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# Merits of advanced constitutive modelling in predicting cyclic and static response of offshore foundations

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## Extended abstract

Foundations of offshore structures (such as wind farms and offshore platforms) represent a substantial problem from the geotechnical engineering point of view. Foundations are typically located in a soft soil with relatively low strength and potential for pore pressure buildup during foundation installation and subsequent loading. During operation, offshore structures are subject to cyclic loading by horisontal forces from winds, waves and currents. Irrespectively of these complexities, their design is typically based on simple elastic perfectly plastic constitutive models. These models are unable to represent pore pressure and accummulated displacement development during installation and operation. In this lecture, merits of advanced constitutive modelling are demonstrated by comparing simulation results with results of physical experiments performed in geotechnical centrifuges.

The presented simulations have been performed using constitutive models based on hypoplasticity. Hypoplasticity is an advanced approach to non-linear constitutive modelling of geomaterials. In its general form by (Gudehus 1996) it may be written as

$$\mathring{\boldsymbol{\sigma}} = f_s(\boldsymbol{\mathcal{L}} : \dot{\boldsymbol{\epsilon}} + f_d \mathbf{N} \|\dot{\boldsymbol{\epsilon}}\|) \qquad (1)$$

where $\mathring{\boldsymbol{\sigma}}$ and $\dot{\boldsymbol{\epsilon}}$ represent the objective (Zaremba-Jaumann) stress rate and the Euler stretching tensor respectively, $\boldsymbol{\mathcal{L}}$ and $\mathbf{N}$ are fourth- and second-order constitutive tensors, and $f_s$ and $f_d$ are two scalar factors. In hypoplasticity, stiffness predicted by the model is controlled by the tensor $\boldsymbol{\mathcal{L}}$, while strength (and asymptotic response in general), is governed by a combination of $\boldsymbol{\mathcal{L}}$ and $\mathbf{N}$. Earlier hypoplastic models (such as the model by von Wolffersdorff 1996 and Mašín 2005) did not allow to change the $\boldsymbol{\mathcal{L}}$ formulation arbitrarily, as any modification of the tensor $\boldsymbol{\mathcal{L}}$ undesirably influenced the predicted asymptotic states. This hypoplasticity limitation was overcome by Mašín (2012, 2014). He developed an approach enabling to specify the asymptotic state boundary surface independently of the tensor $\boldsymbol{\mathcal{L}}$.

Depending on the type of soil, either sand (von Wolffersdorff 1996) or clay (Mašín 2014) version of the model can be adopted. The clay hypoplastic model requires five material parameters $\varphi_c$, $N$, $\lambda^*$, $\kappa^*$ and $\nu$. The parameters have the same physical interpretation as parameters of the Modified Cam clay model, and they are thus easy to calibrate based on standard laboratory experiments. The sand hypoplastic model requires 8 parameters ($\varphi_c$, $h_s$, $n$, $e_{c0}$, $e_{d0}$, $e_{i0}$, $\alpha$, $\beta$) and, also, standard laboratory experiments may be adopted for their calibration (drained triaxial tests, oedometric tests and angle of repose test). To represent cyclic loading phenomena, both the models can be enhanced by the so-called intergranular strain concept (Niemunis and Herle, 1997). This concept requires additional parameters to calibrate ($m_R$, $m_T$, $R$, $\beta_r$, $\chi$). These parameters need to be calibrated by more advanced laboratory experiments (triaxial shear tests with local measurement of deformation, bender element tests and cyclic triaxial tests).

In the lecture, two specific examples of hypoplasticity model application to simulate offshore foundations will be presented. The first example has been studied by Ragni et al. (2016) at the Centre for Offshore Foundation Systems at the University of Western Australia. They focused on a simulation of consolidation around jack-up foundations in carbonate silty clay. In particular, they were investigating potential for the so-called consolidation-generated punch-through: installation of a spudcan is desirable to be conducted as quickly as possible, as any delay in installation leads to excess pore water pressure generation. During an undesired pause, the excess pore water pressure dissipates with a consequent increase in soil shear strength and stiffness. This can set conditions where the spudcan quickly advances through the strengthened zone when penetration restarts. In the simulations, clay hypoplasticity model including the effects of structure has been adopted and used within Abaqus finite element code, large strains were allowed for using RITSS strategy (Remeshing and Interpolation Technique with Small Strain). The load-displacement curves measured in the centrifuge were reproduced well by the model (Figure 1). Also, the analyses demonstrated how the advanced model can be used to get more detailed insight into the penetration process: Figure 2 shows undrained shear strength extracted from hypoplastic model equations for the particular value of void ratio and sensitivity. Clearly, after the period of consolidation (Figure 2, right), the undrained shear strength singnificantly increases when compared with the undrained shear strength during continuous installation (Figure 2, left).

The second example represents cyclic lateral response of a semi-rigid pile in soft clay. This example is focusing on a response of pile foundation subject to environmental cyclic loading (wind, waves and currents). The centrifuge experiments performed at the Hong-Kong University of Science and Technology represented horizontal cyclic action (100 cycles) loading semi-rigid pile and jet-grouting reinforced pile. The experiments revealed flexible displacement mechanism after the first cycle and rigid mechanism after the 100's cycle (Figure 3) for this particular pile diameter and soil properties. Different rates of pile head displacement accumulation have been observed for different cyclic loading levels. Hypoplastic model for clays (Mašín, 2014) with intergranular strain concept has been calibrated using the cyclic triaxial shear data (Figure 4) and adopted in cyclic finite element simulations using Abaqus software. As is clear from Figure 5, cyclic accumulation of pile head lateral displacements has been well reproduced by the model for different loading levels.

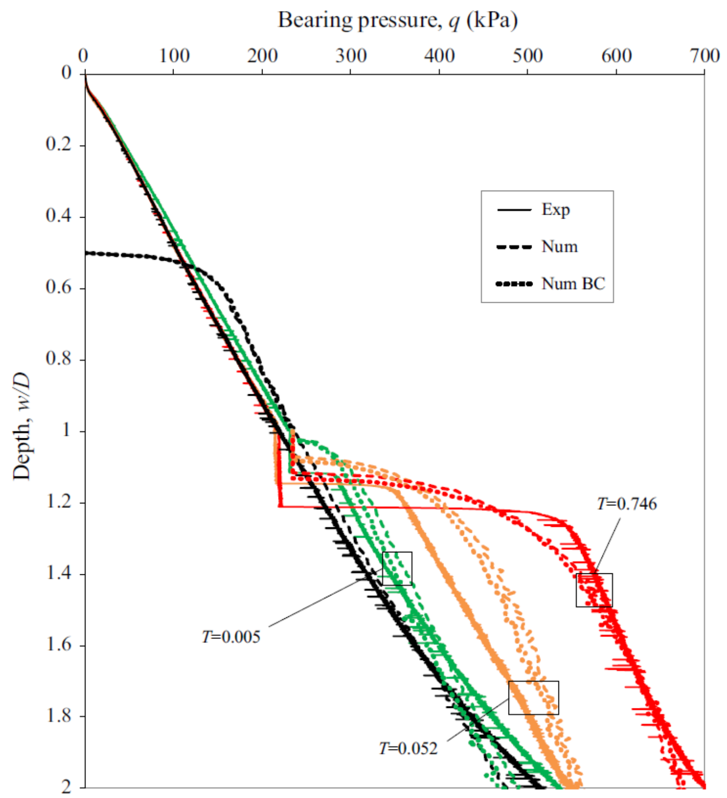


*Figure 1: Load-displacement curve of a spudcan penetration, continuous case and case with three different hold periods. Centrifuge data compared with hypoplastic model predictions (more details in Ragni et al., 2016).*

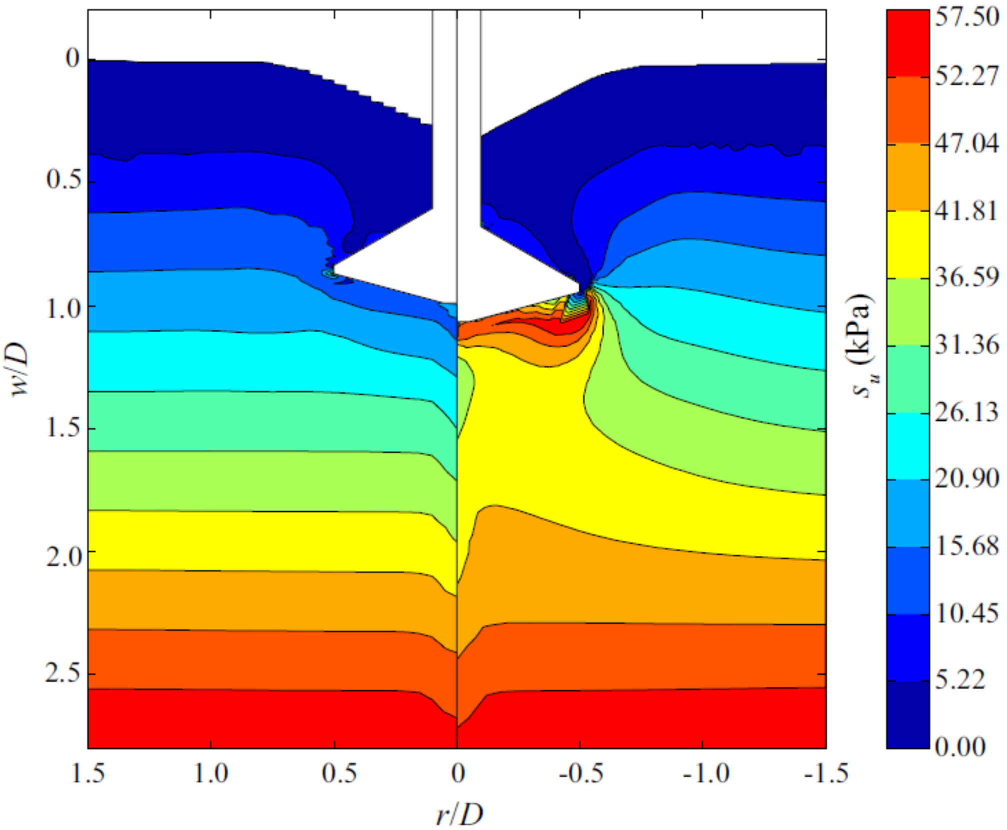


*Figure 2: Undrained shear strength profile during continuous penetration of a spudcan (left) and after hold period (right). More details in Ragni et al., 2016.*

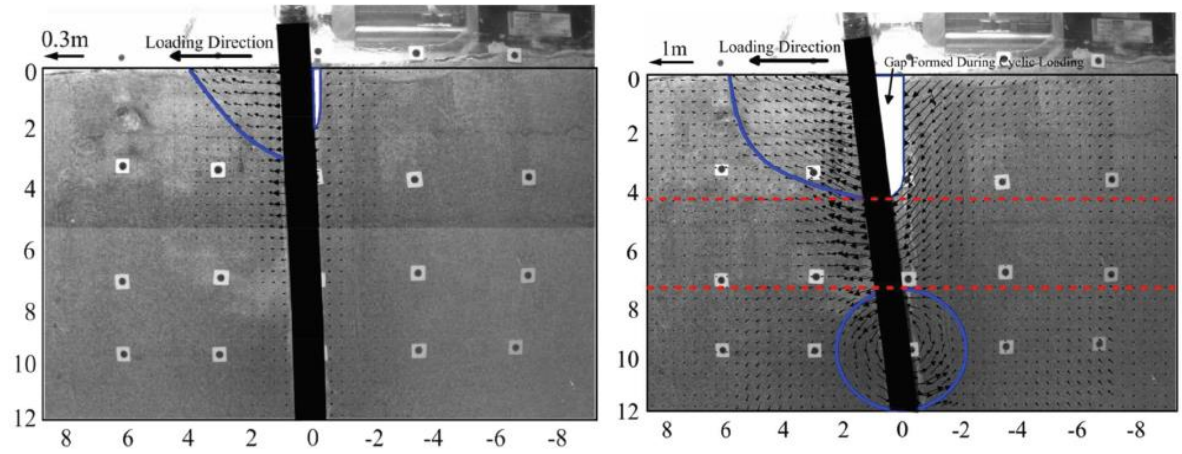


*Figure 3: Flexible (left, 1st cycle) and rigid (right, 100th cycle) displacement mechanism during horisontal cyclic loading of a pile observed in geotechnical centrifuge. More details in Hong et al. (2017)*

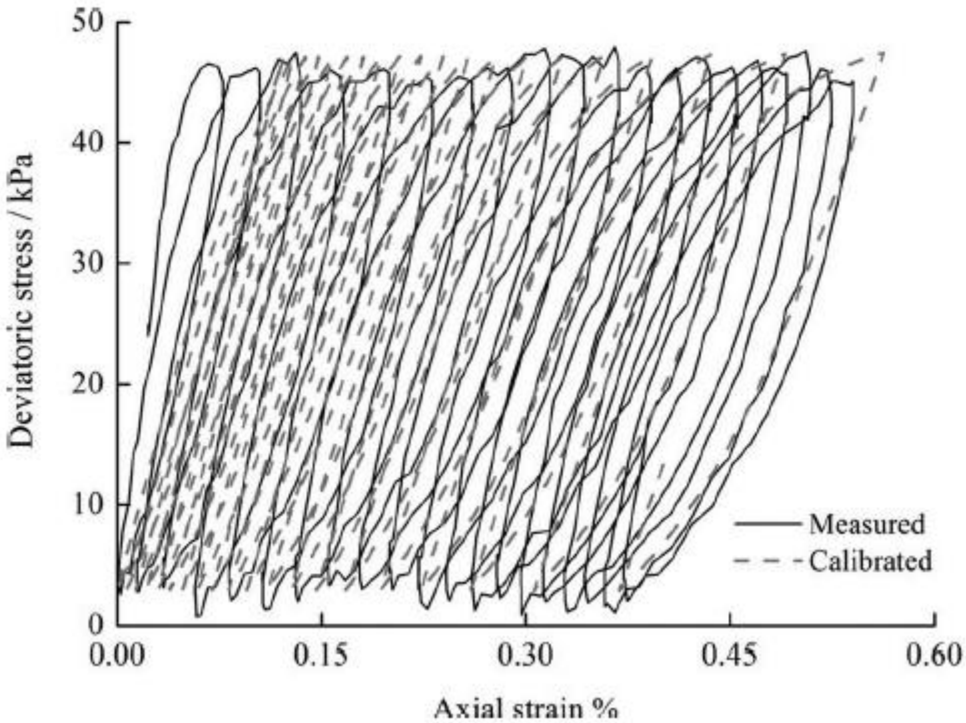


*Figure 4: Cyclic triaxial test results compared with hypoplastic model predictions, more details in Hong et al. (2017).*

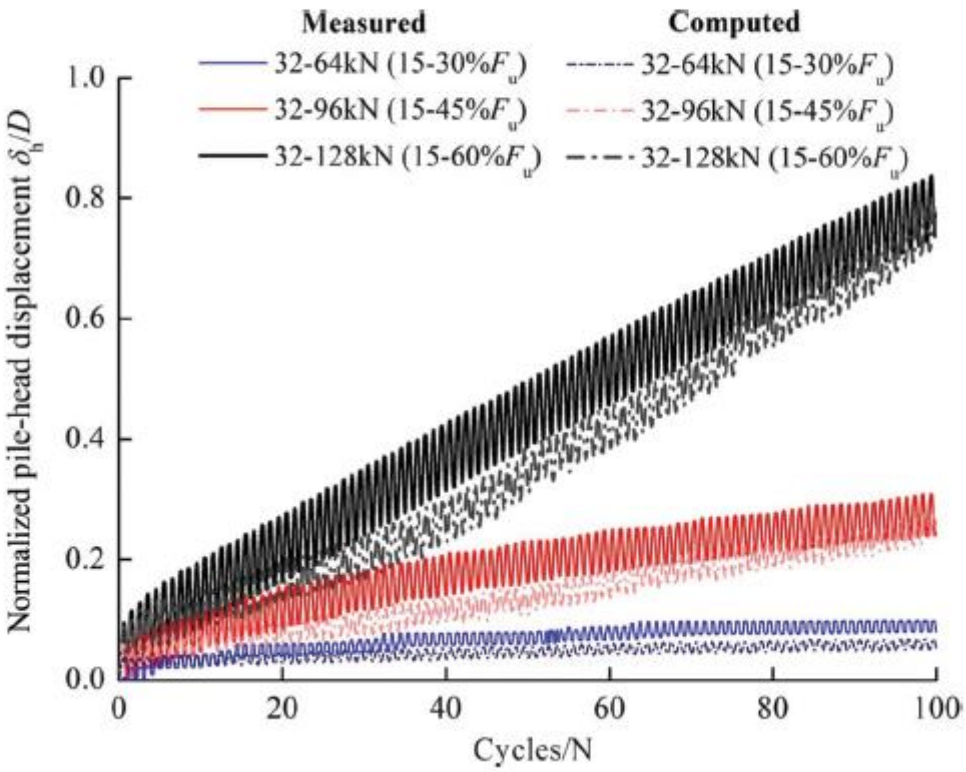


*Figure 5: Experimental results and predictions of cummulative lateral pile head displacement subject to cyclic loading. More details in Hong et al. (2017).*

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