SKIRTED SPUDCAN- SOIL INTERACTION UNDER COMBINED LOADING - GAP CONDITIONS AFTER PRELOADING

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ABSTRACT
When a jack-up rig, equipped with skirted spudcans, is installed on competent seabed soil, limited penetrations (less than full base contact) can be experienced. In such a case, there are limitations in the existing guidelines with regard to the calculations of (V-H-M) capacity based on the conventional methods. In this paper, for a jack-up rig installed in the North Sea, experiencing penetrations less than full base contact, the assessment of footing-soil system stability and stiffness under storm load conditions is carried out. Finite element (FE) analyses are carried out by modelling the spudcan in 2D and in 3D (allowing for accurate modelling of the inner skirts). Due to the gap presence, large deformation, updated mesh (UM) analyses are carried out in order to account for increased (V-H-M) bearing capacity developed due to additional penetrations and gained contact area of the underside of the spudcan and the seabed soil. Important conclusions are derived and recommendations given with regard to identifying the governing failure mechanisms and predicting the behavior and capacity in the elevated conditions of the skirted footings suffering limited penetrations during preloading.

KEY WORDS: skirted spudcans, (V-H-M) capacity, fixity analyses, limit equilibrium, finite element

INTRODUCTION
Jack-up rigs equipped with skirted spudcans are commonly used in the offshore industry. Some of the benefits of the skirted footing include: 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 a major issue.
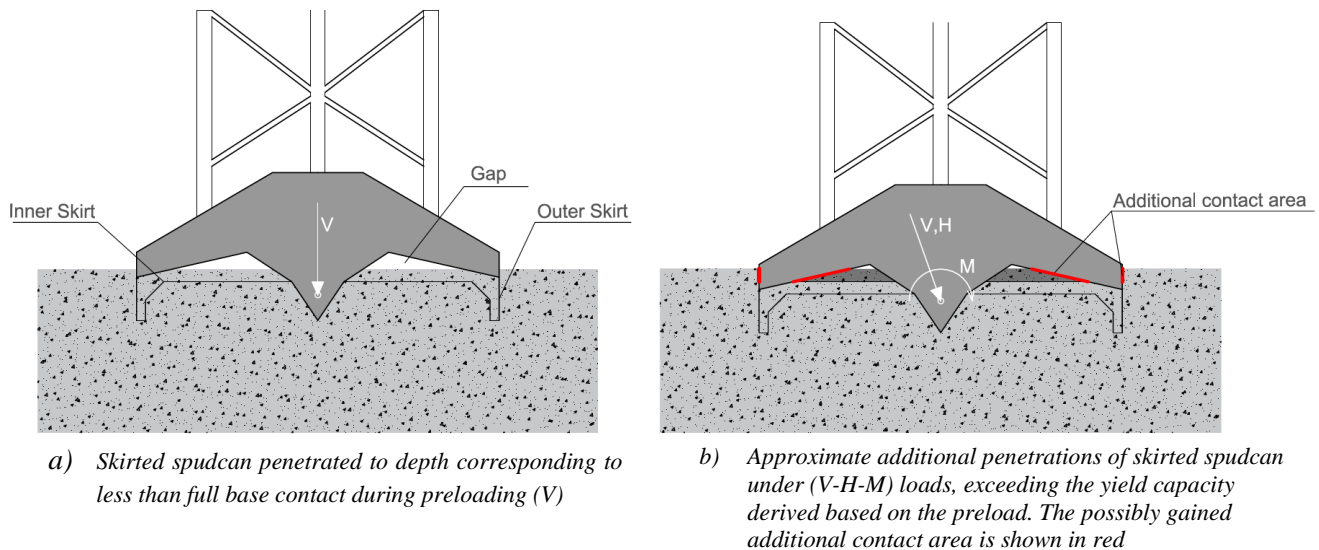

a) *Skirted spudcan penetrated to depth corresponding to less than full base contact during preloading (V)*

b) *Approximate additional penetrations of skirted spudcan under (V-H-M) loads, exceeding the yield capacity derived based on the preload. The possibly gained additional contact area is shown in red*

Figure 1 Skirted spudcan penetrating to depth less than full base contact

The benefits of skirted spudcans are mentioned in the current industry guidelines such as: [1], [2], [3], [4]. However, very limited information is provided with regard to the design methods for predicting their capacity under combined loading. For conditions when combined Vertical (V), Horizontal (H), and Moment (M) loading

apply, the conventional approach has shown to be less reliable. On this aspect, previous research studies have been carried out by [5], [6], [7] using conventional, 2D and 3D FE analyses for skirted footings under combined loads, considering multi-layered soil profiles (sand overlying clay with varying strength, sand overlying soft clay followed by sand and stiff clay) and full base skirted spudcan penetrations. The studies have been based on real industry projects / case histories and supported by feedback from the jack-up installations and operations. Other aspects, such as applying suctions in order to increase the skirt penetration and (V-H-M) capacity are also investigated in [7].

In specific sites, due to the special geometry of the skirted spudcans and due to reduced preload capacity of different rigs, combined sometimes with a dense sandy seabed, penetrations less than full base contact can occur during preloading or rig installation. This is associated with a gap between the seabed and the underside of the spudcan equipped with outer and inner skirts, as seen in Figure 1 a).

In some jack-up rigs, the spudcans have the facilities to apply suction within the created voids, which helps in increasing the skirt penetration. However, in other spudcans it is not possible to apply suction. The presence of the voids is however difficult to be visually confirmed, as the spudcan is confined by the outer skirts. While the spudcan penetrates, it might happen that the soil volume displaced from the spudcan, possibly moves up filling the gaps, before the achievement of full skirt penetration. In other situations, the underside of the spudcan might have already some remaining soil from previous installations, which can block the spudcan to reach full penetrations. However, the presence of the voids is confirmed in different cases by the needed volume of barite, injected to fill these gaps. Some uncertainties are still present though, as the barite is a soft material and it might partly penetrate through the top sandy soil.

Limited skirted spudcan penetrations (less than full base contact) could be the cause for reduced moment capacity of the foundations. In this case, it is assumed that the gaps inside the skirt, at the level of full base contact, remain empty or are filled with water, which can freely move out of the gaps, when the rig does not have facilities to close the valves, trapping the water inside. Generally, non-sufficient moment capacity or fixity at the reaction point of the spudcans could be the reason for structure stability and integrity issues. In such case, according to [1], the yield surface expands with increasing penetration depth. If this is applied to skirted spudcans, additional bearing capacity might develop due to additional penetration and contact area gained with the underside of the spudcan and the seabed soil (Figure 1 b)). This applies only for combined loads with vertical components larger than maximum preload. With regard to this, no quantification exist in the current industry guidelines on how much more capacity it is gained in case of increasing penetrations of skirted spudcans suffering penetrations less than full base contact during preloading.

This paper aims to provide some practical recommendations in assessing the partially embedded skirted spudcans foundation stability by use of FE analyses. The assessment of footing-soil system stability and stiffness (rotational, horizontal and vertical) is carried out for a skirted spudcans installed in the North Sea. The use of different numerical modelling tools, including [8], [9] is investigated. Comparison of different failure mechanism derived from FE analyses (for partially embedded skirted spudcans) assuming different load scenarios, is carried out. Conventional (V-H-M) bearing capacity is also calculated for the same limited skirted spudcan penetration, however assuming filled gaps due to soil heave.

PARTIALLY EMBEDDED SKIRTED FOOTING

Foundation stability assessments are recommended in [1] using the so called 'three steps method'. Different provisions are given with regard to checks of Preload, Sliding, Bearing Capacity, etc. Generally, for the partially embedded spudcans, [1] states that additional footing embedment may result in a considerable increase in the bearing capacity. In case of partial penetration in sand (full bearing area not mobilized), any additional penetration will result in a significant increase of bearing capacity, due to rapid increase in the bearing area. According to [1], an increase of the embedded area of 10%, will increase the horizontal capacity to $0.1V_{L0}$ (Vertical leg reaction during preloading). The above provisions and recommendations are applicable to conventional spudcan design (non-skirted spudcans). No details are given regarding the increase of the capacity for partially skirted spudcans.

Some considerations are given for partially skirted spudcans in [2]. It is especially mentioned that in order to realize the maximum benefits from using a skirted spudcan, full contact area has to be achieved. In addition, in case of partial penetrations, application of suction or filling of the voids with suitable material, introduced through the pipes, should be planned.

Under vertical loading, the skirted spudcans have generally been modelled as solid embedded footings. If the skirted spudcans will reach full base penetrations, this approach has shown to be of practical use. In such a case, the failure mechanism of the skirted spudcan is similar to the embedded footing. In case of partially embedded skirted spudcans, the failure mechanism develops within the spudcan skirts. In this case, the capacity will be highly based on the shearing of the soil inside the skirt compartments and the partial contact with the spudcan area. The distinguishment between these two scenarios (full base or partially embedded) is fundamental with regard to the suitability of the conventional approaches.

SKIRTED SPUDCAN GEOMETRY AND LOADS
Skirted spudcans geometries, including spudcan diameter and skirt length, vary for different jack-up rigs. The investigation of the effect of the spudcan diameter (D), skirt length (L) or their ratio (D/L) is not part of this study, In this case history the skirted spudcan has a diameter of 16 m and full base area of 201 m^2. With the aim to improve the foundation stability and to serve as mean for scour protection, an outer skirt was mounted around the perimeter of the spudcan. The distance from outer skirt to the largest contact footing area is about 3 m. The used geometry is given in Figure 2.
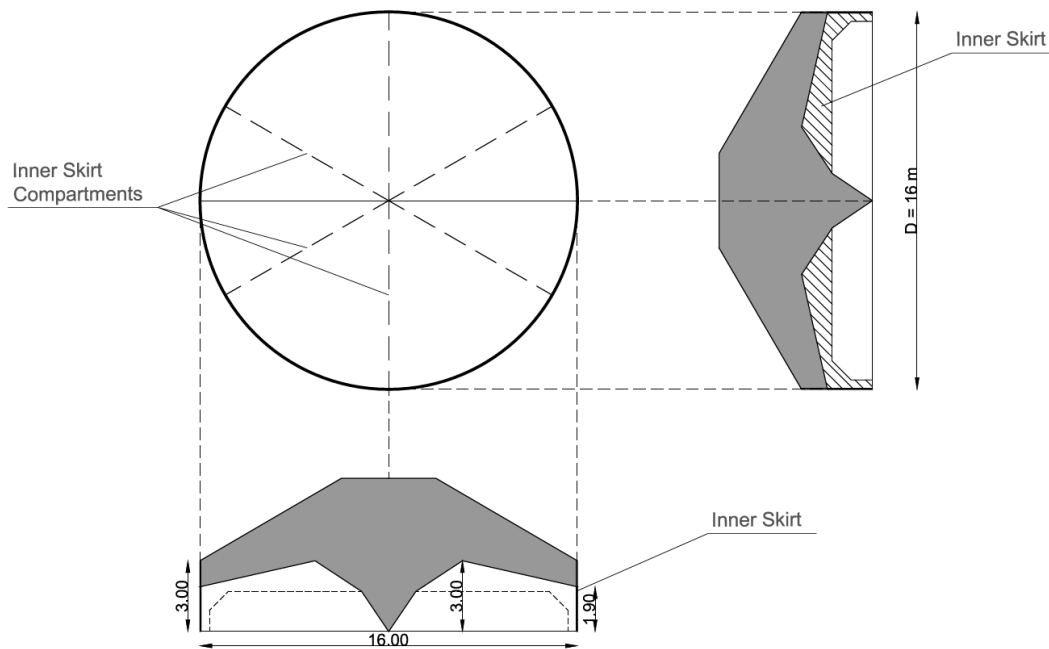

Figure 2 Skirted spudcan geometry

In addition, inner skirts (diaphragms), which are shallower than the outer skirt, divide the volume between the spudcan and the outer skirt into six compartments. The expected maximum preload was about 3200 tonnes/leg.

SOIL CONDITIONS & WATER DEPTH
The soil conditions consisted generally of a sand layer, with a thickness of about (14-15) m, overlying stiff clay to larger depths. The available geotechnical data within the surrounding area consisted of boreholes (BHs) and cone penetration tests (CPTs). However, no BH / CPTs were available at the spudcan locations. The water depth at the site was about 40 m lowest astronomical tide (LAT). Feedbacks from previous rigs (with conventional spudcans) installations were used to back analyze the generalized soil profile at the considered rig location. Hence, the soil

strengths back-calculated based also on the soil stratigraphy interpreted from the nearest BH/CPTs, is given in Table 1.

TABLE 1 GENERALIZED INTERPRETED SOIL PROFILE AND SOIL PARAMETERS

Soil Type	Depth [m]		γ' [kN/m³]	ϕ [°]		c_u [kN/m²]	
	Top	Bottom		LB*	UB**	LB	UB
Sand	0.0	14.5	9.5	25	29	-	-
Clay	14.5	29.0	8.5	-	-	80	200

*LOWER BOUND; **UPPER BOUND

CONVENTIONAL SPUDCAN PENETRATION ANALYSES – INSTALLATION PHASE
Using the skirted spudcan geometry described above and back calculated generalized soil strength profile given in Table 1, conventional penetration predictions have been carried out. The calculations of the skirt resistance is based on [3] Most Propable (MP) and Highest Expected (HE) empirical methods, directly using the CPT data. The spudcan bearing capacity (within the skirt) has been calculated based on [1] and using the method proposed by [10]. The results of the conventional / empirical predictions show skirt tip penetrations of about 2.5 m for all three legs, for upper bound soil conditions and HE skirt resistance (Figure 3).
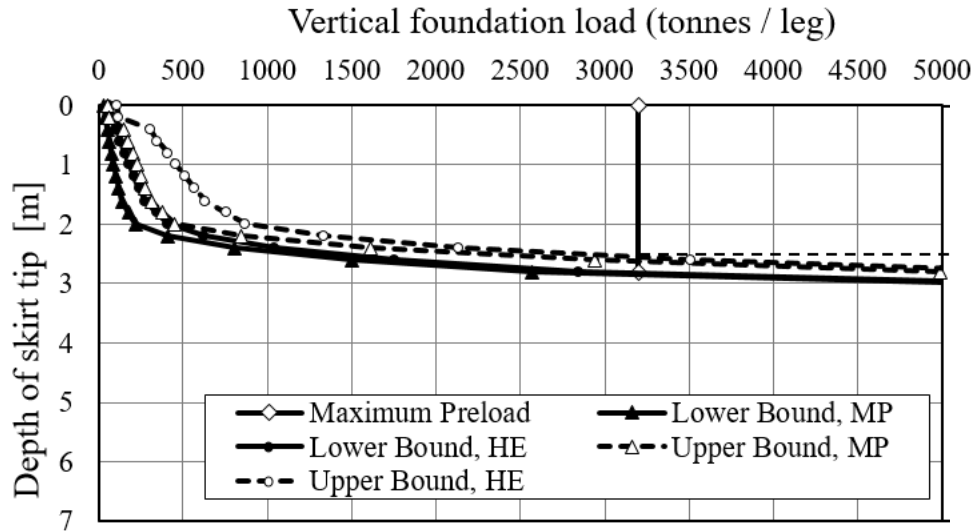
Figure 3 Skirted spudcan penetration analyses

As mentioned above, risk for limited penetrations of skirted spudcans could be the cause for reduced stability and moment capacity of the foundations. In this case, considering also the special shape of the skirted spudcans, the simplified calculations of the initial vertical, horizontal and rotational soil stiffness at the reaction point (RP) following [1] are found not applicable. Therefore, FE analyses for the assessment of non-linear footing-soil system stability and stiffness for (V-H-M) loading would be the target.

DESIGN METHODOLOGY
For the expected skirted spudcan penetrations less than full base contact (2.5 m), structural analyses, applying initial foundation stiffness, resulted in footing reactions for each of the legs. Three of the most critical (V-H-M) load cases (LCs) were then chosen for investigating skirted spudcan stability. Due to its complexity and lack of relevant guidelines, the following analyses are then carried out in order to estimate the skirted spudcans (V-H-M) capacity and stiffness:

1) 2D axisymmetric FE analyses (verification of peak bearing capacity assessment)
2) 2D plain strain analyses for combined loading (converting the spudcan into a skirted strip footing)

3) 3D FE analyses (real spudcan geometry, including outer skirts and the inner compartments created between the skirts and diaphragm walls / inner skirts)
4) Conventional analyses (based on the theory of block embedded footing from [10] and [11]

In order to calculate the footings (V-H-M) ultimate capacities, the generalized FE model has to be constructed, proving first an ultimate vertical capacity (UVC) equal to the applied maximum preload of 3200 tonnes/leg, based on plastic analysis (spudcan in-placed at 2.5 m of penetrations). When the moment is applied, combined with the same vertical component, larger load than 3200 tonnes/leg will result, at least at half of the spudcan area according to the direction of the applied M. In order to simulate the increase of the skirted spudcan capacities while footing penetration increases (due to combined loading resulting in larger vertical load than applied maximum preload), UM analyses (simulation of large deformation) is carried out [8]. The vertical capacity derived from the large deformation (UM) analyses is then checked and compared with the small strain (plastic) (in-placing the spudcan at different depths) capacity, for the same penetrations.

2D AXISYMMETRIC FE ANALYSES

To verify footing UVC at the predicted penetration, FE modeling is carried out in Plaxis starting with the embedded skirted spudcan in-placed at 2.5 m depth. The footing and the soil are modeled in an axisymmetric geometry taking into account the 3D effect. The skirted spudcan is assumed weightless. The outer skirt is modeled employing plate elements and the inner skirts / diaphragm walls, by an equivalent anchor. Regarding the soil, Mohr Coulomb soil model is applied for the sand layer in drained conditions and for the clay layer, in the undrained conditions. An overview of the Plaxis 2D axisymmetric model is given in Figure 4.
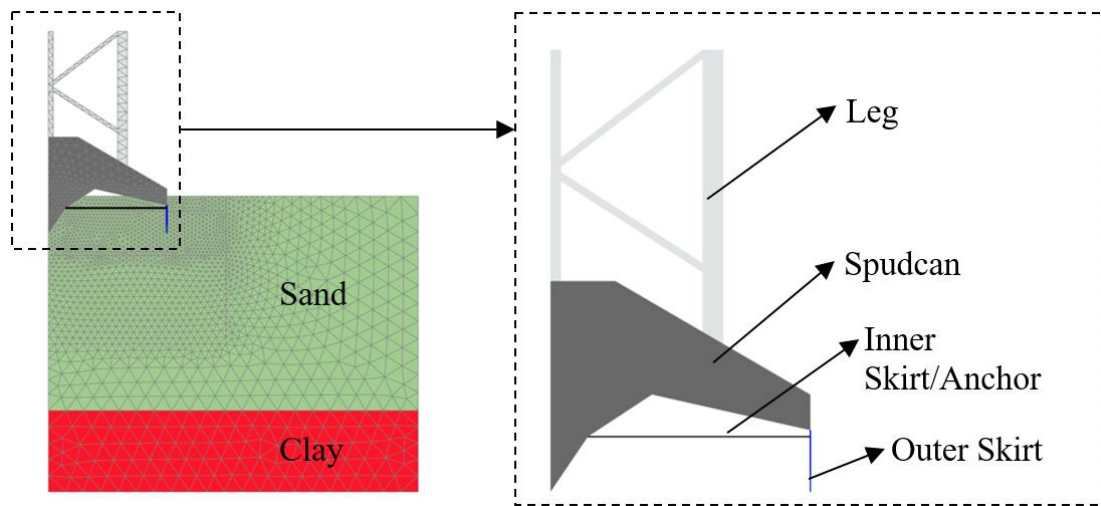

Figure 4 2D axisymmetric model of skirted spudcan-soil interaction

2D PLAIN STRAIN FE ANALYSES

Although the original 3D footing configuration is not circular, its total area (A = 201 m^2) has been adopted to be circular. One commonly used method [3] is to transform the circular area into a rectangular area having equal area and moment of inertia as the idealized circular footing. Combining these two criteria give: A = B*L where B = 13.9 m and L = 14.5 m. B is the width of the rectangular area in the moment loading direction. L is the width in the normal direction. The loads are applied for unit width L of the rectangular. The outer and inner skirts are modeled employing plate elements and anchors in 2D. Modeling of the inner skirts is a difficult issue in the current 2D footing analysis. They comprise six compartments where suction will develop during dynamic loading. Considering the depth of the outer skirt and the depth where inner skirts start, (at 1.7 m from the outer skirt tip), several ways are tried to approximate the inner skirt in 2D. After trial and error analyses the inner skirts were modeled by node-to-node anchors at the level of the inner skirt tip. However, for the considered footing, only 3D modeling makes it possible to exactly model the effects of the inner skirt compartments because it is an out of plane effect. An overview of the 2D Plain Strain model is given in Figure 5.
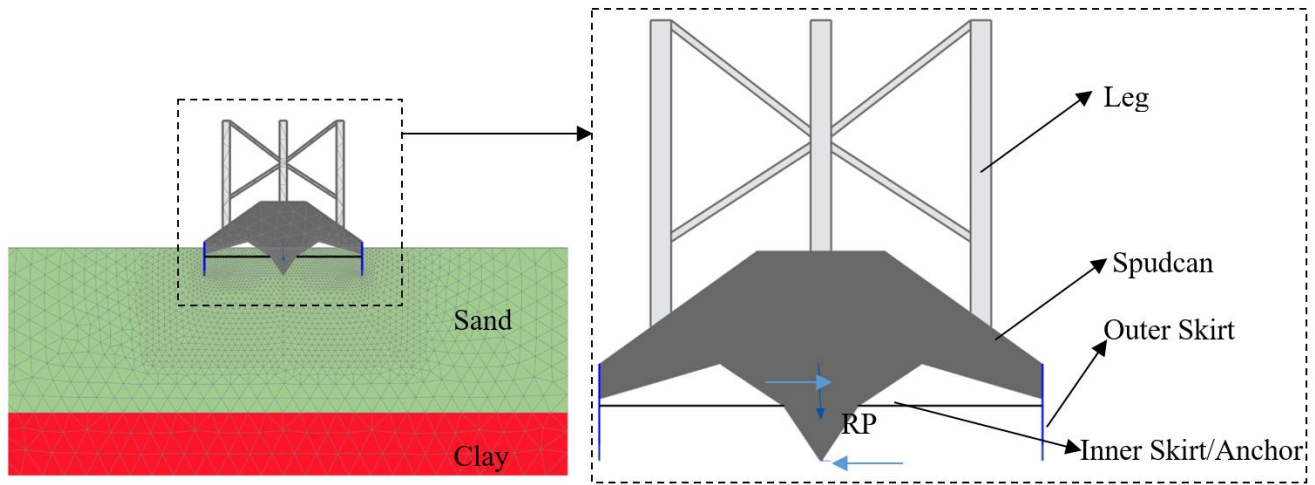
Figure 5 2D Plain strain model of skirted spudcan-soil interaction

3D FE ANALYSES

The skirted spudcan is modeled in Plaxis 3D using its real geometry and dimensions as shown in Figure 2. Compared with Plaxis 2D (15 nodes), Plaxis 3D uses a 10-node tetrahedral elements for the numerical integration of volume elements. This type of elements provides a second-order interpolation of displacements. Using symmetrical conditions, half of the spudcan is modeled and half of the loads are applied. The outer and inner skirts are modelled using plate elements. The thicknesses of the outer and inner skirts are taken the same as the real thickness, equal to 20 mm. It's clear that for the considered footing, only 3D modeling makes it possible to exactly model the effects of the inner skirts and inner compartments. An overview of the 3D model is given in Figure 6.
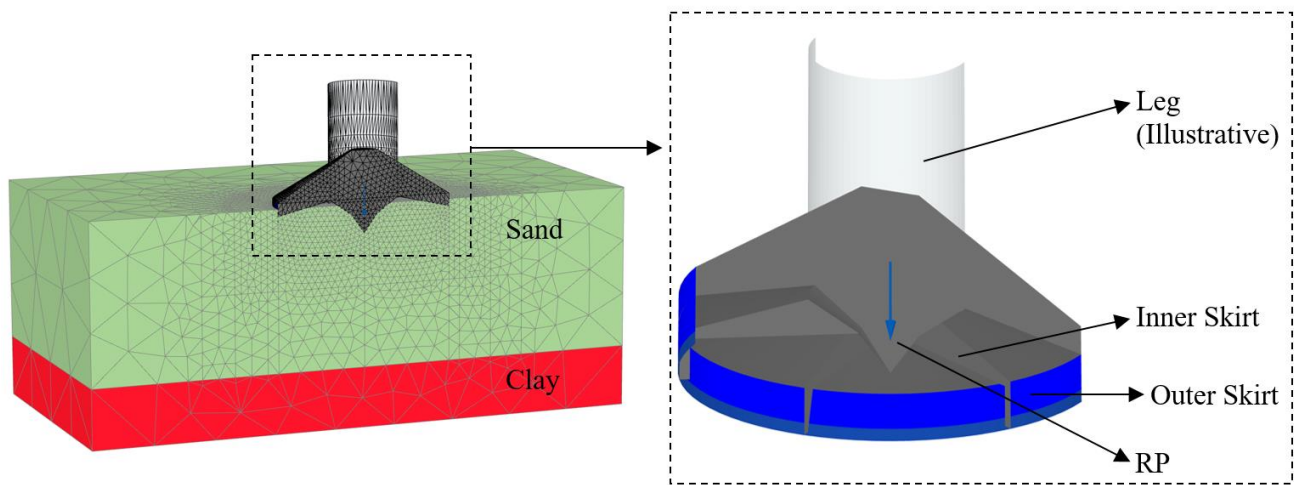
Figure 6 Full 3D model of skirted spudcan-soil interaction

(V-H-M) LOADS

The three most critical (V-H-M) LCs (outer points in the north, east & south of the V-H & V-M planes) are chosen and investigated, being applied in both 2D plane strain and 3D FE skirted spudcan-soil interaction models. These LCs are given in Table 2 and each scenario represents a specific failure mode, depending on the (V-H-M) load component or the location of the LC / footing RP in the V-H & V-M planes. The three chosen (V-H-M) loads are applied following different phases according to the installation and operation procedures and following the load vectors. The yield points are then found by loading more in the direction of the load vectors, respectively.

TABLE 2 CONSIDERED FOOTING REACTION (V-H-M) LOADS

Loads Description	Vertical (V)	Horizontal (H)	Moment (M)	Eccentricity e = M/V
Units	[tonnes/leg]	[tonnes/leg]	[tonnes*m/leg]	[m]
Preload Reaction	3200	-	-	-
Still Water Reaction (SWR)	2325	-	-	-
Load Case 1 (LC1)	4020	300	3267	0.81
Load Case 2 (LC2)	2293	404	4647	2.03
Load Case 3 (LC3)	1447	457	2138	1.48

FOUNDATION CAPACITIES

For the considered preload of 3200 tonnes/leg, the predicted V-H and V-M bearing capacity envelopes, according to SNAME [1] and considering the contact area for 2.5 m penetration, do not cover the most critical environmental loads, as shown in Figure 17 in thin dashed line. Therefore, in order to satisfy SNAME [1] requirements regarding structural utilizations, virtual bearing capacities can be adopted. These capacities are supposed to be larger than the ones developed during preloading. In order to confirm these capacities, FE analyses, described above, are undertaken, calculating the yield envelope by increasing the loads following the (V-H-M) load vector. Alternatively, the yield envelope could be checked by keeping constant the V-H and increasing M or keeping constant V-M and increasing H.

RESULTS – 2D AXISYMMETRIC FE ANALYSES

Plaxis 2D axisymmetric analyses are carried out to confirm the UVC for penetration 2.5 m, based on generalized back-analyzed soil conditions / profile, as given in Table 1. A prescribed displacement is applied on top of the spudcan to simulate the penetration of the footing. The mesh is refined at the skirt level and mesh sensitivity analyses carried out coparing the results for different mesh coarseness. Plaxis output results are given in Figure 7 for the applied preload.
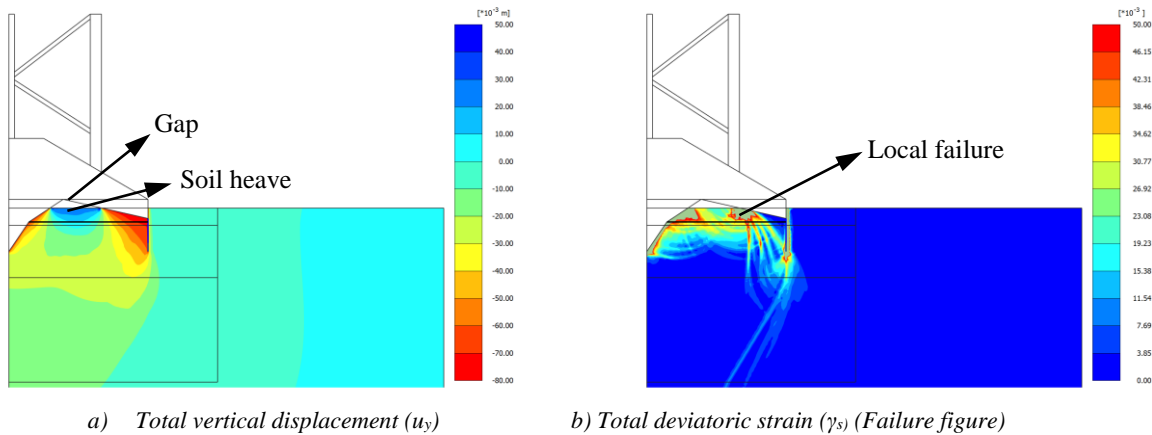

a)   Total vertical displacement (u_y)   b) Total deviatoric strain (γ_s) (Failure figure)

Figure 7 Plaxis 2D axisymmetric (plastic), UVC equal to 3200 tonnes/leg, spudcan in-placed at 2.5 m depth.

RESULTS – 2D PLANE STRAIN FE ANALYSES

Plaxis 2D plain strain analyses (small strain) are carried out first for vertical loading in order to confirm the UVC for skirted spudcan in-placed at 2.5 m penetration. For achieving UVC=3200 tonnes/leg, the friction angle in 2D plain strain is slightly increased (about 7%) from the one used in the axisymmetric model (25°), accounting for the 3D and plane strain friction angles. The results from Plaxis (plastic) are given in Figure 8, where deformed mesh, vertical displacements (u_y), total deviatoric strain (γ_s) & cartesian effective stress (σ'_{yy}), are shown.

a)   *Deformed mesh (Scale 2.5)*

b) Vertical displacement (u_y)

c) Total deviatoric strain (γs) (failure figure)

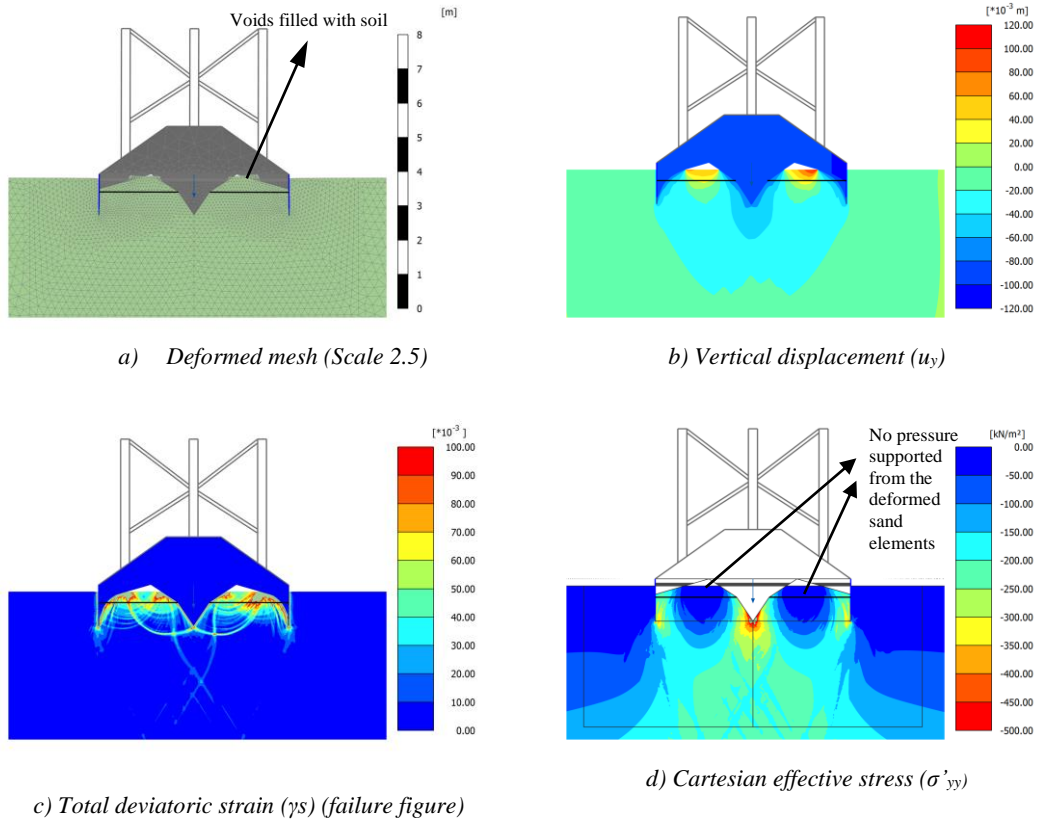*d) Cartesian effective stress (σ'_{yy})*

Figure 8 Plaxis 2D (plastic), spudcan in-placed at 2.5 m penetration, UVC of 3200 tonnes/leg

As the intention is to confirm the increase in the (V-H-M) bearing capacities for slightly increased penetrations, the UVC is calculated by plastic analyses for skirted spudcan in-placed at penetrations 2.55m, 2.60m, 2.65m, 2.7m and 3.0m. UM analyses are then conducted for spudcan penetration 2.5m and load-displacement curve is compared with the achieved capacities based on the in-placed conditions (plastic). The comparison of UVC from small strain and large deformation analyses are given in Figure 9.
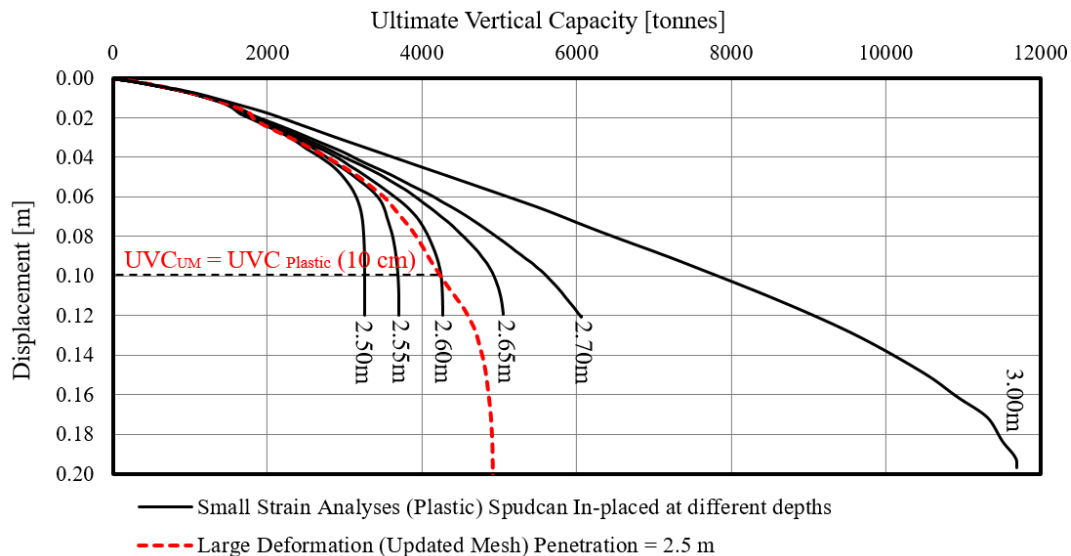
Figure 9 Comparison of UVC (plastic) and UM analyses

RESULTS – 2D ANALYSES - (V-H-M) YIELD CAPACITY

The load scenarios in Table 2, are applied in Plaxis 2D following the load vector, as indicated in Figure 17. The ultimate (V-H-M) capacities achieved from Plaxis 2D are summarized in Table 3. Plaxis outputs are given in Figures (10-12) for each load case.
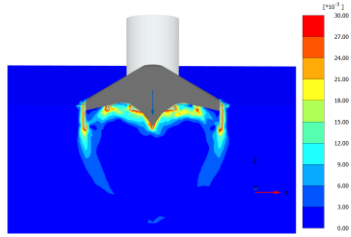

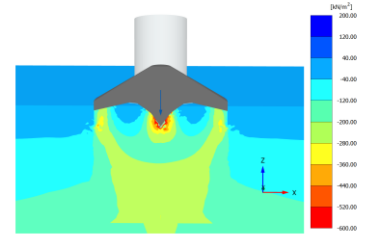*a)   Vertical Displacement (u_y)*   *b)   Total deviatoric strain (γ_s)*   *c)   Cartesian effective stresses (σ'_{yy})*

Figure 10) LC1 results

a)   Vertical Displacement (u_y)   *b)   Total deviatoric strain (γ_s)*   *c)   Cartesian effective stresses (σ'_{yy})*

Figure 11) LC2 results

a)   Vertical Displacement (u_y)   *b)   Total deviatoric strain (γ_s)*   *c)   Cartesian effective stresses (σ'_{yy})*

Figure 12) LC3 results
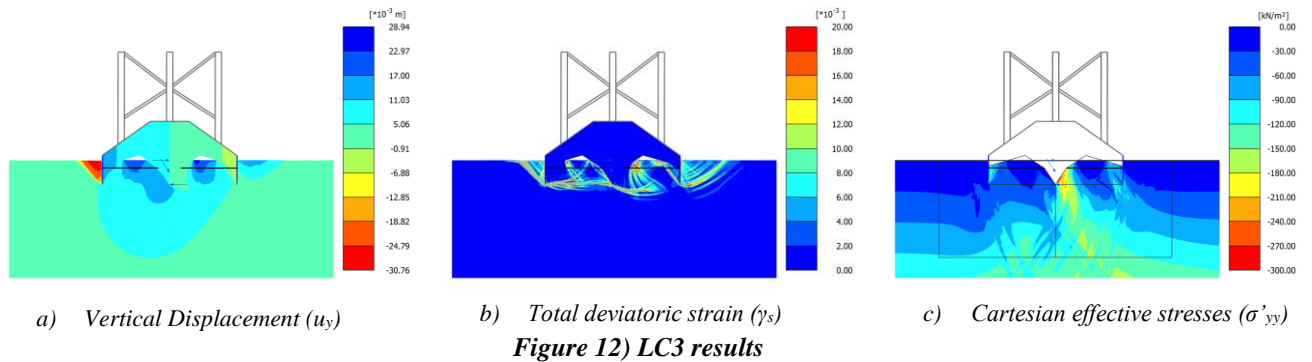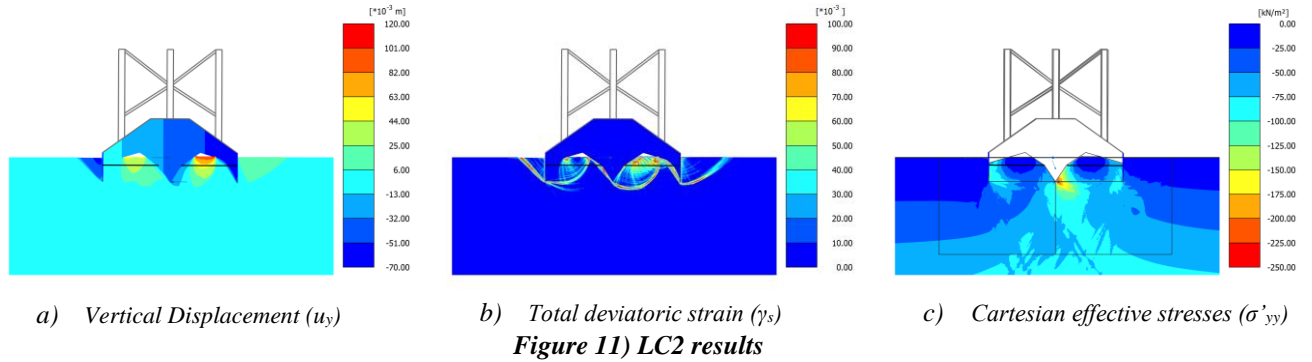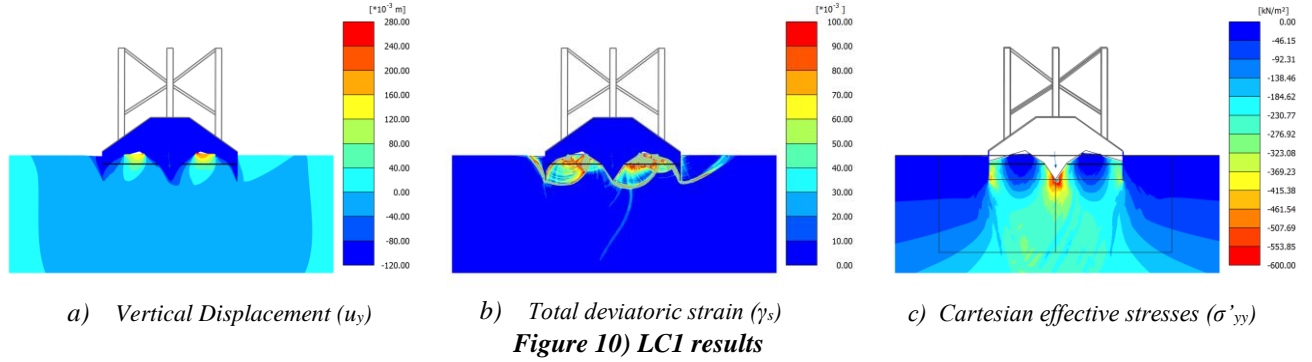
RESULTS - FULL 3D ANALYSES

The ultimate (V-H-M) capacities achieved from Plaxis 3D are summarized in Table 3. Plaxis outputs from the preloading phase are given in Figure 13. In order to investigate closely the soil behavior within the skirt, the spudcan is deactivated in Figure 13 d) and e). Results from each load case, similar to 2D plane strain as shown in Figure 10 -12, are given in Figures (14-16).
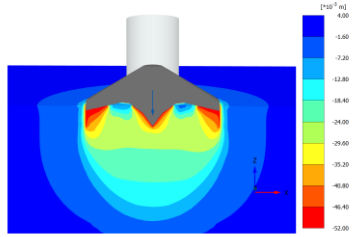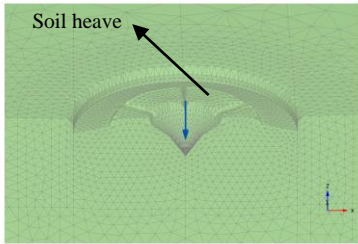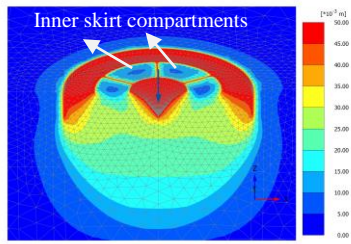
a)   *Vertical Displacement (u_y)*
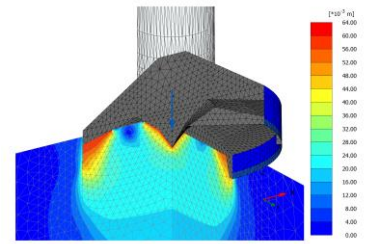

b)   *Total deviatoric strain (γ_s)*

c)   *Cartesian effective stresses (σ'_zz)*
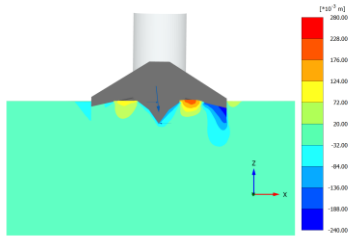

d)   *Deformed mesh under the skirt*

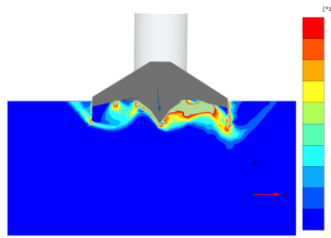e)   *Total displacements (u)*

f)   *Soil movement underside*
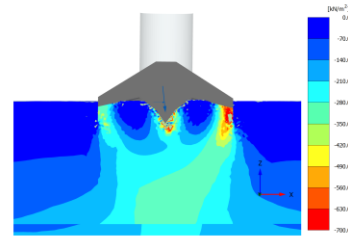
Figure 13 3D results from preloading phase

a)   Vertical Displacement (u_y)
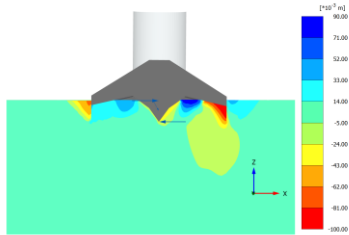

b)   Total deviatoric strain (γ_s)
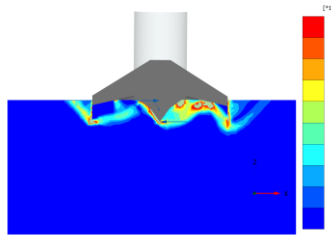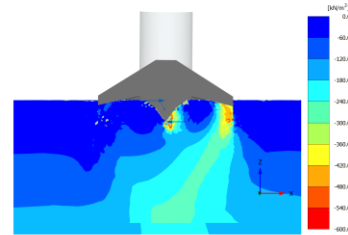
Figure 14 LC1 results

c)   Cartesian effective stresses (σ'_zz)

a)   *Vertical Displacement (u_y)*

b)   *Total deviatoric strain (γ_s)*

Figure 15 LC2 results
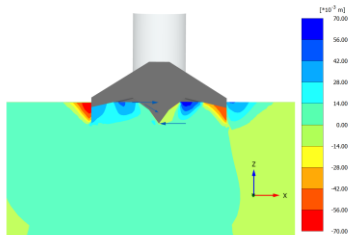
c)   *Cartesian effective stresses (σ'_zz)*

a)   *Vertical Displacement (u_y)*

b)   *Total deviatoric strain (γ_s)*

Figure 16 LC3 results

c)   *Cartesian effective stresses (σ'_zz)*

RESULTS – ULTIMATE (V-H-M) YIELD CAPACITY

The (V-H-M) yield capacities derived from 2D and 3D FE analyses are summarized in Table 3. In addition, the conventional yield capacities, considering the skirted spudcan as a block footing [10] with full base penetrations at 2.5 m (gap filled with soil) are also included. In Figure 17 the achieved yield capacities are plotted in the corresponding V-H and V-M envelopes. The numbers in the table represent how much more load can the model hold until reaching the yield. So despite of limited penetrations and limited preload capacity, the skirted spudcans can support the most critical (V-H-M) LCs and as expected, the 3D FE analyses give larger safety for those load vectors than 2D FE analyses.

TABLE 3 ULTIMATE (V-H-M) CAPACITIES

LC	2D (V-H-M)	3D (V-H-M)	Conv. (V-H-M)
LC1	1.13	1.38	2.00
LC2	1.40	1.41	1.60
LC3	1.30	1.50	1.40

a)   Ultimate V-H capacity   b   Ultimate V-M capacity
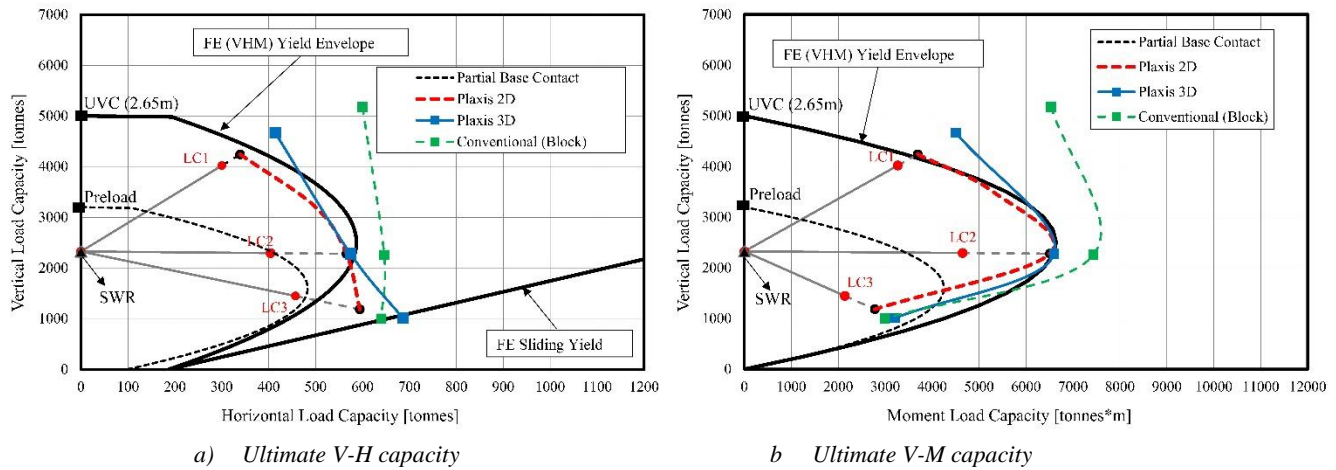
Figure 17 Results, ultimate V-H & V-M capacities,
2D FE plane strain, (10-15) cm additional penetrations, maximum 2.65 m penetration-still gap;
3D FE (10-15) cm additional penetration, maximum 2.65 m penetration-still gap;
Conventional, maxim,um 2.5 m penetration and assumming gap is filled with heaving sand)

NONLINEAR SOIL STIFFNESS

The vertical, horizontal, and rotational stiffness can be derived from Plaxis 2D and 3D FE analyses, based on the load displacement curves (vertical, horizontal) given in Figures (19-21) (for 2D) and based on the footing rotation for each LC, as shown in Figure 18 (for 2D).
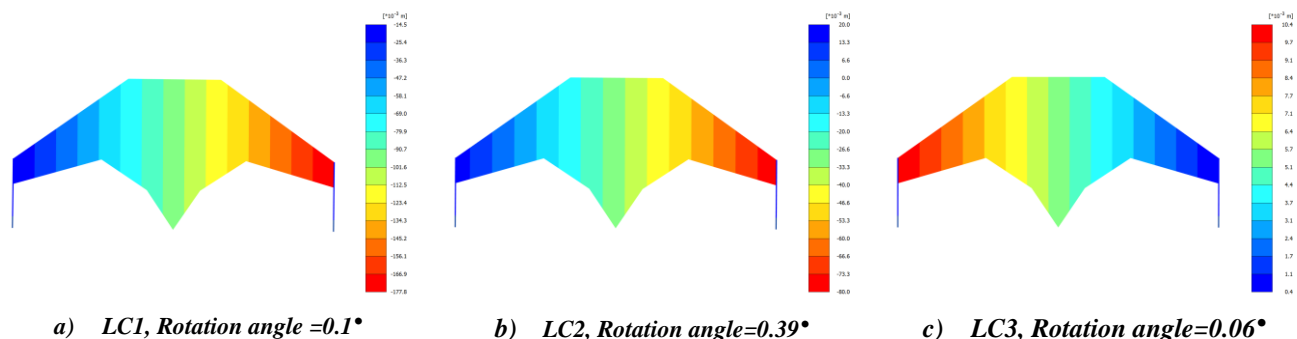

a)   *LC1, Rotation angle =0.1*°   b)   *LC2, Rotation angle=0.39*°   c)   *LC3, Rotation angle=0.06*°

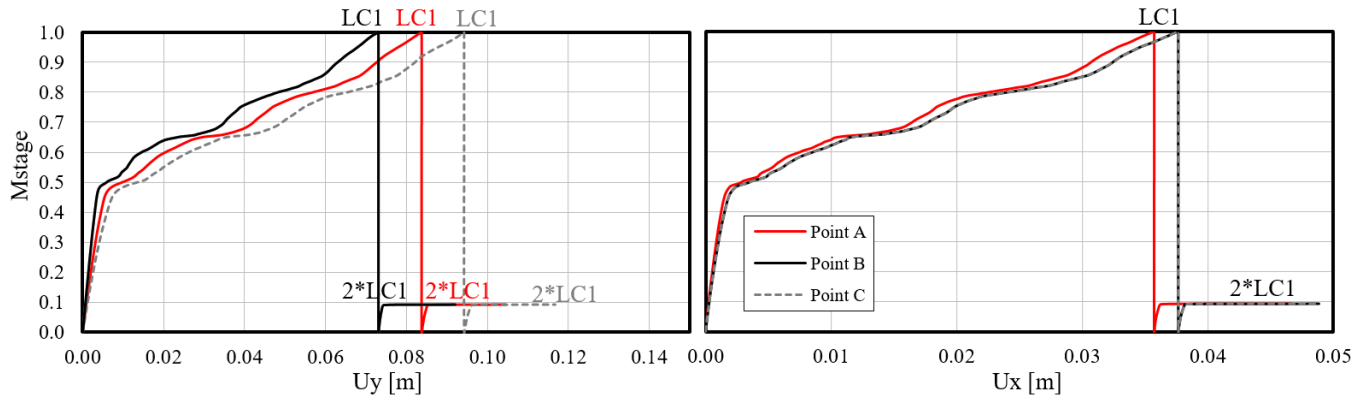*Figure 18 Footing rotation angles for the considered LCs*

Figure 19 LC1, Skirted spudcan load displacement curves for Point A (center), Point B (Left) and Point C (right)
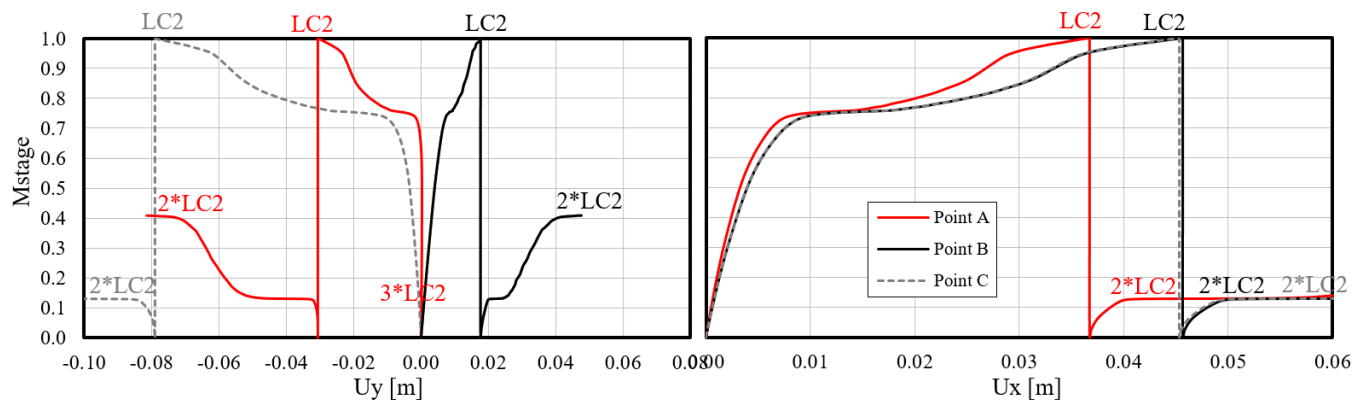

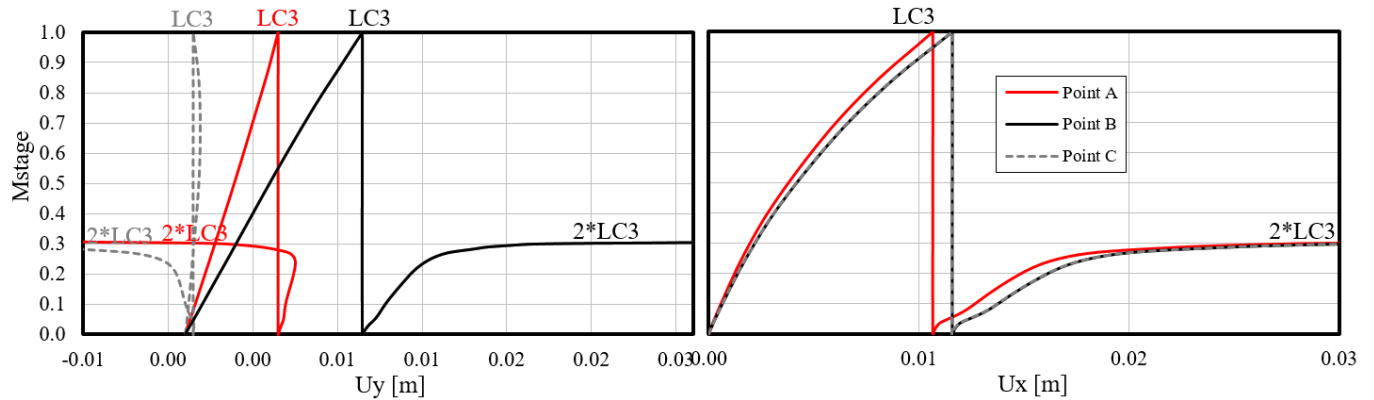*Figure 20 LC2, Skirted spudcan load displacement curves for Point A (center), Point B (Left) and Point C (right)*

Figure 21 LC3, Skirted spudcan load displacement curves for Point A (center), Point B (Left) and Point C (right)

CONCLUSIONS AND DISCUSSIONS

- If skirted spudcans do not reach full base contact, their capacity under combined loading is reduced (compared to the case when they reach full base), as the governing failure mechanisms are developed within the skirt. Modern jack-ups have the facilities needed to overcome this situation by filling with barite the remaining gap, apply suction to help the skirt penetrate more or closing the valves 'trapping' the water inside the gap. However, when these precautions are not possible to be used for different reasons (jack-up does not have these facilities or application of those assets will increase overall cost), the assessment of the partially embedded skirted footing under combined loading, is to be carried out.

- It is known and applied in [1] that in case of partial penetration in sand (full bearing area not mobilized), any additional penetration will result in a significant increase in bearing capacity, due to rapid increase in

the bearing area. To make use of this 'benefit', FE analysis is found as the best approach to model the spudcan and the soil inside the skirt compartments. UM analyses is used to account for additional capacity while the underside of the spudcan gets more contact with the soil.

- The analyses performed include preloading of the spudcan and unloading to Still Water Reaction (SWR), prior to the application of the most critical (V-H-M) LC.

Vertical Loading
- The skirted spudcan (partially penetrated) under preloading conditions will develop a failure pattern as given in Figure 7, Figure 8 and Figure 13.
- While the spudcan penetrates further, a soil heave will develop within the skirt compartments, as seen from 3D analyses in Figure 13 d) and e). The additional vertical capacity that comes due to additional contact area is investigated by large deformation (UM) analyses (spudcan in-placed at 2.5 m of penetration) and by small strain (plastic) analyses (spudcan in-placed at different depths until reaching full base). The results given in Figure 9 show that for additional 10 cm penetration under vertical load, the UM and plastic analyses give the same vertical capacity of about 4300 tonnes/leg. For larger penetrations, UM analyses underestimate the vertical capacity. This is believed to come due to deformation of the mesh elements under the spudcan and therefore limitation of the current modelling tool (Plaxis). Further analyses are expected in the future by applying Abaqus or other FE programs.

Combined (V-H-M) Loading
- The results of FE analyses indicate that due to application of (V-H-M) LCs, additional settlements and rotation of the spudcan occur. The failure mechanism has been seen to be local and developed within the skirt, in all three LCs. However, as LC1 has the largest V-component and the other two LCs have large H and M, the failure mechanism changes from failure at skirt base with local failure around the skirt (LC1) to sliding along base of the skirt and skirt tip (LC1, LC3).
- The foundation bearing capacities indicate that the soil can hold the combined loads, with a minimum safety for LC1 (1.13 2D; 1.34 3D) and larger safety for LC2 and LC3. Considering the results of FE analyses (2D & 3D), a FE (V-H-M) yield envelope has been derived and plotted in Figure 17. This envelope represents the ultimate (V-H-M) yield capacity, derived by considering additional contact area that is developed while the spudcan rotate and penetrate further. The vertical capacity for this additional penetrations is limited to about 5000 tonnes/leg, which is the capacity derived from small strain (plastic) analyses for skirted spudcan in-placed at 2.65 m (15 cm additional vertical penetration).
- Some differences are seen in the results derived from the 2D and 3D analyses, especially for LC1 and LC3, where Plaxis 3D has shown more capacity. One reason for this might be the low order FE element type (10 nodes) used in 3D, and the 3D coarser mesh. In addition, more capacity in 3D might also come due to accurate modelling of the inner skirts, simulated by anchors in 2D.
- The conventional analyses, considering the skirted spudcan as a block embedded footing to penetration 2.5 m (equivalent to assuming the gap filled with heaving seabed sand), has shown much larger capacity for LC1, and similar capacities for LC2 and LC3. As the method assumes a full base spudcan, the failure mechanism doesn't consider failure of the soil within the skirt, but a more general bearing failure, similar to the one from shallow foundations on sand or thick sand over stiff clay.
- The proposed method and the analyses presented in this paper are expected to be applicable for similar situations, jack-ups with skirted spudcans suffering limited penetrations during preloading. The method can help in calculating additional capacity for each of the skirted spudcan legs, (due to expected larger vertical pressure (larger than the applied maximum preload) on the spudcans (generally for aft legs) in the elevated conditions) from the increase of the contact area while the skirted spudcans penetrates deeper. In such a case, if the capacities (V-H-M) capacities are confirmed with satisfactory safety levels, it might be no need for applying barite injection of suction during preloading.
- For the current jack-up rig, the calculated 3D skirted spudcan yield capacities (for gap conditions), and the large conventional capacities (for the assumed filled gaps due to heave of seabed sand, which was

considered possible), were found sufficient for installing the rig, which confirmed skirted spudcan penetrations less than full base contact, similar to the predicted ones.

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