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Impact of stiffness properties and overconsolidation on the lateral behaviour of monopile foundations in clay deposits

Impact des propriétés de rigidité et de surconsolidation sur le comportement latéral des fondations monopieux dans les massifs argileux

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ABSTRACT: The adoption of advanced constitutive models based on the Critical State Soil Mechanics framework present both advantages and challenges. The former are well established and relate to improvements in accuracy and, due to the frequent use of the framework in explaining soil behaviour, a calibration process which is frequently simpler. However, their use in modelling of clays means that consistency between different soil properties, such as undrained shear strength and overconsolidation ratio, needs to be insured. The application of one of such models is explored in this paper in the context of offshore foundations. The influence on the lateral capacity of the foundations of different profiles of undrained shear strength, a property which is not prescribed but rather interpreted from the model parameters and initial conditions, is shown to be substantial at all values of displacement. Similarly, the use of a highly non-linear model for the shear stiffness is explored and the impact of the associated parameters is observed to be confined to the lateral stiffness of the monopile under small lateral loads.

RÉSUMÉ: L'adoption de modèles constitutifs avancés basés sur la mécanique des sols à l'état critique présente des avantages et des défis. Les premières sont bien établies et concernent l'amélioration de la précision et, en raison de l'utilisation fréquente de la mécanique des sols à l'état critique pour expliquer le comportement du sol, il est plus facile de calibrer le modèle de sol. Cependant, leur utilisation dans la modélisation des argiles signifie que la cohérence entre les différentes propriétés du sol, telles que la résistance au cisaillement non drainée et l'état de surconsolidation, doit être assurée. L'application de l'un de ces modèles est explorée dans cet article dans le contexte des fondations monopieux. La capacité latérale des fondations de différents profils de résistance au cisaillement non drainé, une propriété qui n'est pas prescrite mais interprétée à partir des paramètres du modèle et des conditions initiales, est substantielle à toutes les valeurs de déplacement. L'utilisation d'un modèle non linéaire pour la rigidité au cisaillement est explorée et l'impact des paramètres de ce modèle est limité à la rigidité latérale des fondations monopieux soumises à de faibles charges latérales.

Keywords: Monopile foundations; offshore geotechnics; numerical modelling; clays.

1 INTRODUCTION

The use in design of constitutive models based on Critical State Soil Mechanics (Schofield and Wroth, 1968), a framework employed for explaining the observed behaviour of clays prepared to a variety of initial conditions, facilitates their effective calibration, as model parameters tend to match well described properties (e.g. compressibility, shear strength at Critical State, effect of overconsolidation). However, there are considerable challenges arising from translating properties that are often measured, but are not intrinsic to the material, as they depend fundamentally on its current state, such as the undrained shear strength. This paper explores these issues using the extended version of the Modified Cam-clay model (MCC) described in Tsiampousi et al. (2023) in the context of the capacity of monopile foundations subjected to lateral loading.

2 NUMERICAL MODEL

2.1 Details of the model

A monopile foundation with diameter $D = 5\ m$ and embedment depth $L = 50\ m$ (i.e. embedment ratio $L/D = 10$) was considered in this study. The load was applied as a prescribed displacement at a height $H = 50\ m$ (i.e $H/D = 10$) The problem was simulated in

PLAXIS 3D, with the soil domain extending to $50\ m$ (i.e $10D$) either side of the monopile and down to a depth of $70\ m$ (i.e. $14D$). The soil was modelled using 193167 10-noded tetrahedral elements, with smaller elements used in the immediate vicinity of the pile. The monopile was modelled using 4402 6-noded plate elements (linear-elastic, $E = 200\ GPa$, $\nu = 0.3$), with a simulated thickness of $t = 62.5\ mm$ ($t/D = 80$). The interaction between the monopile and the surrounding ground was modelled using 12-noded interface elements, the strength of which (denoted herein by τ_{int}) was obtained using the methodology proposed in API (2011) and DNV (2014):

$$\tau_{int} = \alpha \cdot S_{u,TXC} \tag{1}$$

$$\alpha = \begin{cases} 0.5 \cdot R^{-0.5}, & R \leq 1 \\ 0.5 \cdot R^{-0.25}, & R > 1 \end{cases} \tag{2}$$

where $R = S_{u,TXC}/\sigma'_v$, σ'_v is the vertical effective stress and $S_{u,TXC}$ is the undrained shear strength of the soil under triaxial compression loading conditions. In general, this approach produces a slight non-linear variation close to the surface, where σ'_v approaches 0. Therefore, linear profiles approximating the outcome of Equation (1) were used, described in Section 2.3. Crucially, for this type of problems, these elements are able to simulate the opening of a gap under tensile stresses that tend to be observed at the back the pile when subjected to lateral loading.

2.2 Constitutive model

An enhanced Modified Cam-clay model was used, combining the original formulation for normally consolidated and lightly overconsolidated clays with a non-linear Hvorslev surface (Tsiampousi et al., 2013) on the dry side of critical and a hypoelastic model linking the shear stiffness of the material to the stress and strain levels (Taborda et al., 2016). This model differs from that used previously in the PISA project for the simulation of Cowden till (Zdravkovic et al., 2020b) only in the fact that it employs a Mohr-Coulomb shape in the deviatoric plane, rather than a generalised shape. Therefore, the strength at Critical state, as measured by the mobilised angle of shearing resistance, is independent of the loading conditions, which means that the slight stress-induced anisotropy observed for Cowden till (Zdravkovic et al., 2020a) cannot be reproduced using the formulation adopted herein. The full formulation of the model, designated IC MAGE M06, is described in Tsiampousi et al. (2023). It has been implemented as a User-Defined Soil Model in PLAXIS within the UMIP framework (Taborda et al., 2023) and is integrated using a modified Euler scheme with automatic substepping and error control.

The model parameters adopted for Cowden till are outlined in Table 1 and are based on those reported in Zdravkovic et al. (2020a, 2020b).

Table 1. Parameters for Cowden till based on Zdravkovic et al. (2020b).

Parameters for Cowden till			
G_{ref}	$110\ MPa$	ν_1	2.200
p'_{ref}	$100\ kPa$	κ	0.021
m_G	1.0	λ	0.115
a	9.78×10^{-5}	α_{HV}	0.250
b	0.987	n	0.400
$R_{G,min}$	0.050	β_{HV}	0.200
ϕ	27.0°	m	1.000

2.3 Analysed cases

The first objective of this paper was to evaluate the impact of the assumed undrained shear strength profile. Given that properties, such as compressibility and shear strength at Critical State, are considered to be intrinsic to the material, matching a given value of undrained shear strength is achieved by determining the required value of OCR, a process which is detailed in Zdravkovic et al. (2020b). In the implementation of IC MAGE M06, this is an automatic procedure, i.e. in practice, S_u is supplied as an input parameter, though this is then converted into OCR, which varies in depth. The three profiles studied – listed in Table 2 together with the corresponding undrained shear strength profile for the interfaces – include an approximation to that assumed in Cowden, as well as two variations consisting of lower and higher values of this property ($\pm 60\ kPa$ at surface but same value at a depth of $100\ m$). Moreover, when adjusting the value of OCR, the coefficient of earth pressure at rest, K_0, is also adjusted using $K_0 = (1 - \sin\phi) \cdot \sqrt{OCR}$. The three cases are illustrated in Figure 1.

Table 2. Analysed strength soil and interface strength profiles.

Soil strength	**Interface strength**
$S_u = 90 + 3.2\ z$	$\tau_{int} = 28 + 3.2\ z$
$S_u = 30 + 3.8\ z$	$\tau_{int} = 10 + 3.3\ z$
$S_u = 150 + 2.6\ z$	$\tau_{int} = 48 + 3.0\ z$

The second objective is to analyse the effect of the non-linear law assumed for the elastic shear modulus which is described using the model proposed in Taborda et al. (2016). Of the various parameters employed in this expression, the value of a is chosen for further investigation, since it controls the value of strain at which the stiffness at very small strains

(G_{max}) reduces to half of its value (i.e. larger values of a mean larger values of shear modulus).

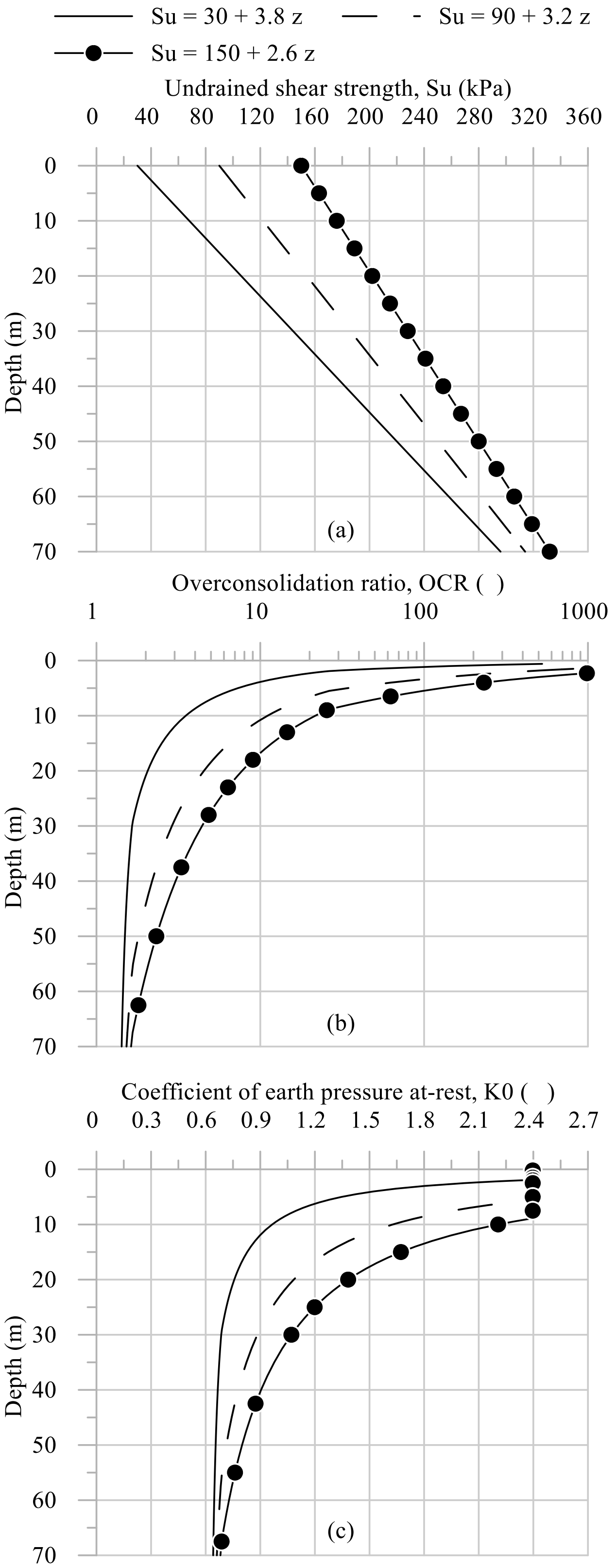

Figure 1. Profiles of (a) undrained shear strength in triaxial compression conditions, (b) overconsolidation ratio and (c) coefficient of earth pressure at-rest.

3 RESULTS

3.1 Effect of undrained strength profile

The obtained results for the three considered profiles are illustrated in Figure 2. As expected, the larger undrained shear strength leads to considerably larger capacities at failure, ranging from about 42 MN to almost 70 MN. It is also interesting to note that the shapes of the three load-displacement curves are similar at very small displacements ($< 0.1\% \, D$), suggesting that this aspect of the response is controlled by the elastic stiffness, which is identical for the three cases considered. Moreover, the capacity of the monopile is reached at different deformations: $50\% \, D$ for the lower strength profile, increasing to $100\% \, D$ for the larger strength case. This shows the difference in the hardening process associated with the various initial OCR profiles, i.e. larger $OCRs$ require larger strains to reach Critical State.

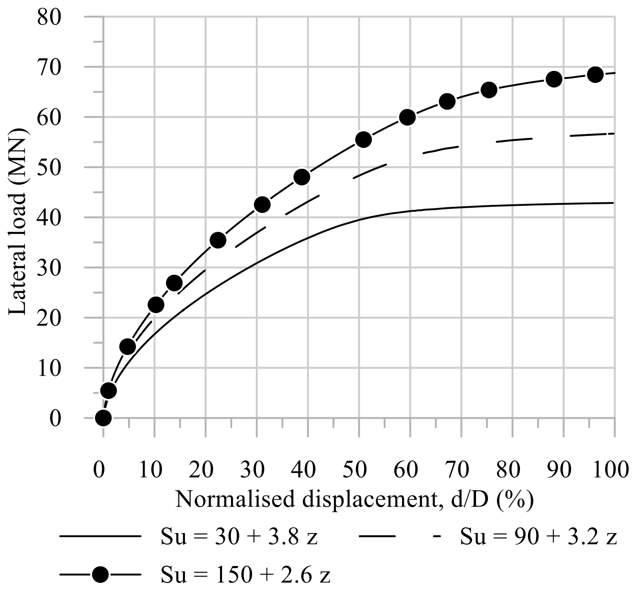

Figure 2. Lateral load-normalised displacement obtained for the various undrained shear strength profiles.

3.2 Effect of stiffness reduction parameters

The impact of varying the value of parameter a by an order of magnitude is shown in Figure 3. As expected, this parameter does not affect the ultimate capacity, though a measurable impact on the load at $10\% \, D$ is still visible ($\pm$ 1 MN). Clearly, a much greater impact is observed in terms of lateral stiffness, where a smaller value of a is naturally characterised by a sharper reduction in pile stiffness with lateral deformation. At very small displacements (e.g. $0.1\% \, D$), the stiffness values vary considerably.

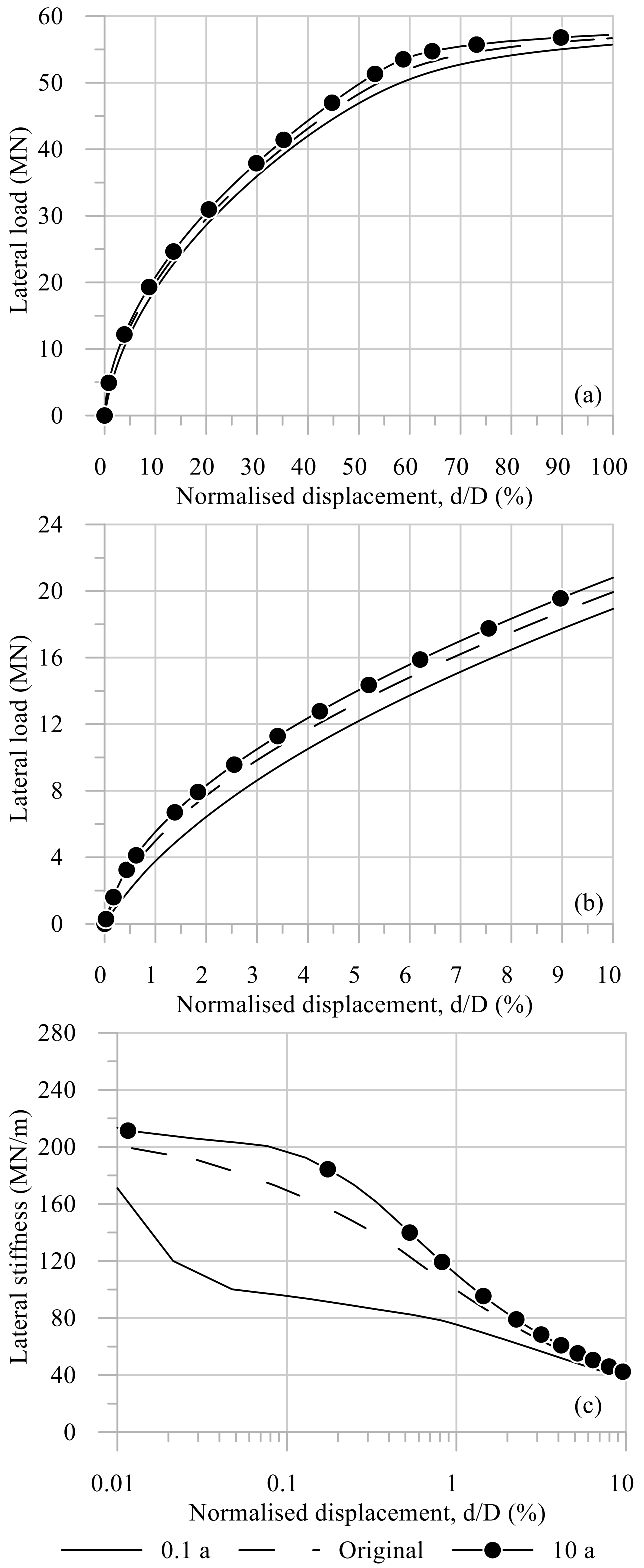

Figure 3. Effect of a *on pile response for displacements up to (a) 100%D and (b) 10%D, and on (c) lateral stiffness.*

4 CONCLUSIONS

Detailed finite element simulations of laterally loaded monopile foundations in clay deposits using an advanced constitutive model based on Critical State Soil Mechanics highlight the impact of the S_u profile on the pile response – not only in terms of results, but also in terms of the procedure followed to determine the initial conditions (OCR and K_0). Moreover, while the non-linear elastic shear modulus was shown to have limited impact on pile capacity, a substantial effect on monopile stiffness was observed, indicating the importance of adequately characterising and modelling this aspect of soil behaviour.

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