combination of these geotechnical and structural conditions, structural maximal pressures allowable to avoid pile lateral buckling was reached several times during MF.1 installation.

7 BACK-ANALYSIS

During design phase, installation analysis presented in section 5 is performed considering the following combinations of undrained shear strength profile and soil sensitivity:

- Low Estimate (LE) soil strength S_u combined with Best Estimate (BE) soil sensitivity S_t.
- High Estimate (HE) soil strength S_u combined with BE soil sensitivity S_t.

The first combination allows to assess the upper bound (UB) of self-weight penetration and lower bound (LB) of suction pressure. The second combination allows to assess the LB of self-weight penetration and the UB of suction pressure.

In this section, measured self-weight penetrations are used to identify the most accurate combination of S_u and S_t during suction pile installation (self-weight penetration phase). Therefore, for each suction pile, a sensitivity analysis is performed using the soils parameters presented in Table 8.

Table 8 : Soil Parameters Considered in Sensitivity Analysis

Calculation	S_u	S_t	Adhesion Factor α (-)
1	LE	LE	0.34
2	LE	BE	0.26
3	LE	HE	0.20
4	HE	LE	0.34
5	HE	BE	0.26
6	HE	HE	0.20

Figure 6 plots the results of the sensitivity analysis applied on pile MF.1. Back analysis realised on MF.1 suction pile shows that the most accurate calculation to match the measured self-weight penetration corresponds to a combination of S_{u_HE} and S_{t_HE} with an adhesion factor $\alpha = 0.2$.

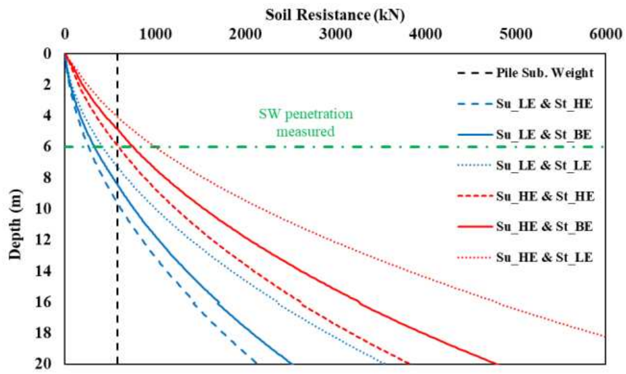

Figure 6. MF.1 sensitivity analysis results and comparison with measured self-weight penetration

Table 9 summarises back analyses results performed on each suction pile MF.1, MF.2, MF.3, RP.1, RP.2 to match measured self-weight penetrations. The selected S_u and S_t profiles in Table 9 present the optimal combination to match measured self-weight penetration (SWP). The values of adhesion factors presented in Table 9 enable an exact match with measured SWP.

Table 9. Back-analyses results and proposed adhesion factors to match measured SWP

Pile	Measured SWP (m)	S_u	S_t	Adhesion Factor α (-)
MF.1	6.0	HE	HE	0.20
MF.2	8.5	LE	HE	0.20
MF.3	5.4	HE	HE	0.17
RP.1	5.3	LE	LE	0.31
RP.2	5.5	LE	LE	0.31

The obtained results indicate that manifolds piles located in the southern part of the field present soil sensitivity values close the upper bound. The soil strength varies from LE and HE conditions. In contrast, the results for restraining piles reveal softer soil conditions, with soil sensitivity values close to lower bound.

The analysis also highlights that considering a combination of HE soil strength with a BE or LE soil sensitivity during design phase is overly conservative, leading to suction pile overdesign. The back-analyses performed recommend the following combinations for installation analyses :

- HE undrained shear strength combined with HE soil sensitivity.
- LE undrained shear strength combined with LE soil sensitivity.

8 CONCLUSIONS

The present paper provides valuable feedback on the offshore installation campaign of six suction piles conducted in West African deep-water field. It presents a comparison between measured and computed self-weight penetrations (SWP) and required suction pressures (RSP). Based on this comparison, measured SWP are in the range predicted by API RP 2SK approach for 80 % of the cases (5 out of 6 piles). For all piles, the measured RSP lies between lower and upper bounds defined during design phase. Furthermore, a back analysis is performed for 5 piles in order to evaluate adhesion factors during pile installation. The results indicate that, in the northern part of the field, soil sensitivity is close to LE value, combined with LE soil strength. In the southern part of the field, soil sensitivity is close to HE value combined with HE soil strength. For this field, the combination of HE soil strength with BE or LE soil sensitivity leads to SWP underestimation and RSP overestimation. Indeed, lower bound of SWP and upper bound RSP can be predicted by assuming HE soil strength and HE soil sensitivity to avoid suction pile overdesign, leading to excessive procurement and manufacturing costs and installation constraints.

AUTHOR CONTRIBUTION STATEMENT

Z. ABCHIR: Data curation, Formal Analysis, Writing- Original draft. **J. KENNEDY**.: Supervison, Methodolgy and Project Administration. **D. MEYER**: Project Administration. **M. BOUAZIZ**: Data curation, Formal Analysis, Writing- Reviewing and Editing.

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