FE skirted footings analyses for combined loads and layered soil profile

Analyses EF des fondations à jupe pour charges combinées et sol stratifié

L. Kellezi & H. Denver
GEO – Danish Geotechnical Institute, Denmark

G. Kudsk & H. Stadsgaard
Maersk Contractors, Denmark

ABSTRACT

FE soil-foundation interaction modelling is carried out in 2D and 3D for a three-leg jack-up skirted footings resting on layered soil conditions consisting of sand overlying clay with varying strength, and subjected to general combined (V-H-M) loadings. As conventional bearing capacity methods are not considered sufficient, 2D and 3D FE footings yield capacities and some correction procedure are discussed for different load combinations emphasizing (V-H) variation and (V-M) variation for rather constant H. Nonlinear footing stiffness /fixity is also investigated. Some experience and recommendations for offshore foundation design are drawn.

RÉSUMÉ

Modélisation 2D et 3D de l'interaction sol-ancrage d'une structure autoélévatrice tripode sur sol stratifié (sable sur couche d'argile de force variable) soumise à des charges générales combinées (V, H et M). Les méthodes classiques étant considérées comme peu fiables, nous examinons les rendements de l'analyse 2D et 3D et la procédure de dimensionnement recommandée pour différentes combinaisons de charge, en mettant l'accent sur la variation des contraintes V et M pour une contrainte H donnée relativement constante. Nous étudions également la rigidité / fixité non-linéaire des fondations. Nous communiquons les connaissances tirées de l'étude et quelques recommandations utiles à la construction des fondations des ouvrages offshore.

Keywords: finite element (FE), skirted spudcan, jack-up structure, yield / ultimate capacity, combined loads

1 INTRODUCTION

Design of offshore foundations is often based on their capacity / integrity under monotonic combined total vertical (V), moment (M) and horizontal (H) load as limiting conditions due to environmental impacts and other factors during the operation.

The present industry guidelines, DNV (1992), SNAME 2002, applicable to offshore foundations are generally based on the theoretical bearing capacity solution for failure of a strip / two-dimensional (2D) footing under vertical load. Alternative foundation geometry, embedment, load inclination and eccentricity, are accounted for by various modification factors and effective / equivalent area method e.g. Hansen (1970), Meyerhof (1980) etc.

However, the conventional approach seems to be not always reliable for conditions when V, H and M loads act together on a three-dimensional (3D) footing geometry located on layered soil conditions, which are often encountered offshore.

Furthermore, jack-up rig foundations are often equipped with outer and inner skirts, which penetrate the seabed during installation confining a soil plug. The skirt enhances additional moment capacity, which increases due to suction developed within the skirt during moment loading.

Skirted footings under combined loadings were numerically investigated by Ukritchon (1998), Bransby and Randolph (1999), Gourvenec (2003) etc. for clay soil with constant and varying undrained shear strength c_u with depth. Byrne et al (2003) carried out laboratory testing for skirted footing on sand. Not much investigation is however, performed for footings resting on sand overlying clay. Kellezi and Stromann (2003) and Kellezi et al (2005a,b), calculated conventionally and numerically bearing capacity during footing penetration and for combined loading in similar soil conditions.

The conventional approach based on the effective footing area A' and bearing capacity for inclined load applied at the centre of A', may underestimate / overestimate footing capacity when the soil profile consists of layered soil.

In such conditions practitioners prefer to apply 2D FE analyses as a fast way to determine ultimate skirted footing capacity and strength. The 3D effects are considered by implementing some kind of scaling procedure, Gourvenec (2003) or correction to M, Kellezi et al (2005b).

Aiming for a more safe design both 2D and 3D finite element (FE) skirted footing-soil interaction analyses under (V, H, M) loadings are carried out for the world's largest jack up foundations in the North Sea. In this paper the differences in the 2D / 3D ultimate capacities, failure mechanisms, nonlinear stiffnesses and conventional approach are discussed.

2 JACK-UP FOUNDATION ANALYSES

Initial structural analyses including weight, environmental loads and soil conditions as expected at the site are carried out. However, foundation fixity or the rotational stiffness of the footings is an important aspect in the overall assessment. Therefore, soil-foundation interaction effect is required in the structural design. The fixity ranges in fact from zero for pinned conditions to fully fixed.

Fixity conditions will significantly affect structure dynamic response. At yield, fixity will influence the structural capacity and therefore the design of foundations and distribution of the forces.

In the following the interpretation of the soil conditions at the jack-up location is carried out first. As FE analyses give upper bound solutions, lower bound soil parameters are considered. For the installation, footing penetration is initially predicted. No risk for punch through / rapid penetration is assessed at the site and full base contact is assumed.

2.1 Footing geometry

The considered jack-up footings have a diameter D = 22 m and are fitted with outer and internal skirts, which divide the spudcan into 6 compartments.

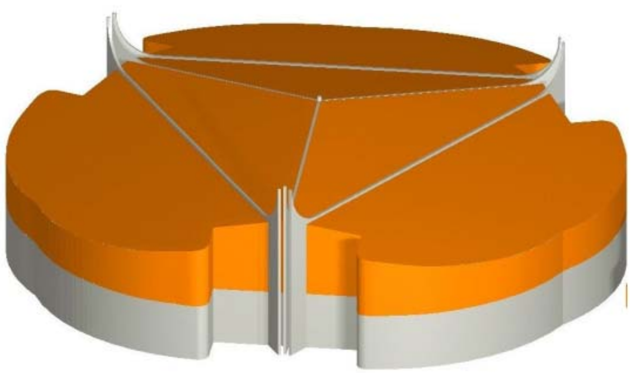

Figure 1. 3D skirted spudcan geometry.

The main vertical geometry of the spudcan structure is: Distance from spudcan base to tip of outer skirts 2.3 m; Distance from spudcan base to tip of internal skirts 1.1 m;

The spudcan itself is a flat rigid plate. A 3D view is given in Figure 1. The transverse stiffnesses of the skirts are derived from the structural FE model of the spudcan. Based on these, equivalent plate thicknesses are calculated for the outer skirt and the internal skirts. These thicknesses are applied in the 2D and 3D FE analyses employing beam and wall structural elements, respectively.

2.2 Soil conditions

The site investigation carried out at the location comprises two continuous cone penetration tests (CPTs), one sampling, borehole (BH) to 30 m depth and laboratory testing.

The soil conditions at the three BH / CPTs appear to be generally similar. They show from the seabed very dense, (relative density D_r > 80%), fine sand with shell fragments and organic material to (10 - 11) m depth. Firm to stiff sandy clay is found below this depth.

The interpreted generalized soil profile with the strength and deformation parameters as applied in the 2D and 3D FE analyses, is given in Table 1. For all soil layers Poison's ratio $\nu = 0.3$ is used. There is gab in the available soil data regarding the Young's modulus E for the clay layers. Therefore, a correlation $E = N*c_u$ has been applied where N the correlation factor is chosen based on the experiences in the North Sea as N = 200.

Table 1. Soil profile applied in the 2D and 3D FE analyses

Soil Type	h (m)	γ' (kN/m^3)	φ (°)	c_u (kN/m^2)	E (kN /m^2)
SAND, very dense.	0.0 – 2.3	10.0	40	-	17500+ 25000*z/m
SAND, very dense	2.3 – 10.5	10.0	40	-	75000
CLAY, stiff	10.5 – 11.2	10.0	-	90	18000
CLAY, stiff	11.2 – 15.0	11.0	-	125	25000
CLAY, stiff to firm	15.0 – 20.0	11.0	-	100	20000
CLAY, firm	20.0 – 27.0	11.0	-	75	15000
CLAY, stiff	27.5 – 30.0	10.0	-	105	21000

2.3 Storm load cases

For the considered jack-up the lightship load is 105 MN / leg and the maximum preload 194 MN / leg. With the weight and buoyancy of the legs and spudcans (no soil plug), approximate pseudo static loads are derived from the structural model where the spudcan and the surrounding soil are modelled as elastic springs, reflecting rotation and displacements.

Final combined pseudo-static storm load types are defined from iterative structural and soil-foundation interaction analyses as shown in Table 2.

The large differences in the V, M loads between the jack-up aft legs (Starboard (ST) and Portside (PS)) and forward (FW) leg is due to the eccentricity of the hull's centre of gravity.

Table 2. Combined loads applied in the 2D and 3D FE analyses

Factored load types (LTs)	V (MN)	H (MN)	M (MNm)
(ST & PS) Aft legs (LT1 & LT2)	105	13.5	500
	190		
FW leg (LT3 & LT4)	45	12.5	365
	75		

2.4 Discussions on the modelling issues

As given in the introduction, conventional bearing capacity methods, where several failure surfaces are analysed in order to find the most critical one have been applied for idealised soil conditions. For layered soil profiles, such as found at the considered location FE method is preferred, employing non-linear constitutive soil models able to seek the critical failure surfaces as part of the analyses.

2D FE modelling was carried out first. As footings showed limited strength and stiffness 3D modelling was performed as alternative. The following phases are calculated: Assessment of the initial stress conditions; Footing installation and preloading to 194 MN; Unloading to 105 MN; Application of quasi-static combined (V, H, M) storm loadings; Assessment of the ultimate H capacity in the (V–H) plane for V constant; Assessment of the ultimate M capacity in the (V–H–M) plane for V, H constant;

2D and 3D FE analyses are carried out with programs Plaxis 2D (2002) and Plaxis 3D (2006). Considering the available geotechnical data, the Mohr Coulomb elastic - plastic constitutive soil model is applied assuming drained conditions for the sand and undrained conditions for the clay soil. Hardening soil model is also applied but not finally chosen, as the current assessment is a lower bound one.

2.4.1 2D FE modelling

In a 2D plane strain FE modelling one commonly used method, DNV (1992), is transforming the footing circular area into a rectangular one with the same area and moment of inertia. Combining these two criteria gives $A = B*L$ where $B = \sqrt{3}*R$ and $L = \pi*R/\sqrt{3}$. 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 as shown in Figure 2.

Triangular 6-noded finite elements are used to discrete the soil and the spudcan modelled as a rigid weightless (elastic, non-porous) body. The FE mesh is designed as shown in Figure 2. At the footing-soil contact area interface elements with reduced strength are implemented.

The 2D FE analyses provide in general quick results but tend to underestimate capacities and stiffnesses due to representation of the circular spudcan by a strip footing. The beneficial effects of the skirts cannot be accurately accounted for.

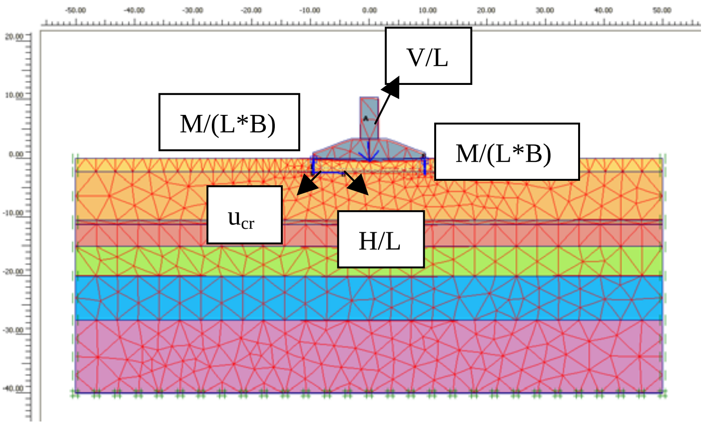

Figure 2. 2D FE soil- skirted spudcan model

2.4.2 3D FE modelling

In the 3D FE analyses the skirted spudcan is modelled as shown in Figure 3, very similar to the real footing geometry given in Figure 1. Plate structural elements are used for the spudcan with an average thickness allowing full base contact with the seabed soil, and wall structural elements are applied for the outer, inner and middle skirts with the lengths and thicknesses as given in section 2.1.

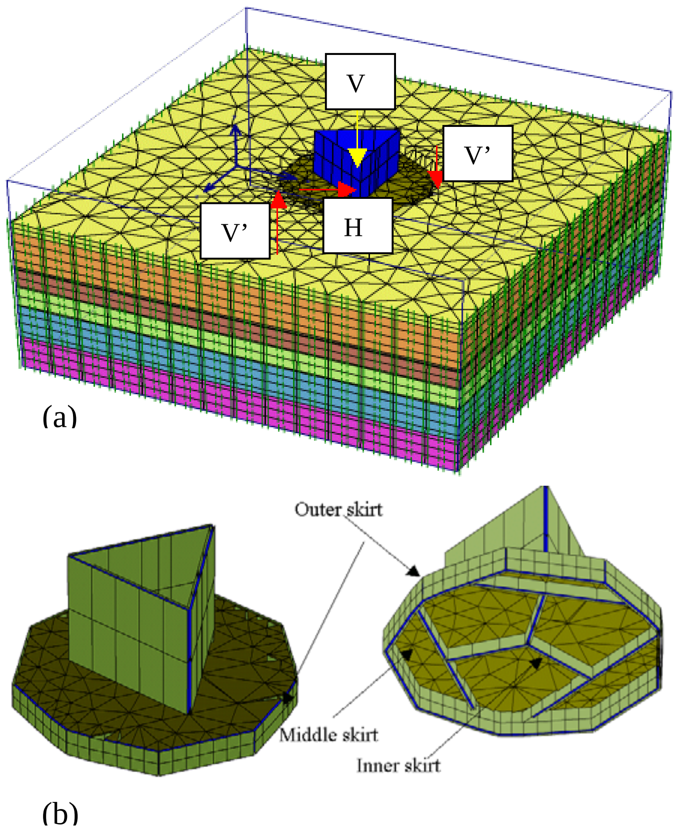

Figure 3. (a) 3D FE soil-skirted spudcan model (b) 3D skirted spudcan in two different views.

The 3D FE model is built up in horizontal planes, whose elevations correspond to the start and the end of the footing elements in the y-direction. Tetrahedron 15-noded finite elements are used to discrete the soil. Some strength reduction in the footing-soil interface is included. The combined loads are applied as given in Figure 3. Standard boundary conditions are incorporated at the far field. The size of the model in the two horizontal and the vertical directions is chosen so that the boundaries will not affect the full development of the failure mechanisms.

2.5 Critical suction in the FE analyses,

In the current FE analyses an effort is made to implement the suction effect based on the critical suction value, which is a theoretical parameter only valid for frictional materials as found at the considered location.

For large diameter footings, such as the current one, a simple approach is to assume the skirt tip is a sheet pile wall. A point of interest is the exit gradient, where the seeping water emerges behind the wall. Hansen (1978) estimated the normalized critical suction as $u_{cr}=\pi*H*\gamma'$ where H is the skirt length. Based upon axisymmetric numerical steady state flow solutions with $H/D < 0.5$ the equation $u_{cr}=H*\gamma'/(1.0 - 0.68/(1.46*H/D+1))$ is proposed by Clausen and Tjelta (1996).

Based on the above, the suction effect in the FE footing-soil analyses under combined loading is approximated by applying a distributed load equal to $u_{cr} = 3*2.3*10 = 69$ kPa at the level of outer skirt tip on the tension side of the footing as in Figure 2. The width in 2D or the area of the applied suction load in 3D is a function of the eccentricity value e and is equal to 2e and A-A' respectively considering the LTs in Table 2.

3 RESULTS FROM FOOTING-SOIL ANALYSES

For the four combined LTs the FE calculated ultimate / yield capacities for H and M loads are shown in Table 3. These values correspond to α=1, DNV (1992), which means that those are the maximum loads footings can resist disregarding any deformation criterion.

The failure mechanisms in 2D and 3D are given in Figure 4-7 for the two chosen extreme load combinations LT2 (small eccentricity, $e = M/V = 2.65$ m $< 0.3*\sqrt{A}$) and LT3 (large eccentricity, $e = M/V = 8.1\text{m} > 0.3*\sqrt{A}$), considering foundation sliding and rotation, respectively. The differences in 2D and 3D yield capacities are due to the differences in the failure mechanisms, which are large for LT2 compared to LT3. Typical failure modes encountered are: Sliding along the stiff clay layer below the sand; Deep-seated failures governed by moment equilibrium with centre located anywhere; Sliding along base of skirt tip; Sliding at base with local failure around skirt tips; etc.

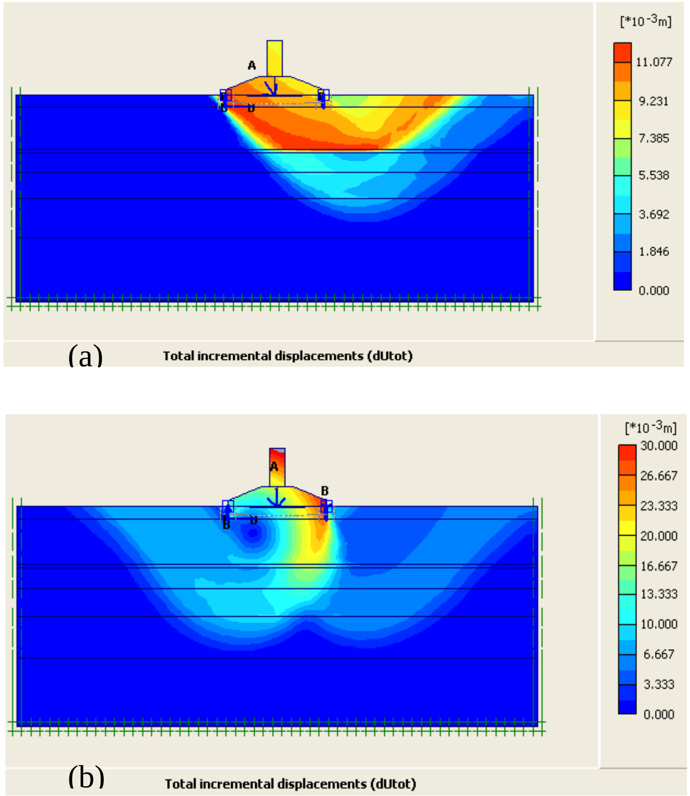

Figure 4. LT2. (a) 2D FE sliding failure figure (b) 2D FE moment failure figure

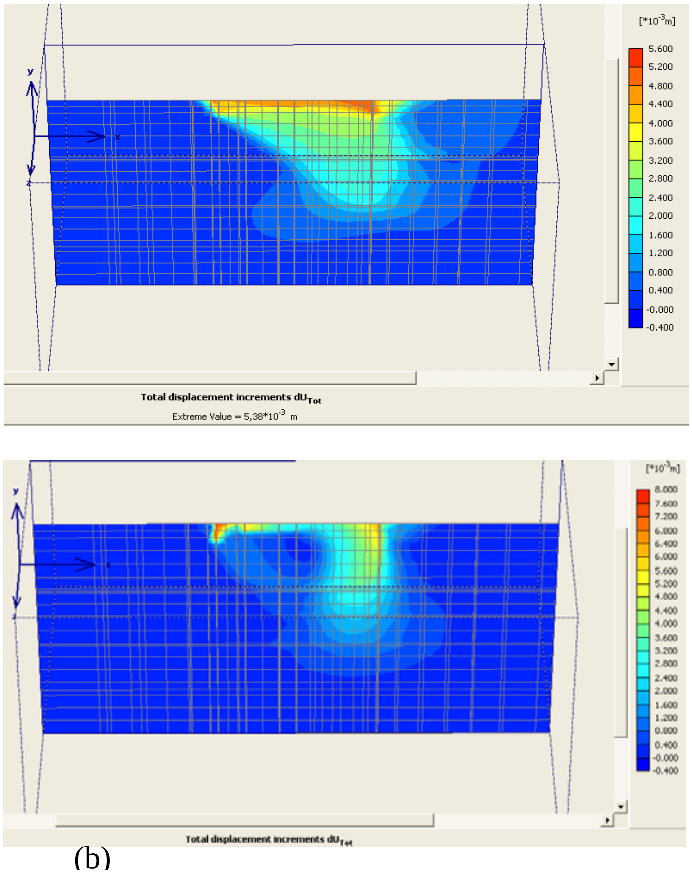

Figure 5. LT2 (a) 3D FE sliding failure figure (b) 3D FE moment failure figure

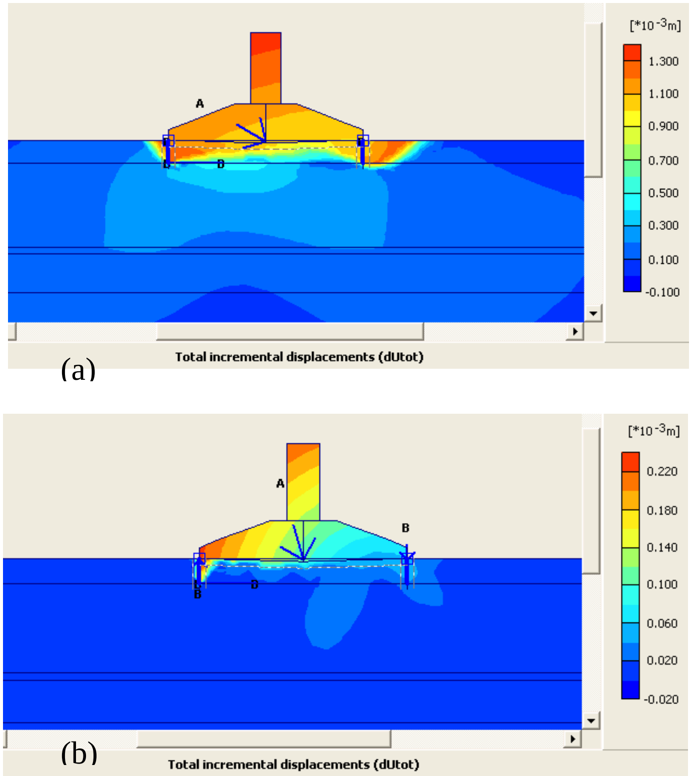

Figure 6. LT3 (a) 2D FE sliding failure mechanism (b) 2D FE moment failure mechanism

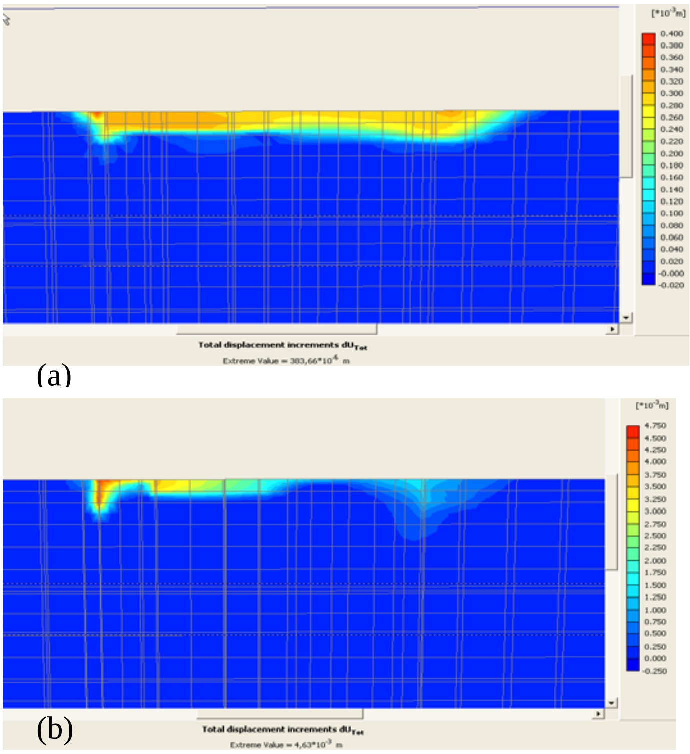

Figure 7. LT3 (a) 3D FE sliding failure mechanism (b) 3D FE moment failure mechanism

The results in Table 3 are plotted in Figure 8 representing part of the (V-H) and (V-M) envelopes in 2D and 3D, respectively. The footings load fall inside the envelopes. The 3D capacities are larger than 2D. For LTs where the failure figure is located at the footing area the difference is about 10%. For deep failure figures the differences are up to 40 %.

Results from conventional bearing capacity, modified Hansen (1970), are also included assuming a block / embedded footing, confined by the skirt, resting on sand over clay (with c_u = 100 kPa) profile.

Table 3. 2D and 3D FE yield capacities

(LTs)	V (MN)	H_{yield} (MN)		M_{yield} (MNm)	
		2D	3D	2D	3D
Aft LT1	105	85	91	(H = 13.5 MN)	
				810	880
AFT LT2	190	80	143	(H = 13.5 MN)	
				1005	1465
FW (LT3)	45	43	48	(H = 12.5 MN)	
				365	460
FW LT4	75	64	71	(H = 12.5 MN)	
				610	730

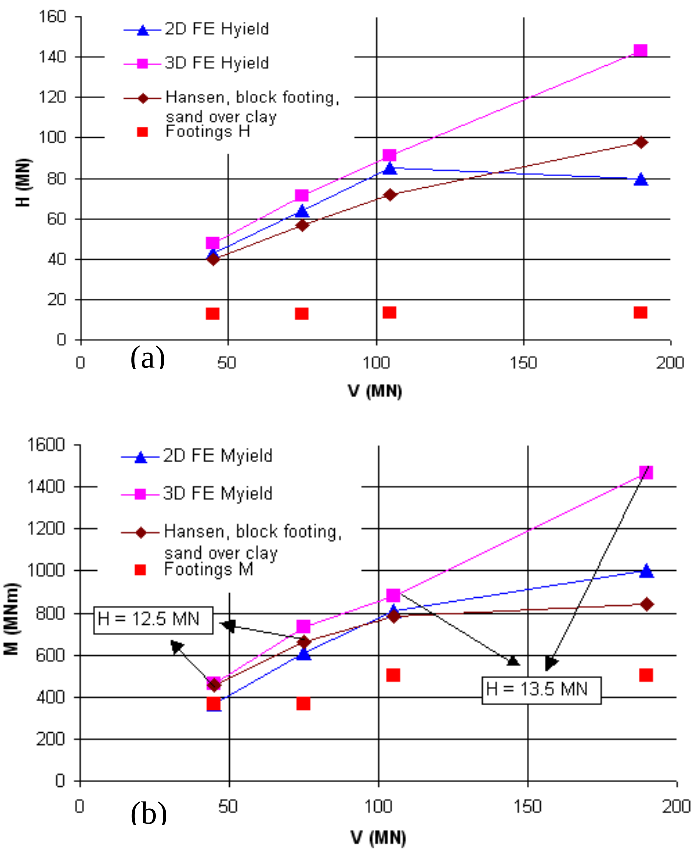

Figure 8. (a) FE ultimate sliding capacity (b) FE ultimate moment capacity

2.6 Footing-soil nonlinear stiffness

The horizontal, vertical and the rotational foundation stiffness, applied in the structural analyses, are derived direct from the 2D and 3D FE soil-footing modelling. The vertical stiffnesses (force displacement curves) for LT3 are for illustration given in Figure 9. The rotation stiffness, which together with M comprise footing fixity, is derived from the vertical stiffnesses for the left and the right points in the footing circumference. As noted from Figure 9 the 3D stiffness differs from the 2D one and both are mesh and deformation parameters dependent.

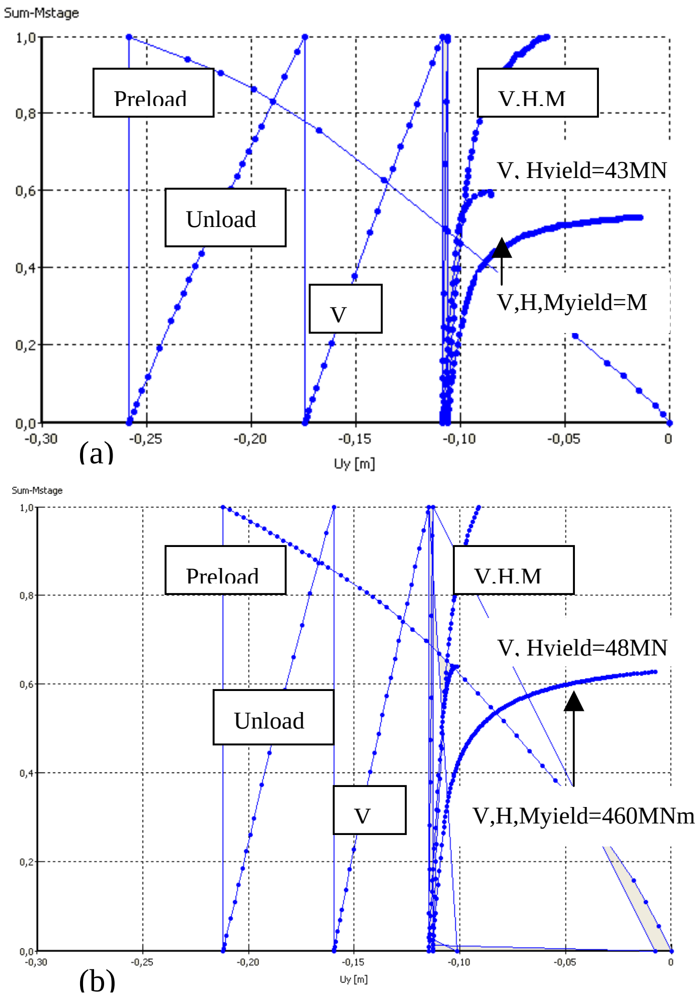

Figure 9 LT3 (a) 2D FE vertical stiffness (b) 3D FE vertical stiffness

CONCLUSIONS

2D and 3D FE soil-skirted foundation interaction modelling under four general combined LTs is carried out for a jack-up rig in the North Sea. The soil conditions consist of very dense sand overlying firm / stiff clay with varying strength.

As expected, 2D FE analyses give conservative ultimate capacities and stiffnesses compared to the 3D ones. However, the differences in the capacities are marginal when 2D failure mechanism is located at the footing area. In this case the 3D effect could be included by multiplying the 2D capacities by a correction / shape factor $F_c = (1.05 – 1.20)$. For deep failure mechanism the 3D capacities are significantly larger than 2D, about 40 %.

These results are valid for the current analyses and cannot be generalized. The yield capacities are not strongly dependent of the mesh refinement. The stiffnesses though are meshing dependent and should be evaluated by an experienced engineer.

The current analyses take into account the operational loads for the considered jack-up and are focused on the variation in (V-H) and (V-M) planes.

Conventional analyses applied for block / embedded footings and a soil profile consisting of the seabed sand overlying clay with constant c_u give yield capacities close to 2D or 3D FE analyses depending on the (V-H) and (V-M) variation and the applied clay strength.

Based on the above, 2D FE analyses are recommended for initial design of jack-up skirted footings resting on layered soil profile. Depending on the developed failure mechanism (shallow / deep) application of the correction factors or 3D FE soil-foundation interaction modelling is recommended for the final design.

ACKNOWLEDGEMENT

The authors are grateful to Marine Structure Consultants, the Netherlands for calculation of the jack-up footings combined loads.

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