

Skirted Spudcan – Sheet Pile Wall Interaction during Jack-Up Rig Installation and Removal in a Harbour Area

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Abstract

For the jack-up rig locations in harbor areas the minimum distance of the closest skirted spudcans to the quay walls is related to the spudcan–sheet pile wall interaction issues during the rig installations and removals. This problem is part of the other aspects of jack-up rig foundation performances such as spudcan-pile interaction, spudcan-pipeline interaction etc. The interaction of a jack-up spudcans with skirts with the quay wall at a particular harbor area, offshore Denmark is investigated. The analyses are based on conventional and finite element (FE) modeling of the skirted spudcan-soil-sheet pile wall interaction. The soil conditions at the harbor area consist of soft to firm clay at the upper (3-4) m from the seabed, followed by very stiff to hard clay to larger depths. The anchored quay wall is modeled as it is and the jack-up skirted spudcans are investigated at different distances from the wall. The impact on the sheet pile wall structural forces, such as the additional bending moment, shear force etc. and additional deformations and changes in the safety factor due to the rig installation and removal are evaluated. The rig was installed next to the quay and later removed. Observations during the rig installation and removal related to skirted spudcan penetrations and the impact on the quay wall are discussed. General conclusions useful to engineering assessments for jack-up rigs locations in the harbor areas are drawn.

Keywords

Jack-up platform, sheet pile wall, skirted spudcan, conventional analysis, finite element (FE) analysis, failure mechanism, bending moment, shear force, safety factor

Introduction

Engineering assessment for the installation and removal of a jack-up rig platform at a harbour area, offshore Denmark is carried out. The jack-up platform, which is equipped with skirted spudcans will be temporarily installed next to a quay of a Danish yard in order to be upgraded for further production work in the North Sea.

The current assessment consists of the conventional skirted spudcan penetration analysis based on [1]-[3] and the finite element (FE) modelling based on [4] of the interaction of the skirted spudcans with the existing quay wall during both, rig installation and removal phases. For other aspects of jack-up foundation performance and analyses of skirted spudcans see [5]-[9].

The interaction of the skirted spudcans with the quay wall during the preloading and pullout phases is investigated by modelling one single free footing (one of the skirted spudcans closest to the quay) and the quay sheet pile wall at different relative positions. As the intension was to be as close as possible to the quay, the aim of the

FE analyses was to define the minimum distance from the quay wall the rig skirted spudcan could be located, ensuring a safe installation and removal, not affecting the stability and integrity of the quay structure.

A reference level, the current state of the quay wall integrity and stability, is modelled as good as possible using the available information. The changes in the quay wall structural forces and stability during the skirted spudcan installation / preloading and removal / pullout are investigated for different applied distances of the skirted spudcan to the wall.

Skirted Spudcan Geometry and Loads

The skirted spudcans have a largest radius of about 9.0 m, giving a full contact area of 253 m². Distance from spudcan base (full contact) to spudcan tip is 1.8 m, to bottom of permanent skirts is 4.7 m and to chord tips is 5.15 m (the three chords extend 0.45 m below the skirt tip). A cross section view is given in Fig. 1. The bearing and the skin friction areas are calculated based on the skirt geometry.

The initial load is about 7238 tons / leg and the maximum preload is 12416 tons / leg. At the current location the rig is expected to be preloaded to 50 % of maximum preload corresponding to 9827 tons / leg.

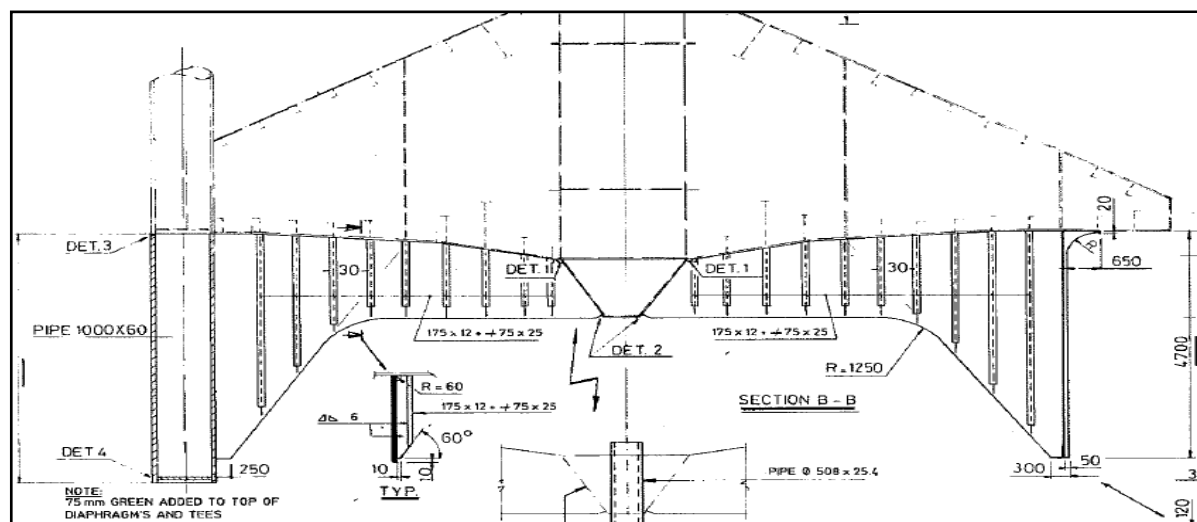


Figure 1 Cross section of the skirted spudcan geometry

Quay Sheet Pile Wall Structure

The data regarding the sheet pile wall (the type of the steel profile), the type of the anchor, the elevations of the sheet pile and the anchor, the water table behind and in front of the wall, the soil layering behind the wall etc are extracted as good as possible from the information available. A cross section of the quay at the area of the planned rig location is shown in Fig. 2.

General Soil Conditions and Back Analysed Soil Profiles at the Rig Area

The soil conditions along the harbour location have been determined from available boreholes carried out before the harbour dredging was performed. The harbour has been dredged and soft postglacial deposits have been removed. For the soil below the dredged level, the boreholes indicate rather uniform and competent soil. Based on the results of the soil investigations and previous experience at the harbour location lower / upper bound soil profiles for the depth relevant to spudcan penetration analyses have been interpreted. The soils along the quay, below the dredged level consisted of stiff to hard clay deposits.

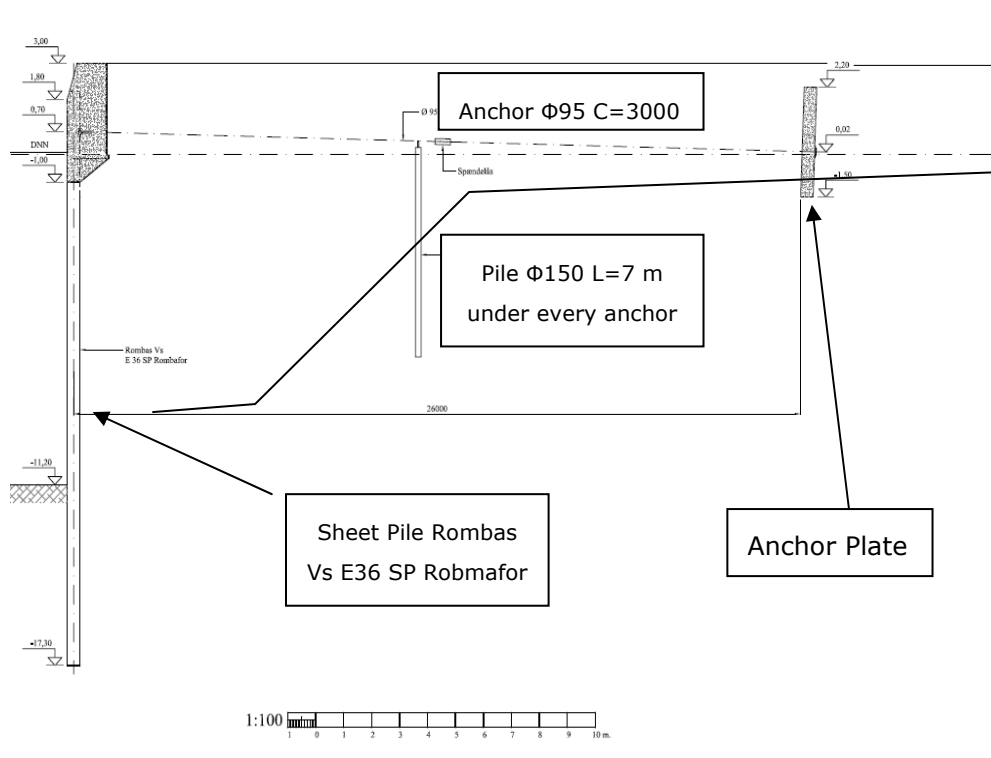


Figure 2 FE Skirted Spudcan-Quay wall Interaction Model, Drained

Spudcan penetrations of (1.8 – 2.5) m were observed for another jack-up platform (equipped with spudcans without skirts) installed at the same considered location at the harbour area applying 50% of maximum preload. Taking into account the pressure at the previous rig spudcans for the applied loads, lower / upper bound back analysed soil profiles are derived and given in Table 1. In estimating the strength parameters for the upper clay layer the fact that other rigs have been at the location is also taken into account. The soil layers are considered in the undrained conditions for the conventional spudcan penetration analyses.

Table 1 Lower / upper bound soil profiles

Soil Type	Depth of Layer (m)	Unit Weight γ' (kN/m ³)	Angle of Internal Friction ϕ (°)	Undrained Shear Strength c_u (kN/m ²)
CLAY, soft to firm	0.0 – 3.0	8.0	-	35 / 80
CLAY, very stiff to hard	3.0 – 9.5	10.0	-	250 / 300
CLAY, hard to very hard	> 9.5	10.0	-	400 / 450

Conventional Penetration Analyses

To conventionally define footing penetration depth versus load, calculation of the static bearing capacity of the skirted spudcans at various depths, is carried out. When the skirted spudcan reaches full base contact the assumption for an embedded footing is applied. This analytical calculation method is previously verified from the FE modelling of the skirted spudcan resting on different soil conditions.

The spudcan bearing capacity is calculated conventionally based on [1] and [2] and authors experience with spudcan penetration predictions. The spudcan is simplified to a circular footing having a flat bottom. However, the effect of the actual spudcan shape is taken into account. The calculations are based on design soil parameters with partial coefficients $\gamma_m = 1$. Squeezing of the seabed clay layer during the footing penetration is included in the analysis accounting that the maximum bearing capacity does not exceed that of the clay till below. The penetration resistance of the skirt elements is calculated as the sum of the end resistance and skin resistance. Danish

Code of Practice [3] based on the conventional pile theory, is used. From the previous experiences with penetration predictions and observations, this is considered realistic.

The results show that there is no risk of punch through or rapid penetration at the location. The penetrations calculated for 50% of the maximum preload is (4.9 – 5.1) m for the upper and the lower bound soil parameters respectively. The penetration curves are shown in Figure 3. The skirted spudcan penetration depth refers to the chord tip.

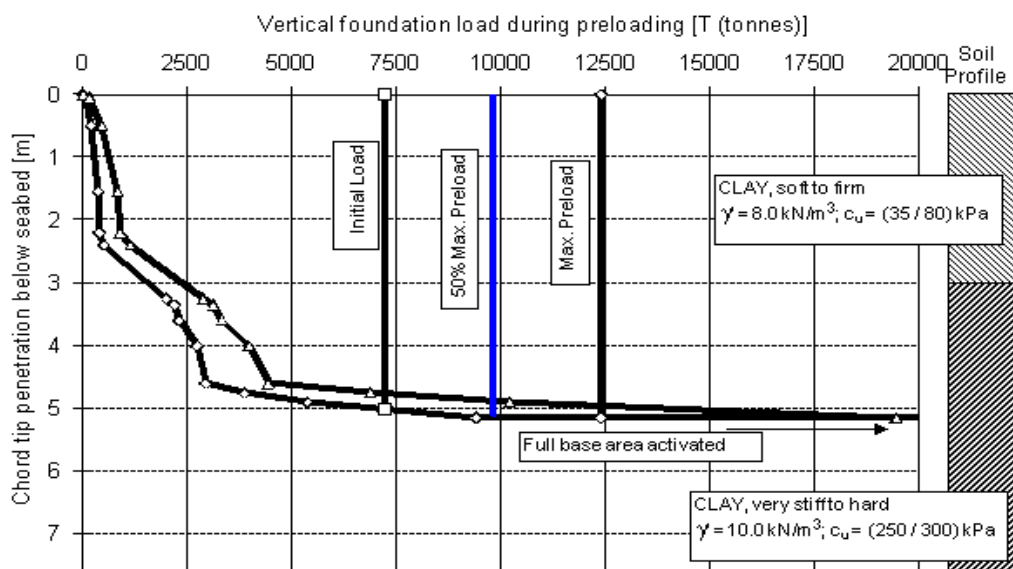


Figure 3 Conventional Penetration Predictions

Skirted Spudcan - Quay Wall Structure Interaction

Related to the purpose of the rig location at the harbour area it is of interest to install the rig as close as possible to the quay wall. For this reason different relative distances of the closest skirted spudcans to the quay wall are investigated.

Depending on the rig position relative to the wall and the amount of experienced spudcan penetrations from previous installation, some interaction of the closest skirted spudcans with the quay structure is expected. The distance $D = 21$ m from the centre of the skirted spudcan to the quay wall was finally recommended and is described here.

Considering the complexity of the problem, to analyse this interaction, plane strain FE modelling is applied with Plaxis program [4]. Undrained soil conditions for the jack-up area and the soil behind the quay were first investigated, as for the conventional penetration analyses. However, drained soil conditions were found most critical with regard to the sheet pile wall deformation and stability analyses, as expected.

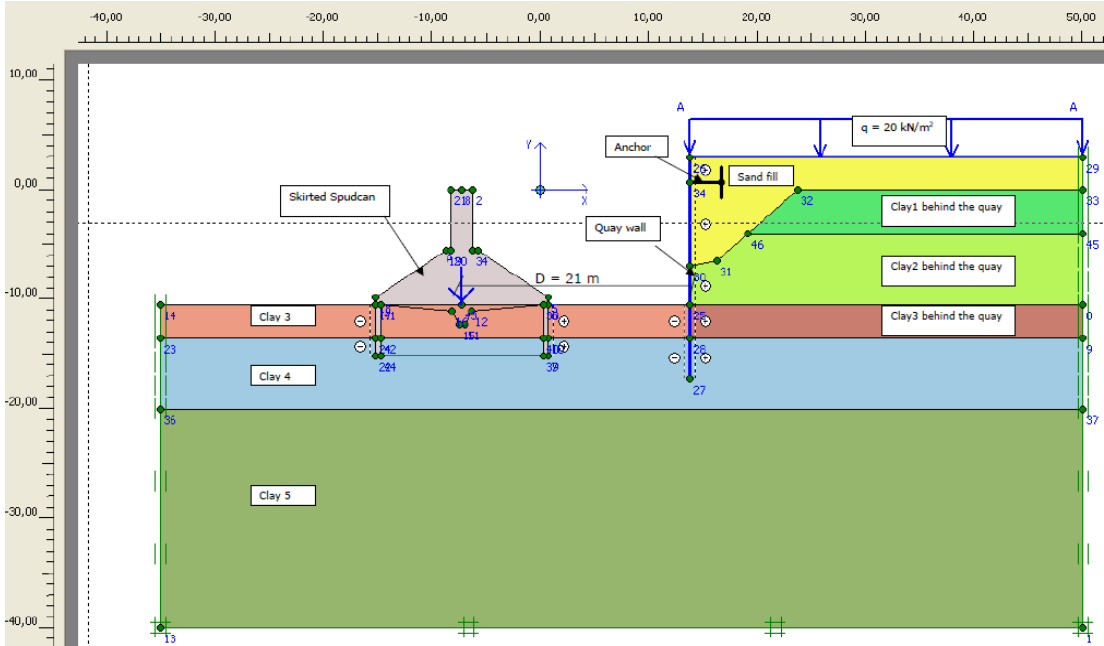
Soil Parameters, Drained Conditions

As the stability and integrity of the quay wall is determined from the soil strength and stiffness in the active and the passive zones only drained soil conditions were considered in the final integrated FE skirted spudcan – quay wall interaction model.

The drained parameters are estimated based on the undrained shear strength data and the geological description given in the available boreholes. The undrained soil parameters at the skirted spudcan area are taken the same as

in the conventional penetration analyses, while behind the quay they are approximately evaluated based on the information from the boreholes and the cross sections through the quay shown in Fig. 2.

From the undrained data the drained soil strength and deformation parameters are derived based on authors experience with ‘yoldialer’ in the current harbour. Focus is given to the lower bound undrained soil parameters. The FE model for the final distance $D = 21$ m of the skirted spudcan centre to the quay wall and the applied drained soil parameters are given in Fig. 4.



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ID	Name	Type	γ_{unsat} [kN/m ³]	γ_{sat} [kN/m ³]	k_x [m/day]	k_y [m/day]	ν [-]	E_{ref} [kN/m ²]	c_{ref} [kN/m ²]	φ [°]
2	Clay 3	Drained	18,0	18,0	0,0000	0,0000	0,30	3500,0	3,5	22,0
3	Clay 4	Drained	20,0	20,0	0,0000	0,0000	0,30	25000,0	20,0	22,0
4	Sand fill	Drained	18,0	18,0	0,0000	0,0000	0,30	25000,0	0,0	35,0
5	Clay1 behind the quay	Drained	18,0	18,0	0,0000	0,0000	0,30	6000,0	6,0	22,0
6	Clay5	Drained	20,0	20,0	0,0000	0,0000	0,30	40010,0	20,0	22,0
7	Clay3 behind the quay	Drained	20,0	20,0	0,0000	0,0000	0,30	10000,0	10,0	22,0
10	Clay2 behind the quay	Drained	20,0	20,0	0,0000	0,0000	0,30	10000,0	10,0	22,0
11	Clay 3 (no strength)	Drained	18,0	18,0	0,0000	0,0000	0,30	1000,0	1,0	0,0
12	Clay 4 (no strength)	Drained	20,0	20,0	0,0000	0,0000	0,30	2500,0	1,0	0,0

Figure 4, FE Skirted – Spudcan Quay Wall Interaction Model and applied Soil Data

An effective friction angle $\varphi' = 22^\circ$ and cohesion $c' = 10\%$ of the undrained shear strength c_u , is applied for the clay layers. For the sand fill behind the quay $\varphi' = 35^\circ$ and $c' = 0$ are applied. The deformation parameters, E module is calculated as $E_{ref} = 100 * c_u$. The soil parameters at the interface zone close to the wall are reduced applying the parameter $R_{inter} = 0.67$ according to [4].

FE Models and Analyses

All the distances $D = 13.8$ m, $D = 16$ m, $D = 18$ m and $D = 21$ m of the spudcan centre to the quay wall are investigated. $D = 21$ m was finally recommended by the authors. Only the results for $D = 21$ m are presented here. To see the changes in the stability and the quay structural forces the two last distances are compared in the next section.

The FE model is given in Fig. 4. The skirted spudcan is modelled as elastic weightless solid. The quay wall is modelled by beam / plate elements, steel profile Rombas Vs with top elevation at +3.0 m and tip elevation at -17.3 m. The seabed elevation where the skirted spudcan will be installed is at -10.5 m. The water table is kept constant at -1.0 m. The anchor $\phi 95$ is installed at +0.7 m with a slight inclination equal to -1° , length 26 m and every 1.26 m along the quay wall.

The considered distributed load on the soil surface behind the quay is shown in Fig. 4. The load applied on the skirted spudcan (50% of maximum preload converted in plane strain) during the installation phase is 6036 kN/m.

The FE analyses are performed in three phases applying design soil parameters with partial coefficients $\gamma_m = 1$, as for the conventional analyses. Firstly, the initial, current conditions, (before the rig is installed), are modelled or simulated as good as possible considering the available information. The intention is not to accurately model and check the quay wall stability and structural forces (as more detailed information and modelling issues might have been needed), but to define a state to be used as a reference level.

The quay stability and structural forces at the reference level are compared with the corresponding values calculated during the rig installation and removal. As the change in the quay structural forces is related to the additional deformations initiated during installation and removal, the partial coefficient $\gamma_m = 1$ is found applicable.

Initial / Reference Phase

The quay structure – soil interaction model and results in the initial phase (before the rig installation) are given in Fig. 5. This should be taken as a best estimate of the sheet pile wall current stability and structural forces. In this figure the location of the skirted spudcan can be seen. However, the spudcan is missing in the initial phase and it will be activated in the installation phase.

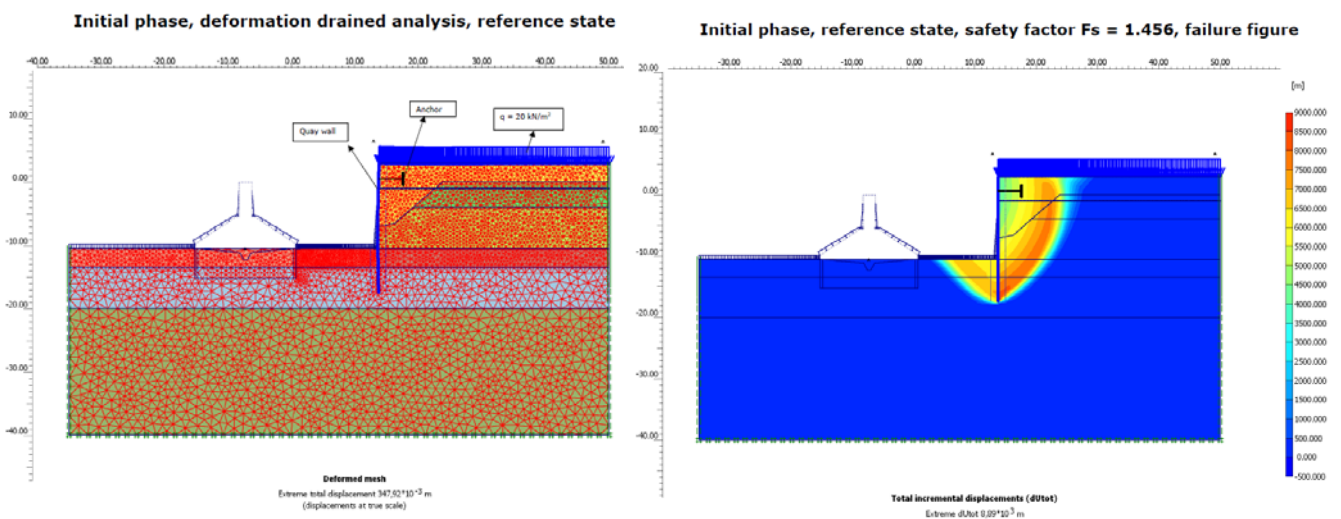


Figure 5 FE Skirted Spudcan-Quay Wall Interaction Model for the Initial Phase – Deformation (left) and Safety (right) Analyses

The maximum bending moment for the sheet pile wall is calculated in this phase as $M = 698.08 \text{ kNm / m}$, the maximum shear force $Q = 241.39 \text{ kN / m}$ and the anchor force $H = 393.85 \text{ kN / m}$. The safety factor is $F_s = 1.456$ as shown in Fig. 5 where the critical failure figure is given.

Rig Installation Phase

The calculation for the installation phase starts after the initial phase, as mentioned above, resetting all the displacements to zero. The skirted spudcan is modelled at full base contact as shown in Fig. 6. To avoid non-realistic lateral movements of the skirt in plane strain, the soil inside the skirt is modelled as elastic, (just like the spudcan body), but with its own weight, (different from the spudcan which is considered weightless). The results for the installation phase are given in Fig. 6.

The horizontal deformations due to skirted spudcan preloading to 50% preload are about 0.9 cm at the sheet pile wall tip due to lateral soil movement during skirted spudcan preloading. The vertical and horizontal displacements in the model are given in Fig. 7.

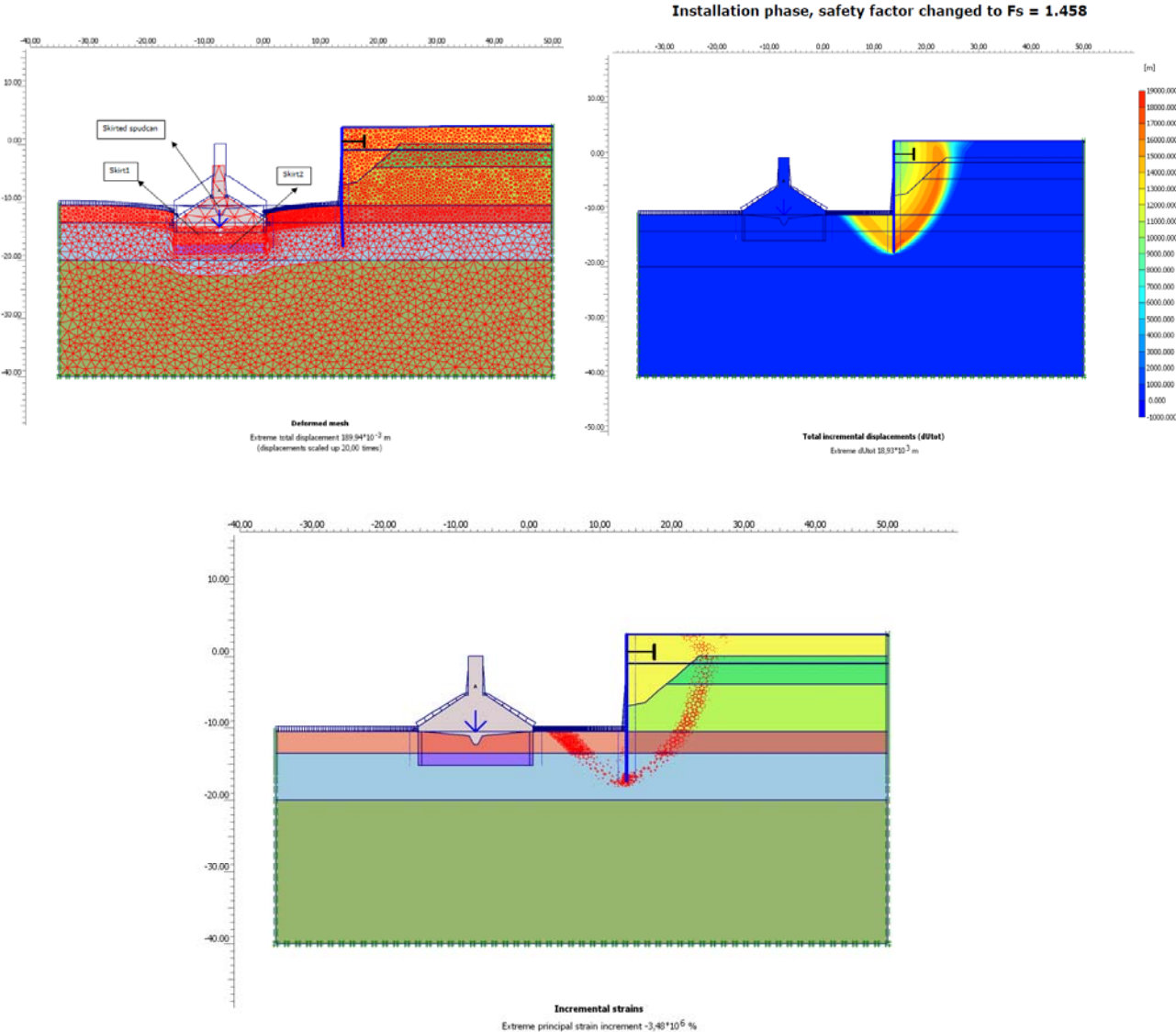


Figure 6 FE Skirted Spudcan-Quay Wall Interaction Model for the Rig Installation Phase – Deformation (left) and Safety Analyses (Two Different Illustrations of the Failure Figure)

The maximum bending moment for the sheet pile wall is calculated in this phase to be $M = 731.23 \text{ kNm / m}$, the maximum shear force $Q = 252.34 \text{ kN / m}$ and the anchor force $H = 416.25 \text{ kN / m}$. The safety factor is $F_s = 1.458$ as shown in Fig. 6 (right) where the critical failure figure is given for illustration.

As expected, during the installation phase, depending on the applied distance of the skirted spudcan to the quay wall the sheet pile structural forces will be affected / increased. This is investigated for different distances. Taking into account that the plane strain FE modelling gives larger deformations the increase in the M , Q , H for the $D = 21 \text{ m}$ is considered acceptable and not critical for the quay wall integrity.

On the other hand, the stability of the quay wall is not changed, maybe slightly increased during the installation. This means that the two skirted spudcans installed / preloaded closest to the quay wall have stabilizing effects.

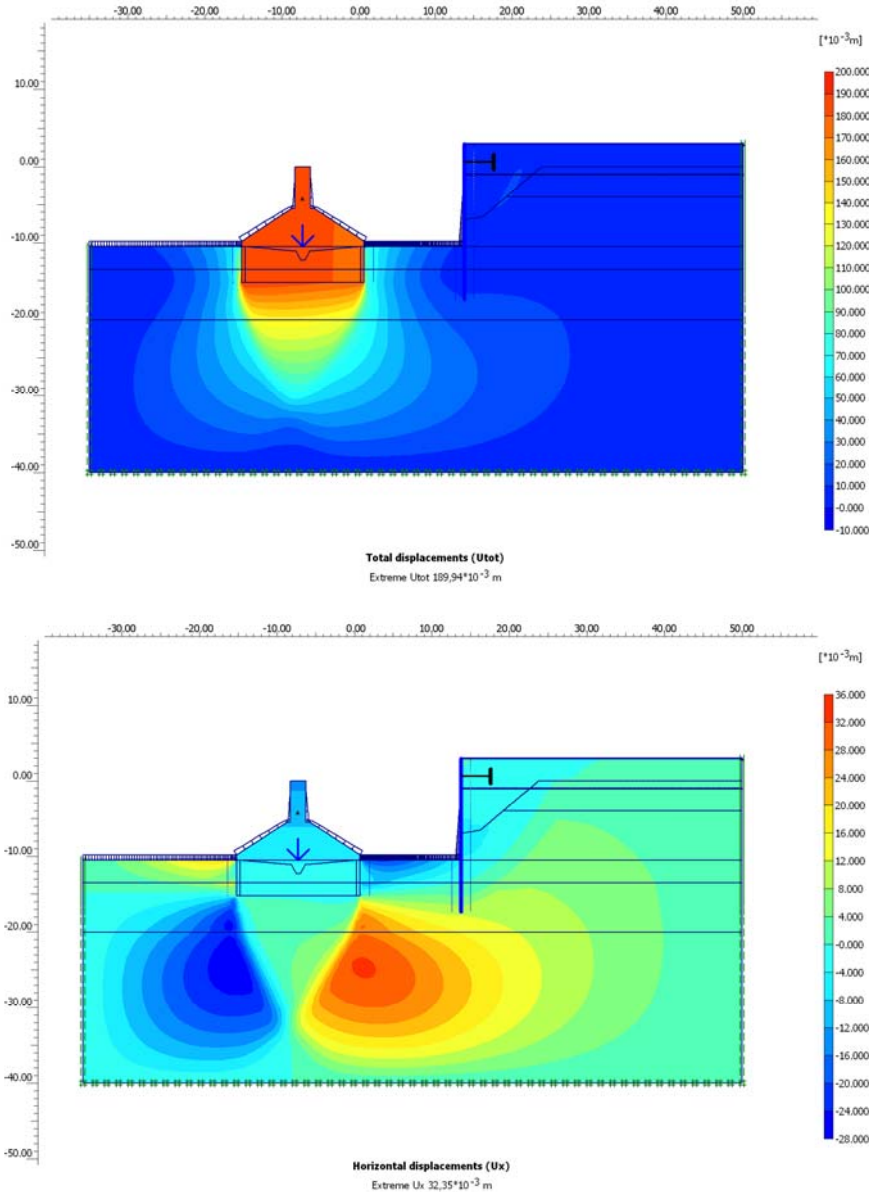


Figure 7 FE Skirted Spudcan-Quay Wall Interaction Model for the Rig Installation Phase –Vertical and Horizontal Displacements

Rig Removal Phase

The calculation for the rig removal phase starts after the installation phase. The skirted spudcan is unloaded first. After that, it is deactivated and the soil inside the skirts is replaced with disturbed / remoulded soil with almost zero strength. As shown in Fig. 4 (clay 3 and clay 4 (no strengths)). The assumption that the soil inside the skirt physically remains at the location (having gravity load but no strength) is made. The results for the removal phase are given in Fig. 8.

The soil deformations after the skirted spudcan removal are calculated. The horizontal deformation at the sheet pile wall tip is reduced to 0.6 cm as shown in Fig. 9. This is caused, due to lateral soil movement (in the opposite direction) during skirted spudcan pullout.

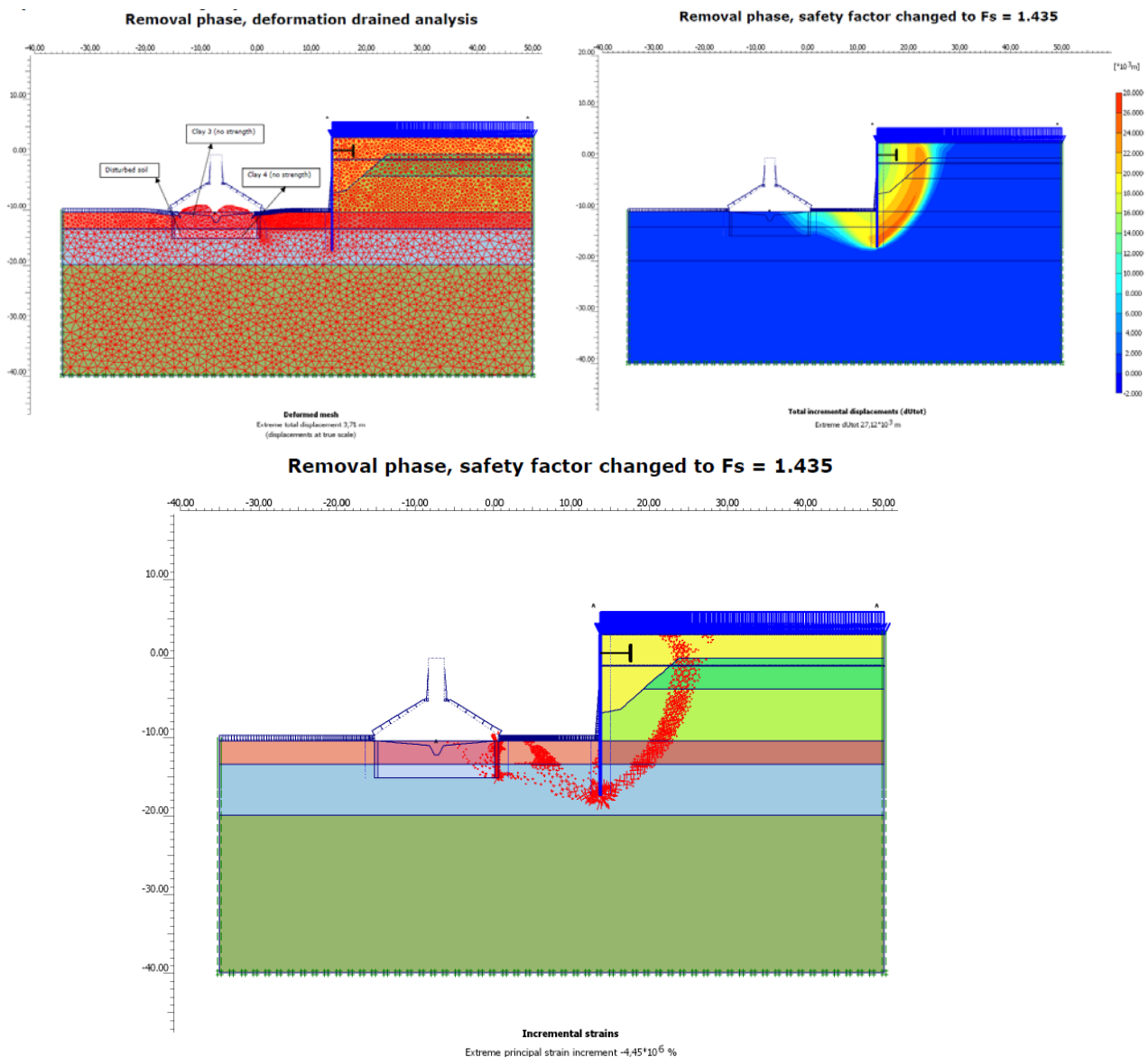


Figure 8 FE Skirted Spudcan-Quay Wall Interaction Model for the Rig Removal Phase – Deformation (left) and Safety Analyse (Two Different Illustrations of the Failure Figure)

The maximum bending moment for the sheet pile wall is calculated in this phase to be $M = 732.2$ kNm / m, the maximum shear force $Q = 251.5$ kN / m and the anchor force $H = 406.81$ kN / m. The results in the diagram

form are given in Fig. 8. The safety factor is reduced to $F_s = 1.435$ as shown in Fig. 8 where the critical failure figure is given in different ways for illustration.

During the removal phase, the sheet pile structural forces are slightly reduced compared to the installation phase but slightly increased compared to the initial / reference state.

The stability of the quay wall will in general be reduced during the removal phase in comparison to the reference state. This means that the two skirted spudcans closest to the quay wall, when pulling them out will affect the stability of the quay. Considering the assumption made in the calculation, (the remoulded soil inside the skirt remains at the original location but with almost zero strength), for $D = 21$ m the slight decrease in the safety factor is not considered critical.

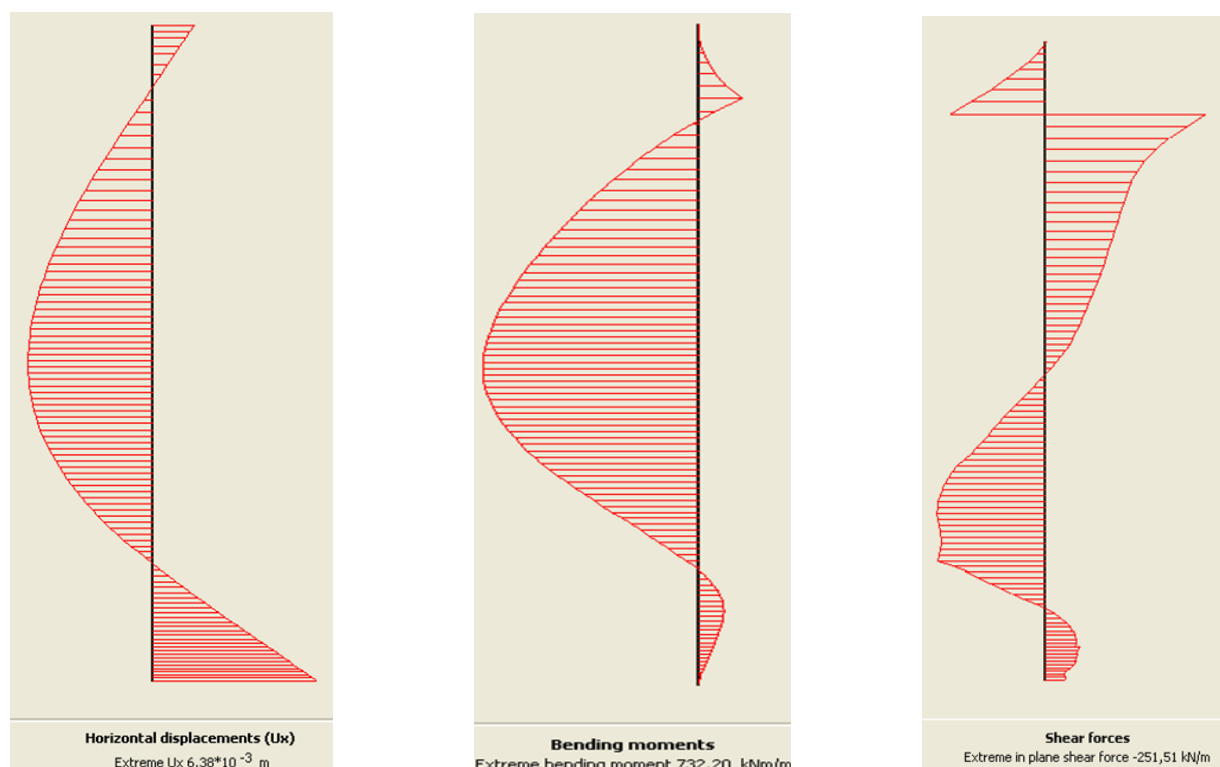


Figure 9 FE Skirted Spudcan-Quay wall Interaction Model, Drained – Initial Phase

Sensitivity Analyses Related to the Applied Distance

For sensitivity analyses two different distances of the centre of the skirted spudcan to the quay wall are compared with respect to the effect on the sheet pile structural forces and stability during the installation and removal phase. The distance $D = 18$ m and the final one $D = 21$ m are considered.

Distance $D = 18$ m

During the installation phase the sheet pile maximum moment is increased to about 7% and the anchor force to about 10% compared to the reference level. Although the plane strain analyses might be conservative with this respect, this increase is considered unacceptable.

During the removal phase 5% reduction in the safety factor or about 15% reduction in the quay wall safety compared to the reference level is calculated. The reason is the change in the failure figure from installation to re-

removal phase. This is considered unacceptable even if jetting system is applied. The jetting pipes, one for each compartment might not be able to ensure the necessary pressure to separate the clay soil from the spudcan and the skirt. For this reason a larger distance was investigated.

Distance D = 21 m

During the installation phase the sheet pile maximum moment and the anchor force are increased to about 5% based on the plane strain FE analyses. This is considered acceptable.

During the removal phase about 1% reduction in the safety factor or about 3% reduction in the quay wall safety is expected. This is due to the combined failure figures shown in Fig. 8 developed in the removal phase. Considering the plane strain modelling and the low strength used for the soil previously inside the skirt this is considered acceptable.

Conclusions and Recommendations

Conventional and plane strain FE analyses of the skirted spudcan penetration and skirted spudcan - quay wall interaction analyses, respectively are carried out for a jack up platform located at a harbour in Denmark. There is no risk for punch through or rapid penetration at the considered location and skirted spudcan penetrations (4.9 - 5.1) m are predicted for the planned 50 % of maximum preload.

From the plane strain FE analyses the minimum distance D=21 m from the skirted spudcan centre to quay wall, (corresponding to about 1.2 times skirted spudcan diameter) is recommended. The sheet pile and anchor maximum forces and safety factor / stability for the initial state, installation and removal phases for this applied distance are summarised in Table 2.

Table 2 Summary of the Plane Strain FE Analyses Results

Phases	Sheet Pile Wall Maximum Forces		Anchor force H (kN/m)	Sheet Pile Wall Tip Horizontal Displacement (cm)	Safety Factor Fs
	M (kNm/m)	Q (kN/m)			
Initial / Reference	698.08	241.39	393.85	0 (assumed)	1.456
Installation	731.23	252.34	416.25	0.9	1.458
Removal	732.2	251.5	406.81	0.6	1.435

In the analyses the initial phase is taken as a reference state. This means that the results given in Table 2 for this phase might not be exactly as they are in reality. However, this is not considered important as the changes in the quay wall structural forces and stability during the installation and the removal phases, relative to the initial phase are of main interest.

From the results in Table 2, in the installation phase the sheet pile maximum moment and the anchor force are increased to about 5% relative to the reference state. This is considered acceptable when taking into account that the results are based on the plane strain FE modelling, which is accurate for modelling the quay sheet pile wall and rather conservative for modelling the skirted spudcan.. The stability though is not changed or probably slightly increased.

From the results in Table 2 for the removal phase, the sheet pile maximum moment and the anchor force are increased in the same amount, or maybe slightly less, than the ones during the installation phase. They are considered acceptable for the same reasons given above. In addition, about 1% reduction in the safety factor or about 3% reduction in the quay wall safety is calculated relative to the initial phase. This is also considered acceptable considering the assumption made in the calculation regarding the almost zero strength applied for the remoulded soil previously inside the skirt.

Taking into account the assumption made in the calculation of the removal phase, (the remoulded soil inside the skirt physically remains at the original location having gravity but almost zero strength, the distance $D = 21$ m is considered acceptable under the condition that the skirted spudcans should be pulled out slowly or applying a special procedure in order that the soil inside the skirt remains back at the original position, ensuring almost the current state and safety of the quay wall.

Based on the skirted spudcan – quay wall interaction analyses carried out for this location, it can be concluded that the minimum distance of the skirted spudcan from the quay wall (in order not to impact the quay structure), depends on the soil conditions (hence predicted skirted spudcan penetrations) at the location and the static conditions of the sheet pile wall (free or anchored wall). The rig was installed at the location (with skirted spudcans centre 21 m from the quay wall) and later removed. The leg penetrations did comply with the prediction and no impact on the quay structure was observed during the installation and removal.

Acknowledgement

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