Influence of jack-up footprints on mudmat stability – How beneficial are 3D effects?

Influence des dépressions laissées par les jack-ups sur la capacité portante des mudmats – quels sont les effets bénéfiques d'une analyse en 3D?

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ABSTRACT: Jacket platforms are piled into the seabed but need to be supported temporarily by mudmats during installation. They sometimes need to be located next to seabed features such as pug marks formed by previous deployments of jack-up rigs. These features may influence the bearing capacity of the mudmats. This is a 3D problem for which simplified approaches are unsatisfactory, simplified 2D plane strain simulations can lead to over-conservative results. This paper presents a project example in very soft clay for which the software package Plaxis 3D has been successfully used. The presence of a pug mark was found to degrade significantly the yield surface in the VHM load space. A comparison between 2D and 3D analyses shows that the beneficial 3D effects are substantial, especially when the pug mark is located at the corner of the mudmat. The zone of influence of the pug mark is also much more limited when the problem is modelled in 3D.

RÉSUMÉ : Les platesformes de type « Jacket » sont fondées sur pieux mais nécessitent d'être supportées temporairement pendant l'installation par des mudmats (fondations de type superficiel). Ces jackets sont parfois situées à proximité de dépressions laissées par l'installation antérieure de jack-ups. Ces dépressions peuvent influencer la capacité portante des mudmats. Il s'agit d'un problème 3D typique pour lequel aucune solution simplifiée n'existe. Une approche 2D (en état plan de déformation) peut même mener à des résultats trop conservatifs. Cet article présente un exemple dans de l'argile molle pour lequel la suite de logiciels Plaxis a été utilisée avec succès. Les conclusions sont les suivantes : la présence des dépressions modifie singulièrement la surface de rupture dans l'espace VHM. Une comparaison entre les approches 2D et 3D montre que les avantages à faire appel au 3D sont substantiels, spécialement quand la dépression est située à proximité du coin du mudmat. La zone d'influence de la dépression est aussi bien plus limitée lorsque le problème est modélisé en 3D.

KEYWORDS: Pug mark, mudmat, stability, VHM, 2D, 3D, Finite Element Analysis, soft clay, remoulded, jack-up, mesh

1 INTRODUCTION

Jacket platforms are the most common type of offshore structure in the offshore hydrocarbons industry (Dean, 2010). They consist of open-framed steel structures made of tubular leg chords, horizontal bracing, and diagonal bracing. These structures are piled into the seabed but need to be supported temporarily by mudmats during installation. Mudmats are essentially flat stiffened metal plates attached to legs or the lower braces. In soft soils, mudmats can cover the entire surface between the legs to maximise the bearing area. They are generally subjected to combined Vertical, Horizontal and Moment (VHM) loads induced by the jacket weight, wind, waves and currents.

Jacket platforms are not always installed on a virgin seabed and are sometimes located next to features such as pug marks formed by previous deployments of jack-up rigs. A jack-up is a mobile, self-elevating offshore platform consisting of a hull and three or more retractable legs passing through the hull (McClelland et al, 1982). A unit moves onto location, sets its legs onto the seabed, and raises its hull out of the water. The legs are supported on independent foundations called spudcans. Penetration and extraction of spudcans in soft grounds create zones of remoulded soil and seabed depressions (Hossain et al, 2012). These seabed features potentially influence the bearing capacity of the mudmats and need to be accounted for in the stability verification.

Mudmats subjected to combined VHM loads and located next to a jack-up footprint is a 3D problem for which simplified approaches for analysis do not exist. Simplified 2D plane strain simulations are generally performed but they can lead to over-conservative results. This type of problem is better analysed by means of 3D Finite Element (FE) analyses.

This paper presents a project example in very soft clay for which the software package Plaxis 3D (Plaxis, 2011) has been used successfully. The analysis allowed confidence to be established for the selected location of the mudmat with respect to a pug mark. In contrast, a simplified 2D analysis suggested that the proximity of the mudmat to the pug mark was unacceptable.

It is shown for this particular example how the presence of a pug mark degrades the yield surface in the VHM load space. 3D analyses are compared with 2D analyses to quantify the beneficial 3D effects for different pug mark locations.

2 PROBLEM GEOMETRY AND SOIL CONDITIONS

A 30 m by 30 m square mudmat is considered. The mudmat is located next to a circular pug mark of 30 m in diameter. Analyses were performed for 2 positions of the mudmat. The first position considers a pug mark located along the width of the mudmat while the second position considers a pug mark located at the corner of the mudmat, as illustrated on Figure 1. The distance d between the edges of the mudmat and the pug mark is varied in the analysis.

Soil conditions in this example consist of very soft clay. The soft deposit is considered to be 15 m thick and underlain by stiffer soils, which are not modelled. The intact undrained shear strength increases linearly with depth according to $s_u = 4 + 0.8z$ (in kPa), where z is the depth below ground level in meter. This gives a strength heterogeneity $\kappa = 6$ where $\kappa = kB/s_{u0}$, k is the shear strength gradient, B the mudmat width and s_{u0} the undrained shear strength at mudline.

A cylinder of soil with remoulded properties is considered to model the pug mark. This cylinder extends to the bottom of the soft layer. A 30 m diameter cylinder corresponds approximately to a 15 m diameter spudcan. The remoulded zone created by the penetration and extraction of a spudcan has indeed been observed to be of the order of 2 times the spudcan diameter (Hossain, 2012). On removal of the jack-up unit, the spudcans leave depressions at the site. The depth and configuration of the depression depends on several factors including soil strength, spudcan final penetration, amount of soil backfill during installation, etc. A seabed depression of 2m is considered in this paper. To keep the model geometry simple, a horizontal depression with vertical walls is modelled, as illustrated on Figure 1. A remoulded undrained shear strength profile s_{ur} = 2 + 0.4z (in kPa), where z is the depth in meter below original ground level, is considered within the pug mark area.

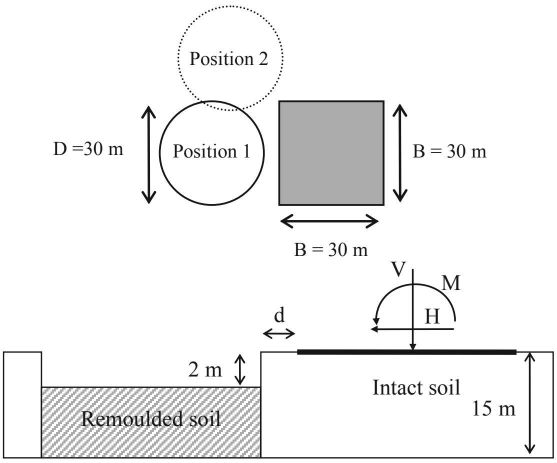

Figure 1. Problem geometry: plan view and cross-section

3 FINITE ELEMENT MODEL

2D plane strain and 3D FE simulations were carried out using Plaxis (Plaxis, 2011). The 2D analyses only consider a pug mark along the width of the mudmat while the 3D analyses consider two positions for the pug mark: along the width and at the corner.

An example of 3D finite element mesh is shown on Figure 2. Similar mesh discretization was adopted for the different analyses. The external boundaries were set sufficiently remote so as not to intercept the different failure mechanisms.

Preliminary analyses were first performed for the base case without a pug mark and for which analytical and/or numerical solutions exist. The aim was to check for any effects due to mesh size on the accuracy of the solution. A compromise was found between the accuracy of the solution and computational time. It is estimated that the over-estimation of the true solution due to discretization errors was maximum 10% for the selected mesh, which was judged to be reasonable.

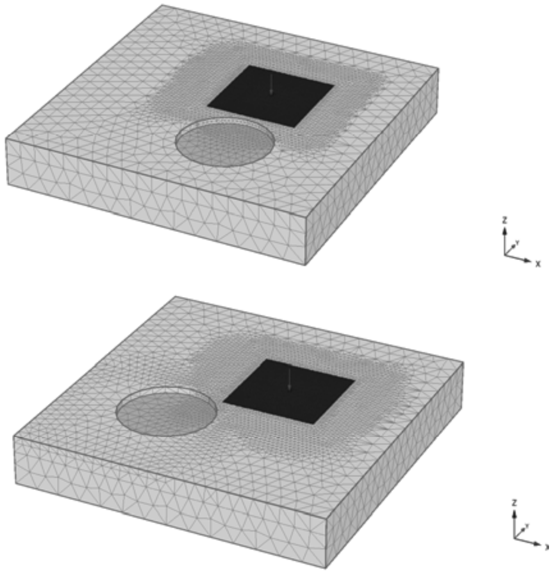

Figure 2. 3D Finite Element meshes

The soil is modelled as an isotropic elasto-perfectly plastic continuum, with failure described by the Mohr-Coulomb yield criterion. It is assumed to behave "undrained" and is characterized by a cohesion equal to the undrained shear strength s_u with ϕ_u=0. The elastic behaviour was defined by a Poisson's ratio ν=0.495, and a constant ratio of Young's modulus to undrained shear strength E/s_u=300 for both undisturbed and remoulded clays.

The strength of the mudmat/clay interface is modelled using an interface factor α, where the maximum shear stress at the interface $\tau_{max} = \alpha s_u$. The "rough" and "smooth extremes of interface strength correspond to α = 1 and α = 0 respectively. An intermediate roughness was assumed with α = 0.5, which is a typical assumption for steel/soft clay interface. A no-tension condition allowing separation of the mudmat from the seabed was permitted at the mudmat/clay interface.

The jacket mudmat is modelled as a 30 m by 30 m rigid plain square plate. The seabed is assumed to be perfectly flat below the mudmat.

4 DESIGN PROCESS

The vertical load V from the mudmat and jacket structure is generally known and well-defined. It should typically be limited to a maximum of 50% the uniaxial vertical capacity. Then, for a given mobilisation ratio of the uniaxial vertical capacity $v = V/V_{ult}$, the stability verification consists of ensuring that there is adequate factor of safety on the 'live' loading M and H. This can be performed by comparing design load combinations to the MH failure envelope. The higher the mobilisation of the uniaxial vertical capacity, the lower the moment and horizontal capacity, i.e. the MH failure envelope shrinks with increasing v. M and H loads are applied in the direction of the pug mark centre, namely perpendicular to the side of the mudmat or along its diagonal.

The presence of a pug mark with remoulded soil conditions in the vicinity of a mudmat has two adverse effects. First, it affects the moment and horizontal capacities for a given v. Second, it reduces V_{ult} and therefore increases v, reducing further the moment and horizontal capacities.

5 RESULTS AND DISCUSSION

5.1 2D Analyses

The accuracy of the 2D FE model was verified by computing the uniaxial vertical capacity and comparing with results published in the literature. An interface factor at the mudmat/soil interface $\alpha = 1$ was assumed for this comparison. A normalized vertical capacity $V_{ult}/s_{uo}B = 10.45$ was found. This compares well with the analyses results published by Salgado (2008) who found 10.42 using ABC program (Martin, 2004). When the interface factor is reduced to $\alpha = 0.5$, the vertical capacity $V_{ult}/s_{uo}B$ reduces to 9.8.

The MH failure envelope for the case without pug mark is shown on Figure 3 assuming a vertical load V so that v = 0.4, which is equivalent to a safety factor of 2.5 on the uniaxial vertical capacity. The results are plotted in a non-dimensional way: $M/s_{uo}B^2$ versus $H/s_{uo}B$. This case is for an inter-distance d = 2 m (i.e. d/B = 0.07).

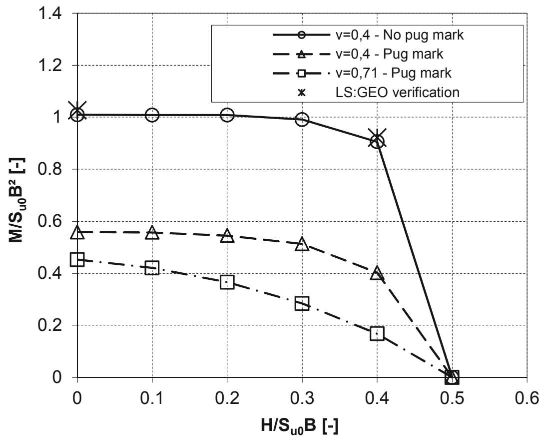

Figure 3. Influence of pug mark on MH failure envelope

A few comparison runs were performed with Limitstate:Geo v2 (Limistate, 2009). Limitstate:Geo is designed to analyze the ultimate limit (or "collapse") state for a wide variety of geotechnical problems. The current version is however limited to 2D plane strain analyses. The ultimate limit state is determined using the Discontinuity Layout Optimization (DLO) algorithm (Smith & Gilbert, 2007). The agreement with the FE results is found to be excellent.

The effect of the pug mark on the MH failure envelope is significant. The normalized uniaxial vertical capacity $V_{ult}/s_{uo}B$ is reduced to 5.5 leading to a mobilisation ratio v = 0.71 instead of 0.4 (i.e. a safety factor of 1.4 instead of 2.5). The moment capacity is reduced by 55% to 80% depending on the applied horizontal load.

The inter-distance between the mudmat and the pug mark was then progressively increased and results are presented on Figure 4. The maximum moment capacity increases progressively with the inter-distance towards the capacity obtained for the case without a pug mark. From an inter-distance d/B = 0.2, the difference in mobilisation ratio of the vertical capacity does not affect the maximum moment capacity and, at an inter-distance d/B = 0.5, the pug mark has no effect at all.

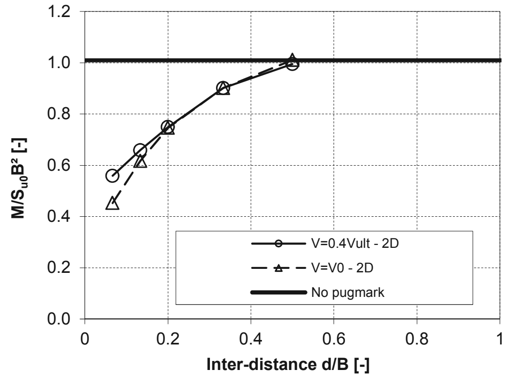

Figure 4. Influence of pugmark / mudmat inter-distance on maximum moment capacity – 2D analyses

5.2 3D Analyses

The accuracy of the 3D FE model was also checked by computing the uniaxial vertical capacity for a square footing resting on soft clay, with s_u constant with depth and $\alpha = 1$, and comparing with available literature results. A normalized vertical capacity $V_{ult}/s_{uo}B^2 = 5.96$ was found. This compares well with the results published by Gourvenec et al. (2006) who found 6.02. When the interface factor is reduced to $\alpha = 0.5$ and s_u increases with depth (as defined in Section 2), the vertical capacity $V_{ult}/s_{uo}B^2$ is about 9.1, which is slightly lower that the 2D plane strain capacity.

Similarly to the 2D plane strain FE analyses, the MH failure envelope for the case without a pug mark assumes a vertical load V so that v = 0.4. As discussed above and shown on Figure 1, the 3D analyses consider two positions for the pug mark: along the width and at the corner of the mudmat. The results are plotted on Figures 5 and 6 for the first and second positions, respectively, using the following non-dimensional groups: $M/s_{uo}B^3$ and $H/s_{uo}B^2$. This case is for an inter-distance d = 2 m (i.e. d/B = 0.07). The moment capacity is not affected for small mobilisation ratios of the horizontal capacity. However, when $H/s_{uo}B$ approaches 0.5, the failure mechanism switches rapidly from a general shear mechanism to a sliding mechanism.

For the first position (along the width), the effect of the pug mark on the MH failure envelope is noticeable but not as significant as for the 2D plane strain simulations. The normalized uniaxial vertical capacity $V_{ult}/s_{uo}B^2$ is reduced to only 8.4 leading to a mobilisation ratio v = 0.44 instead of 0.4 (i.e. a safety factor of 2.29). The moment capacity is reduced by 20% to 28% depending on the applied horizontal load. There is very little difference in the results between a vertical mobilisation factor of 0.4 and 0.44 (Figure 5).

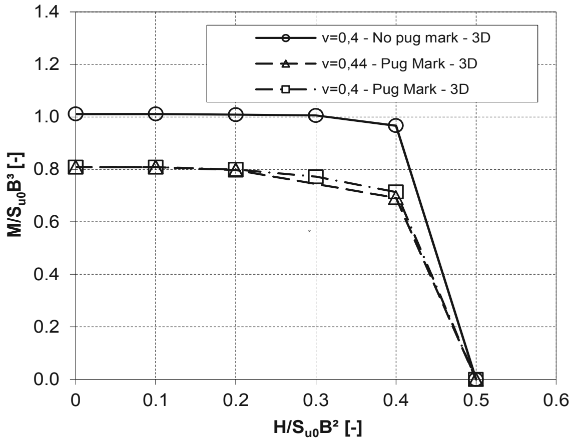

Figure 5. Influence of pug mark on MH failure envelope – Position 1 (along width of mudmat)

For the second position (at the corner), the normalized uniaxial vertical capacity is not affected, meaning that the safety factor for a pure vertical load remains 2.5. The moment capacity is only reduced by 1 to 3 % (Figure 6) depending on the applied horizontal load. This is a negligible difference.

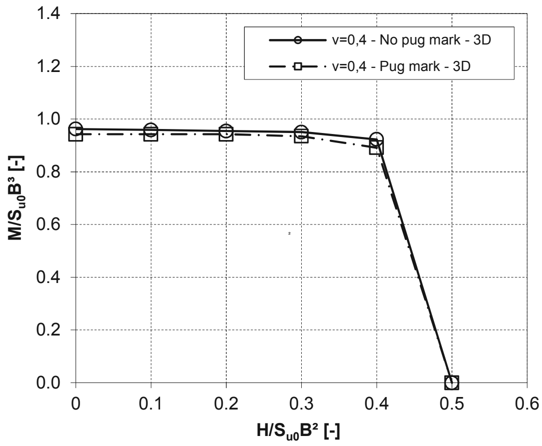

Figure 6. Influence of pug mark on MH failure envelope – Position 2 (at mudmat corner)

Similarly to the 2D plane strain approach, the inter-distance between the mudmat and the pug mark was progressively increased for the position of the pugmark along the width of the mudmat and the results are presented on Figure 7. The maximum moment capacity increases progressively with the inter-distance towards the capacity obtained for the case without pug mark. From an inter-distance d/B = 0.25, the pug mark has no effect anymore. This result illustrates the benefit of considering a more realistic 3D analysis when facing this kind of problem. The inter-distance required to have no influence of the pug mark in the 3D model is half the inter-distance required in the 2D plane strain model.

Finally, Figures 5 and 6 allow the comparison of the effect of the orientation of the moment and the horizontal loads on the MH envelope. The moment capacity for the loads in the direction of the corner is about 5% lower than for the case where the loads are towards the width of the mudmat. This geometrical effect is however limited.

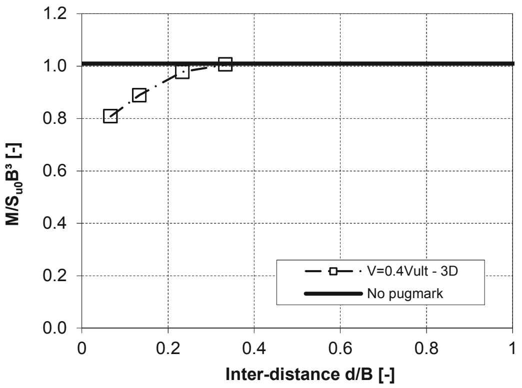

Figure 7. Influence of pugmark / mudmat inter-distance on maximum moment capacity – 3D analyses

5.3 Conservativeness of 2D Analyses

Simplified 2D plane strain and more realistic 3D simulations give similar results if the pug mark is not considered.

In the case where the pug mark is located along the width of the mudmat, the MH failure envelope is degraded in both 2D and 3D analyses. However, the effect is significantly larger in the 2D analyses for which the moment capacity is reduced by 55% to 80% depending on the applied horizontal load. In the more realistic 3D analyses, the moment capacity is only reduced by 20 to 28%. When the pug mark is located at the corner of the mudmat, the 3D analyses show very little impact on the mudmat capacity.

The analyses show also that the distance of influence of the pug mark on the mudmat stability is 2 times less in 3D compared to 2D analyses. The maximum moment capacity is not affected from an inter-distance d/B = 0.25 in 3D analyses while the distance is d/B = 0.5 in 2D analyses.

1 CONCLUSION

The presence of a pug mark has been found to degrade significantly the yield surface of a square mudmat in the VHM load space. However, a comparison between simplified 2D plane strain and 3D analyses has shown that the beneficial 3D effects are substantial. If the pug mark is located along the width of the mudmat, the more realistic 3D model shows that the moment capacity is only reduced by 20 to 28% depending on the applied horizontal load. The impact of the pug mark is significantly larger when a more simplified 2D plane strain approach is followed. Moreover, in the particular example treated in this paper, it was observed that a pug mark located at the corner of the mudmat does not influence its stability. The zone of influence of the pug mark is also much more limited when the problem is modeled in 3D and the orientation of a complex VHM loading scheme can be considered in the global stability. Simplified 2D plane strain simulations can lead to over-conservative results for this particular problem.

6 ACKNOWLEDGEMENTS

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