SEABED REMEDIATION AVOIDING CRITICAL SPUDCAN-BOULDER INTERACTION DURING JACK-UP VESSEL INSTALLATIONS IN OFFSHORE WIND

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ABSTRACT

Jack-up vessels are often used for the installation of wind turbine generators (WTG), or their foundations etc., at different offshore wind farms (OWFs). In this framework, for a six-legged jack-up vessel, to be installed at a relatively small OWF, seabed survey, soil investigation and engineering are carried out. Due to hard seabed conditions and existence of a large number of boulders (at the seabed and subseabed) in the areas around the WTGs, the locations generally posed a significant risk for spudcan - boulders interaction during vessel installations. Considering the seabed soil conditions (interpreted from the boreholes (BHs) and laboratory tests), consisting of sand till layers with varying thickness, overlying limestone, after removing the large boulders, design and construction of the gravel pads (GPs), (covering the boulders at the spudcan locations), was carried out, remediating the seabed. Based on the spudcan dimensions and rectangular shape, the GPs were designed as truncated pyramids with height = 1.5 m and slope 1:2 for all 6 legs and all WTG locations and top dimensions (11.8 x 13.2) m and (9.8 x 11.2) m, respectively for outer and middle legs. The design was mainly based on Plaxis finite element (FE) 2D plane strain analyses documenting the integrity of the GPs for the preloading phase and elevated conditions.

KEY WORDS: Jack-up vessel, spudcan penetration, spudcan-boulder interaction, seabed remediation measures, gravel pads (GPs), conventional analysis, finite element (FE) analysis, etc.

INTRODUCTION

After seabed survey and seabed feature interpretations, showing a large number of boulders / stones with different sizes covering the seabed, (as the jack-up vessel was already chosen for the job), removal of relatively large boulders (with diameter larger than 0.5 m) was first carried out. However, the smaller boulders remained at the expected jack-up vessel locations next to the WTGs.

Under those circumstances, the problem during jack-up vessel installation and the proposed solution / design method (GPs) for solving it, are to some extent illustrated in Figure 1.

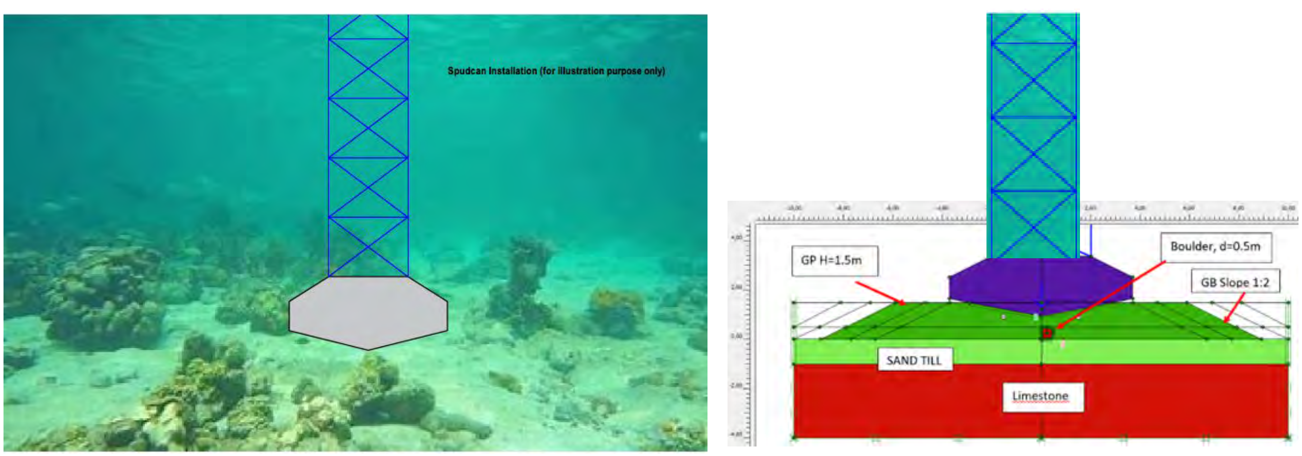


Figure 1 Photo of Boulders at the OWF Seabed (left) & GP Design, Plaxis FE 2D Model (right)

Considering the spudcan geometry, the preliminary analyses showed that the GPs should generally be minimum 1.5 m in height (with at least 1.0 m thickness above the highest point of the largest boulders) and have sufficient capacity to insure safe preloading and uniform spudcan penetrations and no spudcan rotation occurring. Six GPs were constructed for each pre-chosen jack-up vessel location, at each WTG location, respectively. After that, the jack-up vessel was generally successfully installed over the GPs, measuring mostly shallow and uniform spudcan penetrations at the majority of the WTGs. Conclusions and recommendations are drawn through the paper possibly useful for engineers and practitioners working in the wind industry and particularly dealing with jack-up vessel installations / operations in featured seabed.

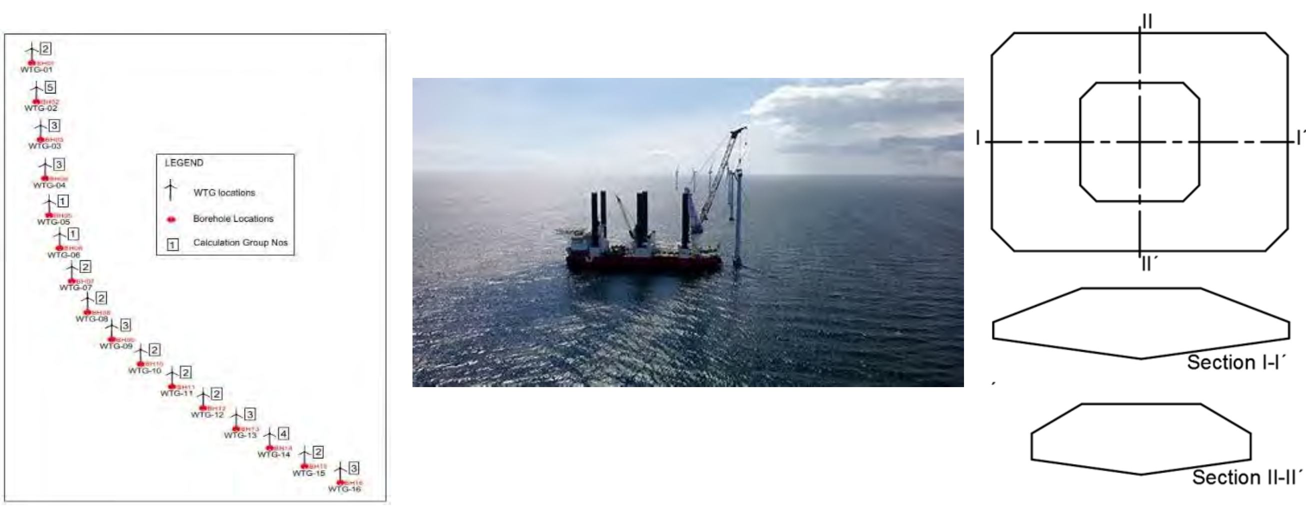
JACK-UP VESSEL CASE HISTORY

A case history related to a jack-up vessel installation (in hard seabed covered by boulders/stones) in the Baltic Sea is chosen and elaborated. Different challenges are encountered during jack-up vessel installations on a seabed consisting of very dense sand or hard clay where boulders pose a significant risk for spudcan-boulder interaction. The reason is that when the spudcans come in contact with the boulders overlying a hard strata, they can impart high concentrated loads on the spudcan underside, at the contact points with the boulders, possibly causing damages to the underside spudcan plates [1].

If the boulder are located over relatively soft seabed (firm / stiff clay), they can be pushed by the spudcans in the underlying soil, reducing the consequences of the spudcan-boulder interaction or making the interaction less critical. Alternatively, when applicable, removing the spudcans and using the jack-up legs directly on the seabed will reduce the contact area with the boulders probably solve the problem. However, the current jack-up was equipped with spudcans, hence, seabed remediation / GPs was found as the best way to solve the problem, as after the removal of the large boulder, smaller boulders (less than 0.5 m in diameter) were also evaluated to be critical, The details on the design methodology and result of analyses are given in the following sections.

OWF SITE & JACK-UP VESSEL, SPUDCAN GEOMETRY AND LOADS

The OWF layout is shown in Figure 2a**Error! Reference source not found.**.The jack-up vessel has six legs, each with a spudcan equipped with a trapezium shaped bottom plate. The distance between the centers of the legs is 32 m and 38 m in width and length, respectively. The spudcans are rectangular with dimensions 7.4 m x 10.0 m, with a bearing area of 74 m^2 per leg, resulting in an equivalent diameter of 9.7 m and tip to full base contact of 0.7 m as presented in Figure (2b & 2c). Based on the environmental load analyses, the required maximum preload to be applied during spudcan installation is calculated to about 5252 tons/leg.



(a) Location plan *(b) Jack-up vessel during WTG Installation* *(c) Spudcan geometry*

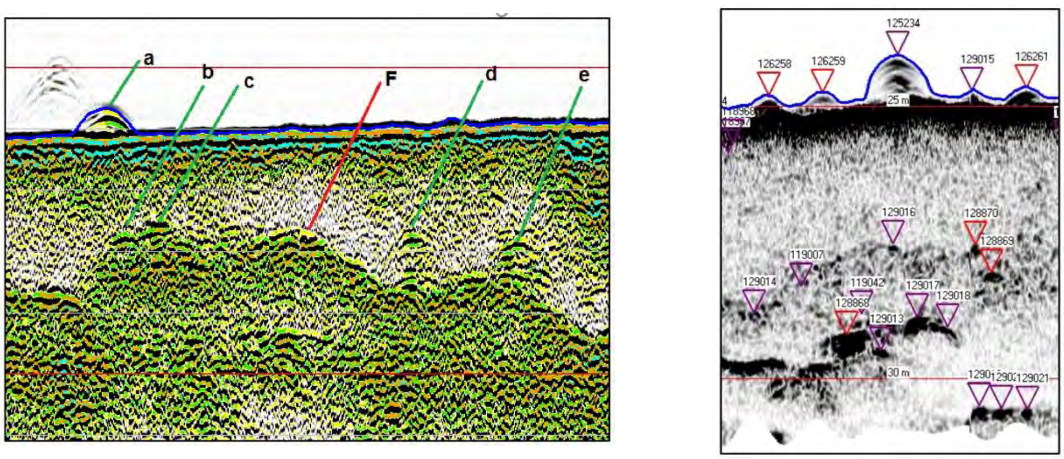
Figure 2 General WTG location plan, jack-up vessel & spudcan geometry

SEABED SURVEY - BOULDER DETECTION - GENERAL

High-resolution sides can sonar (SSS) is the preferred surveying tool to image and map seabed features such as boulders, pipelines, cables and other debris items. According to [2] & [3], the dimensions of each seabed feature can be estimated by analysing the size and form of the resulting shadow zone caused by each seabed feature on the SSS record, when knowing the position of the sonar towfish. Dimension estimation of seabed features are nowadays standardized and completely automated in most commercial SSS processing software and are a common practice when performing a site survey in the oil and gas, and wind industry.

Mapping sub seabed features is less common and more challenging. High frequency sub bottom profiling (SBP) surveying is often performed to record sub seabed 2D reflection seismic sections of the shallow soils (Figure 3a) On these seismic sections, boulders or other sub seabed features will be evident as hyperbolic reflections, where the top of the actual seabed feature is located at the focus of the hyperbole (Figure 3b).

Automated detection of sub seabed features from SBP records works by trying to identify these hyperbolas in the seismic sections and to quantify their semblance and power [4]. However, this type of software is only successful when the frequency of the seismic source signal is sufficiently high and the signal to noise ratio is satisfactory. Furthermore, in order to access the presence of sub seabed boulders with an acceptable degree of confidence, survey line spacing needs to be unrealistically close and the shot spacing must be less than the dimensions of the boulders. In addition, only the top of the sub seabed feature will be mapped, not the full extend of it.



a) Example of seismic boulder registration at seabed surface (a) and below seabed (b, c, d, e)

b) Example of validated boulder contacts in seismic power display (red and purple triangles)

Figure 3 Mapping of Sub Seabed Surface

The development of a new type of sub seabed imaging tool named SBI (PanGeo Subsea) renders the problems mentioned above. The SBI uses high frequency CHIRP transmitters (4 – 14) kHz) and 5 x 8 hydrophone arrays. This particular combination results in a high-resolution 3D cone image of the upper 5 m below seabed (bsb). Any sub seabed feature with a significant acoustic impedance contrast is easily detectable and will be imaged in its full extent. The SBI can be attached to a vessel by a trailing arm mount at shallow waters or on a ROV at greater water depth.

BATHYMETRY AND SEABED FEATURES

Site survey carried out by Geo, showed that the water depths around the OWF increases from approximately 8.0 m in the northern part to 27.0 m in the southern part. The water depth measurements are in mean sea level (MSL). The variation in the water depth given in Figure 4, indicates the seabed elevation changes within the area of interest.

The sloping seabed was not regarded to be an issue for jack-up installation due to the size of the spudcans relative to the OWF.

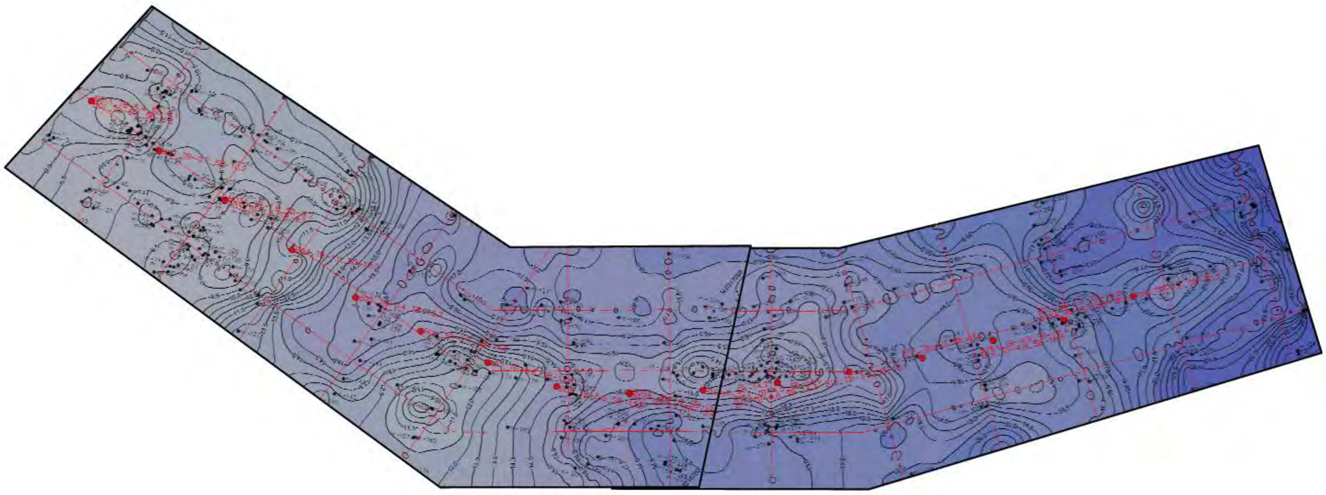


Figure 4: Bathymetry chart covering the area near WTG (01-16) and BH at these location

At the WTG locations, several jack-up positions were studied, due to the generally hard seabed surface and the presence of boulders. Attention is paid to the seabed feature charts and coordinates of the boulders while positioning the jack-up vessel. The positions of boulders (less than 0.5 m) are most accurate along the track plots shown in Figure 4, hence the vessel is positioned in alignment with the tracks plots, to the extent possible.

SOIL INVESTIGATION & GENERALIZED SOIL PROFILES

The available geotechnical investigation / location of the BHs at each WTG location, carried out by Geo, is shown in Figure 2a, It consisted of BH sampling, standard penetration tests (SPTs) and laboratory tests. Based on the BH logs interpretations and similarities, in order to optimize the calculations, all 16 WTG locations are organized into 5 groups. Each group has been assigned one representative generalized soil profile derived based on the BH logs as given in Figure 5.

TABLE 1 INTERPRETATION OF THE SOIL CONDITIONS WITHIN THE OWF

Soil Group Numbers	**BHs and Geological Descriptions**
Group 1	BH05 & BH06: The top 0.5 m Sand/Gravel Till is overlaying Limestone.
Group 2	BH01, BH07, BH08, BH10, BH11, BH12 & BH15: The top (3.3 - 6.4) m Sand Till (with some gravel) is overlying Limestone.
Group 3	BH03, BH04, BH09, BH13 & BH16: The top (1.4 - 4.4) m Sand/Clay Till is overlying Limestone.
Group 4	BH14: The top 2.0 m highly plastic clay is overlaying a 2.5 m thick layer of Sand/Clay Till, which is overlaying Limestone.
Group 5	BH02: The top 0.7 m multi-layered Silt, Gravel and Sand is overlaying Limestone.

It should be mentioned that the BHs are carried out at the WTG location. Hence, no BHs are available at the jack-up locations. Therefore, some soil variation was expected, particularly for the jack-up legs further away from the WTG / BH. A subsurface longitudinal section of the BHs with the group numbers is shown in Figure 5.

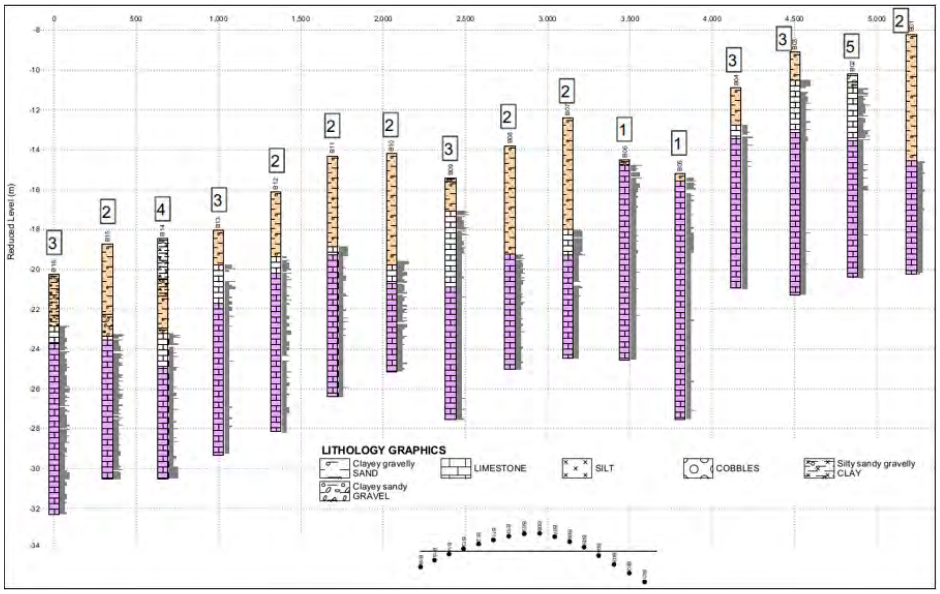


Figure 5: Available BHs with the Group Numbers

Based on the sample geological description and simple and advanced laboratory strength tests, high friction angles φ=>50 ° are assigned to the Sand / Gravel Till and high undrained shear strength c_u>=20 MPa to the Limestone. For the areas where shallow soft seabed / pocket of clays were found to be present, (not being able to be interpreted from the geophysical survey), c_u>=100 kPa was assigned to the plastic Clay Till.

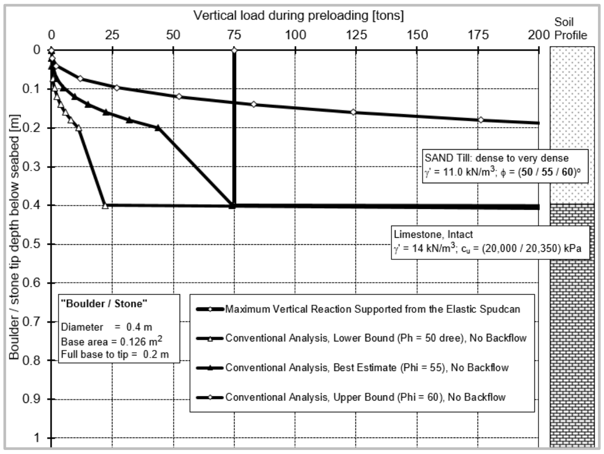
CONVENTIONAL ANALYSES FOR VIRGIN SEABED

The soil profiles at the OWF site, consisting of a sand layers with varying thickness, overlying the limestone, are applied in the conventional prediction for boulder penetration and spudcan penetration (virgin seabed). The reason for making penetration prediction for the boulder, (considering it as a small spudcan) is to estimate the load needed to push he boulder into the seabed, evaluating this way the possible boulder reaction force at the underside of the spudcan surface. Based on that, the risk for spudcan damage is assessed.

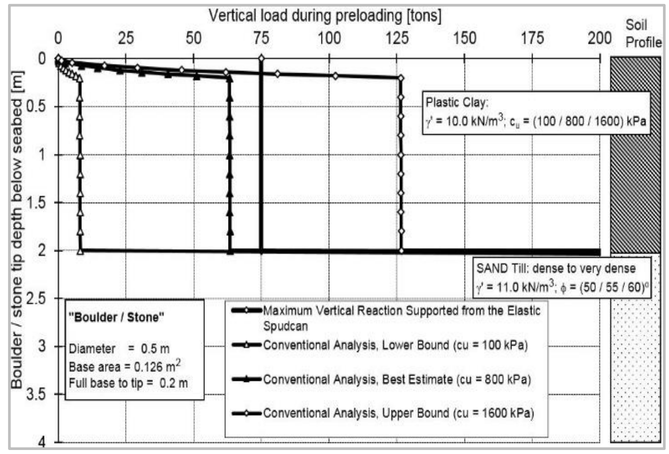
Considering the varying laboratory tests results, the strengths assigned to the sand, clay and limestone are assumed to be lower bound (LB) / best estimate (BE) / upper bound values as shown in the following conventional predictions and FE analyses. In general, the characteristic soil parameters are selected as a cautious estimate of the value affecting the occurrence of the relevant limit state [8].

Boulder penetration analyses are carried out for the boulders / stones assumed with a diameter of 0.4 m lying on the seabed at the WTG locations. For the penetration of the boulders with the considered size, the strength of the upper sand layer is decisive. Conventional bearing capacity analyses are often based on limit equilibrium methods, which is a state of equilibrium corresponding to a failure criterion that defines the strength of the soil. Failure is usually defined as a state when the strength is fully mobilized along the entire failure surface.

For the large values of the friction angles assigned to the seabed sand and assuming the boulder similar material as the limestone, the results of boulder penetration prediction for areas represented by Group (1,2 3 &,5) and Group 4 (representing the pocket areas with soft seabed), are given in Figure 6. The BE soil profiles corresponding to φ = 55° or c_u = 800 kPa are expected to result in 75 tons vertical reaction forces (within a small area corresponding to the boulder size) on the elastic steel spudcan (Figure 6). Any reaction force larger than 75 tons (like for UB soil parameters) was interpreted to be critical and deform / damage the bottom of the spudcan.



Boulder / Stone Analyses for Group (1, 2, 3 & 5)



Boulder / Stone Analyses for Group 4.

Figure 6: Boulder / Stone Tip Penetration Analyses for Virgin Seabed Conditions

The boulder penetration predictions were also confirmed by the site feedback as during jack-up installation attempts, for the applied maximum preload, no penetration where achieved what so ever for either spudcan or boulders / stones. As a result, cursed stones and a slight deformation in one of the leg was experienced. Therefore, the solution of designing / building GPs, covering the boulders with gravel with a minimum height above the seabed, one at each spudcan location respectively, was proposed as a way to avoid damage to the spudcans during vessel installation.

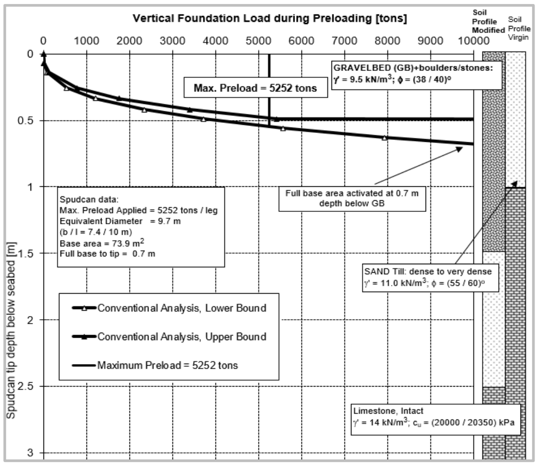
With the hard seabed, except the spudcan-boulder interaction issue, spudcan penetration predictions showed also limited penetrations. The penetration analyses follow the guidelines given in [5] & [6] (Same guidelines were also followed for boulder penetration predictions). The calculations are based on design soil parameters with partial coefficients, $\gamma_m = 1.0$. To define footing penetration versus load, assessment of the static bearing capacity of the spudcan at various depths is carried out. The bearing capacity is calculated based on [7] theory and Geo in-house program developed from the experience with spudcan penetration predictions. The spudcan is simplified to a circular footing having a flat bottom. The effect of the actual spudcan shape is taken into account. Squeezing of the clay layers (were present) during footing penetration is considered and implemented.

CONVENTIONAL & FE ANALYSES FOR REMEDIATED SEABED

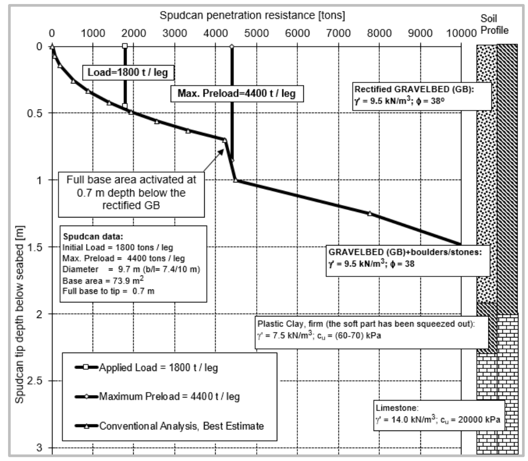
Based on the bearing capacity analyses for virgin seabed conditions, GPs are designed and constructed at each spudcan locations in order to avoid spudcan – boulder / stones interaction [9], [10], [11], [12], [13] & [14]. The following procedures is applied:

- Conventional calculation of the spudcan penetration, assuming a modified seabed by adding a sand layer of different thickness (consisting of GP material), allowing sufficient spudcan penetrations.
- Considering the bouldered seabed and boulder dimensions, predetermine the minimum height of the GPs, (to cover the boulders and allow sufficient spudcan penetrations) referring to the seabed level.
- Design the GPs based on Plaxis FE 2D plane strain analyses constructing spudcan-GP-boulder-soil model vertically loaded to maximum preload of 5252 tons/leg, determining the area at the top and the bottom (larger than the spudcan contact area at predicted penetration), insuring side pressure.
- Check spudcan capacity for preloading phase and operation phase for tolerances during vessel positioning at the center of the GPs and for (V-H) loads.
- Check spudcan sliding capacity for operation conditions and limited spudcan penetrations (less than full base contact.

For the seabed modified by adding an infinite layer of GP material with thickness 1.5 m (determined as minimum thickness, covering for the boulders and avoiding critical interaction of the spudcan with the boulder), and assuming LB / UB friction angle φ = (38 / 40)° for the gravel, spudcan penetration analyses for the different soil groups are shown in Figure 7.



Valid for Groups (1, 2, 3 & 5)



Valid for Groups 4

Figure 7: Leg Penetration Analyses for Modified Seabed Conditions for Groups (1, 2, 3, 5 & 4)

Design of GPs is carried out with Plaxis 2D [15]. Based on the interpreted BE soil profiles, FE analyses are conducted for all six legs designing the shapes of the GPs. Considering the rectangular shape of the spudcans, rectangular GPs are designed. Hence, 2D plane strain FE modelling is applied. As a critical scenario, a single boulder is assumed, placed within the GP, non-symmetrically to the spudcan.

In such modelling the GPs are simplified to truncated pyramids. Gravel & Sand are modelled as Mohr-Coulomb (MC) drained material and Limestone/clay as MC undrained (Tresca) material, utilizing effective unit weights for the soil layers. Mesh has been generated using 15-noded triangular FE and mesh sensitivity analyses conducted. The spudcan is modelled as a weightless elastic body. The boulder generally modelled with height / diameter 0.5m (in 2D plane strain corresponding to a cylinder) is modelled with the same parameters as of the limestone. The vertical and environmental loads are applied at the spudcan reaction point located at depth equal to half the spudcan penetration on top of GP.

The actual gravel material was expected to be loosely compacted, but relatively uniformly graded material. However, it consists of high strength particles meaning that the particle interlocking is not easy destroyed by crushing. Hence, the chosen strength (φ = (38 / 40)°) was considered realistic. The deformation module for the gravel was chosen E=35000 kPa.

The GPs is initially assumed infinitely extended (InfGP) with height H=1.5 m (ensuring at least 1.0 m thickness above the highest boulder top within the area) and based on the results, its horizontal dimensions are determined designing the (DesignGP).

DESIGN OF GPs FOR THE JACK-UP VESSEL OUTER LEGS

The calculations for InfGP (Figure 8) and DesignGP (Figure 9-12) are carried out as per following:

- Calculation of the initial soil stress conditions for virgin seabed.
- Construct GP with H=1.5 m and a boulder with diameter, d= (0.5 m & 1.0 m) placed non-symmetrically below in-placed spudcan at (0.55 m & 0.7 m) according to predicted penetration in Figure 7..
- After trying different scenarios, dimensions at the GP top are considered (11.8 x 13.2) m.

- In-place the spudcan on top of InfGP with tip at 0.55 m (Figures 8, 9, 10 & 11) & 0.7 m (Figure 12) depth below the top of the InfGP.
- Reset displacements to zero and apply the maximum preload (Table 2).
- Apply environmental loads (Table 2).
- Carry out the safety analyses and calculate the safety factor (SF) to assess the stability of the spudcan on top of the InfGP and DesignGP.

TABLE 2 CONSIDERED FOOTING REACTIONS

Loads Description	Vertical (V)	Horizontal (H)	Moment (M)
Units	[tones/leg]	[tones/leg]	[tones*m/leg]
Preload Reaction	5252	-	-
Environmental Loads	4726	141	-

RESULTS OF ANALYSES FOR JACK-UP VESSEL OUTER LEGS

Plaxis 2D plane strain analyses (small strain) are carried out first for vertical loading in order to confirm the ultimate vertical capacity for spudcan in-placed at (0.55 m & 0.7) m penetration. The results are given in Figure (8-12), where zoomed model, effective normal stress, vertical displacements (u_y), incremental displacement (Δu) & total deviatoric strain (γs), are shown.

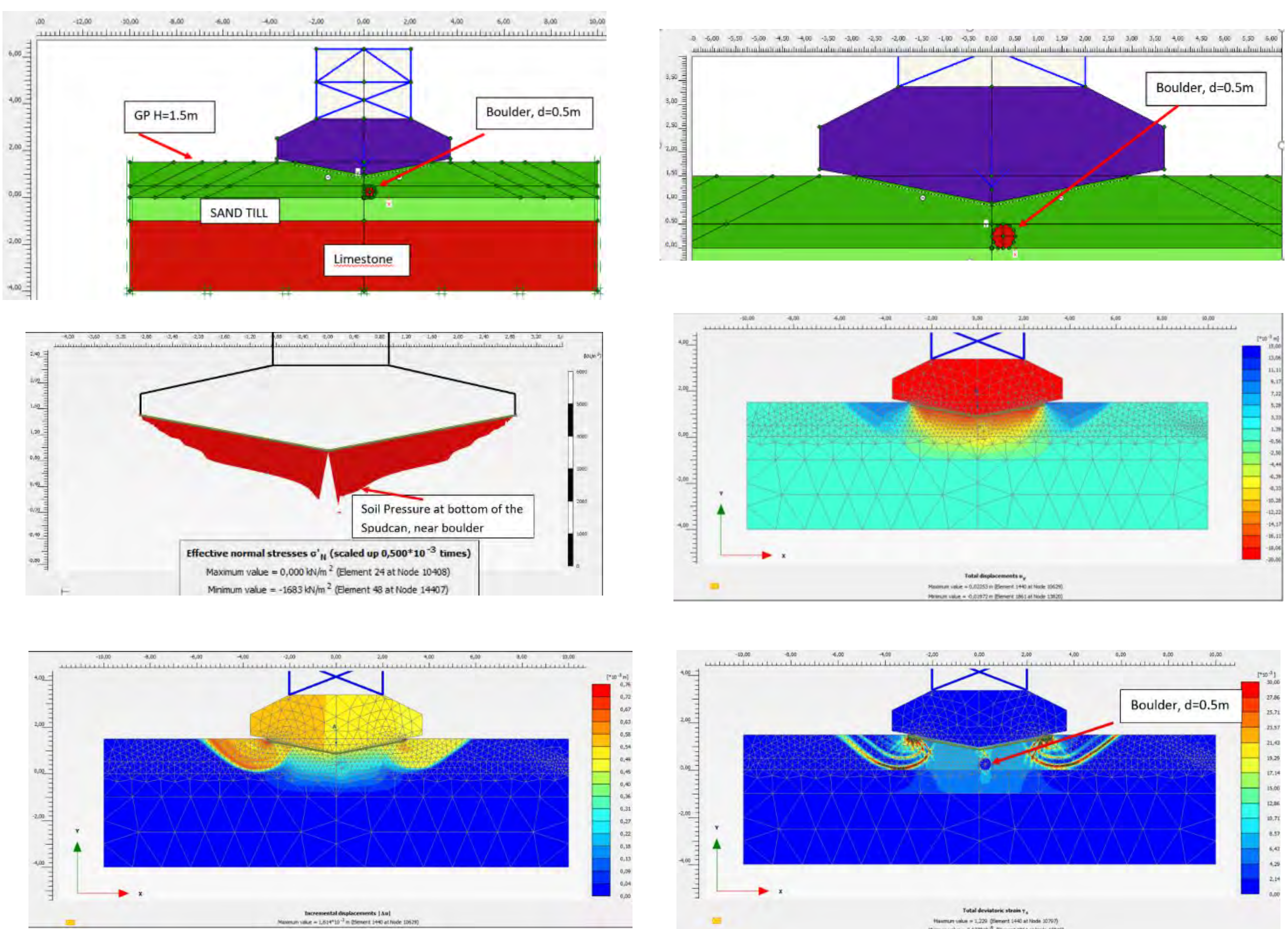


Figure 8 Plaxis FE Spudcan-InfGB-Boulder Interaction Models & Results for GP H=1.5m (Spudcan In-placed =0.55 m), Preload (V)=5252 tons/leg, GP Material, φ = 38°

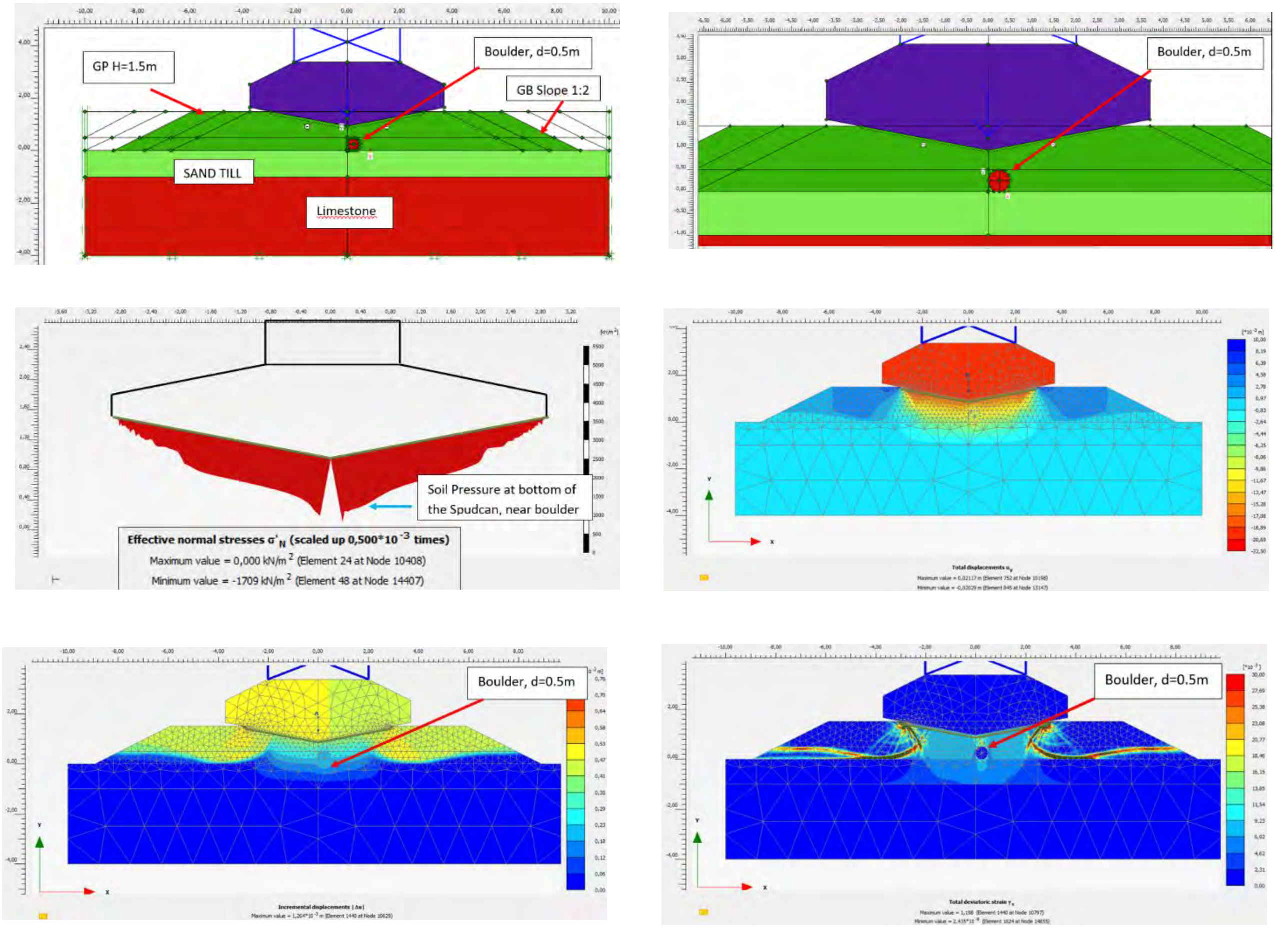
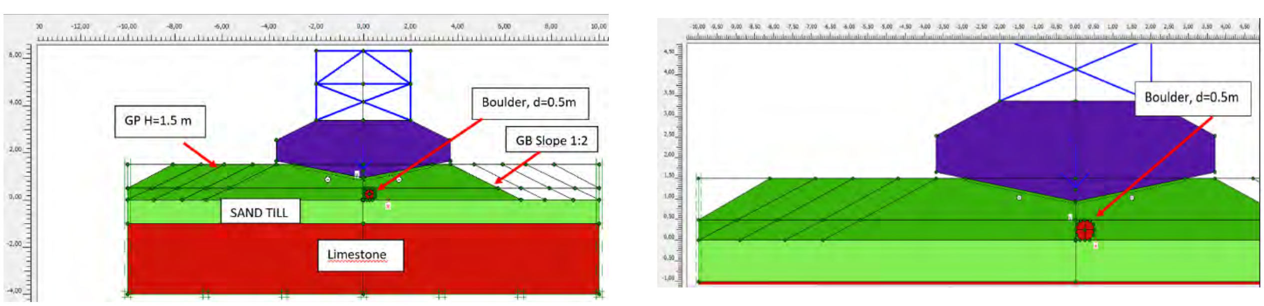


Figure 9 Plaxis FE Spudcan-DesignGB-Boulder Interaction Models & Results for GP H=1.5m (Spudcan In-placed =0.55 m), Spudcan tip 0.0 m from the DesignGP Central Line (CL), V=5252 tons/leg, GP Top Width = 11. 80m, GP Material, φ = 38°



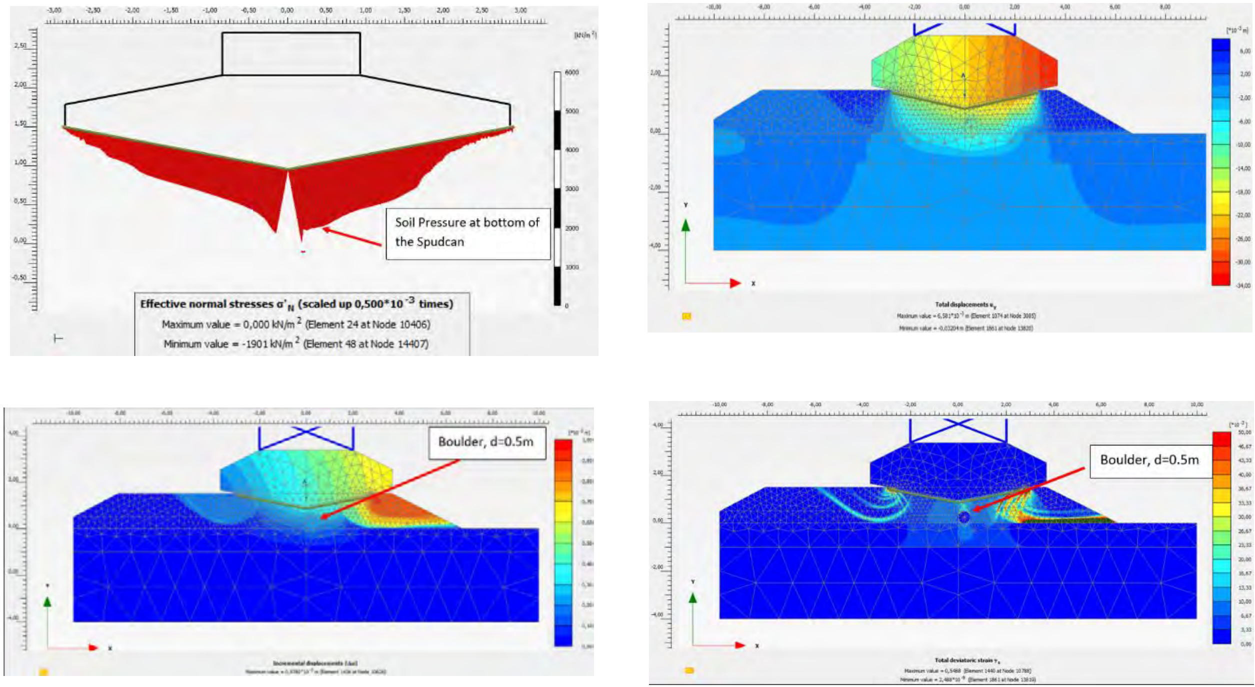


Figure 10 Plaxis FE Spudcan-DesignGB-Boulder Interaction Models & Results for GP H=1.5m (Spudcan In-placed =0.55 m), Spudcan tip 2.2 m from the DesignGP CL, V=5252 tons/leg, GP Top Width = 11. 80m, GP Material, φ = 38°

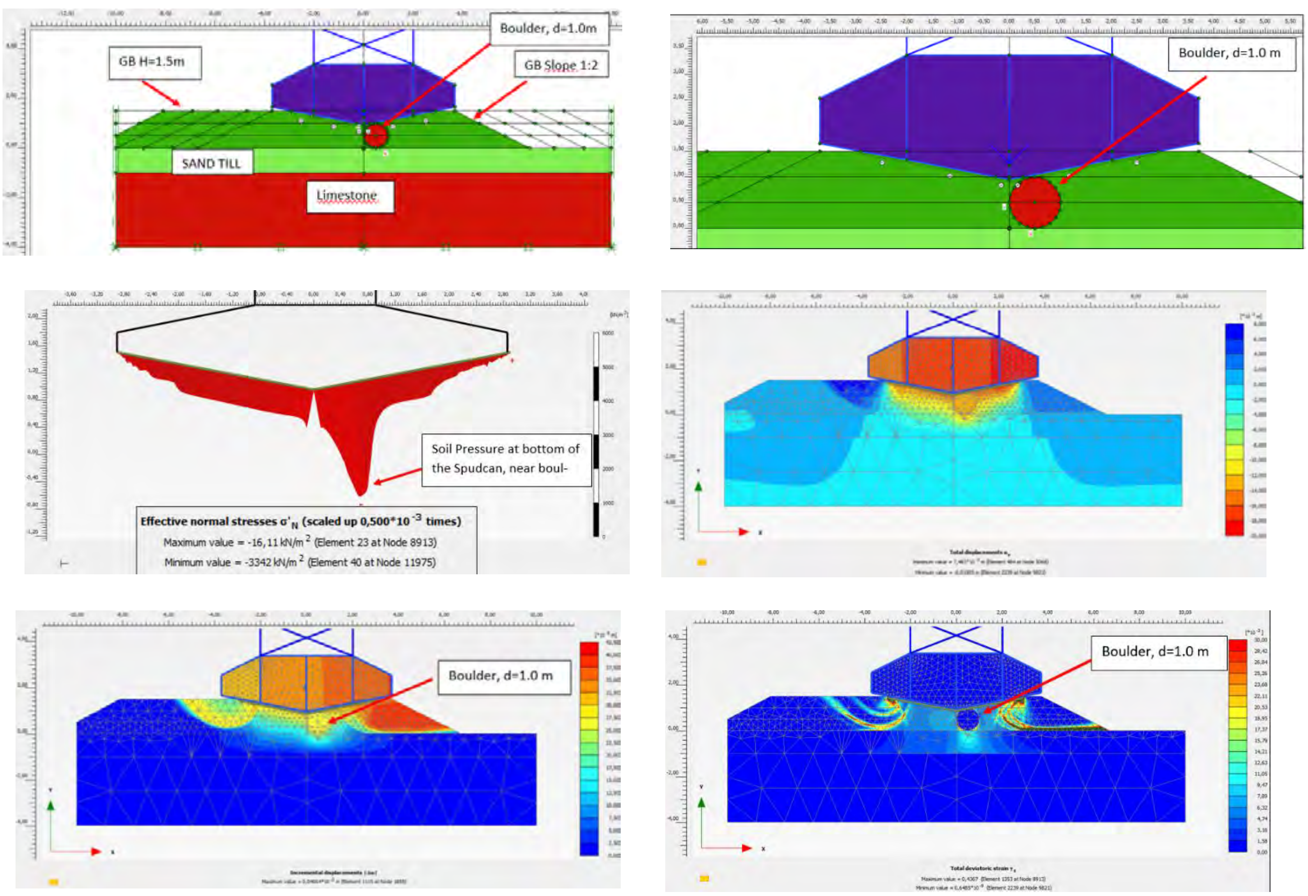


Figure 11 Plaxis FE Spudcan-DesignGB-Boulder Interaction Models & Results for GP H=1.5m (Spudcan In-placed =0.55 m), Spudcan tip 2.2 m from the DesignGP CL, V=5252 tons/leg, GP Top Width = 11. 80m, GP Material, φ = 38°, Boulder Dia.=1m

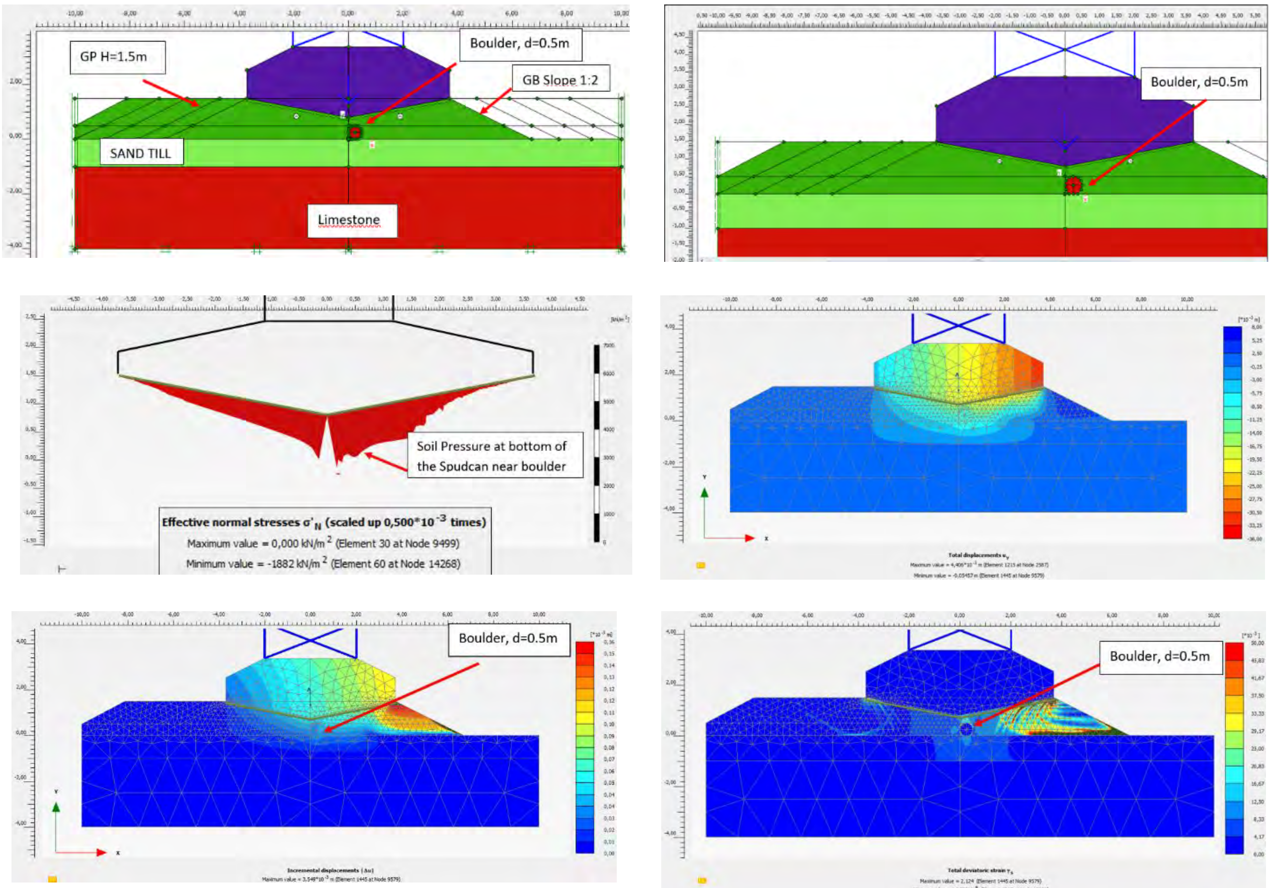


Figure 12 Plaxis FE Spudcan-DesignGB-Boulder Interaction Models & Results for GP H=1.5m (Spudcan In-placed =0.7 m), Spudcan tip 2.2 m CL, V=5252 tons/leg, GP Top Width = 11. 80m, GP Material, φ = 38°, Boulder Diameter=0.5m

The calculated safety factor in this case (and the allowable pressure on the spudcan underside) determines the height of the GP. The horizontal dimension (the top width) and the slope of the DesignGP (Figure 9 - 12) is confirmed based on the extension of the shear failure zone. Slope 1:2 is applied in the model and assumed to be the same in all DesignGP sides.

Based on the above results, the DesignGP is stable for the centred spudcan and for the non centered spudcan (up to edge to edge) (considering tolerances during jack-up installation) with spudcan in-placed at full base contact, 0.55 m or 0.7 m spudcan tip penetration.

From 2D plane strain modelling, a bottom pressure up to 1910 KPa is derived for the load conditions given in Table 2. The structural steel designer has consider the above pressure. An effort is made to model the spudcan with the bottom plates and brackets, considering the yield stress for the steel. However, 2D modeling of this is not found realistic. The derived the bottom pressure from the FE calculation for different scenario are summarized in the Table 3:

TABLE 3 MAXIMUM PRESSURE UNDER THE SPUDCAN BOTTOM PLATE

Shown in Figure	Preloading Max pressure under the spudcan (kPa)	(V-H) Max pressure under the spudcan (kPa)
8	1683	1641
9	1709	1710
10	1731	1721
11	1901	1892
12	1882	1906

The safety factor reduces from centred spudcan to non centered spudcan as shown in Figure 13.

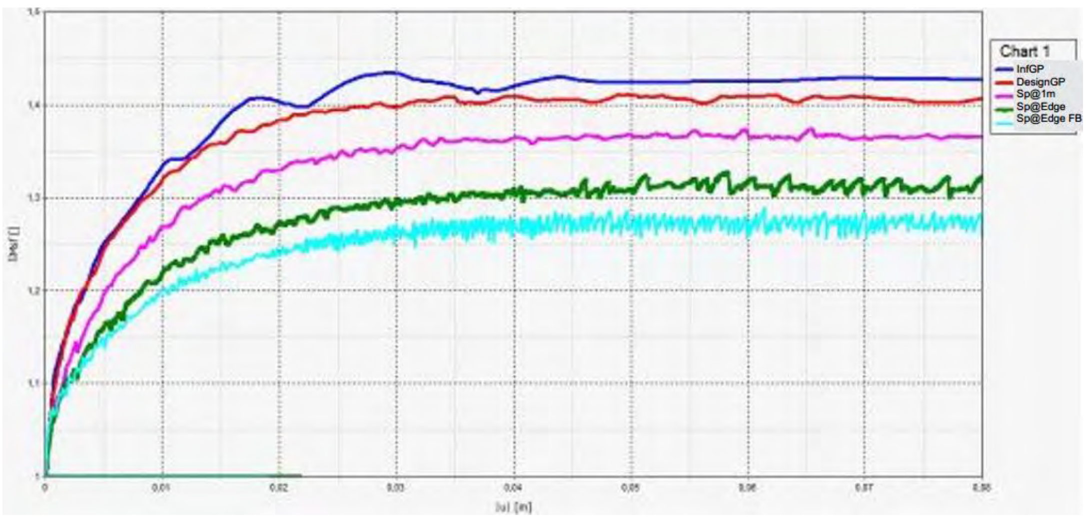
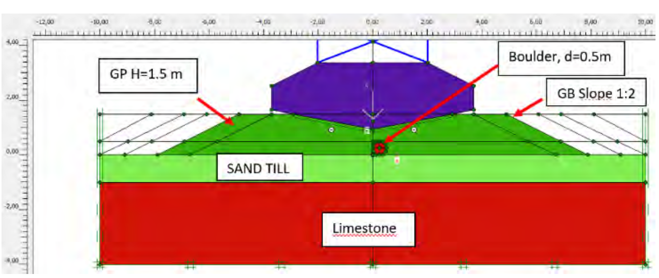
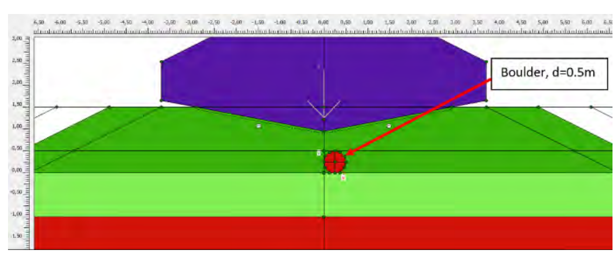


Figure 13: Safety Curves for centered spudcan and for the non-centered spudcan (up to edge-to edge)

RESULTS OF ANALYSES FOR JACK-UP VESSEL MIDDLE LEGS

Plaxis 2D plane strain analyses are carried out first for vertical loading for spudcan in-placed at 0.55 m penetration. Dimensions at the GP top are considered as (9.8 x 11.2) m. The results from Plaxis are given in Figure (14 & 15), where zoomed model, effective normal stress, vertical displacements (u_y), incremental displacement (Δu) & total deviatoric strain (γs), are shown.





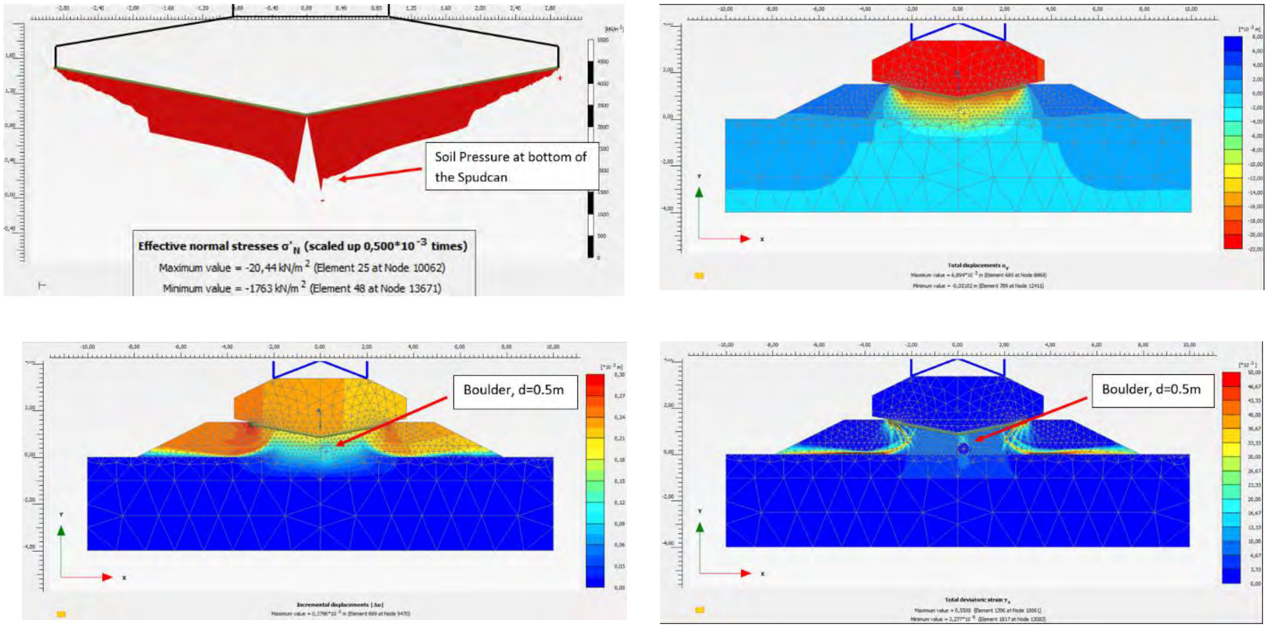


Figure 14 Plaxis FE Spudcan-DesignGB-Boulder Interaction Models & Results for GP H=1.5m (Spudcan In-placed =0.55 m), Spudcan tip 0.0 m from the DesignGP CL, V=5252 tons/leg, GP Top Width = 9.8m, GP Material, φ = 38°

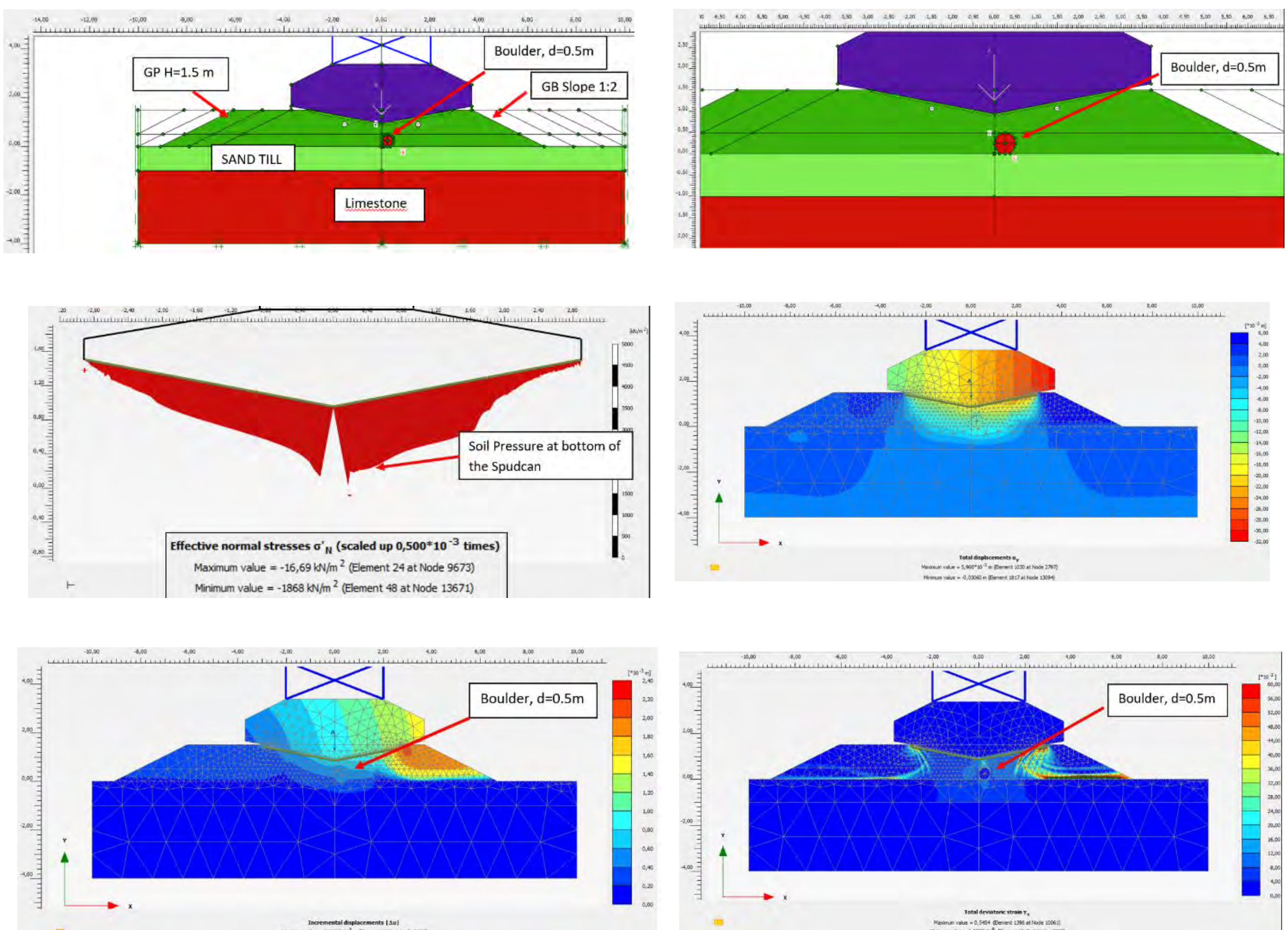


Figure 15 Plaxis FE Spudcan-DesignGB-Boulder Interaction Models & Results for GP H=1.5m (Spudcan In-placed =0.55 m), Spudcan tip 1.19 m from the DesignGP CL, V=5252 tons/leg, GP Top Width = 9.8m, GP Material, φ = 38°

SAFETY ANALYSES & RESULTS

For the loads given in Table 2, the safety factor for middle legs slightly decreased in comparison to the large GPs as shown in Figure 16 and the values are given in Table 4.

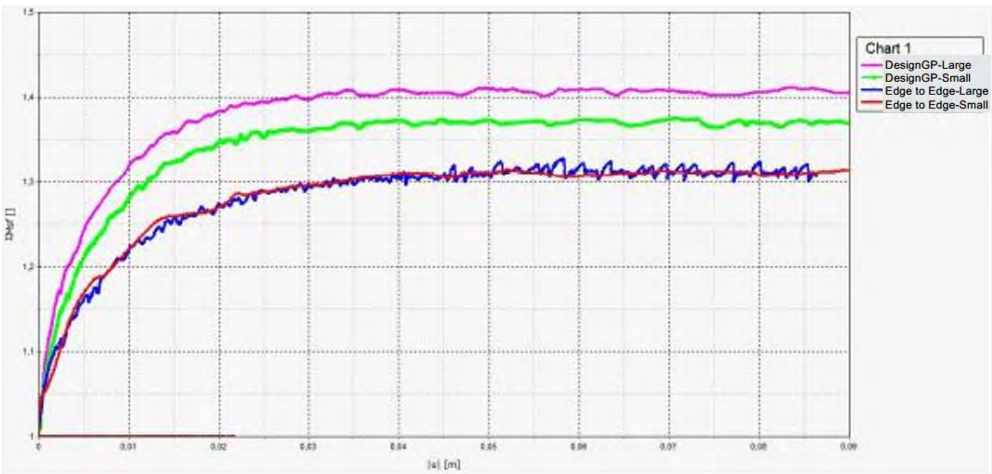


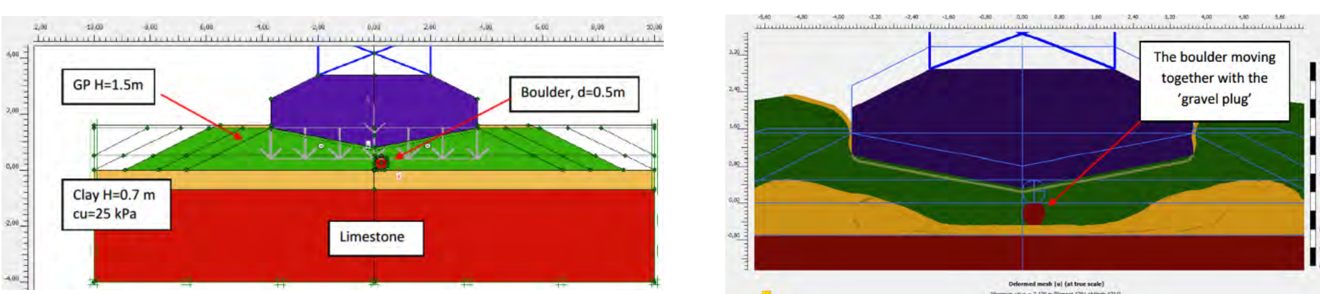
Figure 16 Safety Curves for Large (Outer Legs) and Small (Middle Legs) Designed GP

TABLE 4 CALCULATED SAFETY FACTORS

Design GPs	Safety Factor	
	Centred	Edge to edge
Large (Jack-up Outer Legs)	1.410	1.313
Small (Jack-up Middle Legs)	1.369	1.308

RESULT OF ANALYSES FOR SOFT SOIL CONDITIONS

Calculation and results for this scenario are shown in Figure 17.



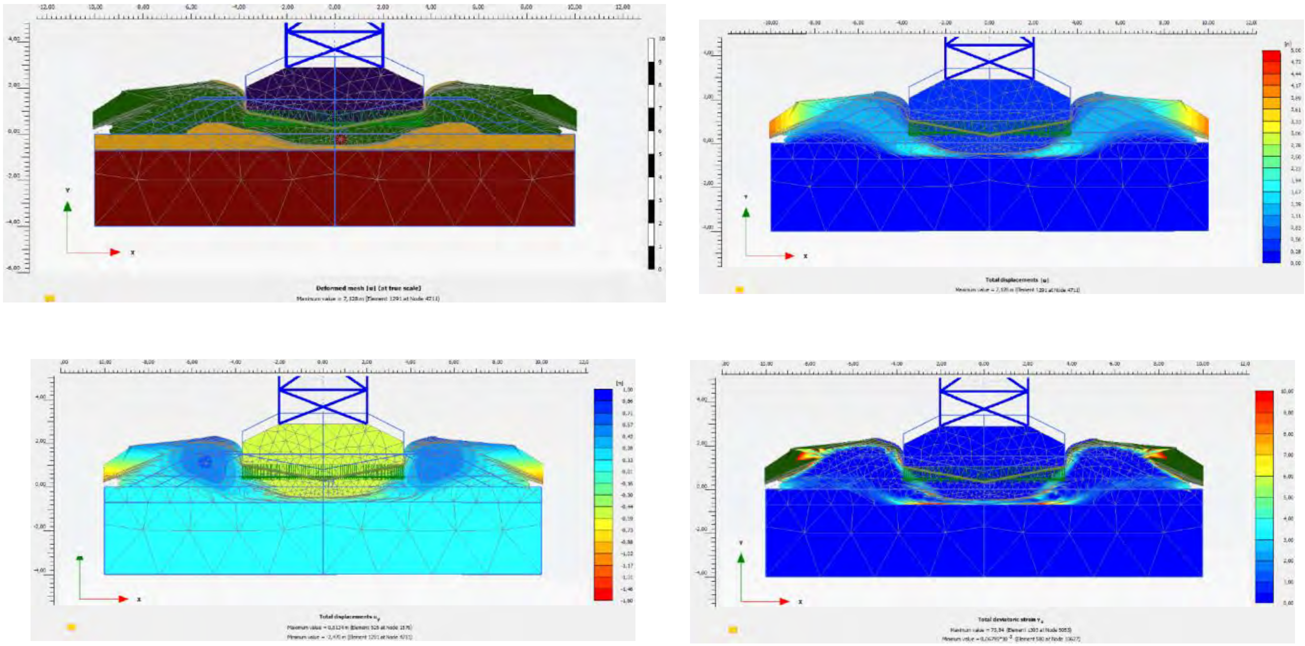


Figure 17 Plaxis FE Spudcan-DesignGB-Boulder Interaction Models & Results for GP H=1.5m (Spudcan In-placed =0.7 m), Spudcan tip 0.0 m from the DesignGP CL, V=5252 tons/leg, GP Top Width = 11.8m, GP Material, φ = 38°

REVIEW OF DESIGNED GPs AFTER CONSTRUCTION & JACK-UP OPERATIONS

Based on the current design, the GPs were constructed as shown in Figure 18, where the bathymetry from the post-survey (after the jack-up vessel has been installed, operated and left the location) is shown. The tolerances during GP construction (in the dimensions and flatness of the top surface) were discussed and agreed. They behaved as predicted showing their integrity during preloading and operation loads.

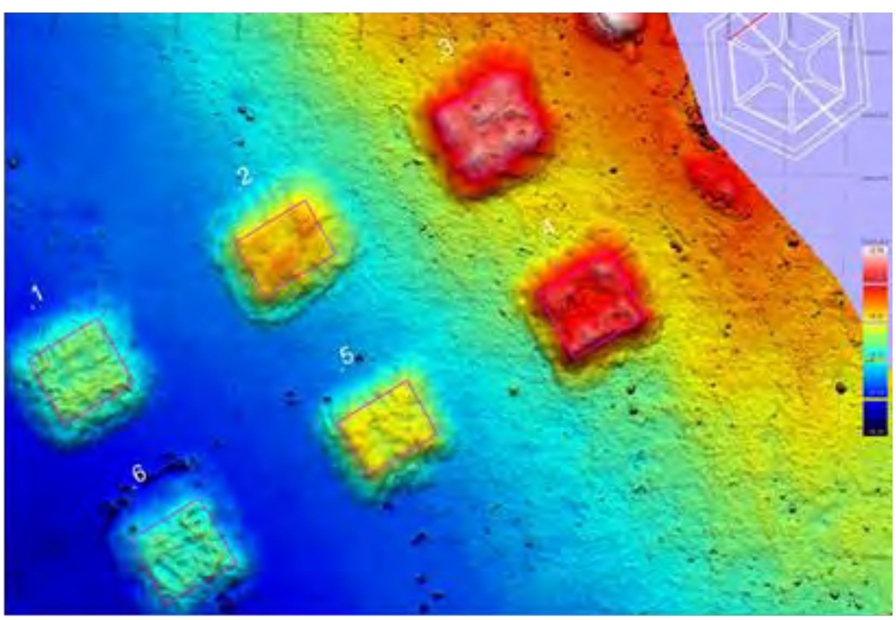


Figure 18: Bathymetry after construction of GPs and Jack-Up Operation

CONCLUSIONS AND RECCOMENDATIONS

A case history, of a jack-up vessel, installed at an OWF in the Baltic Sea, (for installing the WTGs), generally posing a significant risk for spudcan-boulders interaction during preloading, is presented. To monitor the risk, seabed remediation / GPs were constructed for each WTG chosen jack-up vessel location, consisting of six GPs, one for each spudcan leg, respectively.

The GPs, following the rectangular spudcan shape, are designed as truncated pyramids with height = 1.5 m and slope 1:2 for all six legs and top dimensions for outer and middle legs (11.8 x 13.2) m and (9.8 x 11.2) m, respectively. After the construction of the GPs, the jack-up vessel was successfully installed and the measured penetration data for each leg were received. The spudcans were preloaded to maximum preload, measuring penetrations as predicted (according to the interpreted soil conditions), and successfully operated in the elevated conditions, proving the integrity of the GPs for environmental loads.

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