DESIGN OF ‘HIGH & NARROW’ GRAVEL BANKS APPLICABLE TO SKIRTED SPUDCANS & JACK INSTALLATION CLOSE TO JACKET STRUCTURE

L. Kellezi* & H. Stadsgaard

Geo & Maersk Drilling, Copenhagen, Denmark

**corresponding author: Lindita Kellezi: LKE@geo.dk*

ABSTRACT

For Oil & Gas jack-up rig locations, preliminary assessed (for virgin seabed conditions), to be associated with risk for punch through / rapid penetrations during installation / preloading, gravel banks (GBs) are more and more been used as a way to mitigate the risks. The GB design methodologies are described and presented by the authors in previous works. However, through a recent jack-up case history, some new aspects are considered in this paper such as: Application of GBs for jack-ups with skirted spudcans (instead of conventional spudcans); Application of ‘high & narrow’ GBs, (as alternative to common GBs, which are designed to be ‘low & wide’), being more applicable for jack-up installations closer to Jacket Platforms. Advantages and disadvatages of such GBs for skirted spudcans, are elaborated, illustrated with the case history in the North Sea. Conclusions and recommendations are drawn through the paper on how to remediate the seabed when necessary, before the jack-up entry, possibly useful for engineers and practitioners working in Oil & Gas industry and particularly dealing with jack-up vessel installations / operations in areas with punch through / critical soil conditions.

KEY WORDS: Skirted spudcan; Conventional (limit equilibrium) analyses; Finite element analyses; Punch through risk; Gravel bank (GB) design; ‘High & narrow’ GB; ‘Low & wide’ GB; Spudcan-pile interaction;

INTRODUCTION

Jack-up rig locations, with virgin soil conditions consisting of a stronger layer overlying a weaker one (typically sand over clay), are generally associated with risks for punch through, For this reason, design and construction of GBs, has in some areas been used as a way to remediate the seabed and mitigate the punch through. The GB design methodologies are described and presented by the authors etc. in [6], [7], [10], [12]. However, some new aspects, shown also in Figure 1, are considered in this paper as listed below:

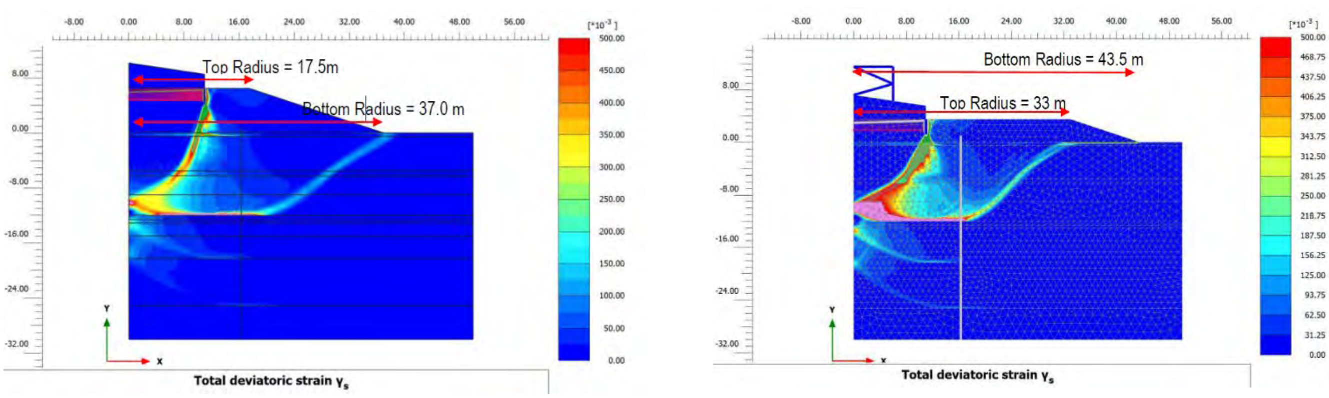

Figure 1 Remediated Seabed: ‘High & Narrow‘ (left) & ‘Low & Wide’ (right) GBs Plaxis FE 2D Axisymmetric Models

- Application of GBs for jack-up rigs with skirted spudcans, where the upper part of the GBs within the spudcan areas is ‘eaten’ by the spudcan outer skirts, almost disabling the entire GB top volume (to the skirt depth) in contributing to the underlying clay bearing capacity increase, through load spreading. In addition, the GB material has to be properly chosen in order to avoid any damages to the outer and inner skirts and ensure more or less skirted spudcan full base contact at the top of the GBs, producing sufficient moment capacity (fixity).

- Instead of common GBs, which are designed to be ‘low & wide’ as illustrated in Figure 1, right (in a way artificially increasing the thickness of seabed sand layer), in the form of trungated cones with top radius equal to 1.5*spudcan equivalent radius and heights comparable to spudcan outer skirt height, ‘high & narrow’ GBs (Figure 1, left) are presented, being more applicable for jack-ups closer to Jacket Platforms. The advantage of such GBs is that, they interact less with the Jacket foundations, as being concentrated around the jack-up aft legs. In addition, from the construction point of view, they are easier to be constructed as the amount of gravel needed to be dumped and shaped under the Jacket, is reduced. However, there are also disadvantages as related to larger material weight at and around the spudcans, opposing the positive effects of the GBs in increasing the spudcans bearing capacities.

JACK-UP INSTALLATION CASE HISTORY

As for the case history, for a jack-up rig with skirted spudcans, to be installed and operated at a location with about 70 m water depth in the North Sea, based on the available borehole / cone penetration tests (BH/CPTs) carried out at the site, the virgin soil conditions at the legs were interpreted. They consisted of medium dense sand to about 6 m below seabed (bsb), overlying firm to stiff clays to about 26 m bsb. Based on the interpreted soil profiles for each leg, conventional spudcan penetration analyses, correlated with Plaxis FE axisymmetric modelling with regard to peak bearing capacity to punch through, showed risk for punch through / rapid penetrations at all 3 legs for loads approaching maximum preloads.

To mitigate the punch through, ‘low and wide’ GBs were initially designed resulting in GB heights (2.5-3.5) m and top radius 33 m, slope 1:3. Due to jack-up rig position close to the Jacket, and as a result aft legs GB extension towards and under the Jacket, ‘high & narrow’ GBs were recommended and finally designed and constructed resulting in heights (5.0-7.0) m and top radius 17.5 m, slope 1:2. The advantages and disadvantages of both GB types are discussed and assessed conventionally and numerically, also with regard to operation loads and skirted spudcan-Jacket pile / pile group interaction. Finally, the ‘high & narrow’ GBs were constructed and the rig was successfully installed and not showing any critical impact on the jacket structure or its foundations.

JACK-UP RIG WITH SKIRTED SPUDCANS

The ultra-harsh environment jack-up rig, designed for year-round operation in the North Sea with skirted spudcans (Figure 2), is among world’s largest and most advanced drilling rigs at the time.

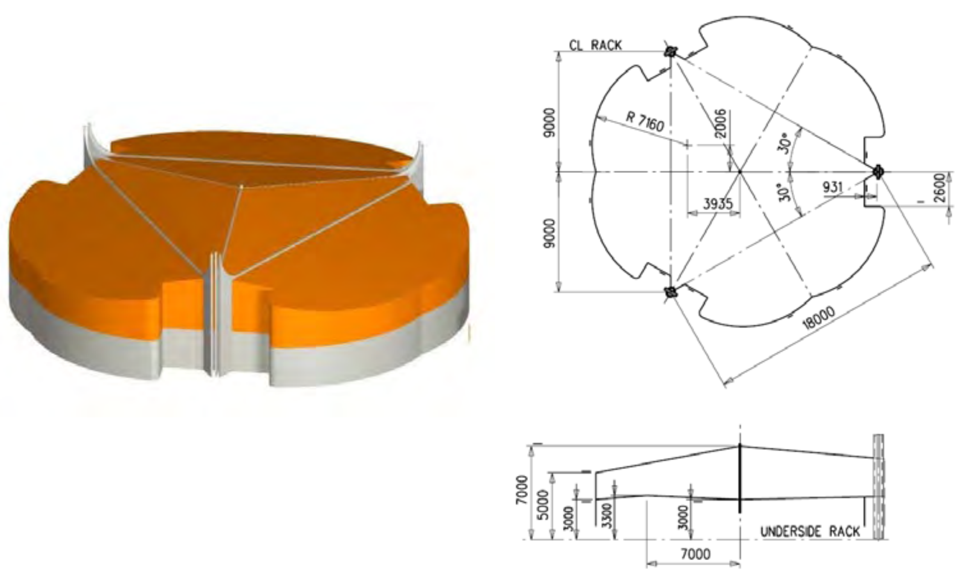

Figure 2 Skirted Spudcan View & Geometry

Jack-up rigs equipped with skirted spudcans, commonly used in the offshore industry have the benefits of: improvement of the foundation capacity by increasing the effective depth of the footing; improvement of the horizontal capacity by reducing the risk for sliding; improvement of the foundation fixity and provision of protection from scour when that is expected to be an issue. The benefits of skirted spudcans are mentioned in the current industry guidelines such as: [2], [3], [16].

The skirted spudcans shown in Figure 2 have an equivalent diameter of about 22 m and full contact area of about 380 m^2. The chord extensions continue to 3.3 m below the spudcan base, (which has spudcan tip to 0.3 m), while the outer skirts continue to 2.3 m and the inner skirts to 1.1 m, giving a total friction area of about 551 m^2.

OIL & GAS FIELD

A general location plan, showing the jack-up rig location and the three Jacket Platforms, used for Production, Drilling and Accommodation, respectively, including all the available BH/CPTs and the finally designed 'high & narrow' GBs, is given in Figure 3. Details on the design are given in the following sections.

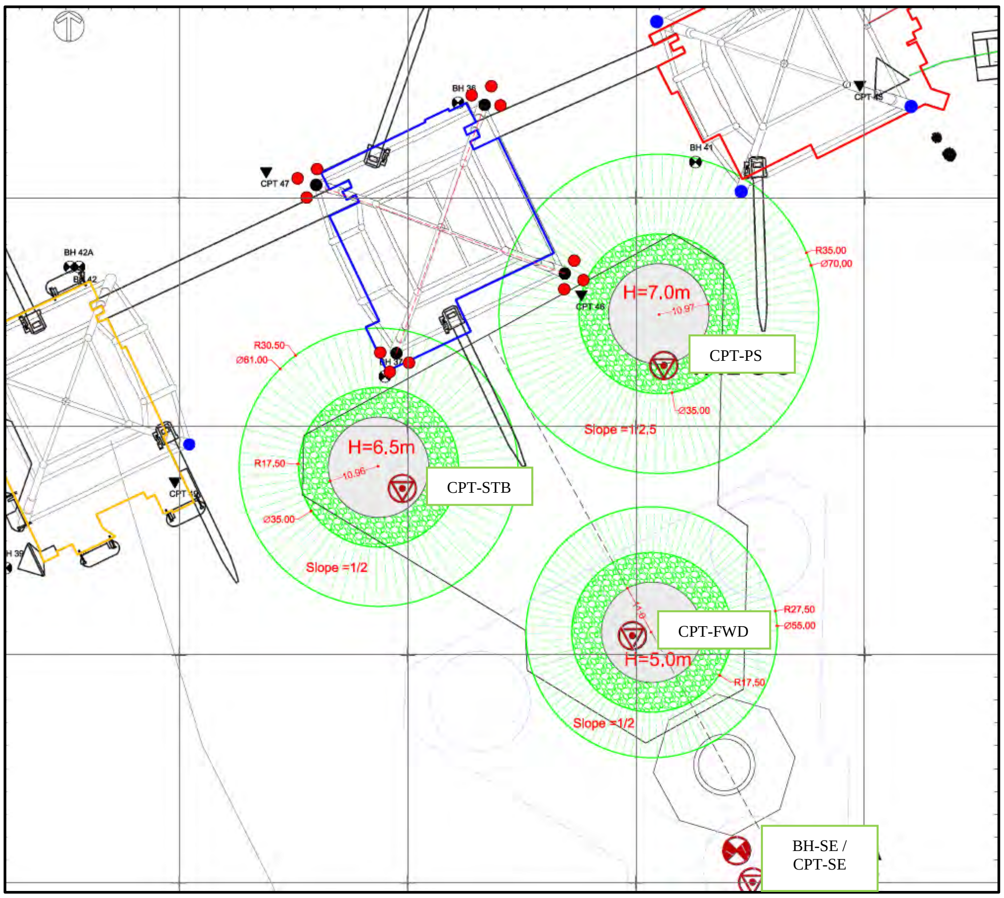

Figure 3. Location Plan - Final Design of GBs 'High & Narrow' (N_{kt}=26/29 & φ_{cs} [22])

SEABED / GEOPHYSICAL SURVEY

The water depth within the area is about 70 m mean sea level (MSL). Regarding the geological conditions at the site, a summary of the identified geological units and their corresponding depths interpreted from all the BH/CPTs shown in Figure 3, are given in Table 1. The interpretation considers also regional geological information in the North Sea. No geophysical / shallow seismic data have been applicable particularly for the current jack-up rig location, in order to correlate with the BH/CPTs, meaning that following [2] & [3], the BH/CPTs available at the leg locations, are assumed to represent the soil conditions within the skirted spudcan areas and vicinities.

TABLE 1 SUMMARY OF THE SHALLOW GEOLOGY INTERPRETED AT THE LOCATION

Soil Unit	Geological Formation	Base of the Unit Depth *[m bsb]*	Geological Description
I	Holocene	0.4 - 0.6	Loose to medium dense SAND
II	Forth Formation	5.0 - 6.3	Dense to very dense SAND
III (IIIa, IIIb, IIIc, IIId)	Coal Pit Formation	25.0 – 26.4	Medium strength to high strength slightly sandy CLAY (with very closely to widely spaced thin beds of clay at unit IIIc). At BH/CPT U-7 & 7A, unit IIIb has shown medium dense to very dense SAND
IV	Fisher Formation	End of BH/CPT	Extremely high strength CLAY with widely spaced medium to thick beds of sand

GEOTECHNICAL INVESTIGATION

Within the proposed rig area and surroundings, two main geotechnical site investigations are carried out during the years, providing soil information applicable to design of the jacket structures (1982) and recently, applicable to jack-up rig site assessments (2017). The recent site investigation consisted of four CPTs and one sampling BH (southeast (SE) of the rig location), to about 30 m bsb. The location of the CPTs at the spudcans areas and the BH/CPT SE, are shown in Figure 3.

Basic index laboratory tests were conducted on the selected samples in 2017, including also triaxial tests like; undrained unconsolidated (UU); anisotropically consolidated undrained tests in compression (CAUc) and isotropically consolidated undrained test in compression (CIUc);. However, the chosen location of the BH-SE was not considered proper especially when the CPT-SE (useful for a Standoff location) showed somewhat different soil conditions than the CPTs (CPT-STB, CPT-PS, CPT-FWD) at the Drilling location. In addition, no soil samples were taken in the sand layers. Hence, no triaxial tests were available to measure the friction angles.

The 1982 soil investigation consisted of ten CPTs and eight BHs, being six of them within a distance of (25-110) m away from the 2017 soil investigation (Figure 3). In general, the soil layering from the previous BH/CPTs is similar to the one interpreted from the recent investigation. The main difference is the inclusion of occasional fissures along with the high plasticity silty laminated clays below approximately 15 m depth, which were not identified in the 2017 survey.

INTERPRETED SOIL CONDITIONS AND DESIGN PROFILES

Based on the available soil data, lower bound (LB) and upper bound (UB) soil profiles applicable to skirted spudcan penetration analyses at the jack-up rig location, were assessed. Regarding the interpretation of the N_{kt} factor for clay soils, initially, N_{kt} = (15-20) was estimated (based on the CAU triaxial test), for deriving UB and LB undrained shear strengths (c_u) from the CPT (q_{net}) data.

However, considering all the laboratory tests (UU and CAU from 2017 & 1982 soil investigations) N_{kt} = (17-20-29) were then interpreted for UB, best estimate (BE) and LB clay strength parameters. Likelihood of the clay soil behaving with $N_{kt} > 20$ was found possible as the previous geotechnical investigation classified the main clay layer from (6.0-26) m bsb as occasionally fissured showing high plasticity behaviour. From recent experiences in the North Sea, high plasticity clays show tendency for larger N_{kt} values, applicable to deriving LB soil parameters.

After further investigations though it was noted that the main CLAY unit from (6-12/13) m, underlying the seabed sand, had lower plasticity, less notable fissuring, and tended to yield higher c_u values than the clay below. Therefore, a varying N_{kt} factor with depth was proposed and applied for deriving LB clay strength parameters being N_{kt}=26 for the upper CLAY (6-12/13) m and N_{kt}=29 for the CLAY below. The design soil profiles for the c_u are then chosen as characteristic LB, based on the interpretation from CPT data using N_{kt}=26/29. In absence of cyclic tests, this approach is also expected to cover for any cyclic degradation of the soil strength during jack-up operation under environmental loads.

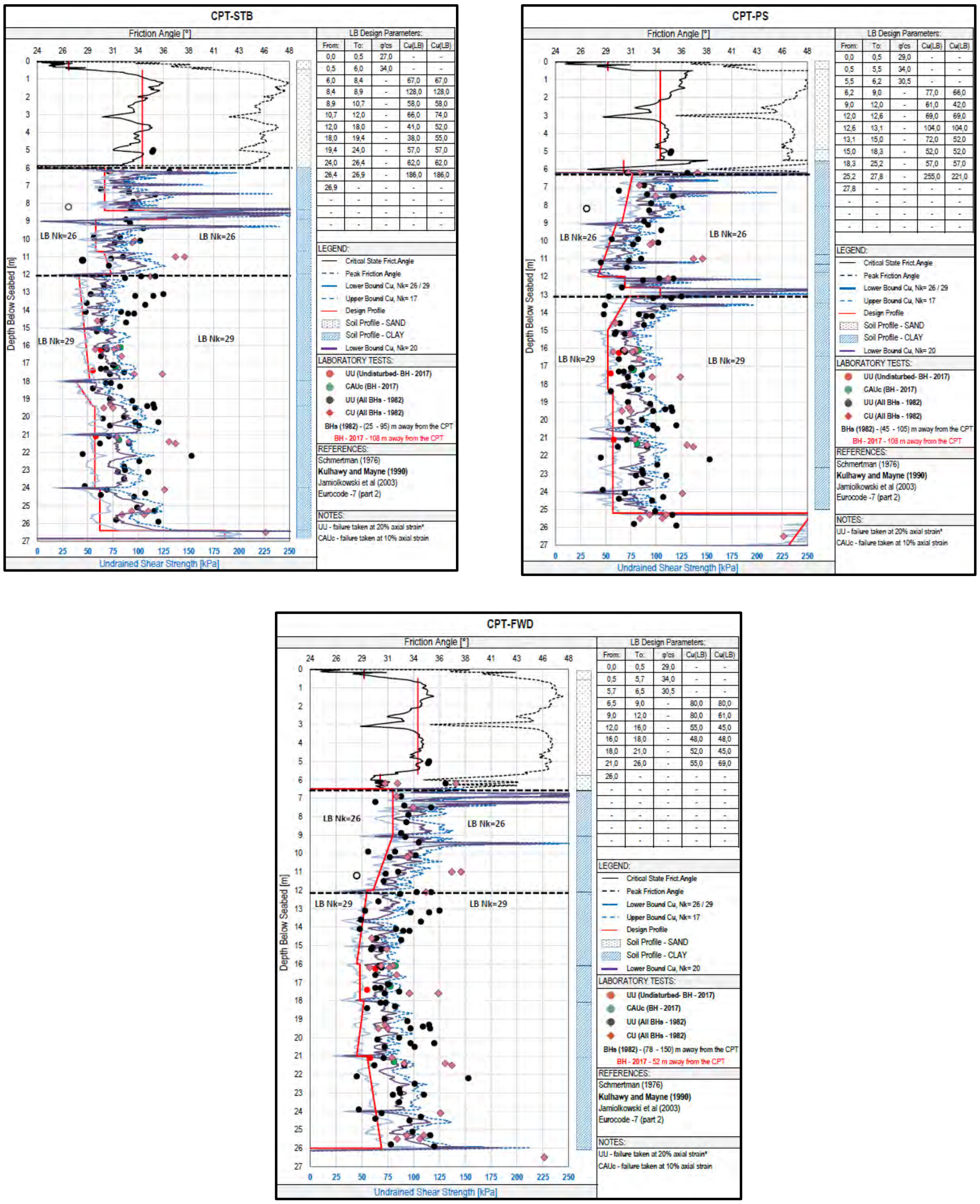

Figure 4 Interpreted Final Design Soil Profiles based on CPT and Laboratory Test Results (N_{kt}=26/29 & φ_{cs} [22])

Regarding the interpretation of the strength for the sand layer (from seabed to about 6.0 m bsb), considering lack of soil tests, the calculation of the friction angles (φ) has been based on the correlation with the CPT (q_c) data. [21] approach, (generally more conservative, giving lower values) is applied for the 'low & wide' GB design, while [22] approach, (which gives critical state friction angles φ_{cs} of about (3-4)° larger than the ones derived from [21], is applied for the 'high & narrow' GB design. For 'low and wide' GBs it is preferred to be more conservative with the assessment of the LB design φ than for 'higher & narrow' GBs. In conclusion, the LB design φ are generally based on the critical state values taking also into account the reduction for the footing size effect as recommended by [2] & [3].

In general, the UB / LB characteristic soil parameters are selected as a cautious estimate of the value affecting the occurrence of the relevant limit state [1]. The characteristic values from CPT data are chosen as best-fit lines (constant or through a linear regression) of the CPT, based on a cautious approach. Compared to the design profile of all triaxial laboratory tests, the design stands between -1 standard deviation (SD) from the average value (considered as constant strength) and a confidence interval of 10%. The final soil parameter interpretations at the spudcan locations are given in Figure 4 for each leg, respectively.

Applicable to FE analyses, the deformation parameters (E moduli) for sand are based on the CPT data using the correlation proposed by [23] and in absence of laboratory tests, for clays on strength assuming $E=300*c_u$.

SKIRTED SPUDCAN PENETRATION, CONVENTIONAL & FE ANALYSES

The conventional penetration analyses follow the guidelines given in [2], [3], [4], [5]-[14]. The calculations are based on design soil parameters with partial coefficients $\gamma_M = 1.0$. Penetration analyses are carried out considering virgin seabed and remediated seabed. The same soil parameters are applied in both cases, being able to assess the gained capacities after the construction of the GBs. Using critical state φ_{cs} for the sand layers and LB c_u, (derived initially by N_{kt}=29 and finally by (N_{kt}=26/29), for the clay layers), is considered equivalent to applying BE soil parameters reduced by material factors.

The penetration resistance of skirt elements is calculated as sum of tip and skin resistances applying the bearing and skin friction areas. Generally, conventional pile theory [15] is used for calculating skirt resistance during penetration in GB material (CPTs through GBs are generally not available). As an alternative to pile theory, the Most Probable (MP) and High Expected (HE) skirt resistances are generally calculated based on [16] employing the CPT (q_c) data with depth (generally applicable to virgin soil conditions). The UB prediction from [15], comply generally well with MP prediction from [16]. In addition, the experience from different jack-up installations with skirted spudcans in the North Sea has shown that MP skirt resistance is more realistic than HE resistance. Therefore, in the current assessments MP prediction is used as UB assessment.

FE modelling of skirted spudcan penetration is carried out with Plaxis FE software [17] as an alternative to conventional analyses for multi-layered soil conditions, in order to confirm the peak LB vertical bearing capacity to punch through / rapid penetration, (but not to produce the full penetration curve due to program limitations in large deformation analyses). FE analyses are also used for modelling of the GBs, based on predefined GB heights, slopes and horizontal dimensions, and considering the minimum capacities required during preloading.

Two-dimensional (2D) axisymmetric modelling of the skirted spudcan-soil interaction is carried out. Sand is modelled in drained and Clay in undrained conditions, both using Mohr-Coulomb constitutive models. In line with the conventional analyses, FE analyses utilize effective unit weights for the seabed soil layers. Mesh has been generated using 15-noded triangular finite elements. The skirted spudcan is modelled as a weightless elastic body and it is in-placed with full base contact at the seabed. FE results are considered applicable only to the depths where soil backflow / inflow is not expected to affect the results.

Plaxis Plastic analyses (small deformation theory) are carried out, not taking into account the influence of the geometry change, during penetration, on the equilibrium conditions, being on the safe side. Plaxis Updated Mesh (UM) analyses (large deformation theory) are also performed, generally giving larger vertical capacities. Plastic analyses are used to derive / confirm realistic conventional predictions.

As the achieved peak bearing capacities to punch through on virgin seabed, for LB soil conditions, were not enough to satisfy the required preload, seabed remediation measures / GBs were designed as per below.

INITIAL RESULTS OF ANALYSES – VIRGIN & REMEDIATED SEABED

Generally, the results from conventional and Plaxis FE 2D axisymmetric penetration analyses for virgin seabed showed deep chord penetrations ((21-23) m), with risk for punch-through (P-TH) / rapid penetration, for LB soil conditions interpreted for N_{kt}=29.

Initial 'low & wide' GBs: Considering risk for punch through, initially 'low & wide' GBs were designed based on the same LB strength soil parameters (N_{kt}=29 for clays & critical state φ_{cs} based on [21] for sands). The results of the analyses, with regard to peak bearing capacities to punch through, GB dimensions and FE models, plus failure figures, are summarized in Table 2, and shown in Figure 5 & 6.

TABLE 2 SUMMARY OF RESULTS FOR VIRGIN SEABED & INITIAL 'LOW & WIDE' GBs

CPT-Leg	Virgin Seabed Conventional & FE	Design of 'Low & Wide' GBs FE & Conventional Analyses				
	Peak Capacities to P-Th	Peak Capacities to P-Th	GB Height	Top Radius	Bottom Radius	Slope
	LB (N_{kt}=29 & φ_{cs} [21]					
	[tons/leg]	[tons/leg]	[m]	[m]	[m]	[-]
CPT-STB	15400	**19100**	**3.50**	**33.0**	**43.5**	**1:3**
CPT-PS	15220	**19200**	**3.50**	**33.0**	**43.5**	**1:3**
CPT-FWD	17090	**19280**	**2.75**	**33.0**	**41.3**	**1:3**

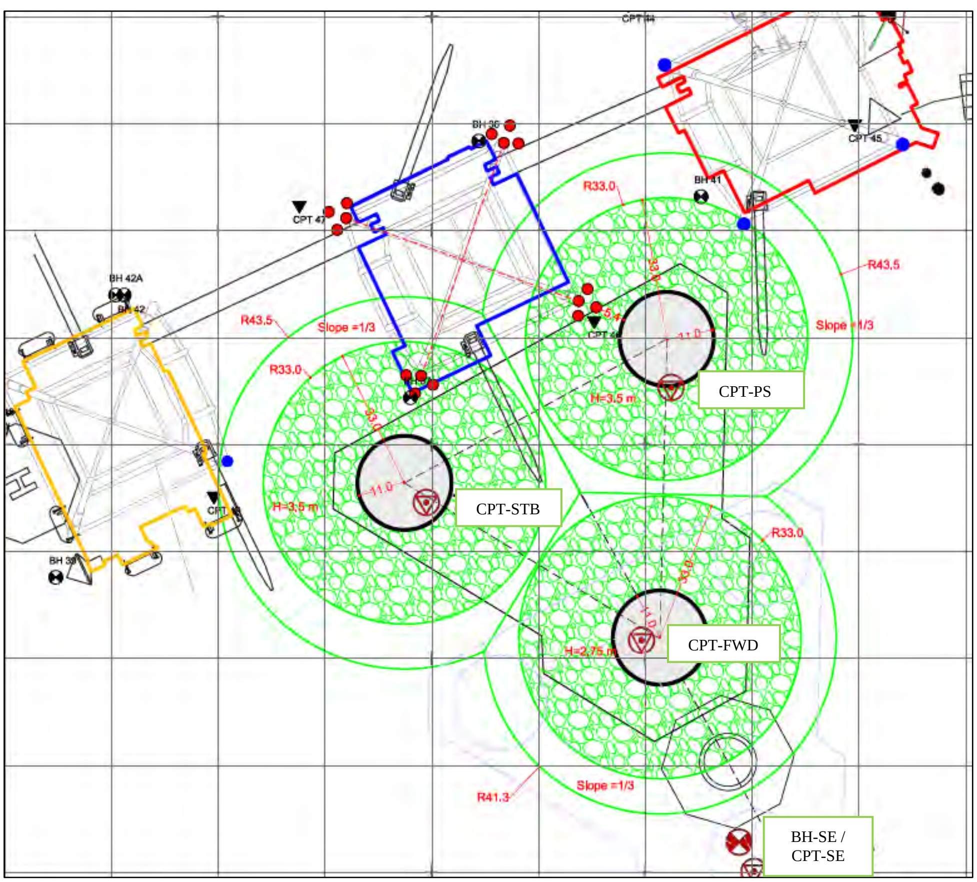

Figure 5. Location Plan - Initial Design of GBs 'Low & Wide' (N_{kt}=29 & φ_{cs} [21])

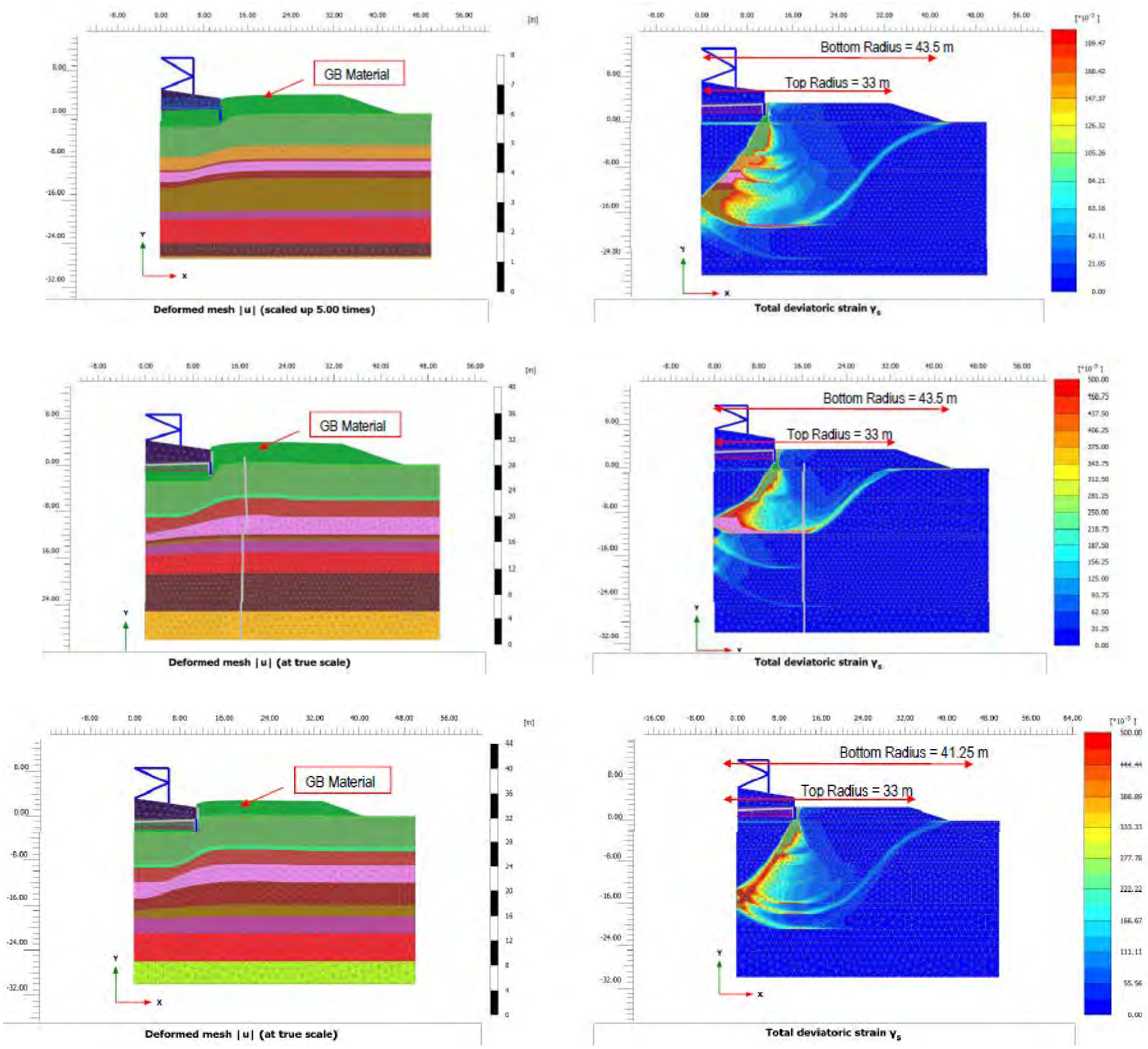

Figure 6 Plaxis FE 2D Axisymmetric Initial Design of GBs 'Low & Wide' (N_{kt}=29 & φ_{cs} [21])

Initial 'high & narrow' GBs: However, due to proximity to the Jacket Platform, in order to reduce the impact on the Jacket piles and make possible the construction of the GBs at the Aft Legs, (the part extended towards/under the Jacket structure) another approach was needed, hence, 'high & narrow' GBs were also initially designed. Due to the shape of the GBs, (concentrated at the spudcan areas and near surroundings, and not approaching an artificial increase in the thickness of the seabed sand layer), the design was mainly based on Plaxis FE 2D axisymmetric modelling.

LB strength soil parameters were applied derived for N_{kt}=29 for clays & critical state φ_{cs} for sands, calculated based on [22] approach (giving larger critical state φ_{cs} than [21], considered to be a better approch for deeper sands), optimizing on the heights of the GBs. The results of the analyses, with regard to peak bearing capacities to punch through, GB dimensions and FE models, plus failure figures, are summarized in Table 3, and shown in Figure 7 & 8.

TABLE 3 SUMMARY OF RESULTS FOR VIRGIN SEABED & INITIAL 'HIGH & NARROW' GBs

CPT- Leg	Virgin Seabed Conventional & FE	Design of 'High & Narrow' GBs FE & Conventional Analyses				
	Peak Capacities to P-Th	Peak Capacities to P-Th	GB Height	Top Radius	Bottom Radius	Slope
	LB (N_{kt}=29 & φ_{cs} [22])					
	[tons/leg]	[tons/leg]	[m]	[m]	[m]	[-]
CPT-STB	16500	**21280**	**6.5**	**17.5**	**37**	**1:3**
CPT-PS	15900	**21220**	**6.5**	**17.5**	**37**	**1:3**
CPT-FWD	18100	**21310**	**5.0**	**17.5**	**32.5**	**1:3**

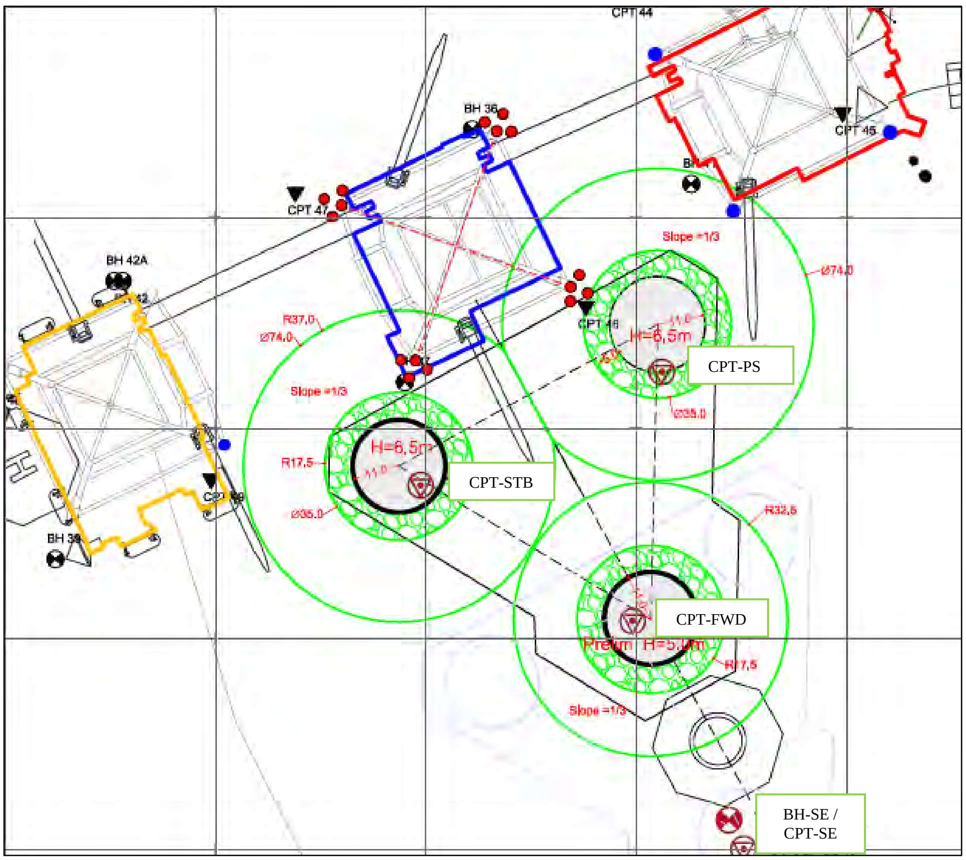

Figure 7. Location Plan - Initial Design of GBs 'High & Narrow' (N_{kt}=29 & φ_{cs} [22])

FINAL RESULTS OF ANALYSES - VIRGIN & REMEDIATED SEABED

Final 'high & narrow' GBs: The final design of the GBs is carried out based on Plaxis FE 2D axisymmetric modelling applying the final soil strength / profile interpretations given in Figure 4, respectively for each leg, corresponding to N_{kt}=26/29 for clays and φ_{cs} [22] for sands. The soil layering and parameters for each layer are also given in the tables in Figure 4. The results of the analyses, with regard to peak bearing capacities to punch through, GB dimensions, FE & adjusted conventional skirted spudcan penetration curves for virgina and remediated seabed, and FE models / failure figures for virgin and remediated seabed, are summarized in Table 4, and shown in Figure 3, 9 & 10. In Figure 9, the required minimum vertical bearing capacities for each GB / leg are also shown.

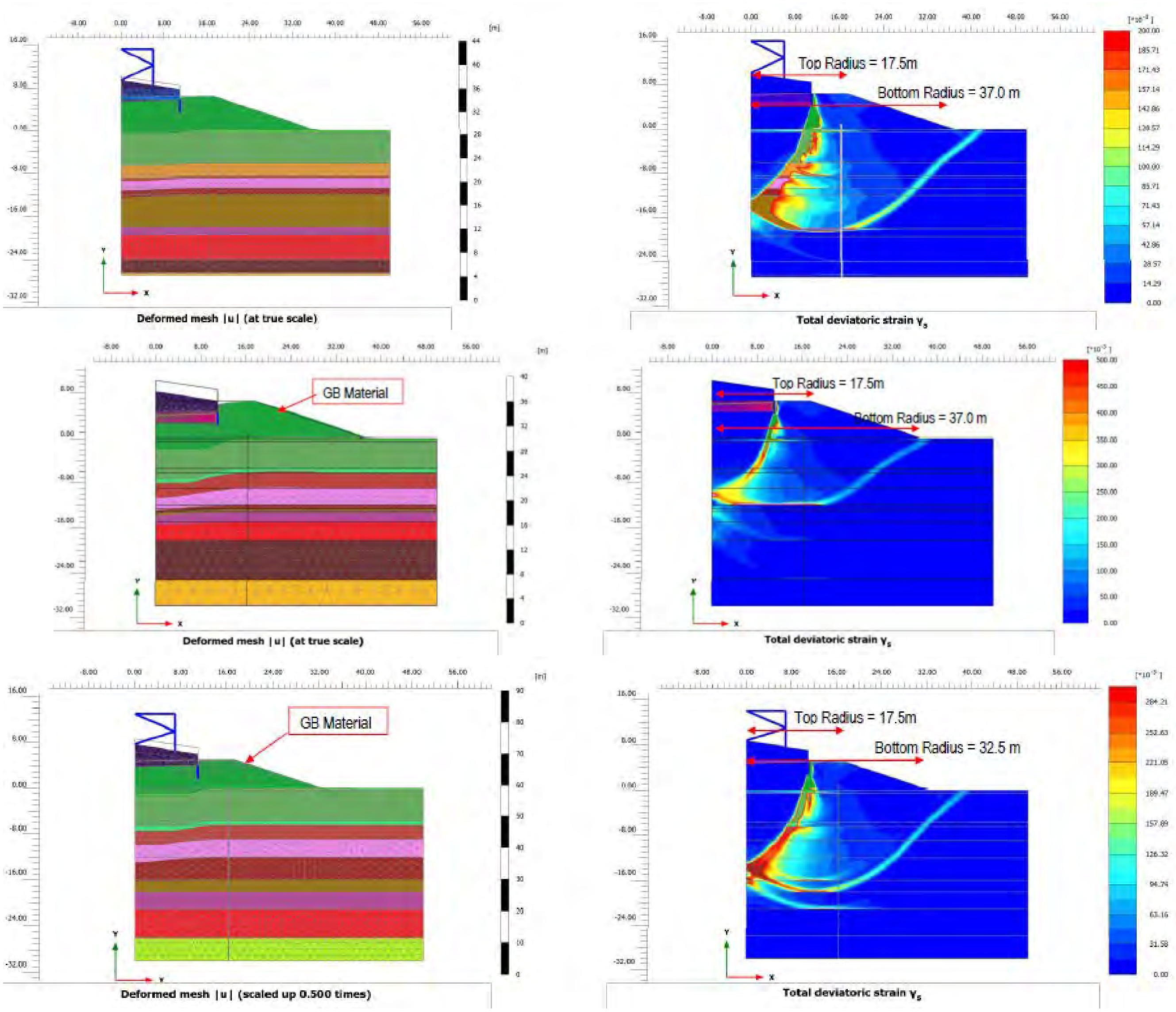

Figure 8 Plaxis FE 2D Axisymmetric Initial Design of GBs ‘High & Narrow’ (N_{kt}=29 & φ_{cs} [22])

TABLE 4 SUMMARY OF RESULTS FOR VIRGIN SEABED & FINAL ‘HIGH & NARROW’ GBs

CPT-Leg	Virgin Seabed Conventional & FE	Design of ‘High & Narrow’ GBs FE & Conventional Analyses				
	Minimum Capacities to P-Th	**Minimum Capacities to P-Th**	**GB Height**	**Top Radius**	**Bottom Radius**	**Slope**
	LB (N_{kt}=26/29 & φ_{cs} [22])					
	[tons/leg]	**[tons/leg]**	**[m]**	**[m]**	**[m]**	**[-]**
CPT-STB	17500	**21200**	**6.5**	**17.5**	**30.5**	**1:2**
CPT-PS	17550	**22200**	**7.0**	**17.5**	**35**	**1:2.5**
CPT-FWD	18900	**21000**	**5.0**	**17.5**	**27.5**	**1:2**

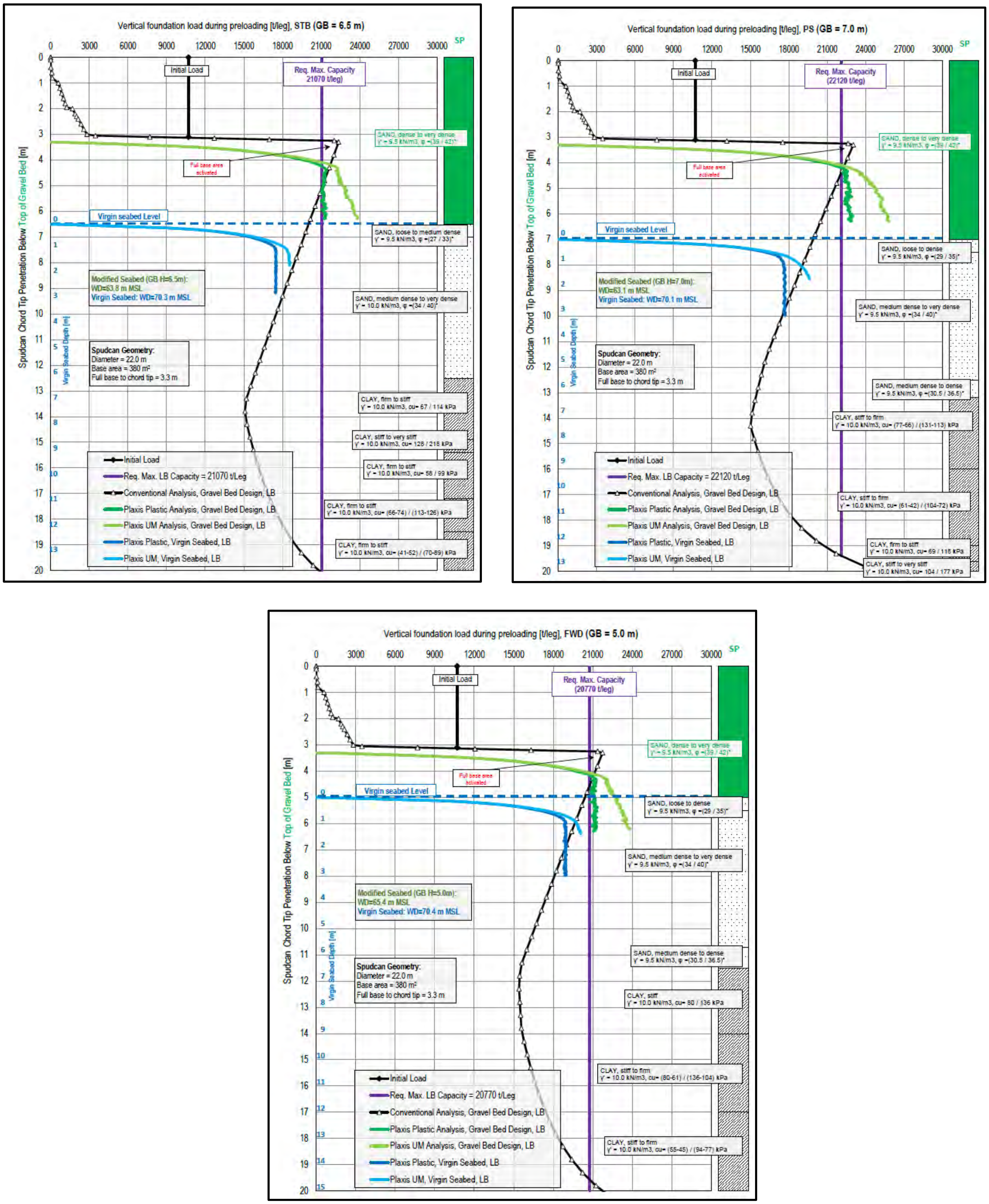

Figure 9 Conventional & FE 2D Axisymmetric Skirted Spudcan Penetration Predictions for Virgin Seabed & Final GB Design (N_{kt}=26/29 & φ_{cs} [22])

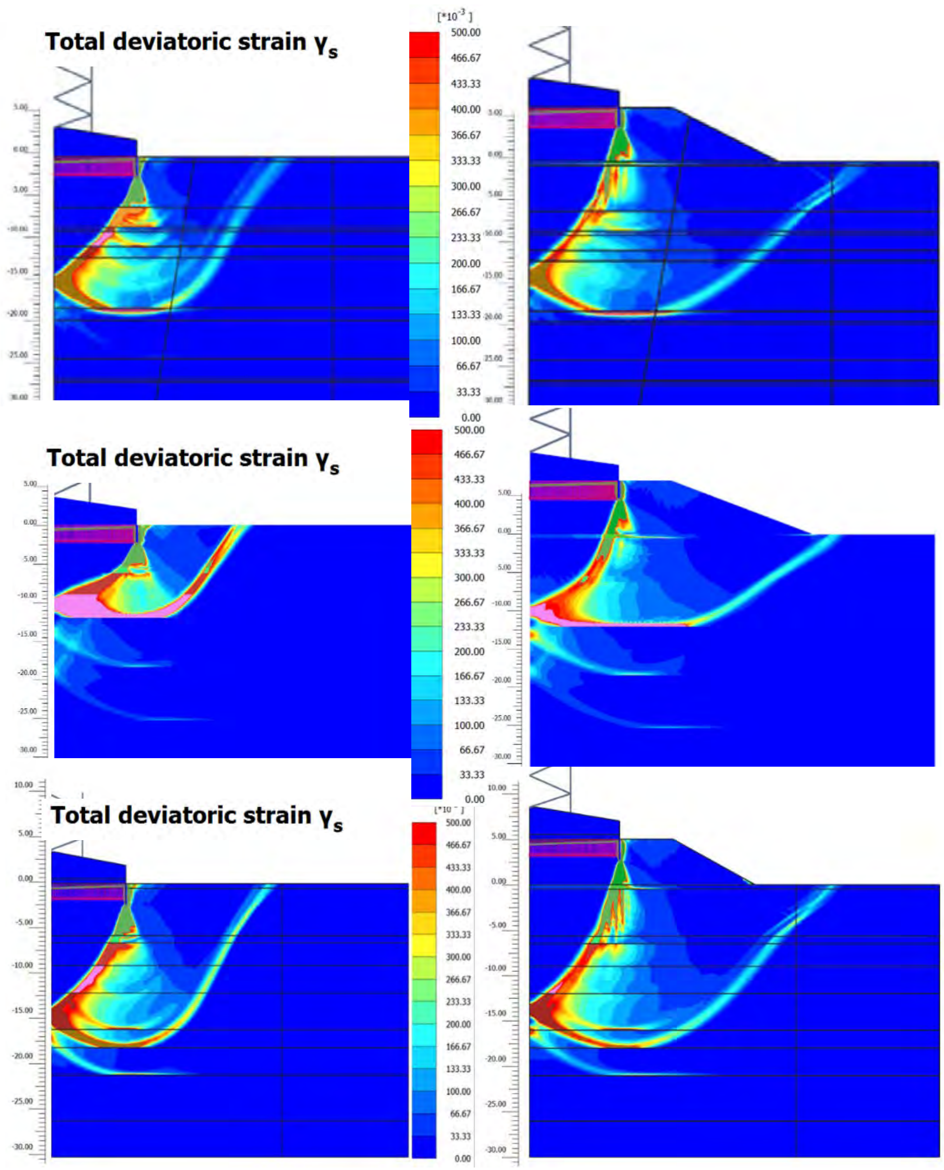

Figure 10 Plaxis FE 2D Axisymmetric Analyses for Virgin Seabed (left) and Final GB Design (right) (N_{kt}=26/29 & φ_{cs} [22])

Tolerances in GB Geometries: It should be noted that the tolerances in the construction of the GBs are not included in the design. Meaning the design geometries of the GBs (heights, top diameters, slopes) are to be considered as minimum required. If construction tolerances are to be included, they must be on the positive side. The same applies also for the rig positioning tolerance or the tolerance of positioning the skirted spudcans at the centre of the GBs. In conclusion, the overall dimensions of the GBs will become slightly larger when the tolerances (which are defined from the contractor and the rig owner) are included giving also some additional safeties.

Strength Requirements to GB Material: The GB design has been carried out, as shown in Figure 9, assuming a GB material with LB frictional angle 39º (angle of repose) while as UB value 42°is assumed. Due to risk for limited skirted spudcan penetrations on top of GBs, which might create gap conditions and reduce the spudcan fixity, very high friction angles are not preferred. In conclusion, the gravel material has to fulfill the following minimum requirements:

- Friction angle: average 40° (minimum 39° – maximum 42°)

- Gravel Size: 1”-3” (25-75mm)
- Curvature coefficient: 1< Cz <3
- Uniformity coefficient: Cu>4

AFT LEGS SKIRTED SPUDCAN-GB-SOIL-PILE INTERACTION

Based on the final jack-up rig position relative to the Drilling Jacket Platform, the closest distance of the Aft Legs skirted spudcan edge, to the Jacket piles (edge-to-edge) is about 5.43 m for PS Leg and 6.12 for STB Leg. As in both legs the distance is smaller than one spudcan radius (11 m), (not following [2] & [3]), skirted spudcan-GB-soil-pile interaction has to be investigated and is initially checked, as per previous work [20], in terms of the soil movements at the pile locations, for both phases: after construction of the GBs & during rig preloading.

‘Initial high & narrow’ GBs: The assessments are carried out employing the same FE models as applied for the initial ‘high & narrow’ GB design (Figure 7). The results, in terms of horizontal soil movement at the pile location, are shown in Figure 11 for STB Leg (up) and PS Leg (down). It can be noted that the soil lateral movement (in absence of the pile(s)) is about (5-10) mm at the nearest pile location, after the GBs are constructed, and about (49-145) mm after preloading, experiencing the largest lateral movement at depth of about 10 m. The initial results were not found critical from the pile designer.

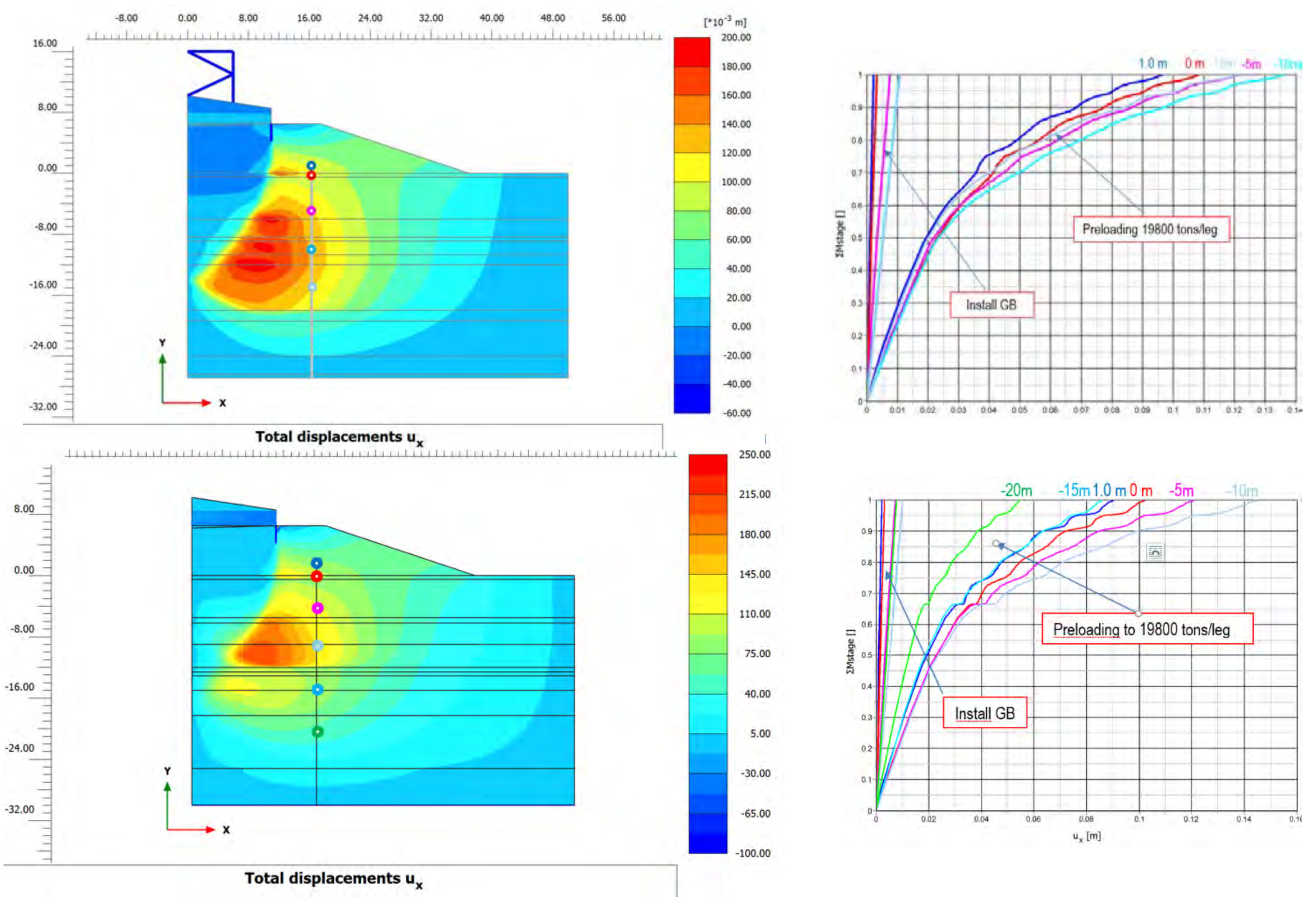

Figure 11 Lateral Soil Movement at the Nearest Pile Location (STB Leg up & PS Leg down) - Plaxis FE 2D Axisymmetric Initial Design of GBs ‘High & Narrow’ (Nkt=29 & φ_{cs} [22])

Final ‘high & narrow’ GBs: For the final Aft Legs GB designs, (location plan shown in Figure 3), the pile structures with diameter approximately 2.1 m, pile tip depth to about 54 m bsb and real pile inclination, three-dimensional (3D) FE modelling, (as per previous work [19], of skirted spudcan-GB-soil-pile/pile group interaction, is carried out with Plaxis 3D [18]. (as per illustration in Figure 12). In such modelling, the additional stresses, and structural forces on the piles, investigated for the final GB geometries and the final preloadings, are interpreted not to be critical for the nearest Jacket pile group foundation.

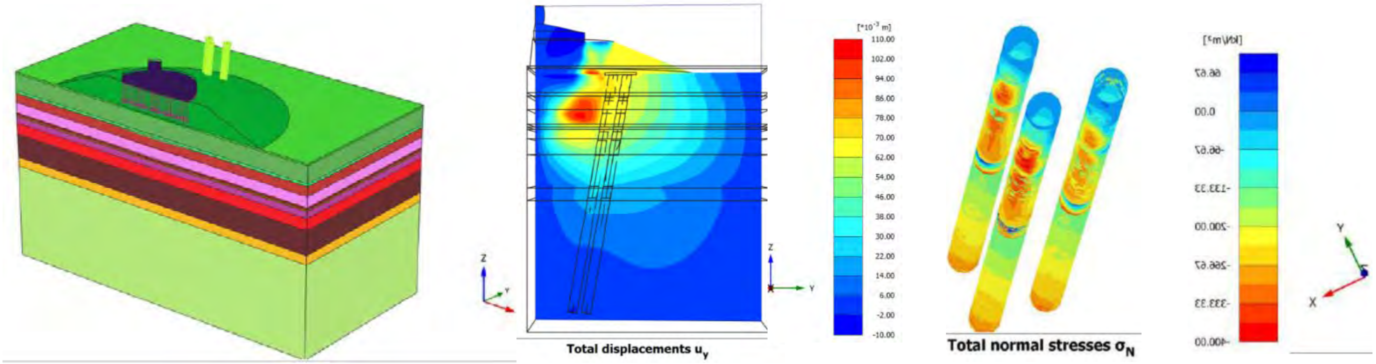

Figure 12 Lateral Soil Movement and the Additional Stresses at the Nearest Piles - Plaxis FE 3D, Final Design of GBs 'High & Narrow' (Nkt=26/29 & φ^{cs} [22])

SKIRTED SPUDCANS VHM ULTIMATE CAPACITIES (FINAL 'HIGH & NARROW GBs)

The results of the site specific assessment (SSA), for ultimate limit state (ULS) all year conditions, concluded that the rig has sufficient overturning stability, preload capacity, foundation bearing and sliding capacity, checked against a sand V-H envelope based on a vertical capacity proven by preloading and subject to confirmation by the GBs designer. Under these conditions, the ultimate VHM capacities for the final 'high & narrow' GBs were checked considering the application of the VHM load vectors starting from the vector origin (Still Water Reaction) and increasing the loads following this vector until reaching the yield point. In addition, safety analyses (phi-c reduction) are performed by reducing the soil strength after the applied load. This gives an indication of the global safety factor, related only with what soil can withstand as total load.

The calculations are performed using Plaxis FE 3D [18] analyses as per previous works [5], [9]-[13]. Due to low order of the 3D FE elements (10 nodes) and mesh sensitivity, Plaxis 3D models are first calibrated with Plaxis 2D axisymmetric models (15 nodes 2D FE elements and very fine mesh) for vertical loading (by applying a correction factor on the loads), in order to avoid overestimation of the GB capacities & safeties. In Plaxis 3D (modelled in half-geometry due to symmetry) the VHM loads (half loads) are applied at the half of skirt penetration depth. Assessment of the ultimate VHM capacities for the GBs, is based on the three chosen most critical loads, named North, East and South (naming considers the location/ orientation of the loads on the VHM bearing capacity envelope). Illustration of the 3D model applicable to VHM analyses for a chosen VHM load is given below. Plaxis 3D FE analyses indicated that the VHM loads are supported by the skirted spudcans in all cases and with sufficient safeties.

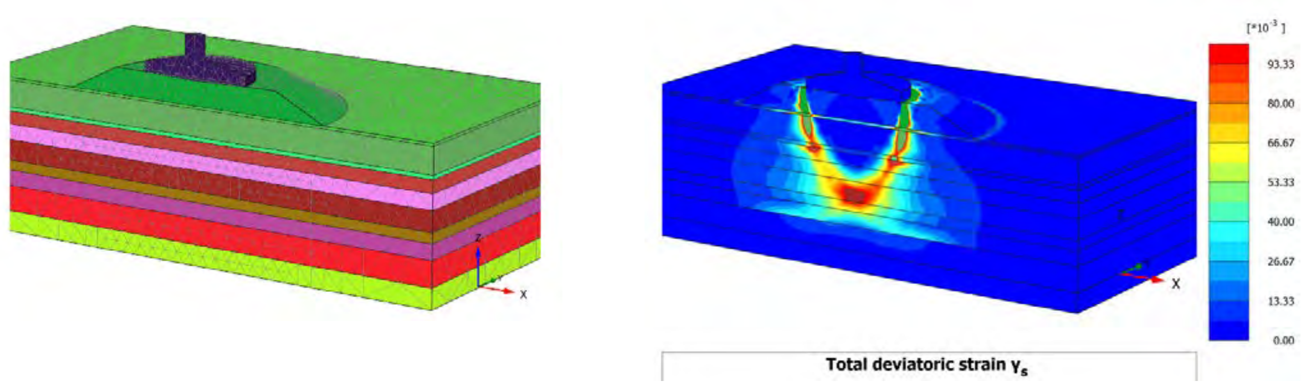

Figure 13 Plaxis FE 3D, Model Type for VHM Analyses. Final Design of GBs 'High & Narrow' (Nkt=26/29 & φ_{cs} [22])

CONCLUSIONS AND RECCOMENDATIONS

Design of GBs for a jack-up rig with skirted spudcans, successfully installed at an Oil & Gas field in the North Sea, has been carried out, fulfilling the requirements on vertical bearing capacities for safe preloading without risk for punch through or rapid penetrations.

As the jack-up rig location, due to operation conditions, was chosen close to the Jacket Platform, (with (5-6) m distance from the Aft Legs skirted spudcan circumferences, to the nearest jacket piles), 'high & narrow' GBs were designed and constructed, minimizing the impact on the nearest jacket piles and making possible the complete construction of the GBs.

The design gives the minimum dimensions of the GBs. However, tolerances during construction, and rig positioning at the centre of the GBs, are always expected to be positive, meaning that the finally constructed GBs are somewhat larger than the design, resulting in slightly larger safety.

From the material volume point of view, there is not a large difference in the material volume between, 'high & narrow' & traditional 'low & wide' GBs. In addition, the 'high & narrow' GBs can only be designed based on the FE modelling as the material concentrated within and at the vicinity of the skirted spudcan has to be modelled following the construction phases at the site. Other aspects are included in the introduction.

REFERENCES

[1] CEN/TC 250, EN-1997-1, Eurocode 7: Geotechnical Design – Part 1; General Rules. 2004.

[2] SNAME T&R Bulletin 5-5A, Site Specific Assessment of Mobile Jack-Up Units, Society of Naval Architects and Marine Engineers. 2008.

[3] EN ISO 19905-1 Petroleum and Natural Gas Industries – Site Specific Assessment of Mobile Offshore Units – Part 1 Jack-ups (ISO 19905-1:2016).

[4] Hansen, J.B., A revised and extended formula for bearing capacity. Bulletin No. 28. The Danish Geotechnical Institute. 1970.

[5] Kellezi, L., Koreta, O., Sundararajan S. (2017), 'Skirted Spudcan-Soil Interaction Under Combined Loading-Gap Conditions After Preloading'. 16th International Conference 'The Jack-up Platform Design, Construction & Operation, September , London, UK

[6] Kellezi, L, Xu, L. Molina, C. (2017) 'Site Investigation & Seabed Remediation to Avoid Sequential Jack-up Punch Through Failure' Offshore Site Investigation Geotechnics 8th Int. Conference Proceeding pp. 1011-1018(8), Publisher: Society for Underwater Technology

[7] Kellezi, L., Stadsgaard, H.(2012), 'Design of Gravel Banks – a Way to Avoid Jack-Up Spudcan Punch Through Type of Failure', OTC 2012, Houston, USA, April-May 2012, Paper no. OTC 23184.

[8] Kellezi, L. & Kudsk, G. (2009), 'Jack-up Foundation, FE Modelling of Punch Through for Sand over Clay' 12th International Conf. on Jack-up Platform. Sept. London UK, Proc. page 1-12.

[9] Kellezi, L., Kudsk, G., Hofstede, H. (2008), 'Skirted Footings Capacity for Combined Loads and Layered Soil Conditions. 2nd BGA International Conf. on Foundations, ICOF 2008, June, Dundee, Scotland, Proc. Volume 1 page 923-935.

[10] Kellezi, L. Kudsk, G. & Hofstede, H. (2008), 'Jack-up Rig Foundation Design Applying 3D FE Structure-Soil Interaction Modelling' 2nd BGA International Conf. on Foundations ICOF 2008, June, Dundee, Scotland, Proc. Volume 1 page 937-948.

[11] Kellezi, L., Denver, H., Kudsk, G., Stadsgaard, H. (2007), 'FE Skirted Footings Analyses for Combined Loads and Layered Soil Profile' 14th European Conf. on Soil Mech. & Geotech. Eng. ECSMGE 2007, September, Madrid, Spain, Proc. Volume 2, page 341 - 346.

[12] Kellezi, L. Kudsk, G. & Hofstede, H. (2007), ’Seabed Instability and 3D FE Jack-up Soil-Structure Interaction Analysis’ 14th European Conf. on Soil Mech. & Geotech. Eng. ECSMGE 2007, September, Madrid, Spain, Proc. Volume 5 page 247 - 252.

[13] Kellezi, L., Hofstede, H., Hansen, P.B. (2005), ‘Jack-up Footing Penetration and Fixity Analyses’. Proceedings, Frontiers in Offshore Geotechnics, ISFOG 2005, September, Perth, Australia, page 559 – 565.

[14] Kellezi, L., Stromann, H. (2003), ‘FEM Analysis of Jack-up Spudcan Penetration for Multi-Layered Critical Soil Conditions’. Proceeding of BGA International Conference on Foundations, ICOF2003, Dundee, Scotland, page 410-420.

[15] Danish Code for Practice for Foundation Engineering, DS415, 1998.

[16] DNVGL-RP-C212. Offshore soil mechanics and geotechnical engineering. August 2017.

[17] Plaxis 2D, 2017 Version, Finite Element Code for Soil and Rock Analysis. Delft University of Technology and Plaxis bv. The Netherlands.

[18] Plaxis 3D, 2017 Version, Finite Element Code for Soil and Rock Analysis. Delft University of Technology and Plaxis bv. The Netherlands.

[19]/ Kellezi. L & Sundararajan. S. S (2013), ’Spudcan-Soil-Jacket Pile Group Foundation – Interaction Analyses During Jack-Up Rig Installation and Removal’, 14th International Conference ‘The Jack-up Platform Design, Construction & Operation, September (17-18), London, England, Paper no. 7.

[20] Kellezi. L & Sundararajan. S.S (2012), ‘Impact of the Jack-up Rig Installation on the Jacket Platform piles, Spudcan-Soil-Pile Interaction Analyses’, EYGEC 2012, Goteborg, Sweden, Proc. page 221-226.

[21] Schmertmann, J.H. (1976) “An Updated Correlation between Relative Density DR and Fugro-Type Electric Cone Bearing, qc.” Contract Report DACW 39-76 M 6646 WES, Vicksburg, Miss., 1976

[22] Kulhawy F.H. & Mayne P.W. (1990), ‘Manual on Estimating Soil Properties for Foundation Design’, Cornell University Geotechnical Engineering Group, New York 14853-3501

[23] Lunne. T. & Christoffersen H.P. (1983), ‘Interpretation of Cone Penetrometer Data for Offshore Sands’, Offshore Technology Conference, Texas 1983