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Jack-up vessel foundation stability during installation next to a Wind Turbine Generator

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ABSTRACT

After the commissioning of an Offshore Wind Farm, proper maintenance of the wind turbine generators (WTG) takes a main role to ensure the energy supply during their life span. For doing this work, jack-up vessels are required, just applied for the installation of WTGs and their foundations. Thus, if the soil conditions are critical, multiple problems could be encountered during the jack-up vessel installation and operation next to the WTG foundation. For a jack-up vessel performing maintenance work near a WTG with gravity base foundation, critical soil / seabed conditions are interpreted with regard to vessel installation. The multi-beam / bathymetry survey indicated that one of the legs was placed on a slope that could compromise the vessel structure stability. Conventional and finite element (FE) analyses are performed for analysing the risks associated with the leg penetrations and stability during the jack-up vessel installation. A back-analysis of the measured penetrations is commented and implemented. Useful conclusions and recommendations for practitioners and engineers working with similar projects are drawn.

Keywords: Jack-up vessel, leg penetration analysis, foundation stability, finite element (FE) analysis.

1. INTRODUCTION

Geotechnical engineering assessments are carried out for the offshore wind industry, not only during the development of an Offshore Wind Farm (OWF) assessing the type of foundations of the Wind Turbines Generators (WTG), but also during the installation and maintenance of the WTGs themselves. The jack-up vessels are entitled to assembly the necessary pieces of the WTGs. In this process, they need to be completely stable and well above the water currents. They are constructed with legs, which penetrate into the seabed soil and elevate the vessel ensuring stability and a safe operation.

From a geotechnical engineering point of view, multiple risks can appear. The most recognized is the so called punch-through. However, other risks such as leg sliding or interaction with boulders, pipelines or other nearby seabed structures, could also appear. For reducing or eliminating such risks, multiple mitigation measures can be

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implemented e.g. gravel pads, excavation, swiss cheesing etc.

For an OWF with gravity base foundations, a quick turnover was needed in order to assess a safe position to install a jack-up vessel. Multiple positions and different vessel configurations were examined. The results from the assessment are therefore explained and analysed in this paper.

2. PROJECT DETAILS

2.1. Scope of work

It was requested to provision with consulting services to ensure a safe installation of the vessel during the expected operation. The scope of work was:

- Geotechnical interpretation of the available soil data
- Correlation of geotechnical and geophysical data if available
- Assessment of suitability of the vessel for doing the installation, reporting possible risks for punch-through, rapid penetration or leg extraction, including leg penetration analysis
- Comment on other possible risks (e.g. seabed features or leg sliding)

2.2. Location

The OWF is located offshore Denmark within a shallow area with water depths ranged from (2-6) m. A close monitoring of water depths, made with a recent topographic map of the seabed (bathymetry), was the first requirement for doing the expected maintenance work. According to a received bathymetry, made prior to the assessment, the water depth within 100 m from the WTG varies from (3.5 - 5.8) m DVR90.

In order to perform the maintenance and reparation works, the vessel needed to be close enough to the WTG, so that the crane could safely operate under the requirements defined in (Guidelines for marine lifting & lowering operations 0027/ND). During the assignment, multiple positions were examined in the vicinity of the WTG.

The final position is shown in Figure 1.

Figure 1 Location of the WTG

2.3. Jack-up geometry and loads

The multi-purpose jack-up has a length of 32 m and a width of 20 m, being the larger distance between legs 24m. Its size gives flexibility in this kind of short operations.

The jack-up system is based on four legs, each of them with a length of 50.6m, equipped with spud piles with a conical shape at the bottom. They are circular with a diameter of 1.42 m and an area of 1.58 m^2. The distance from tip to base is 0.57m.

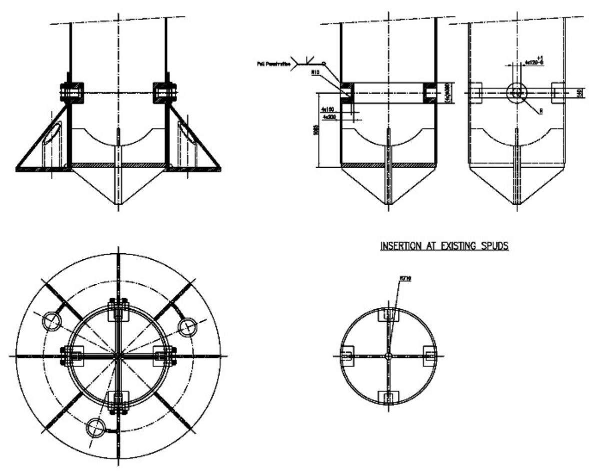

Figure 2 Spudcan configuration (left) and spud leg / pile (right)

Alternatively, the vessel has the capability of working with circular spudcans of 3 m diameter, leading into an area of 7.07 m^2.

For this project, both cases were primarily studied. During the development of the project, the client decided that the vessel would not be assembled with spudcans. Therefore, this paper will explain both cases, but only provide feedback for the configuration without spudcans.

The maximum expected preload was 475 tons / leg.

3. GEOTECHNICAL DATA

3.1. Geotechnical Investigations

The geotechnical investigations and laboratory testing used for this assessment were made by Geo in different phases during 1997-2000. The purpose of these investigations was foundation design of the OWF. These investigations were carried out with Geo´s combined Cone Penetration Test (CPT) and Vibrocore sampling (VC) seabed rig.

3 CPT/VCs were performed for each WTG location, which would be used in this assignment. Furthermore, laboratory testing was made by Geo mainly to confirm the strength of the chalk, common in this site, by means of triaxial tests.

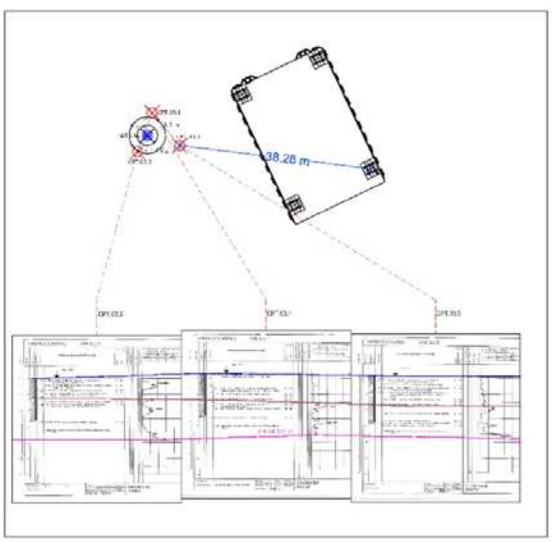

Figure 3 Location of the CPT/VCs, distance to the jack-up and CPT/VCs logs

The relevant CPTs for the assessment have a depth below seabed ranging from 3.4 m to 3.8 m. For the final location, the distance from the nearest CPT to the closest leg is 17 m whilst the furthest is about 38 m (Figure 3).

The geotechnical data shows a soil profile consisting of CLAY with various strengths, underlain by CHALK starting from about (4.0 – 5.0) m below the seabed.

3.2. Interpreted soil conditions

For the installation of jack-ups in the offshore wind industry is frequent the lack of soil data for each leg, different from offshore oil and gas industry, where it has become common to have one CPT for each jack-up rig spudcan.
In an OWF, the geotechnical data used for the installation assessments is usually the obtained for the foundation design of the WTG. Sometimes the distance to the place of installation might be too large that it is needed to correlate geotechnical and geophysical data; like obtained by a Sub Bottom Profiler (SBP). A SBP generates an acoustic wave, which reflects into the subsoil, discerning between layers.

Based on the available soil data, lower / upper bound soil profiles applicable to leg penetration analysis are interpreted and summarized in Table 1.

Soil Layer	Depth of Layer [m]	γ' [kN/m^3]	φ L / U Bound [°]	c_u L / U Bound [kN/m^2]
CLAY, very soft to very stiff	0.0 – 1.7	7.5	-	10-90 / 20-180
CLAY, very stiff to hard	1.7 – 2.2	9.5	-	150 / 300
CLAY, soft to very stiff	2.2 – 4.0/5.0	8.0	-	35-100/70-200
CHALK	4.0/5.0 – 10	12.0	39 / 44	-

Table 1 Interpreted soil profile

The upper / lower bound characteristic soil parameters are selected as a cautious estimate of the value affecting the occurrence of the relevant limit state. The undrained shear strength for the clay layers is based on the CPT data applying cone factor Nk = (10 - 20) for the upper and lower bound soil parameters, respectively.

The Nk factor was chosen considering previous experience in the area, laboratory tests and accounting the distance from the furthest CPTs to the leg location (38 m).

The soil profile exhibits a very soft to stiff upper top clay layer, underlain by a thin layer of very stiff to hard clay, overlying a soft to very stiff layer of clay.

The precise depth to the chalk is uncertain; it has been considered a level of variation of 1 meter. The chalk has been interpreted as drained with lower bound friction angle of 39 degrees. This was decided considering all the results from the triaxial test along the OWF.

4. LEG PENETRATION ANALYSIS

4.1. Bearing capacity formulation and use in jack-up foundations

The limited shear resistance or ultimate bearing capacity has been discussed and developed along the years, since the early Terzaghi equations (1943). Geotechnical engineers such as J. Bowles affirm that 'there is currently no method of obtaining the ultimate bearing capacity of a foundation other than as an estimate'. (Bowles, 2001)

J. Brinch Hansen published in 1970 the revised and extended formula for bearing capacity. This extended formula included shape, depth, load inclination, base inclination and ground inclination factors. These factors were implemented to the original formula (Hansen, 1970). The general formulation is:

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

Where: Q = bearing capacity of foundation base; A = fundamental area, B = fundamental width; γ = soil 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.

In the case of undrained conditions, it would be more correct to introduce additive constants, resulting in a simpler equation:

$$Q/A=(\pi+2)c_u(1+s_c^a+d_c^a-i_c^a-b_c^a-g_c^a) \quad (2)$$

Where: Q = bearing capacity of foundation base; A = fundamental area, c_u = undrained shear strength; s_c^a = shape factor with additive constant; d_c^a = depth factor with additive constant; i_c^a = load inclination factor with additive constant, b_c^a = base inclination factor with additive constant; g_c^a = ground inclination factor with additive constant.

The bearing capacity with depth can assess the risks related with installation of jack-ups. The most described are the 'rapid penetration' and 'punch-through' failures. These failures occur when the bearing pressure dramatically reduces, typically during the penetration of a stiff layer overlying a softer layer (e.g. sand over clay). This sudden penetration may cause damage to the jack-up structure by cause of the large displacement of the leg. In critical cases, an accurate leg penetration prediction is extremely important for ensuring safety.

4.2. General considerations

The limit state analyses of the circular conical spud leg / pile follow the guidelines given in SNAME & ISO. The calculations are based on design soil parameters with partial coefficients γ_m = 1.0.

In the assessment, the applied preload of up to 475 tons/leg is considered as static load. To conventionally define footing penetration depth versus load, the calculation of static bearing capacity of the spud leg / pile at various depths is carried out. Different failure mechanisms are assumed during the footing penetration in multi-layered plastic medium. The spud leg / pile bearing capacity is based on Brinch Hansen's theory and Geo in-house program developed from the experience with spudcan penetration predictions such as (Kellezi, L., Xu, L., Molina, C., 2015).

To account for the backflow conditions, full backflow is considered in the conventional lower bound assessment and no backflow in the upper bound assessment as indicated in the conventional predictions (Figure 4, Figure 5, Figure 17).

The spud leg / pile is simplified to a circular footing with a flat bottom. The effect of the shape is taken into account.

4.3. LPA results - Spudcan

The versatility of the vessel allows it to work with or without spudcans. In an initial assessment, the vessel configuration was with spudcans. As preliminary assessment it was decided to choose a predefined depth of the chalk of 5 m, taking the behaviour of the Chalk as undrained, with unit weight (γ') = 12 kN/m^3 and undrained shear strength (cu) over 800 kPa. Before issuing a final penetration curve, it was needed to further investigate the chalk properties within the OWF. At the same time this desk study was initiated, the configuration of the vessel changed to without spudcans.

From the lower / upper penetration curves, assuming a generalized soil profile to represent the soil conditions at all 4 legs, the spudcan were estimated to penetrate (3.2 – 4.8) m.

The curves (Figure 4) exhibit an increase in the capacity from the seabed to two meters below seabed (bsb), while the spudcan penetrates through a layer of clay with increased strength with depth.

After that, it is estimated a punch through / rapid penetration of around half a meter during the penetration of the stiff clay layer. Posteriorly, a similar soil mechanism as the one occurred within the first layer is expected up to the placement of the spudcan over the chalk.

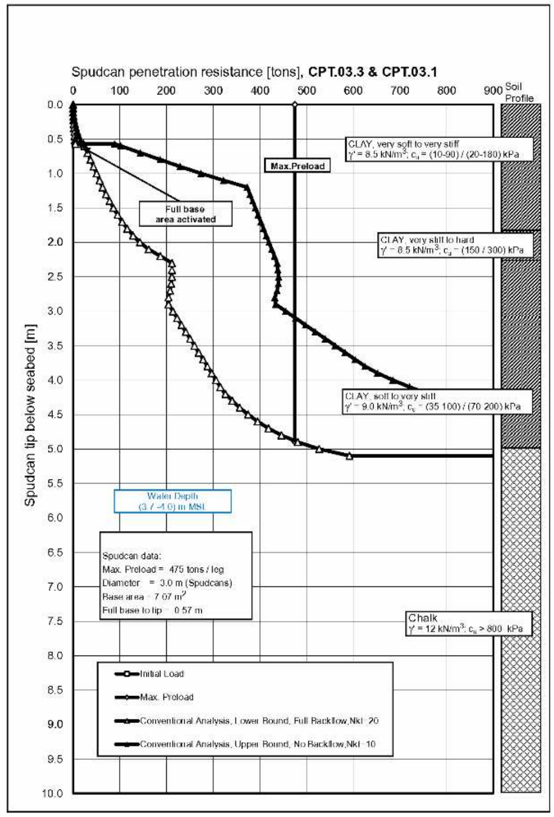

Figure 4 LPA results for the vessel with spudcan

4.4. LPA results - Spud leg / pile

After assessing the results, the final vessel's configuration, without spudcans, was chosen.

A new assessment was therefore needed. In a first view, a reduction in the total base area could lead into further penetration, giving a clear indication of the need of fully assessing the chalk.

After a new review of the data available and Geo's database from projects within the area. It was decided that the chalk would behave as a drained material. Thus, accounting with lower bound soil parameter of 39 degrees, the leg could penetrate into the chalk.

From the lower / upper penetration curves, assuming a generalized soil profile to represent the soil conditions at all 4 legs, the spud leg / piles were estimated to penetrate (4 - 6) m.

The curves show a faster penetration into the soil with less applied load than in the previous case, which was expected as a result of a smaller total area. An increment in the penetration resistance is done in two steps as the interpreted soil strength also increments with depth in two different layers. In the boundary between layers can be shown a pick in the capacity prior to a fast decrease of less than a meter, as shown in Figure 5.

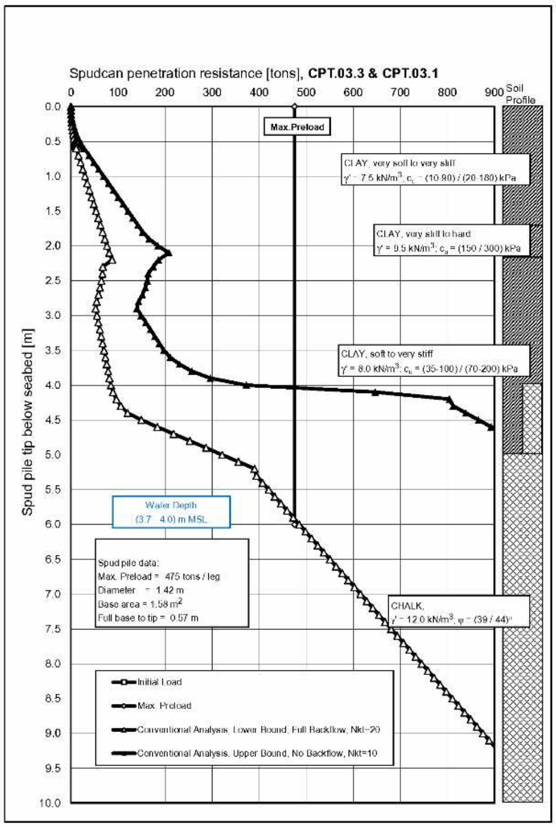

Figure 5 LPA results for the vessel without spudcan (spud leg / pile)

The large range of penetration has its origin in multiple uncertainties such as lack of data at the leg locations or ascertain the top of the chalk situated beneath the clay. Some risks for punch through at low load level are expected, however not critical due to vessel draft conditions.

The results from the leg penetration analysis did not compromise the safety during installation. However, the stability of the vessel could be endanger in a sloping soft clay soil.

5. FOUNDATION STABILITY

5.1. The Stability and seabed instability problems

The stability of a jack-up unit installing WTG is one of the requirements for getting a certificate of approval from a Marine Warranty Surveyor (MWS). During long operations, it is needed to establish the survival airgap range and whether there are any limiting factors for a vessel restricting the time that can be spent on location. Vertical-Horizontal (V-H) capacity envelopes are required in these assessments. A bespoke communication between structural and geotechnical engineers is important when issuing Site Specific Assessments (SSA), where the considered problems are not only for installation but also for operation. The problems of stability during operation are further described in code of practices as ISO, SNAME or (Guidelines for site specific assessments of jack-ups 0009/ND).

Seabed instability can result in slope failures caused by multiple mechanisms. Cyclic mobility or liquefaction starts when progressive pore pressure is build up caused by cyclic stresses within the soils, as described in SNAME. During the installation process, seabed instability might cause risk of sliding, and is precisely that fact studied in this paper.

5.2. Case

After a review of several positions, a final vessel location was chosen, which would be more adequate for the arrangement of the cranes entitled to move the components. However, for the chosen vessel position, the bathymetry indicated that the Starboard (SB) Leg should be jacking on a slope. The fact of having SB leg on top of a soft soil that might already fail due to seabed mobility was a concern and it was decided that a further study should be performed.

For having a clear idea of the inclination of the slope and the total dimensions of the

problem it was drawn a cross section showing the most critical slope situation.
The first uncertainty was to know the seafloor level at the base of the foundation. For doing that, in absence of the corresponding foundation drawing, after reviewing the CPTs, was assumed the proportional depth of the chalk where the foundation was resting.
The final section is shown in Figure 6.

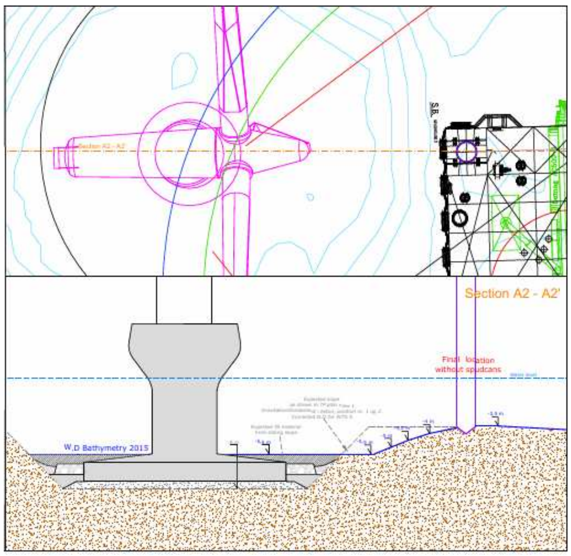

Figure 6 Schematic foundation section

5.3. Computational Finite Element Method (FEM)

The FEM have been used in geotechnical engineering for a large range of problems, both onshore and offshore. The large range of available FE software packages could confuse the user on its decision of which fits better the purpose. The increase in the efficiency of the hardware used for FE, has also augment the popularity of advance programs with a higher computational cost such as two-dimensional (2D) and three-dimensional (3D) Large Deformation FE (LDFE). For certain geotechnical processes which involve large displacements, new recent developments anticipate the combination of FE with other methods such as the Material Point Method (MPM) (Brinkgreve et al, 2015)

The use of FE together with conventional calculations gives a more accurate solution that is specially needed in critical multi-layered soil conditions with high risk of punch-through failure, where the peak bearing capacity prior to failure can be calculated and compare with conventional methods. However, when the soil conditions are favourable, there is no need to carry out other calculations than conventional.

In this case, to calculate the peak bearing capacity of each of the layers was not considered necessary. However, the risk for sliding and therefore how the soil would behave under such circumstances could not be dismissed. Doing a FE model of the situation would help to understand the behaviour of the soil stratigraphy.

5.4. The FE model – Plaxis 2D

The stability (risk for sliding) of the SB Leg towards the WTG is investigated by applying the FE with Plaxis 2D 2015.
It is used a plane strain model with 15-noded elements. The soil material models are based on Mohr-Coulomb following the low bound parameters as in Table 1.
The spud pile is simplified as a circular footing and the soil immediately in contact with the leg is removed from the sides to avoid soil failure problems with origin in the side friction, investigated in previous models.
The geometry of the problem was ready from the CAD section showed in Figure 6 Schematic foundation section; and therefore, imported to Plaxis.
Two FE analyses are carried out assuming SB Leg in-placed at two different depths. One placed on an initial depth of 1.0 m bsb (Figure 7) and another with full base contact at the very stiff to hard clay layer 2.2-4.5 m bsb (Figure 8).

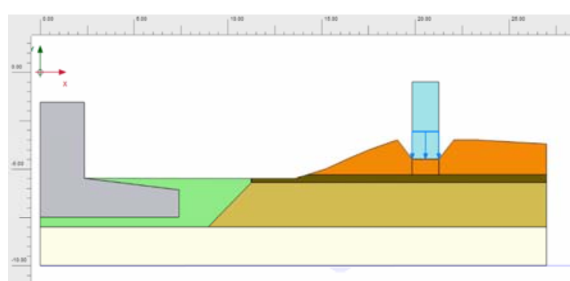

Figure 7 Plaxis geometry, model 1. Leg over first layer of soft to stiff clay.

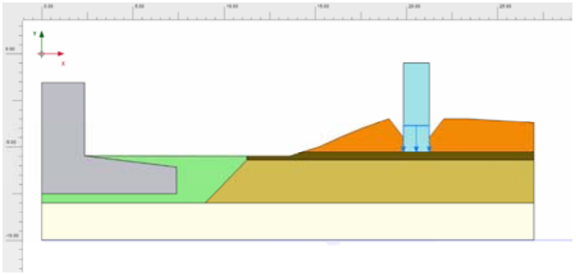

Figure 8 Plaxis geometry, model 2. Leg over second layer of stiff clay.

The first model assumed that after an initial penetration the spud pile would be into a soft to stiff layer of clay.

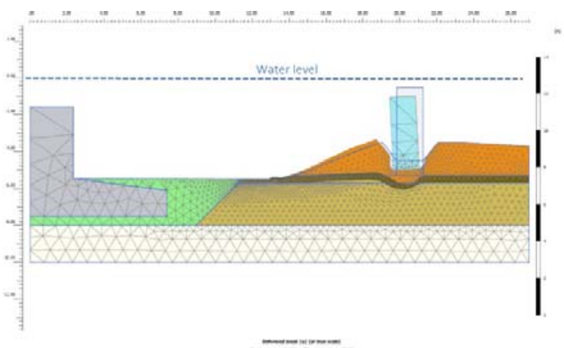

Figure 9 Model 1. Deformed mesh.

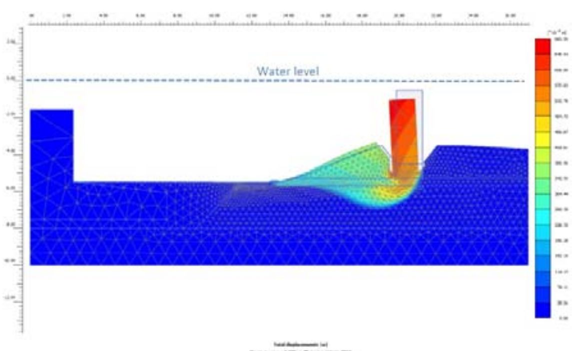

Figure 10 Model 1. Total displacements

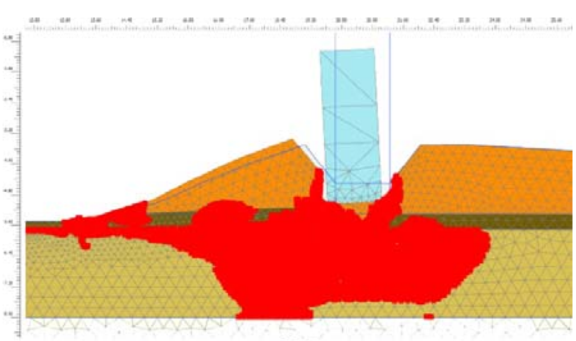

Figure 11 Model 1. Plastic Points

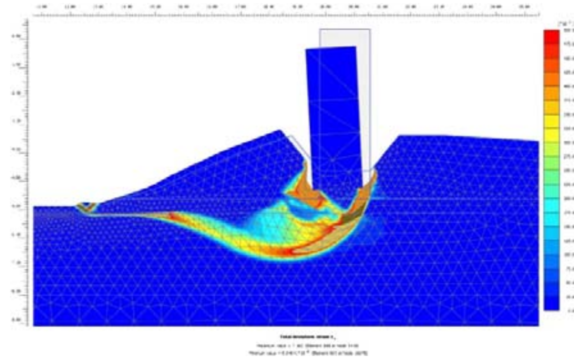

Figure 12 Model 1. Total deviatoric strains

Analysing the deformations, the total displacements showed how the leg could move towards the gravity base foundation and the failure figure goes towards the slope base (Figure 12). The results showed in (Figures 9-12) are for an approximate load equal to 94 tons/leg.

The second model aim to prove the reaction of the soil in a deeper state, which means in place in the stiff boundary layer that separates both softer layers.

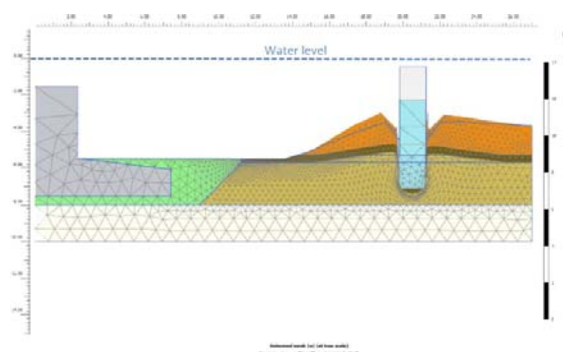

Figure 13 Model 2. Deformed mesh

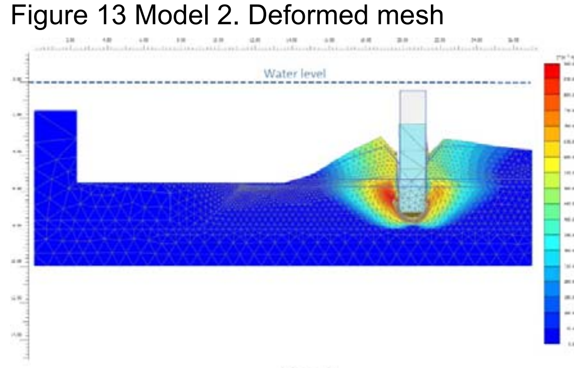

Figure 14 Model 2. Total displacements

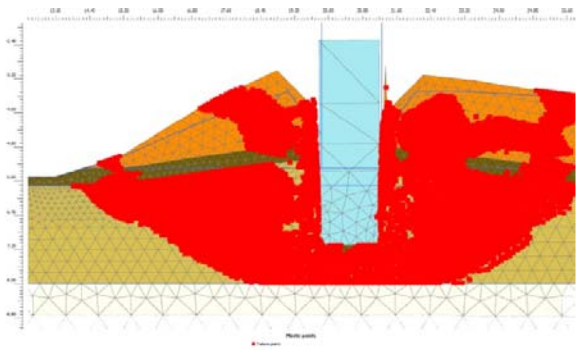

Figure 15 Model 2. Plastic points

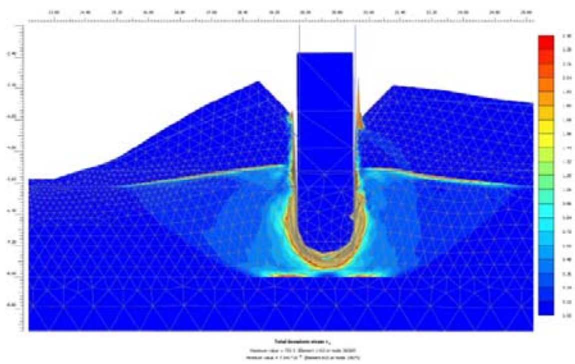

Figure 16 Model 2. Total deviatoric strains

In terms of deformations, both: total displacements (Figure 14) and total deviatoric strains (Figure 16) showed a more stable response with a further penetration affecting the soil below, as expected. The results showed in Figures 13-16 are for an approximate load equal to 144 tons/leg.

Based on these analyses, it can be concluded that there is risk for sliding of SB Leg until penetrations of approximately (2.5 - 4.0) m are reached. In order to avoid this, due to low level of applied loads, stomping of this leg was recommended, while monitoring the rack phase difference (RPD), until a vertical position is ensured while the leg reaches penetrations of (4.0 - 4.5) m. Further preloading after this achieved penetration depth is not expected to be associated with risk for sliding.

However, to increase the safety against sliding for SB Leg, it was recommended (if possible), the vessel could be slightly moved to the northeast, having SB Leg accommodated on virgin seabed, being further away from the slope.

6. BACK ANALYSIS OF MEASURED PENETRATIONS

After installation, corresponding feedback was received and implemented in order to check the results from the analysis.

The feedback received was 4.5 m for the maximum preload. The following description of the leg penetration was delivered by the towmaster: 'a meter of soft material followed by a stiffer material and having another penetration in softer material similar as the first one, until the maximum preload was reached'.

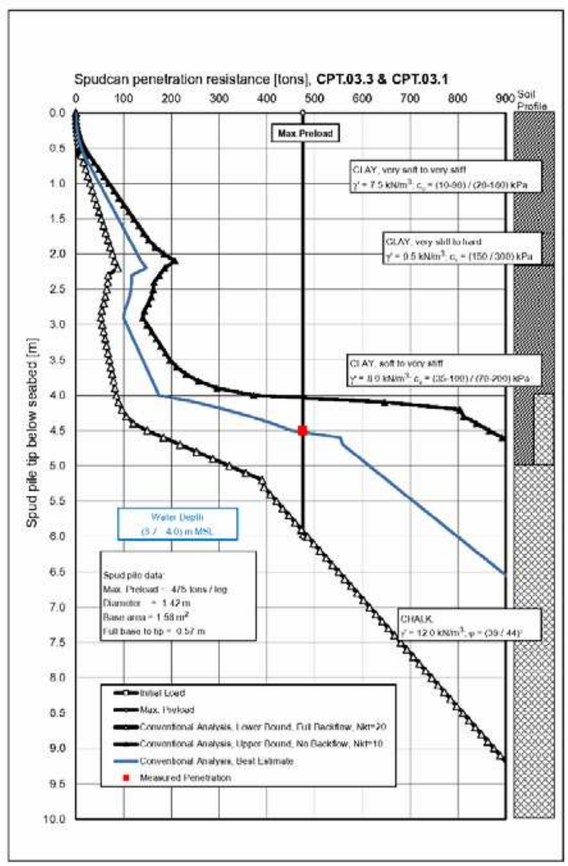

Figure 17 LPA – Back analysis from measured penetrations - Lower / Upper / Best Estimate

This description indicates that the first clay layer was shallower than expected and gives an idea of the variability of the stratigraphy within an area.

A best estimate (BE) curve has been traced averaging both upper / lower bound and adjusting the uncertainty related with the depth of the chalk.

7. CONCLUSIONS

After several attempts, a final vessel position was chosen, close enough to the WTG in order to make possible the maintenance work and taking into account the seabed conditions (slope) at the surrounding of WTG gravity foundation.

The current assessment covers many geotechnical engineering challenges, starting with the: interpretation of the soil data and correlation of in situ and laboratory test; leg penetration analysis for a generalized interpreted soil profile (representing the soil conditions at all four legs); FE calculations of the stability of SB Leg located near the sloping seabed at the vicinity of a gravity base foundation.

The vessel was installed without risk, taking into consideration the suggested conclusions such as monitoring of the RPD during penetration into the top clay layer.

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