Effective-Stress Finite Element Analysis of Spudcan Penetration with Lattice Leg in Clay

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Abstract. An undrained effective-stress method was adopted to examine the pore pressure response by spudcan penetration with and without lattice leg. Coupled Eulerian-Lagrangian analysis technique was conducted using ABAQUS/Explicit v6.11. For spudcan penetration with lattice leg, the computed excess pore pressure at spudcan base shows good agreement with centrifuge experimental results. The comparison result verifies and extends the feasibility of this effective-stress finite element method, in which lattice leg is taken into account. Larger excess pore pressure is found to be developed by the involvement of lattice leg. The soil strength is also shown to influence the pore pressure response.

Keywords: Excess pore pressure, lattice leg, spudcan.
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INTRODUCTION

In offshore exploration and short-term drilling, jack-up rigs are commonly employed. Due to its ability to deploy rapidly, low cost and construction flexibility in the relatively shallow water depth, mobile jack-up rigs have been used extensively in the offshore oil and gas exploration since its first use in 1954. As shown in FIGURE 1, the mobile jack-up rig is usually supported by legs resting on individual foundations known as spudcans. The legs are typically designed as open truss structures, known hereafter as lattice legs. Up to know, the spudcan foundation behavior has been extensively examined. However, the lattice leg influence on the foundation behavior are rarely reported. In this paper, the effect of lattice leg on pore pressure response is further investigated using finite element method, and compared with existing centrifuge experimental results.

Numerical modeling method has been increasingly used to simulate continuous spudcan penetration [1-3], in which the large soil deformation problems are well solved. A practical method was developed by Hu and Randolph [1], in terms of Arbitrary Lagrangian-Eulerican (ALE) concept. In this method, fully automatic remeshing and plane linear stress interpolation techniques are coupled with conventional infinitesimal strain finite element method. Coupled Eulerian-Lagrangian analysis was performed by Tho et al. [3] to model large soil deformation induced by spudcan penetration in clay deposits. However, all these methods are based on total stress analysis, without pore pressure computation.

Great efforts have been made to identify the pore pressure response by spudcan penetration by Dean [4] and Zhou [5]. However, the spudcan footing is assumed to be wished-in-place at prescribed depth, which turns out to be small strain problem and cannot model the real large soil deformation by continuous spudcan penetration.

An undrained effective-stress Eulerian finite element analysis was developed by Yi et al. [6]. This method allows the pore pressure to be computed with continuous spudcan penetration. In the finite element analysis, the soil behavior is defined by effective stress constitutive models. A user defined material subroutine VUMAT is developed by Yi et al. (2012) and linked to constitutive models. Computation results show that Eulerian formulation is stable for the effective stress constitutive models. The computed load-penetration response and pore water pressure is shown to be reasonable in comparison with centrifuge model test results. However, the continuous spudcan penetration is simulated without lattice leg, which is obviously not the case in offshore jack-up spudcan foundation.

Hence, in this paper, the effective-stress finite element method by Yi et al. [6] is used to further identify the pore pressure response by spudcan penetration, in which spudcans are equipped with and without lattice leg. The computed excess pore pressure by spudcan penetration with lattice leg is compared with centrifuge experimental results.

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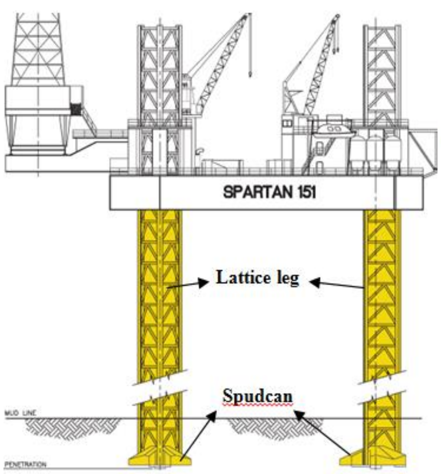
NUMERICAL TECHNIQUE AND FINITE ELEMENT MODEL

Undrained effective-stress finite element analysis using ABAQUS/Explicit was performed to simulate continuous spudcan penetration. Modified Cam-clay model was used to simulate the soil behavior. The soil was assumed to be isotropic and homogeneous; the Malaysia kaolin clay properties adopted in modified Cam-clay model are summarized in Table 1. This is based on physical properties test on kaolin clay by Goh [7]. More details on the numerical modeling technique especially the computation of excess pore pressure could be found in Yi. et al. [6].

The geometry of the three-dimensional finite element model is shown in FIGURE 2; spudcans are equipped with and without lattice leg. Lattice leg was idealized into circular leg with big gaps in between to simulate its big opening (case II). For the purpose of computational efficiency, only one quarter spudcan and soil was modeled, by virtue of its symmetry. A body of soil (30 m in radial extent and 27m in depth) was modeled as Eulearian domain. A 9m thick layer of void Eulerian elements were used above the soil surface to allow for potential soil heave and subsequent flow behavior. The model spudcan footing and lattice leg, on the other hand, were modeled as a rigid Lagrangian body with infinite stiffness. The soil-spudcan interface was automatically computed and tracked using Eulerian-Lagrangian contact algorithm. General contact and defaults were applied to implement the Eulerian-Lagrangian contact, wherein the tensile stresses were not transmitted along its contact interface, and the interface was assumed to be frictionless. The spudcan-soil friction was not taken into account as it was computed based on total stress in ABAQUS/Explicit, which is in conflict with the effective stress method adopted in this finite element analysis. Moreover, the model spudcan employed in current centrifuge test is sufficiently polished and is then assumed to be relatively smooth. Hence, smooth spudcan-soil interface simplification seems to be reasonable.

At the initial step of the analysis, spudcan footing was suspended above the soil domain with geostatic stress field specified. With the subsequent step, the instantaneous self-weight of the soil domain was applied at the beginning iteration, which is in equilibrium with the geostatic stress field. Spudcan footing was then slowly penetrated into soil until the prescribed depth.



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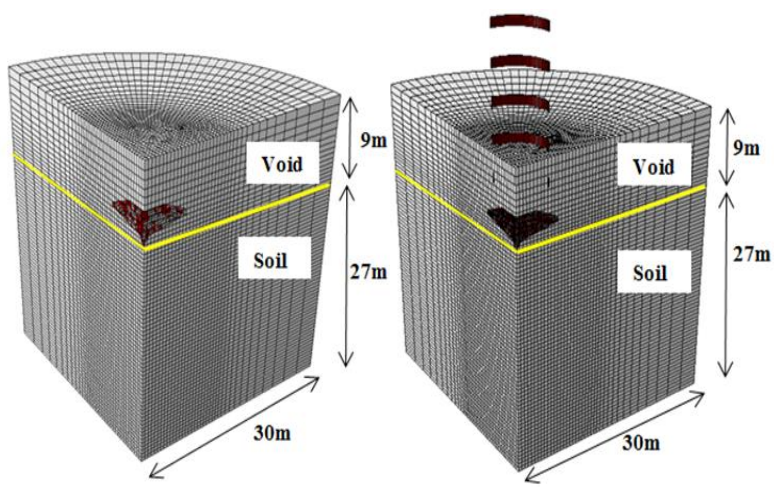

(a) Case I, no leg (b) case II, with lattice leg

FIGURE 1. Mobile offshore jack-up rig

FIGURE 2. FEM model

TABLE (1). Properties of Malaysia kaolin clay adopted in modified Cam-clay model (after Goh 2003)

Properties	Values
Slope of critical state line	0.9
Slope of isotropic normal compression line	0.244
Slope of isotropic swelling and recompression line	0.0523
Specific volume of soil	3.221
Effective Poisson's ratio	0.33
Effective unit weight (kN/m^3)	6.0

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RESULT ANALYSIS

Comparison with centrifuge model tests

To verify the feasibility of this effective-stress finite element method in estimating spudcan penetration with lattice leg (case II), the computed excess pore pressure response is compared with centrifuge experimental results. It should be noted that the geometrical dimensions and boundary conditions shown in FIGURE 2 is consistent with the centrifuge test by Li [8]. In the centrifuge test, two pore water pressure transducers (PPT) are installed at the spudcan base as shown in the top right of FIGURE 3.

The computed excess pore pressure change Δu with penetration at spudcan base is plotted in FIGURE 3. It could be found that Δu increased almost linearly with depth in NC clay; in that case the undrained soil strength shares the similar linear increment with depth. The computed Δu is found to be quite comparable with the measured Δu in centrifuge model tests. This comparison result shows the feasibility of using undrained effective-stress Eulerian finite element analysis to estimate pore pressure response by spudcan penetration with lattice leg.

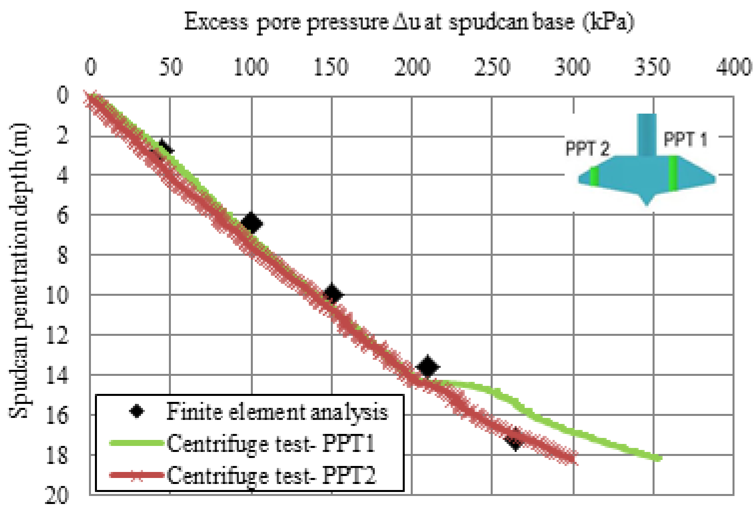

FIGURE 3. Comparison of measured and computed excess pore pressure at spudcan base in NC clay

Effect of lattice leg on excess pore pressure response

FIGURE 4 presents excess pore pressure contours at 1.36D spudcan penetration in normally consolidated (NC) clay, D is the maximum spudcan diameter, equal to 12m; spudcan is equipped with and without lattice leg. As could be observed, the computed excess pore pressure is a bulb-shaped zone around spudcan footing. A maximum excess pore pressure of 260kPa is found to be developed immediately beneath spudcan base in case I. Moreover, spudcan with lattice leg (case II) tends to yield larger excess pore pressure and influence zone than that in case I. Similar findings could be observed by spudcan penetration in over-consolidated (OC) clay (FIGURE 5).

Effect of soil strength on excess pore pressure response

As compared FIGURE 4a and FIGURE 5a, significant larger excess pore pressure is found to be developed in OC clay than that in NC clay for spudcan penetration without leg. A maximum excess pore pressure of 275kPa is generated in OC clay in comparison with 260kPa in NC clay. Similar trend is found for spudcan penetration with lattice leg, with maximum excess pore pressure of 295kPa versus 265kPa for OC and NC clay, this can be explainable by invoking the modified Cam-clay theory. When shearing soil with the same initial stress state, OC clay would have an additional portion of excess pore pressure generated before reaching the yield locus, as compared to the NC clay.

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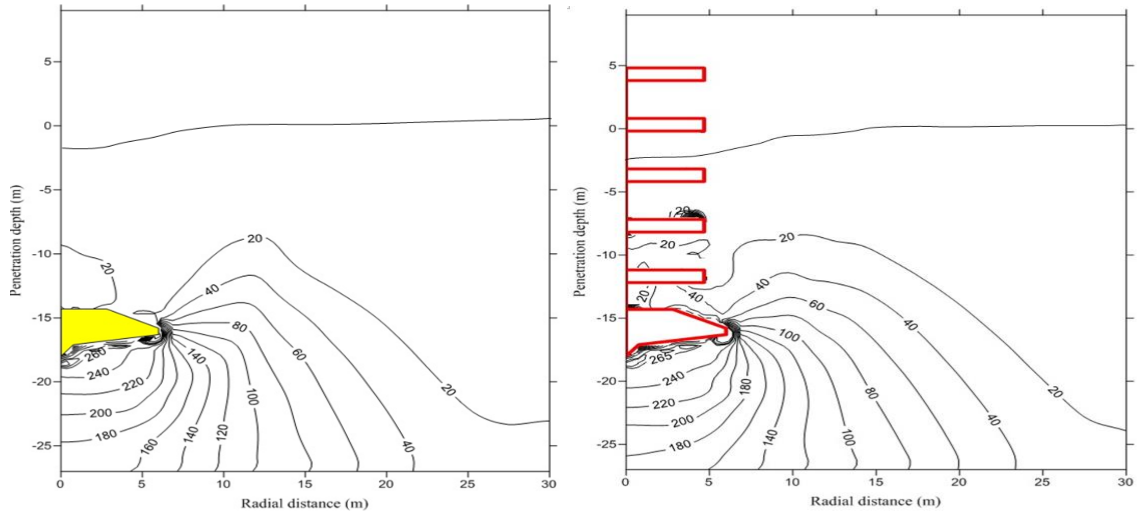
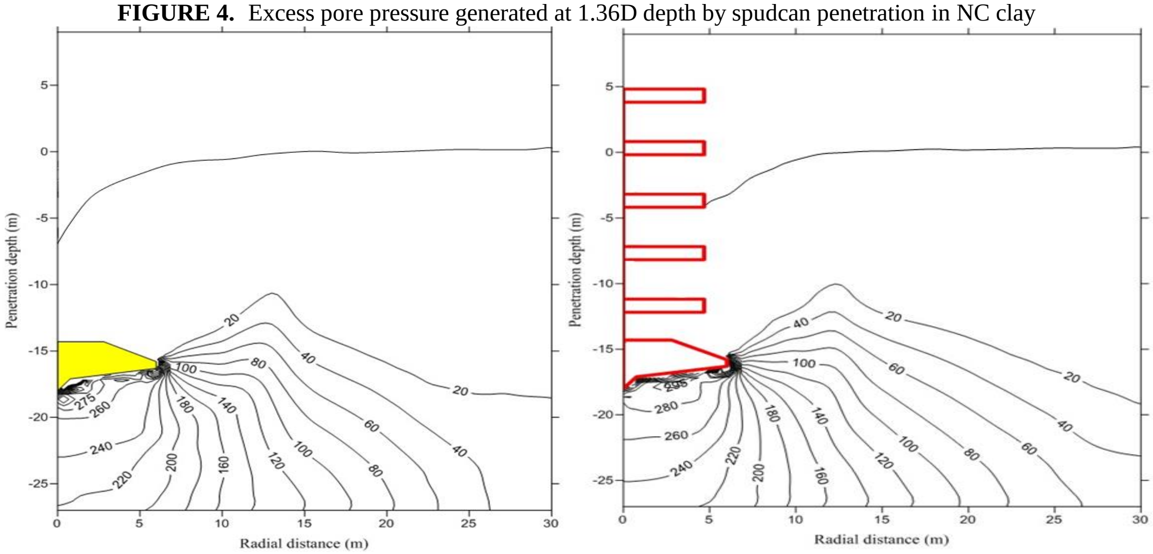


(a) Case I (b) case II

FIGURE 4. Excess pore pressure generated at 1.36D depth by spudcan penetration in NC clay



(a) Case I (b) case II

FIGURE 5. Excess pore pressure generated at 1.36D depth by spudcan penetration in OC clay

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