Seabed Remediation for Safe Sequential Jack-Up Vessel Installations in the Harbour Areas

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Abstract

Geotechnical engineering assessment applicable to sequential installation and operation of a four-leg jack-up vessel, on critical soil conditions in a harbour area, offshore Denmark, is the focus of this paper.

When critical soil conditions reveal, design of seabed remediation measures has proven to be a way to avoid jack-up punch through foundation failure. The jack-up vessel is planned located in the harbor for the purpose of being loaded with wind turbine generators (WTGs) and transporting them to the wind farm location. The soil conditions at the harbor site consist of sand overlying silt and clay, with a high level of variability. In addition, the planned vessel location consisted of disturbed seabed from previous jack-up vessels installations.

Some previous gravel / stone beds (SBs) and depressions are found at the site.
Due to multi-layered soil conditions, FE analyses are performed, applicable to the design of the remediation measures, (which consist of a combination of excavation and new SBs), parallel to the conventional approach. The fact that sequential installations will occur, is taken into account in the measures design, assuming loading and unloading (pull out) of the spudcans. As the vessel is positioned next to the quay, spudcan – quay wall / sheet pile interaction is also discussed and considered in the design of the measures closest to the quay.

Details on the analyses are outlined and discussed. The remediation measures are constructed and the vessel was sequentially safely installed and loaded as planned, with recorded spudcan penetrations similar to predictions.

Keywords

Jack-up vessel, spudcan punch-through, seabed remediation measures, stone bed (SB), excavation, conventional analysis, finite element (FE) analysis, spudcan-quay wall interaction.

1 General Introduction

Different challenges are encountered during the jack-up vessel installation / operation on critical soil conditions often encountered at wind farm sites or harbor areas. Spudcan punch-through type of failure is recognized for soil profiles consisting of a stronger layer overlying a softer one. Consequences from such failure can be drastic, associated among others with increased project cost.

Geo's design methods for such conditions are applied to several projects for Oil & Gas and wind energy. These methods are approved by certifying authorities and presented in international conferences [1-5].

The focus in this paper is the design and consultancy associated with the sequential installation of a jack-up vessel in a harbor area in Denmark.

2 Jack-up Vessel Location and Spudcan Data

The jack-up vessel is located in the harbor area, next to the quay wall, as shown in Figure 1.The water depths at virgin seabed vary between -9.8 to -11.3 m DVR90 (Danish Vertical Reference 1990), being deeper near the quay wall.

The jack-up vessel has four legs, each with a spudcan equipped with a trapezium shaped bottom plate. The vessel operates in water depths of (6.5 – 50) m, depending on the leg penetrations into seabed, weather and tidal conditions. The spudcans are rectangular with dimensions 13.25 m x 8.05 m, with a bearing area of approximately 105 m^2 per leg, resulting in an equivalent diameter of 11.6 m and tip to full base contact of 1.5 m as presented in Figure 2.

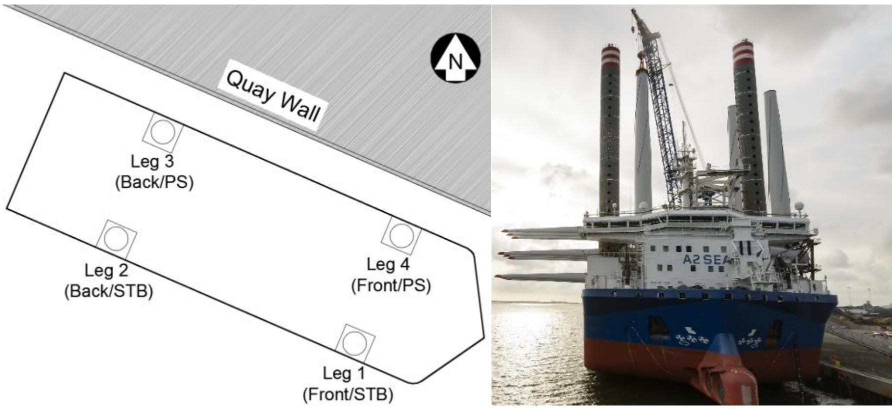

Figure 1. Plan view drawing of the jack-up vessel located in the harbour area.

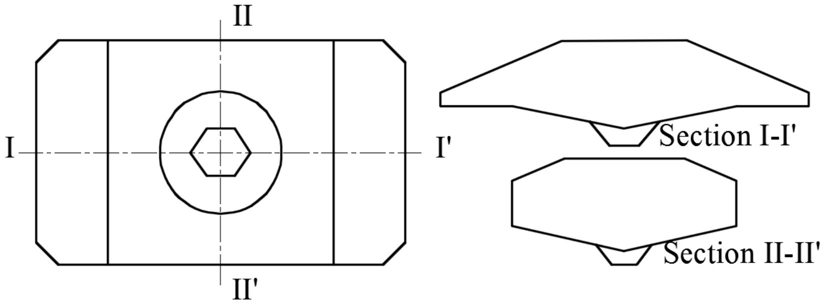

Figure 2. Spudcan drawing: bottom & side view.

Based on the environmental load analyses, the expected maximum preload during spudcan installation, is calculated to 6750 tons / leg.

3 Existing SBs, Previous Installations & Excavated Seabed

The existing SBs at the harbor site were built-up, applicable to other jack-up vessel’s installations. Unclassified stones with size (0-32) mm, were dumped. The location of those beds is presented in Figure 3.

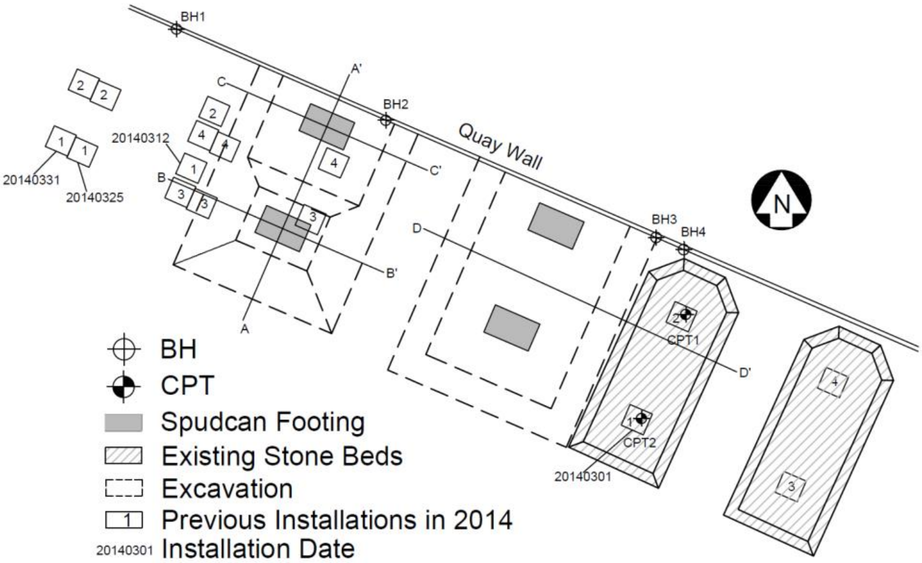

Figure 3. The expected spudcan footprints, excavation area, existing SBs & the location of other jack-ups installed in 2014

The initial designed elevation of the existing SBs was with top / bottom level of (-9.5 / -14.0) m DVR90, resulting in 4.5 m thickness. After several installations and refills over those beds, the elevation was upgraded to approximately top / bottom (-8.5 / -14.0) m DVR90 giving SB thickness of 5.5 m, which covered for soil variations and sensitivity of the SBs and underlying soil to loading-unloading process.

The previous installations of other jack-up vessels, are presented in Figure 3, and the applied maximum preloads and measured penetrations are tabulated in Table 1. The eight footprints / depressions in the northest were originated by previous installations of two jack-up vessels on virgin seabed. Meanwhile, one jack up vessel was previously installed on the existing SBs, generating four footprints / depressions in the southeast.

Table 1. The load-penetration data from previous installations (as shown in Figure 4) and the equivalent. data for the current jack-up vessel.

Installation Date	Leg no.	Load	Penetration. Depth	Equivalent Load	Equivalent Penetration Depth
		tons	M	tons	m
20140331	1	634	6.96	7630	7.63
	2	619	3.0	7450	3.67
	3	649	4.8	7811	5.47
	4	600	4.4	7221	5.07
20140325	1	600	4.4	7221	5.07
	2	600	3.7	7221	4.37
	3	600	3.6	7221	4.27
	4	600	2.7	7221	3.37
20140312	1	600	3.5	7221	4.17
	2	600	3.0	7221	3.67
	3	600	5.1	7221	5.77
	4	600	2.35	7221	3.02
20140301	1	4290	1.66	7265	1.96
	2	4166	1.61	7055	1.91
	3	4260	1.25	7215	1.55
	4	4180	1.66	7079	1.96

The equivalent maximum preload and penetration depths for the current jack-up vessel, are calculated as presented in the right two columns. These data are taken into account to approximately confirm the bearing capacities of the existing SBs at Front Legs (Leg 1 & 4) and back analyses the bearing capacity of the virgin seabed.

As soil excavation is carried out, (in order to maintain the limit water depth for vessel installation), the impact on the quay wall stability / integrity during excavation at the leg positions closest to the quay, is investigated. No critical interaction was assessed. However, deeper excavation was found not applicable. Hence, increase of the SB's thickness by dumping new SBs was the only way to increase the vertical bearing capacities. The excavated depths at each leg locations are provided in Table 2 and the geometry is given in Figure 3.

Table 2. Depth of excavation at each leg location

Leg no.	Virgin seabed level	Bottom level
	(m), DVR90	(m), DVR90
Front/PS	-10.0	-12.5
Front/STB	-10.0	-12.5
Back/PS	-10.5	-13.8
Back/STB	-10.3	-16.8

Prior to the design of the new SBs, the unclassified stone material from the existing SBs, is dumped on top of the excavation level. The height of these pre-built SBs at each leg is presented in Table 3.

Table 3. The height of pre-built SBs (unclassified stone)

Leg no.	SB H	Top / bottom level	γ'	φ
	(m)	(m), DVR90	kN/m^3	°
Front/PS	1.0	-11.5 / -12.5	9.0	40
Front/STB	1.0	-11.5 / -12.5	9.0	40
Back/PS	0.0	-13.8 / -13.8	9.0	40
Back/STB	3.0	-13.8 / -16.8	9.0	40

4 Soil Investigation and Interpreted Soil Profiles

The soil data applicable to the design are interpreted based on two cone penetration tests (CPTs) located at the existing SBs (close to the Front Legs) and four drilling boreholes located along the quay wall (close to the Port (PS) Legs) as shown in Figure 3.

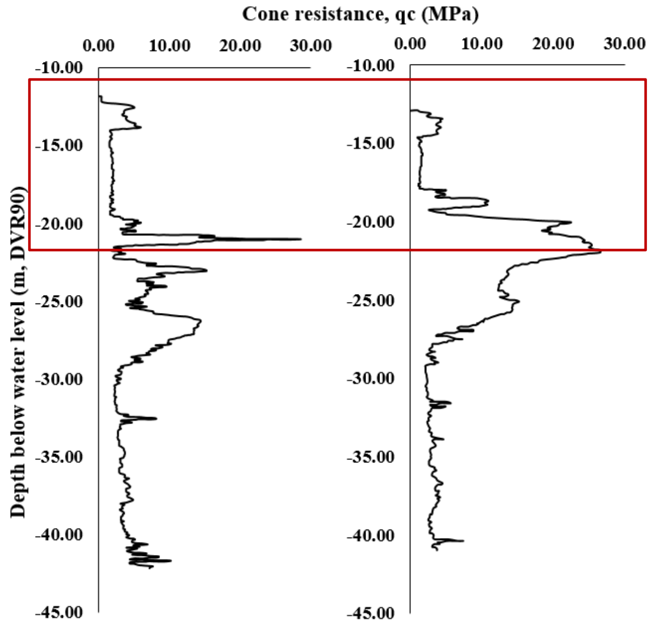

Figure 4. Cone resistance for CPT1 & CPT2. Critical depth marked in red rectangular

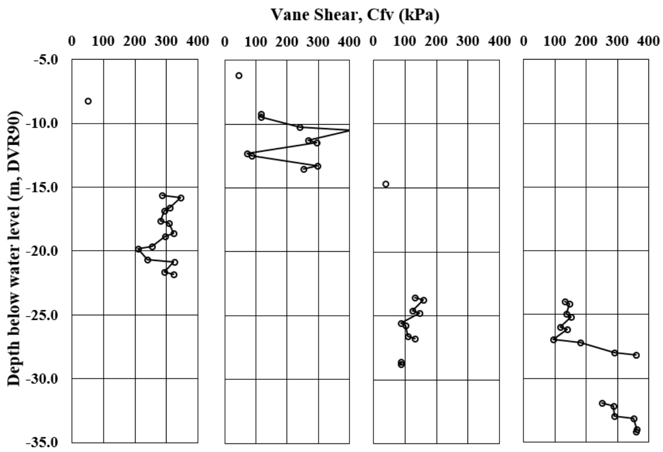

Figure 5. Shear vane versus depth for borehole BH1, BH2, BH3 & BH4.

Based on the available soil data, the sub-soil in the quay area shows a high level of variability. The geology fluctuates irregularly between sand, silt and clay from the postglacial, late glacial, interglacial and glacial ages. The lower / upper bound characteristic soil parameters are selected as a cautious estimate of the value affecting the occurrence of the relevant limit state [6]. For fissured clay found in the boreholes, the undrained shear strength (c_u) was derived from the shear vane test as given in Table 4 (based on previous experience triaxial tests).

Table 4. Calculation of c_u from in-situ shear vane strength (c_{fv})

Vane Shear Strength (c_{fv})	Undrained Shear Strength (c_u)
kPa	kPa
$c_{fv} \leq 40$	$c_u = c_{fv}$
$40 < c_{fv} < 80$	$c_u = 40$
$80 < c_{fv} \leq 300$	$c_u = \mu \cdot c_{fv} = 0.5 \cdot c_{fv}$
$c_{fv} > 300$	$c_u = 0.3 \cdot c_{fv} + 60$

However, the undrained shear strength for clay layers is mainly calculated on the basis of CPT data. Taking into account the fissured clay cone factor N_{kt} = (15 - 20) is applied for the upper and lower bound soil parameters, respectively. The designed soil profiles (after excavation and refills with unclassified stones from the existing SBs), with the lower bound soil parametes at all four legs are summarized in Table 5.

Table 5. Designed lower bound soil profiles

Soil type	Layer level	γ'	φ	c_u
	(m), DVR90	kN/m^3	°	kN/m^2
	Front/STB Leg (Leg 2):			
Unclassified Stone*	(-11.5) – (-12.5)	9.0	40	-
SAND	(-12.5) – (-14.0)	9.5	34	-
CLAY	(-14.0) – (-19.5)	8.0	-	70
CLAY	(-19.5) – (-20.7)	8.0	-	200
SAND	(-20.7) – (-21.5)	9.5	30	-
CLAY	(-21.5) – (-22.3)	8.0	-	120
SAND	(-22.3) – (-25.5)	9.5	30	-
SAND	(-25.5) – (-29.5)	9.5	31	-
CLAY	< (-29.5)	8.0	-	> 100
	Front/PS Leg (Leg 4):			
Unclassified Stone*	(-11.5) – (-12.5)	9.0	40	-
SAND	(-12.5) – (-14.5)	9.5	34	-
CLAY	(-14.5) – (-18.0)	8.0	-	65
CLAY	(-18.0) – (-18.5)	8.0	-	200
SAND	(-18.5) – (-19.7)	9.5	29	-
SAND	(-19.7) – (-22.5)	9.5	32	-
SAND	(-22.5) – (-28.0)	9.5	31	-
CLAY	< (-28.0)	8.0	-	> 100
	Back/STB Leg (Leg 1):			
Unclassified Stone*	(-13.8) – (-16.8)	9.0	40	-
CLAY	(-16.8) – (-17.0)	8.0	-	85
CLAY	< (-17.0)	8.0	-	75
	Back/PS Leg (Leg 3):			
CLAY	(-13.8) – (-19.6)	8.0	-	95
CLAY	(-19.6) – (-20.6)	8.0	-	85
CLAY	< (-20.6)	8.0	-	140
* : Pre-built SB: stone material from the existing SBs				

The geometry of the excavation is presented in Figure 6.

5 Design of New SBs

For avoiding punch through risk and large penetrations of the legs, new SBs are designed with new stone material (crushed stone with size (63-180) mm and friction angle of 40 degrees) chosen.

According to load - penetration data from previous installations of other jack-up vessels, no punch through / rapid penetration was recorded / experienced when the thickness of the existing SBs was 4.5 m. Based on these feedbacks, for the current jack-up vessel installation, new SBs with 3.5 m thickness of crushed stone at Front Legs are designed. Thus, the total SB height is 4.5 m (pre-built SB: 1.0 m of unclassified stone from the existing SB; new SB: 3.5 m of crushed stone), which complies with the initial height of the existing SBs, as shown in Figure 6.

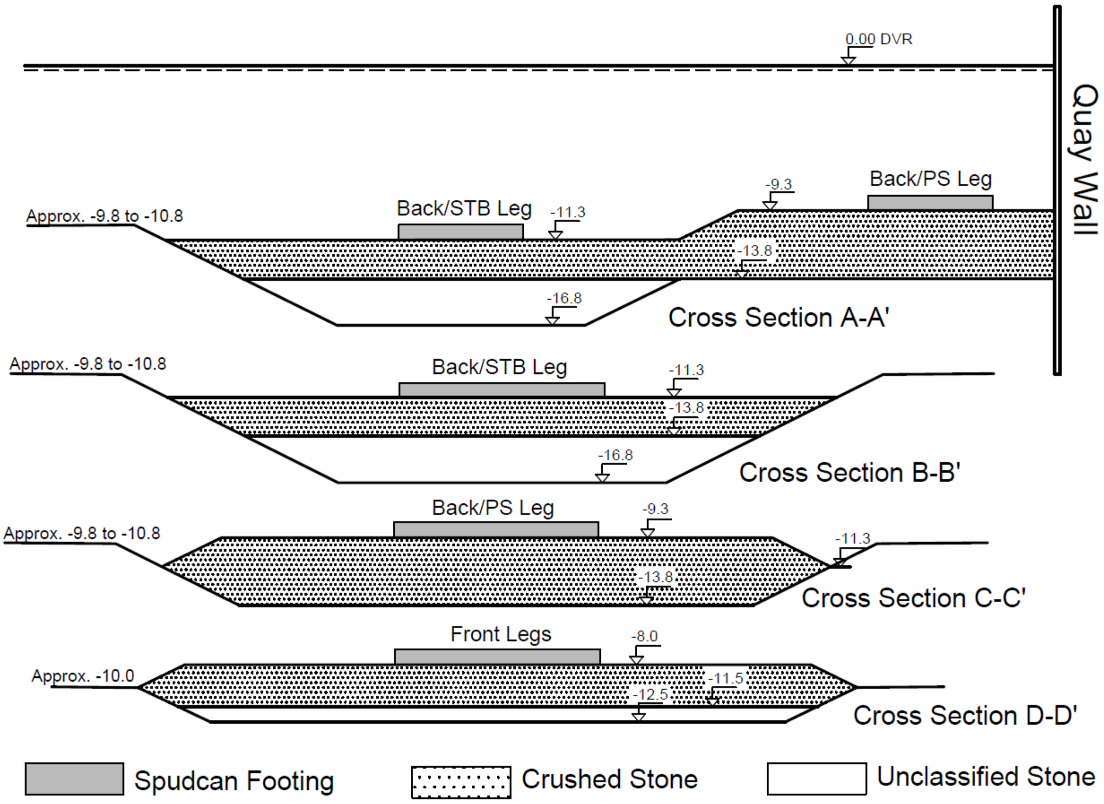

Figure 6. Cross sections of the total height of the SBs.

Considering insufficient soil data at Back / STB leg (Leg 2), a new SB with 2.5 m of crushed stone is designed. Total SB height is 5.5 m (pre-built SB: 3 m of unclassified stone from the existing SB; new SB: 2.5 m of crushed stone) to account any soil variation at this side, as presented in Figure 7. The heights (H) of the new SBs at four legs are summarized in Table 6.

Table 6. Designed height (H) of new SBs (crushed stone)

Leg no.	H	Top / bottom level	γ'	Φ
	(m)	m, DVR90	kN/m^3	°
Front/PS	3.5	-8.0 / -11.5	9.0	40
Front/STB	3.5	-8.0 / -11.5	9.0	40
Back/PS	4.5	-9.3 / -13.8	9.0	40
Back/STB	2.5	-11.3 / -13.8	9.0	40

The top levels of designed new SBs vary between -8.0 and -11.3 m DVR90, which meets the vessel's minimum operating water depth of 6.5 m. The three-dimensional (3D) sketch of the designed SB and the spudcans positioned as planned are presented in Figure 7.

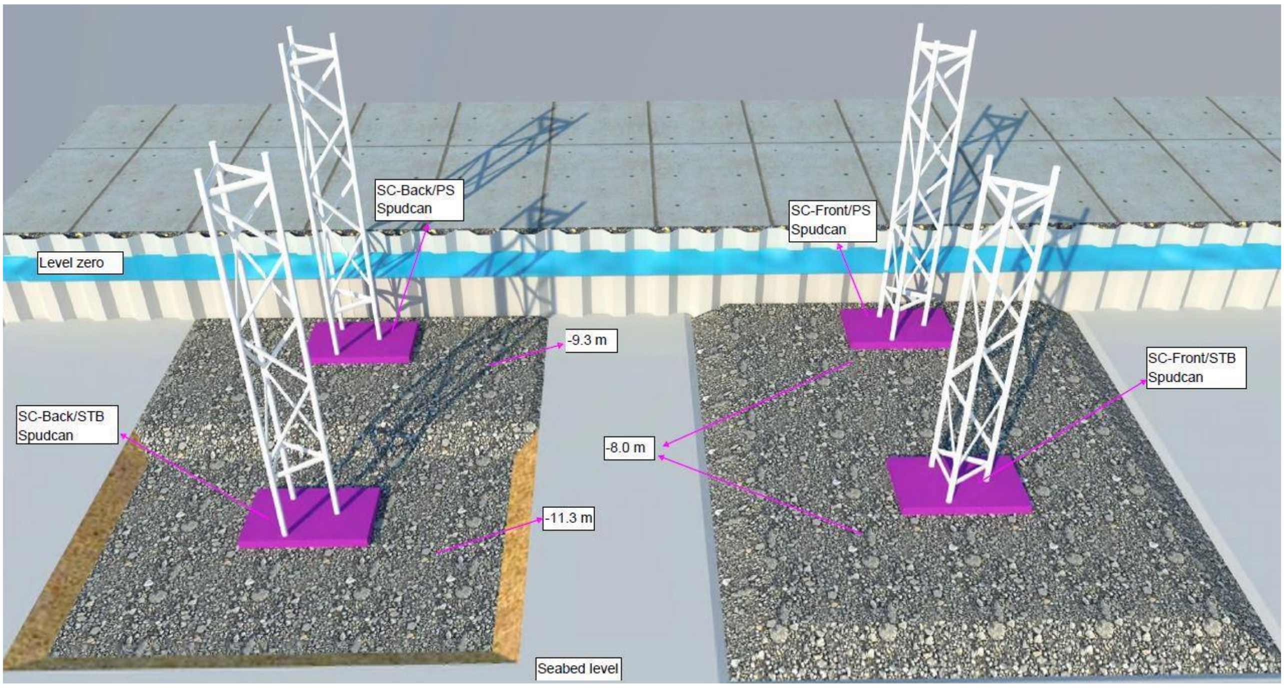

Figure 7. 3D sketch for the designed SBs

6 Leg Penetration Analyses, Spudcans over the SBs

6.1 Conventional analysis

The conventional analyses follow the guidelines given in ISO [7] & SNAME [10]. The derived lower bound soil profiles given in Table 3 have been used in the analyses. The calculations are based on design soil parameters with partial coefficients $\gamma_m = 1.0$. In the assessments, the soil hardening / softening as a result of spudcan load and penetration has been disregarded and the preload is considered as static load. To conventionally define footing penetration depth versus load, the calculation of static bearing capacity of the spudcan at various depths is carried out based on Brinch Hansen's theory [8], which in the general form isgiven in equation 1.

$$Q/A=0.5\gamma BN_\gamma s_\gamma d_\gamma i_\gamma b_\gamma g_\gamma+qN_q s_q d_q i_q b_q g_q+cN_c s_c d_c i_c b_c g_c \quad (1)$$

Where: Q = bearing capacity of foundation base; A = fundamental area, B = fundamental width; γ = density; q = vertical overburden; c = cohesion; s_γ, s_q, s_c = shape factors; N_γ, N_q, N_c = bearing capacity factor; d_γ, d_q, d_c = depth factors; i_γ, i_q, i_c = load inclination factors, b_γ, b_q, b_c = base inclination factors; g_γ, g_q, g_c = ground inclination factors.

The spudcan is assumed circular footing with a flat bottom. The effect of the actual spudcan shape is taken into account. Squeezing of clay layer underlying the seabed sand and the SBs during footing penetration is also considered and implemented.

6.2 FE analyses

The FE modelling of the spudcan penetration is carried out as an alternative to the conventional analysis. Based on the interpreted lower bound soil profiles, FE analyses are carried out for all four legs with designed total height of the SBs. Due to the critical soil conditions and the limited size and the shape of the SBs, the bearing capacity with the designed new SBs is mainly calculated based on FE modelling. Plaxis plastic (small strain) analyses are performed in order to conservatively determine the minimum / lower bound bearing capacity before spudcan's penetrations larger than the full-base-contact occur [9].

Due to the multi-layered soil profiles and considering the program limitations, assumptions / simplifications are made in building the FE models in Plaxis. 2D axisymmetric modelling of the spudcan-soil interaction and the SBs are simplified to truncated cones. Sand is modelled in drained condition and clay in undrained condition utilizing effective unit weights for the seabed soil layers. Mesh has been generated using 15-noded triangular finite elements and the spudcan is modelled as a weightless elastic body.

The calculations are carried out in phases: initial stress conditions, seabed excavation, SB installation, in-place spudcan with full-base-contact with the top of SBs. Vertical displacement is applied at the full-base-contact of the spudcan and the reaction force is computed and recorded. The geometry of the FE model at each leg location is as shown in Figures (8 – 11).

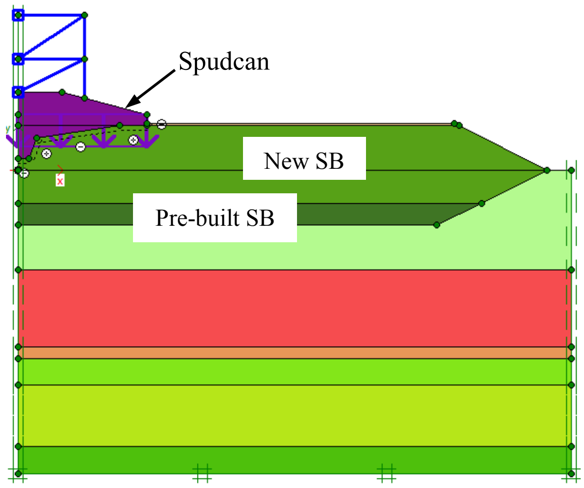

Figure 8. The FE model - Front/PS Leg

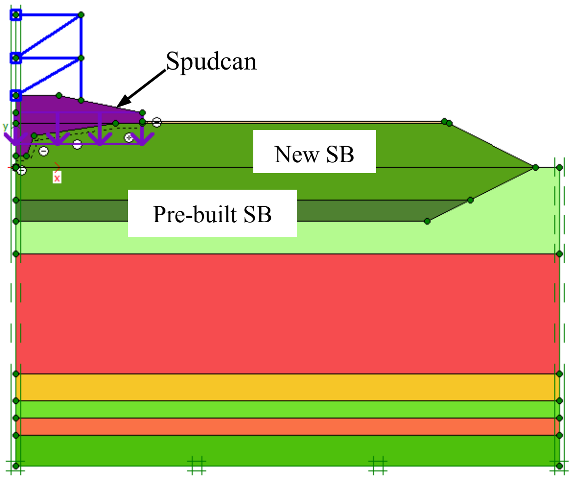

Figure 9. The FE model - Front/STB Leg

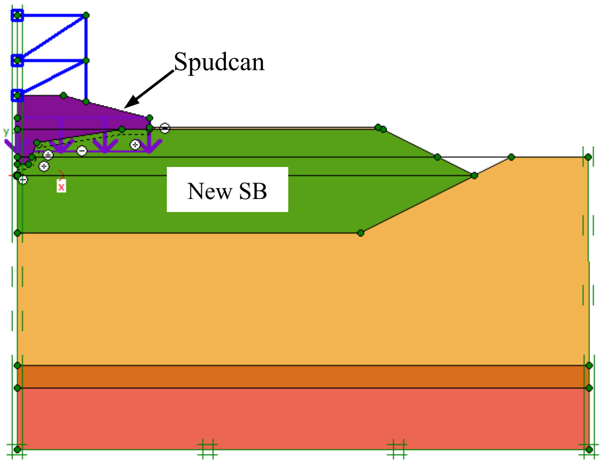

Figure 10. The FE model - Back/PS Leg.

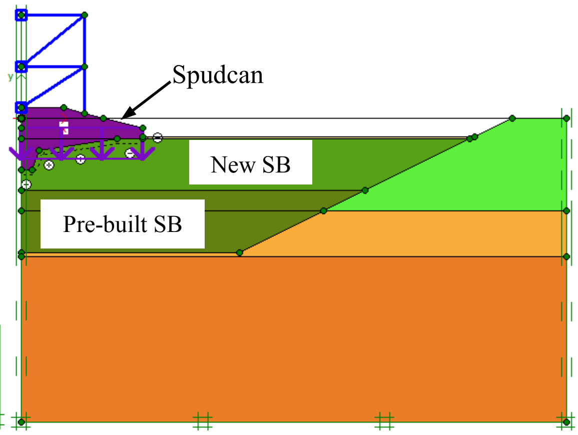

Figure 11. The FE model - Back/STB Leg.

6.3 Results from the Conventional & FE Analyses

The results comprising FE Plaxis plastic analyses, plotted along with the conventional penetration curves (which are adjusted with respect to FE capacities) are presented in Figures (12a – 15a) and the output results of the FE analyses are given in Figures (12b – 15b).

Figure 12a & 12b presents the results at Front/PS leg (Leg 4). The minimum / lower bound bearing capacity for spudcan with full-base-contact is calculated as 7610 tons / leg. Figure 13a & 13b presents the results at Front/STB leg (Leg 1). The minimum / lower bound bearing capacity for spudcan with full-base-contact is calculated as 7490 tons / leg.

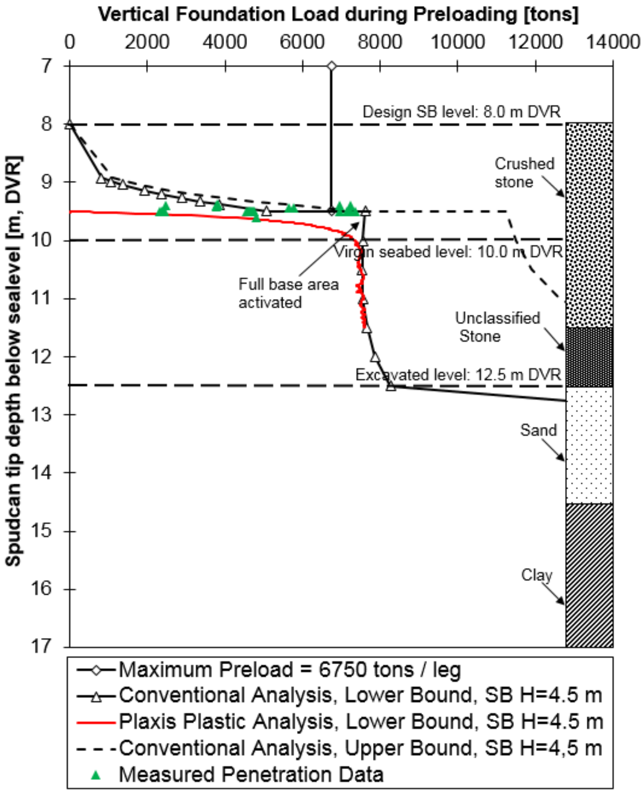

Figure 12a. Conventional & FE penetration curves, Front/PS Leg

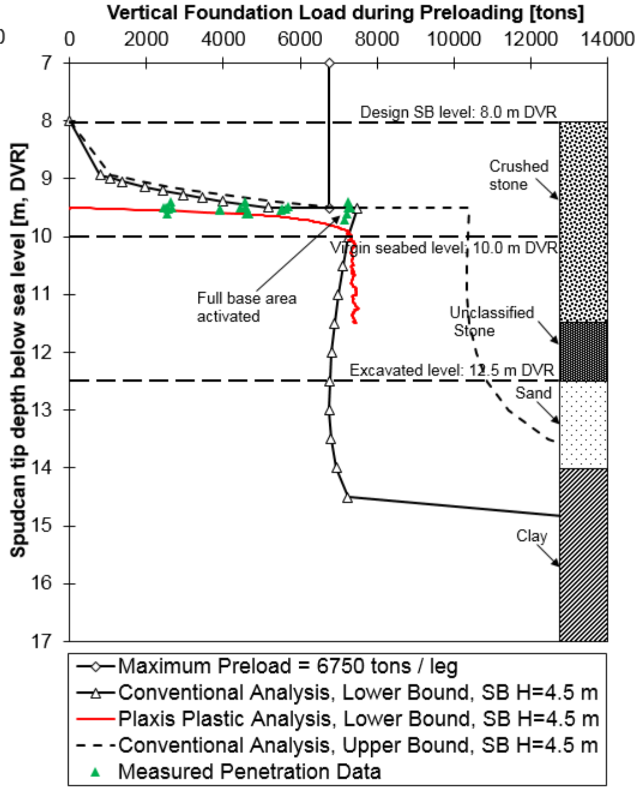

Figure 13a. Conventional & FE penetration curves, Front/STB Leg.

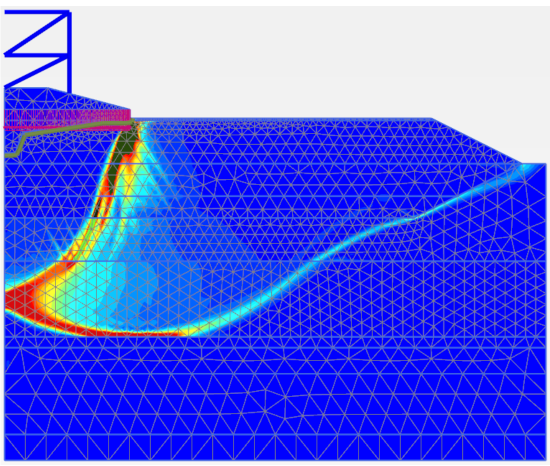

Figure 12b. 2D FE results – Front/PS Leg

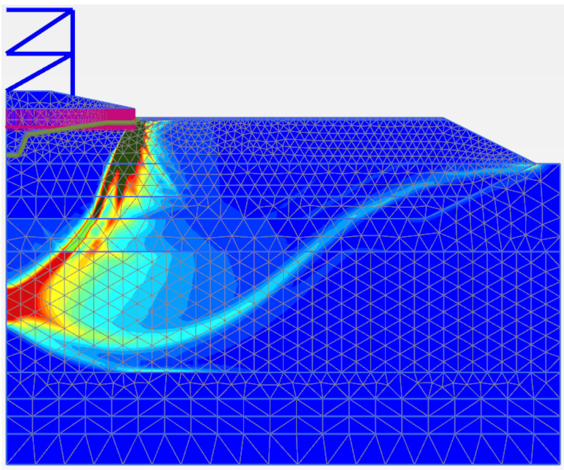

Figure 13b. 2D FE results – Front/STB Leg

Figure 14a & 14b presents the results at Back/PS leg (Leg 3). The minimum / lower bound bearing capacity for spudcan with full-base-contact is calculated as 7700 tons / leg. Figure 15a & 15b presents the results at Back/STB leg (Leg 2). The minimum / lower bound bearing capacity for spudcan with full-base-contact is calculated as 7630 tons / leg.

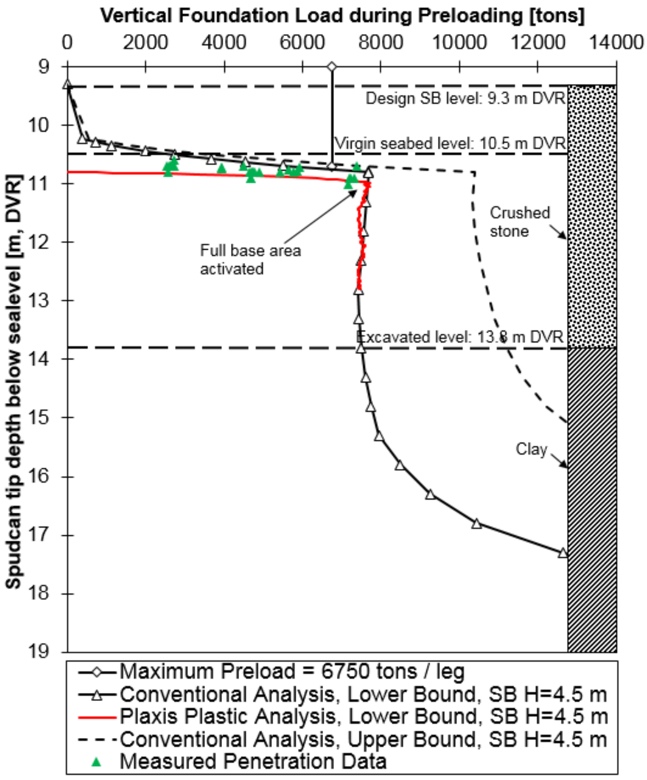

Figure 14a. Conventional & FE penetration curves, Back/PS Leg

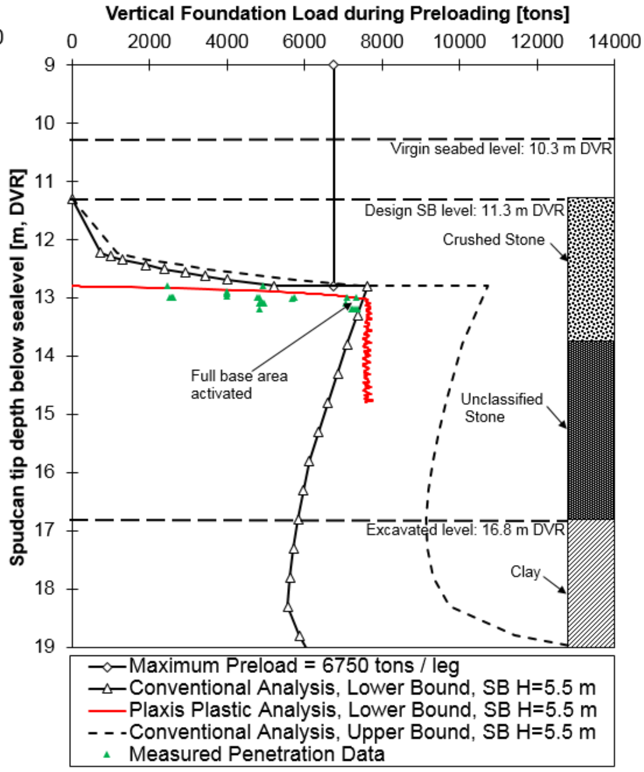

Figure 15a. Conventional & FE penetration curves, Back/STB Leg

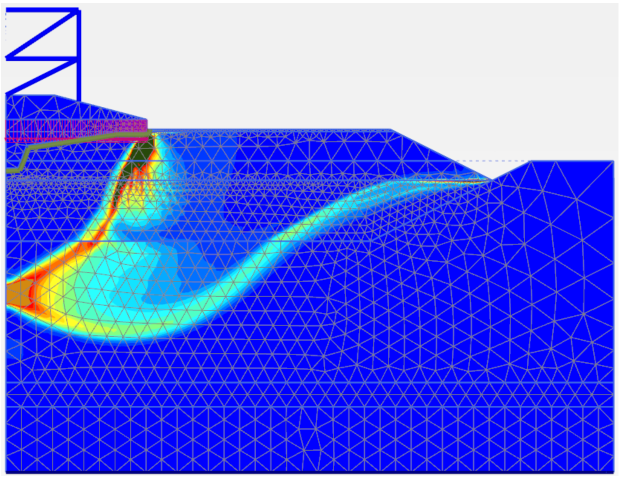

Figure 14b. 2D FE results – Back/PS Leg

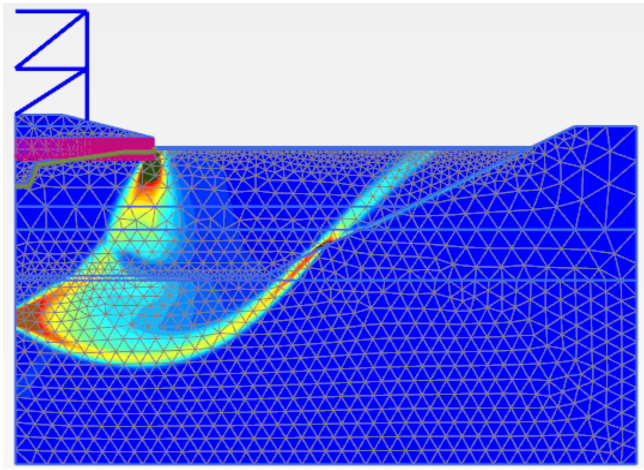

Figure 15b. 2D FE results - Back/STB Leg

The minimum / lower bound bearing capacities of the spudcans with full-base contact are calculated with interpreted lower bound soil profiles as summarized in Table 6.

Table 6. The minimum lower bound bearing capacities.

Leg no.	SB (H) (new + pre-built)	Minimum lLower bound bearing capacity
	(m)	Tons/Leg
Front/PS Leg	3.5 + 1	7610
Front/STB Leg	3.5 + 1	7490
Back/PS Leg	4.5 + 0	7700
Back/STB Leg	2.5 + 3	7630

6.4 Recorded Leg Penetrations / Feedback

The measured penetration data for each leg at different load levels are plotted, together with the conventional & FE penetration curves as provided in Figures (12a – 15a). The final measured penetration depth & applied maximum preload at each leg is summarized in Table 7.

Table 7. The final measured penetration depth & applied maximum preload at each leg.

Leg no.	Measured Penetration. Depth	Applied Maximum Preload
	(m)	Tons / Leg
Front/PS Leg	1.5	7346
Front/STB Leg	1.5	7307
Back/PS Leg	1.4	7366
Back/STB Leg	1.9	7355

According to the recorded data, full-base-contact is reached at all legs. Slightly larger penetration depth was measured at Back/STB Leg where no soil data (CPT / BH) were available.

7 As-Built SBs after Installations

The SBs were built in the harbor and the bathymetry data for the as-built SBs after jack-up vessel installations is presented in Figure 16.

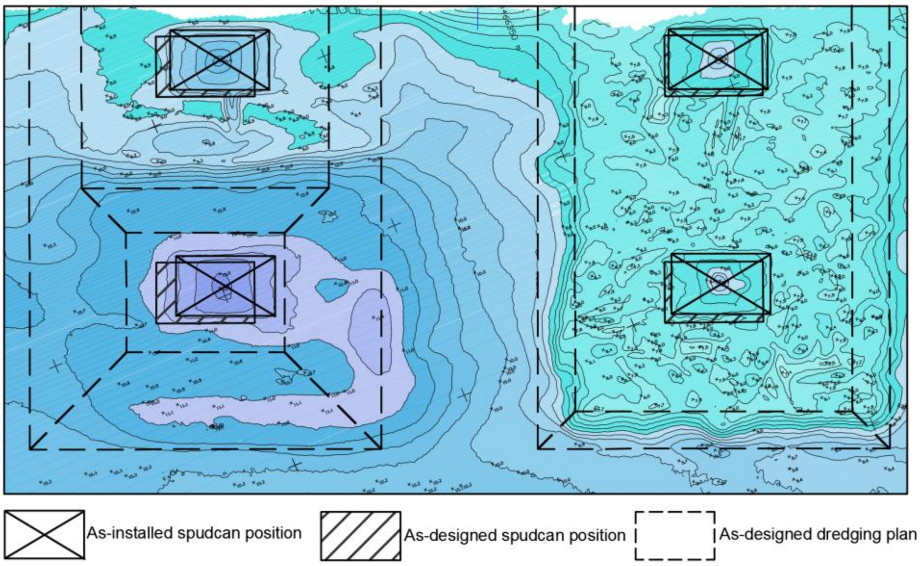

Figure 16. Bathymetry data for the as-built SBs after jack-up vessel installations

According to the bathymetry data as shown in Figure 16, the spudcan footprint level (water level at the spudcan footprint / depression) and the spudcan tip penetration depth are derived, and the results are given in Table 8. Full-base contact is approximately achieved at Front Legs & Back/PS Leg with spudcan tip penetration depth of (1.5 – 1.6) m and the largest penetration depth is measured at Back/STB Leg with spudcan tip penetration depth of 2.1 m, which comply with the feedback.

Table 8. The spudcan footprint level at each leg.

Leg no.	Spudcan footprint top level	Spudcan footprint bottom level	Spudcan tip penetration depth
	(m)	(m)	(m)
Front/PS Leg	8.0	9.5	1.5
Front/STB Leg	8.0	9.6	1.6
Back/PS Leg	9.0	10.6	1.6
Back/STB Leg	11.0	12.1	2.1

8 Conclusions

The design of seabed remediation measures, consisting of a combination of seabed excavation and SBs, is a way to increase the seabed bearing capacity and avoid punch through type of foundation failure in critical soil conditions. The design must provide the required safety, keeping at the same time the low costs.

For the current jack-up vessel location in the harbour area, offshore Denmark,the SBs are designed due to indication of critical soil conditions based on the available data. The purpose is to insure sufficient vertical bearing capacity of the spudcans during preloading, avoiding punch through and large penetrations, which could give spudcan - footprint interaction problems during the sequential vessel installation.

By using the feedback from the previous installations, the SBs are finally designed with total heights (new SB & pre-built SB) of 4.5 m at Front Legs and Back/PS Leg, and 5.5 m at Back/STB Leg. The unclassified stone (stone material from the existing SBs) is reused and dumped on top of the excavation, in order to increase the seabed bearing capacity.

The bearing capacities at four legs installed on top of the designed new SBs, are calculated still slightly larger than the expected maximum preload (6750 tons / leg) for allowing any soil variation within the spudcan areas and vicinity. Sequential vessel installation /preloading was successfully achieved. Predicted spudcan penetrations and the integrity of the SBs were confirmed.

Practitioners involved in the offshore wind industry might benefit from this case history regarding the safe installations of jack-up vessels on critical soil conditions. The engineers involved directly in the geotechnical design and remediation measures, will benefit in understanding how to use the feedback from previous installations, how to carry out FE analyses in combination with conventional methods and how to design such seabed remediation measures.

9 References

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