MODELLING RATE-DEPENDENT SOIL-SPUDCAN INTERACTION FOR JACK-UP PRELOADING IN CLAY

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ABSTRACT

The preloading of four-legged jack-ups is performed by alternately applying vertical loads on diagonally opposite leg pairs, up to achieving a stable condition in which nearly constant load levels are held by each leg. In presence of clayey seabeds, viscous behaviour of the soil is commonly observed, which in turn leads to additional soil deformation and spudcan penetration. Therefore, multiple preloading stages are often required in soft clay to fulfil preload criteria. The process of installing jack-up legs to stable embedment depth can thus take considerable time.

The effects of soil viscosity are investigated through a 2D finite element (FE) soil-spudcan model. Soil behaviour during preloading is modelled via the elasto-viscoplastic Soft Soil Creep model available in the Plaxis FE software. The results presented hereafter support the suitability of the modelling approach, and allow to explore the benefits of an alternative preloading procedure based on the concept of "overshooting".

KEYWORDS: jack-up vessel, clay, preloading, spudcan penetration, creep, overshooting

INTRODUCTION

Installation of offshore wind turbines requires lifting and accurate positioning of heavy components, often at considerable elevation. Jack-up vessels are therefore commonly employed in the industry to provide stable installation platform. Offshore wind jack-up vessels typically have 4 or 6 legs equipped with spudcans to limit penetration and facilitate rapid installation.

Figure 1: Van Oord's jack-up vessels Aeolus and Resolution

When a jack-up vessel arrives at the intended location, legs are lowered until contact with the seabed is made. The jacking process continues until the weight of the vessel is transferred to the seabed. Each leg pair is then temporarily subjected to higher loads prior to operations. The purpose of this preloading process is to provide sufficient margin of safety against failure during lifting operations, and under storm conditions. After preloading, the vessel is jacked to operational height and wind turbine components can be installed.

Jacking at locations with soft clays can result in large leg penetrations. Achieving a stable condition during preloading is time-consuming due to well-known viscous effects in this type of soil. The jack-up vessel typically resides a short period of time at a wind turbine location, in the order of hours to days. The process of installing jack-up legs to stable embedment depth can thus take a considerable portion of the total time for wind farm installation. It is important for offshore wind contractors to estimate the preload duration for planning purposes, as well as to find ways for reducing such time based on adequate understanding of soil-foundation interaction.

Viscous (rate-dependent) behaviour of clays has been recognized as early as the 1930s and has been subject of research since [1], [2]. Recently, such effects have been studied in the context of spudcan penetration [3],[4]. A study by Versteele et al. [5] described an alternative strategy for preloading to counteract the effects of relaxation of the soil with the aim of reducing the time required for preloading.

In this work, viscous effects in the soil are numerically investigated by means of an axisymmetric soil-spudcan finite element (FE) model. The elasto-viscoplastic Soft Soil Creep model available in the Plaxis FE software is adopted to account for clay's time-dependent behaviour in soil-foundation simulations. The suitability of the modelling approach is explored by critically inspecting the results of parametric studies, involving variations in key soil properties. In conclusion, the potential benefits of alternative installation/preloading schemes are also considered, in an effort to reduce the total preloading time based on enhanced understanding and modelling of soil-foundation interaction.

PRELOADING PROCEDURE

This study concerns the modelling of active preloading in four-legged jack-up vessels as schematically presented in Figure 2. Before starting the preloading procedure, the four legs are penetrated into the soil under the self-weight of the vessel (1). Preloading is initiated by lowering one diagonal leg pair (the active leg pair) using the jacking system (2). This results in higher loads in the active legs and lower loads in the opposite (passive) leg pair. The position of the legs with respect to the hull is maintained for several minutes, during which the active legs penetrate further into the soil, and loads are gradually transferred from active to passive leg pair. Load reduction in time, however, should remain within certain limits (preload criterion) in order to demonstrate satisfactory bearing capacity. If the preload criterion is not satisfied, a new preload cycle is performed by extending the active leg pair again. This second cycle results in a smaller reduction over time as the legs have reached a larger depth and consequently encounter a higher bearing capacity. Such loading cycles are repeated until the preload criterion is met, after which the opposite leg pair is preloaded (3). When all legs satisfy the established preload criterion, the vessel is raised to working height and operations can start.

The vertical load applied to the active leg pair is higher than experienced during storm events and lifting operations. The minimum required preload includes a safety margin according to ISO guidance [6] and follows from the site specific assessment.

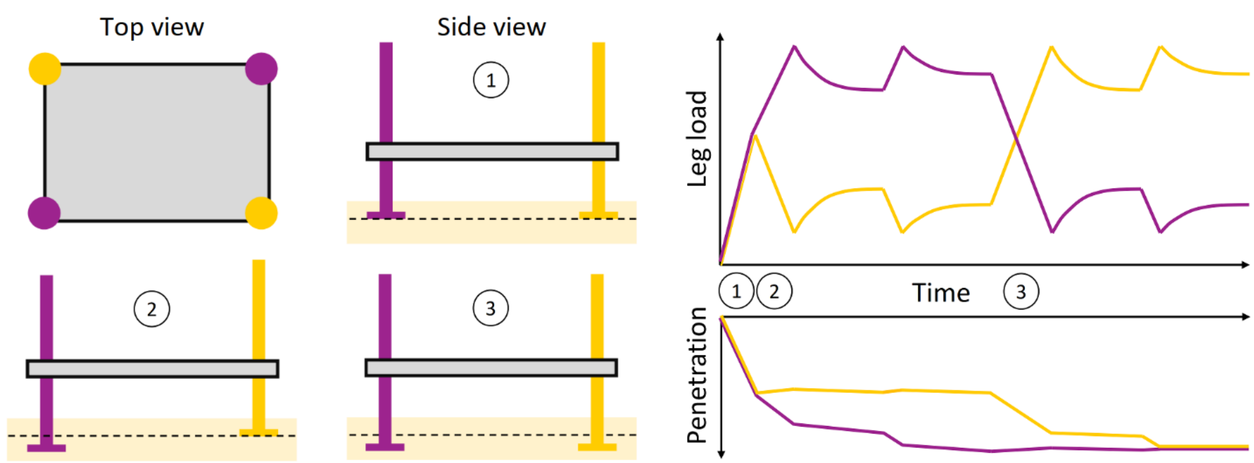

Figure 2: Schematic representation of active preload procedure

SOIL CONSOLIDATION, VISCOSITY AND SOFTENING DURING JACKING IN CLAY

In presence of clayey seabeds, viscous soil behaviour is commonly observed, which in turn leads to additional soil deformation and spudcan penetration under constant load. As a consequence, multiple preloading stages are often required to fulfil preload criteria.

At least three features of soft clay behaviour are to be considered in relation to spudcan penetration and leg preloading: consolidation, viscosity, and strain softening. Consolidation is of importance when the penetration speed of the spudcan is large in relation to soil permeability, leading to development of excess pore pressures. Viscosity is associated with time-dependent changes of the soil structure. Instances of viscous behaviour are multiple, and include (i) time-delayed deformation under constant load (creep) and decrease in stress in response to constant strain level (relaxation); and (ii) genuine dependence of soil stiffness/strength on loading rate (rate-sensitiveness). As a leg penetrates into the soil, large deformations take place as local failure is approached: consequently the reduction of strength for increasing strain (softening) should also be considered.

The literature on clay consolidation and creep is extensive as a result of decades of research in the widest field of soil mechanics and foundation engineering. In closer relation to offshore applications, various researchers [7] [8] have investigated the rate-sensitive response of soft clays to penetration of probes, including ball-cone and T-bar penetrometers. The findings from such studies have enabled to link experimental evidence from laboratory scale experiments [4] and full-scale tests [3] to viscous soil behaviour during spudcan penetration. The extent of strain softening has been evaluated, for instance, in relation to the single penetration-extraction cycle of a penetrometer (or spudcan). The extraction resistance typically was found to vary from 50 to 80% of the penetration resistance ([9] [10]), although lower ratios have been also reported for highly sensitive clays. It appears that strain softening is of importance, however, with gradual loss of shear strength in presence of large shear strains.

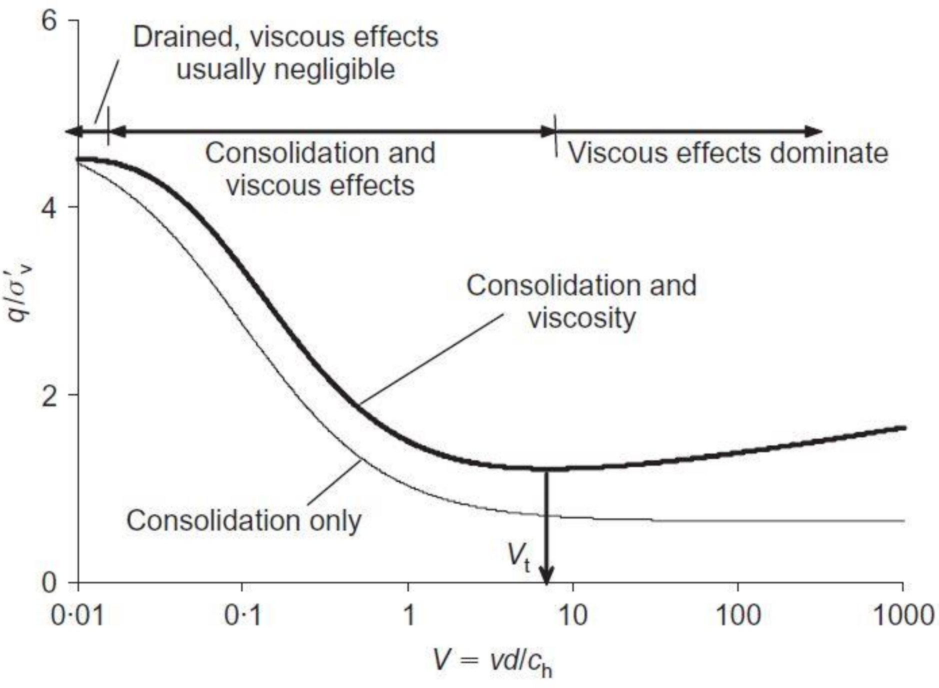

Figure 3: Influence of consolidation and viscous effects on soil resistance during penetration in clay [11]

The relative relevance of rate-dependent phenomena is visually presented in Figure 3, where the normalised penetration resistance is plotted against the penetration velocity normalised with respect to cone (or spudcan) diameter and coefficient of consolidation. It is noted that the effects of strain softening are implicitly considered in this figure as it is derived from the penetration of full-flow penetrometers. Consolidation leads to a reduction of the penetration resistance for increasing penetration speeds, while viscous effects cause an increased resistance for faster penetration. For slow penetration, viscous effects are usually negligible and the penetration resistance is limited to a maximum value equal to the drained penetration resistance. As the cone penetrates the soil faster, excess pore pressure are generated leading to a reduced strength and penetration resistance. Viscous effects provide an increasingly large part of the resistance when the velocity is increased. In the undrained regime, the total resistance increases with higher penetration velocity as the viscous effects dominate the reduction due to consolidation.

For clays with a consolidation coefficient ranging from $1 \cdot 10^{-5}$ m^2/s to $1 \cdot 10^{-9}$ m^2/s, an assumed leg penetration speed of 1 m/hr and a 10 m spudcan diameter would lead to a normalised velocity in excess of 100. Figure 3 indicates that viscous effects are dominant in such conditions. During the preloading process, the velocity reduces as the spudcan approaches the final penetration depth. Nevertheless, the viscous effects on the behaviour of spudcan penetration in clay are expected to be larger than the (counteracting) effects of consolidation and strain softening.

A number of other effects have been described in literature as potentially influencing the behaviour of leg penetration during jacking in clay. Cyclic degradation may play a role in spudcan-soil interaction, as the preload procedure can be considered “one-way” cyclic loading. This effect is thought to be limited due to remoulding of the soil [5]. Soil backfill on top of the spudcan can occur due to flow of soil around the spudcan (backflow) and collapse of the sidewall or sediment transport (infill) [6]. The increased load on the spudcan can lead to additional penetration. These effects are expected to be of minor significance compared to the viscous and strain softening behaviour of the clay during the preloading process.

THE “SOFT SOIL CREEP” MODEL FOR CLAY

Viscous effects in soils may not be reproduced through standard, time-insensitive plasticity theories. In order to overcome this limitation, elasto-viscoplastic constitutive formulations have been devised in the last decades – see the literature reviews compiled e.g. by [12] and [13]. Most elasto-viscoplastic models in the literature assume an additive decomposition of the strains into elastic and irreversible (plastic) components. The latter does not follow load application instantaneously, but takes place in time (hence the term “visco-plastic”) depending on loading (rate) conditions and specific state variables. In this way it possible to unify the modelling of creep, relaxation and rate-dependency for what concerns the irreversible (visco-plastic) part of the response, while the “pre-yielding” elastic response is usually kept instantaneous. Such approach is quite suitable to model the viscous behaviour of normally-consolidated (soft) clays, whose response is plasticity-dominated due to the initial stress state being close to the yield locus. Conversely, over-consolidated (stiff) clays will not exhibit considerable viscous effects in this framework, due to the dominance of elastic rate-independent deformations.

Plaxis offers a valid option for modelling the viscous behaviour of (nearly) normally-consolidated clays, the so-called “Soft Soil Creep” (SSC) model [14]. The SSC model builds on the work of Vermeer and Neher [15], who modified the original formulation of the well-known Cam Clay model to include rate-sensitive plastic strains. In summary, the latest version of the SSC model features the following main characteristics:

- isotropic elastic response for stress states within the yield locus, with pressure-dependent elastic moduli and constant Poisson’s ratio;
- combination of two distinct yield mechanisms, associated with shear-dominated and radial loading paths;
- shear failure occurs when the stress state reaches the Mohr-Coulomb failure envelope, without any strain-softening mechanism;
- strain hardening governed by the evolution of the cap yield surface, triggered by the occurrence of volumetric visco-plastic strains;
- associated plastic flow rule in the cap region, accounting explicitly for the time factor.

As implicit in the visco-plastic formulation, the SSC model returns the time-insensitive response of the Soft Soil elasto-plastic parent model as the loading rate tends to zero. For intermediate situations, the model can capture the abovementioned viscous effects with the same set of parameters, to be calibrated at once in order to optimise the agreement between model predictions and available experimental evidence. Symbols and meaning of all SSC model parameters are listed in Table 1, while interested readers are referred to the cited publications for details concerning mathematical formulation and parameter calibration procedures.

Input parameters for Soft Soil Creep model		
General properties and initial state		
γ_{sat}	Saturated unit weight	$[kN/m^3]$
e_{init}	Initial void ratio	$[-]$
OCR	Overconsolidation ratio	$[-]$
k	Permeability	$[m/day]$
Shear strength and dilation parameters		
c	Effective cohesion	$[kN/m^2]$
ϕ'	Friction angle	$[°]$
ψ	Dilatancy angle	$[°]$
Stiffness and viscosity parameters		
λ^*	Modified compression index	$[-]$
κ^*	Modified swelling index	$[-]$
μ^*	Modified creep index	$[-]$
Other control parameters		
ν_{ur}	Poisson's ratio for unloading-reloading	$[-]$
K_0^{NC}	$\sigma'_{xx}/\sigma'_{yy}$ stress ratio in a state of normal consolidation	$[-]$
M	K_0^{NC}-related parameter	$[-]$

Table 1: Constitutive parameters in the SSC model

The failure parameters for SSC model can be derived from standard consolidated undrained triaxial tests – preferably slow tests not exhibiting strong rate effects. Assigning a cohesion larger than zero will increase the minimum value of the cap in the stress space, and consequently result in a stiffer response at the onset of loading, similar to an overconsolidated state. It is consequently recommended to set the cohesion at or close to zero. Since the SSC is based on an effective stress formulation, the undrained strength is a genuine output of the model – not an input parameter.

Modified compression (λ^*) and swelling (κ^*) indices can be obtained from an isotropic compression test including unloading by plotting the logarithm of the mean effective stress as a function of the volumetric strain. The modified compression index coincides with the slope of the primary loading line, while the modified swelling index corresponds with the slope of the unloading (or swelling) line. The modified creep index μ^* can be obtained from the test data after consolidation has effectively ceased, as the slope of the volumetric strain against the logarithm of time. Alternatively, the basic stiffness parameters can be obtained from the more commonly available one dimensional compression (oedometer) test.

The Poisson's ratio (ν_{ur}) is calibrated against the ratio of horizontal effective stress increment to vertical stress increment in the unloading-reloading cycle of an oedometer test. This parameter is especially relevant for situations where unloading takes place, resulting in a larger horizontal to vertical stress ratio. In the absence of more specific information, the default value of 0.15 [14] is adopted in this study.

At variance with the original Cam Clay model, M is mainly used in the SSC model to tune the plastic flow rule in the cap region. As such, M influences the lateral deformation that results from vertical loading. It is calculated in Plaxis through a formulation based on other input parameters for the SSC model [16], of which the coefficient of lateral earth pressure in normally consolidated condition, K_0^{nc}, is of dominant influence. K_0^{nc} is approximately equal to 1 for normally consolidated soft soils, and the value decreases towards 0.5 for overconsolidated soils. The current study adopts an intermediate K_0^{nc}-value of 0.65.

The initial position of the cap yield surface is determined by the initial pre-consolidation pressure, directly linked to the over-consolidation ratio (OCR). The normally consolidated state of soft soils suggest that an OCR-value of 1.0 could be adopted for the SSC model. However, this choice would initially induce large creep strains under the initial geo-static stresses, even without additional loading. An OCR-value lager than unity is therefore required, typically in the region of 1.2, to represent more realistically the likely stress history of the soil.

The creep strain rate depends on the over-consolidation ratio and the ratio of the compression index over the creep index. The modified compression indices and OCR-value can be established through calibration with compression test data. The soil test facility function in Plaxis provides a suitable tool to simulate the response obtained from lab testing for the stress range and time intervals applicable. Due consideration of potential sample disturbance and quality of the laboratory testing is required to confirm the suitability of the lab data.

Setting soil permeability is necessary to model consolidation and dissipation of excess pore pressures. The permeability can be obtained from literature, in-situ or lab tests. In this study a permeability of 10^{-5} m/day has been assumed based on an in-house reference project.

Further guidance on the selection of soil parameters is provided in [14].

FE MODELLING OF SPUDCAN PRELOADING

Starting from a single spudcan wished-in-place at final penetration depth, soil-foundation interaction under vertical preloading is modelled through a simplified 2D axisymmetric FE model. The FE model in Figure 4 is simplified in several respects, particularly about (i) no-modelling of large-deformation installation effects, and (ii) lack of interaction among different legs. The latter simplification seems especially crude for four-legged jack-ups such as the Aeolus in Figure 1, but does not prevent to gain valuable insight into the influence of time effects in soil-spudcan interaction.

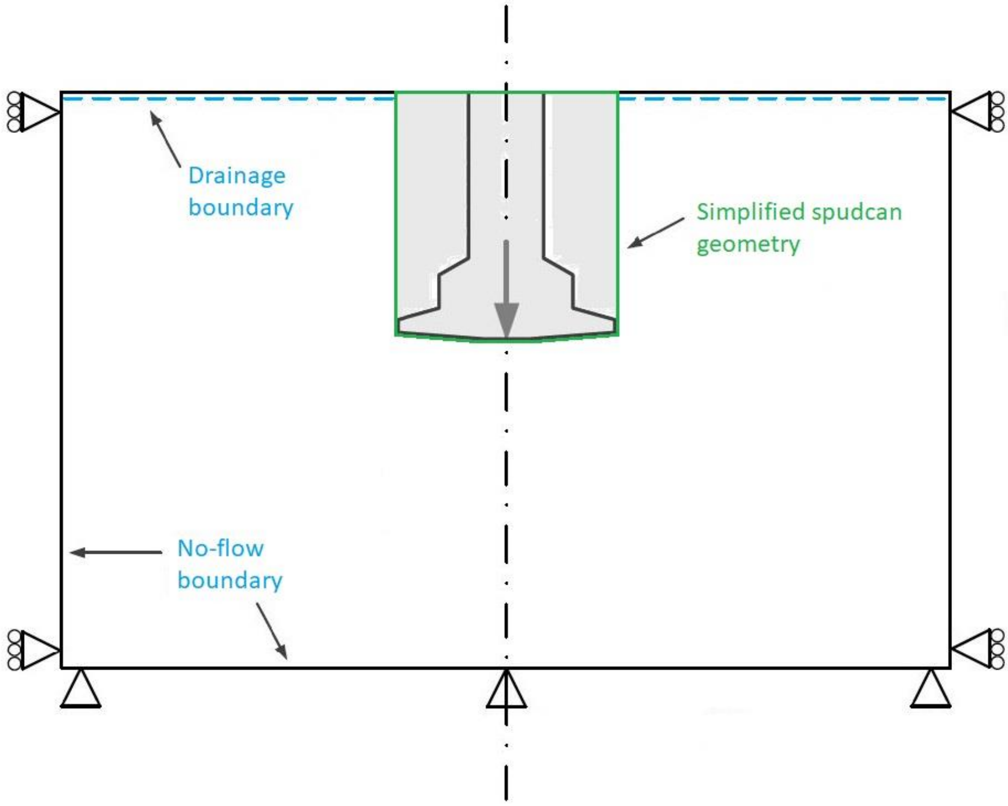

Figure 4: Schematic representation of the soil-foundation model and its boundary conditions

Leg installation and subsequent preloading have been modelled in the following three stages:

1. Wish in place to depth;
2. Apply downward displacement up to reaching a vertical reaction force equivalent to desired preload (loading phase);
3. Maintain leg position from stage 2 and evaluate reduction in load due to relaxation (holding phase)

Prior to performing the preloading, the leg is pushed to depth (Stage 1). Load penetration of the spudcan footing is modelled in a FE model by using a discontinuous wished in place (WIP) method. The footing is installed at each consecutive meter depth after which the vertical prescribed displacements are increased until failure of the soil. This procedure allows to numerically determine the depth at which the bearing capacity equals the preload. Comparable results were also obtained by using the Press-Replace modelling method available in Plaxis, which uses small-strain deformation calculations combined with stepwise update of geometry as the spudcan penetrates into the soil [17]. Undrained soil response is assumed during the loading phase, which is modelled using the effective parameters through the "undrained A" option in Plaxis. It is noted that the resulting effective stress path may be inaccurate, with an impact on the actual undrained strength resulting from effective-stress-based calculations.

The loading phase (Stage 2) is executed by applying the displacement over a prescribed time period such that a realistic strain rate is induced in the soil around the spudcan. In this study a penetration rate of 1 m/hour is adopted.

The holding phase (Stage 3) consists of a time period during which a constant spudcan position is maintained and the response of the soil is detected. In Plaxis this is stage is referred to as the consolidation phase. Owing to the use of a viscoplastic soil model, both soil consolidation and relaxation occur at the same time, resulting in a decrease in leg load over time. This phase is to be regarded as a numerical expedient to approximate the real process, in which the active legs will penetrate into the soil under near constant load and lead to load redistribution in the passive legs.

At the end of the holding phase, the resulting load-time curve is analysed to evaluate whether the preload criterion is satisfied. For the purpose of this study, the load reduction should not exceed 400 tonnes over 15 minutes. In case of excessive load reduction over time, stage 2 and 3 are repeated, gradually bringing the spudcan deeper until sufficient bearing capacity is achieved and the preload criterion finally satisfied.

PARAMETRIC STUDIES

A preloading case study has been first performed for a uniform soft clay profile. The input parameters for this "base case" scenario are presented in Table 2 and are based on typical values from literature and in-house data.

SSC material parameters of soft clay			
	Parameter	Unit	Value
General properties and initial state	γ_{sat}	$[kN/m^3]$	17
	e_{init}	$[-]$	1.0
	OCR	$[-]$	1.3
	k	$[m/day]$	10^{-5}
Shear strength and dilation parameters	c	$[kN/m^2]$	0
	ϕ'	[°]	28
	ψ	[°]	0
Stiffness and viscosity	λ^*	$[-]$	0.060
	κ^*	$[-]$	0.010
	μ^*	$[-]$	0.003
Other control parameters	K_0^{NC}	$[-]$	0.65
	M	$[-]$	1.183
	ν'_{ur}	$[-]$	0.15

Table 2: Soil parameters for base case scenario

The base case assessment considers the spudcan to be wished-in-place at 15m depth, subsequently subjected to the standard preload procedure for a target preload of 5000 tonnes. The influence of permeability and OCR on the results are investigated in the following. Finally, the impact of the alternative "overshooting" preload procedure is studied.

Case 1: influence of permeability

Figure 5 presents the downward displacements relative to the initial wished-in-place position along with the resulting loads on the spudcan as a function of time for a range of permeability values. The base case scenario (10^{-5} m/day) requires four preload cycles in order to reach the established preload criterion – vertical load reduction lower than 400 tonnes in 15 minutes. Increasing the permeability to 10^{-3} m/day yields essentially the same results as the base case. A permeability of 10^{-2} m/day leads to a marginally worse performance, as the fourth loading cycle results in a drop of slightly more than 400 tonnes during a 15 minutes holding period. Significantly larger load reductions during each holding period are observed for a permeability of 10^{-1} m/day. The dashed lines regarding the imposed displacement show that the spudcan also needs to be pushed further downwards in the latter case, in order to reach the target preload during each loading cycle.

It is concluded that consolidation plays no significant role during the preloading for permeability values typical for soft clays. This is in agreement with the expectations supported by Figure 3. Nevertheless, consolidation can still lead to a marked improvement in soil strength in case of prolonged presence at a given location, which may impact the force required for leg extraction.

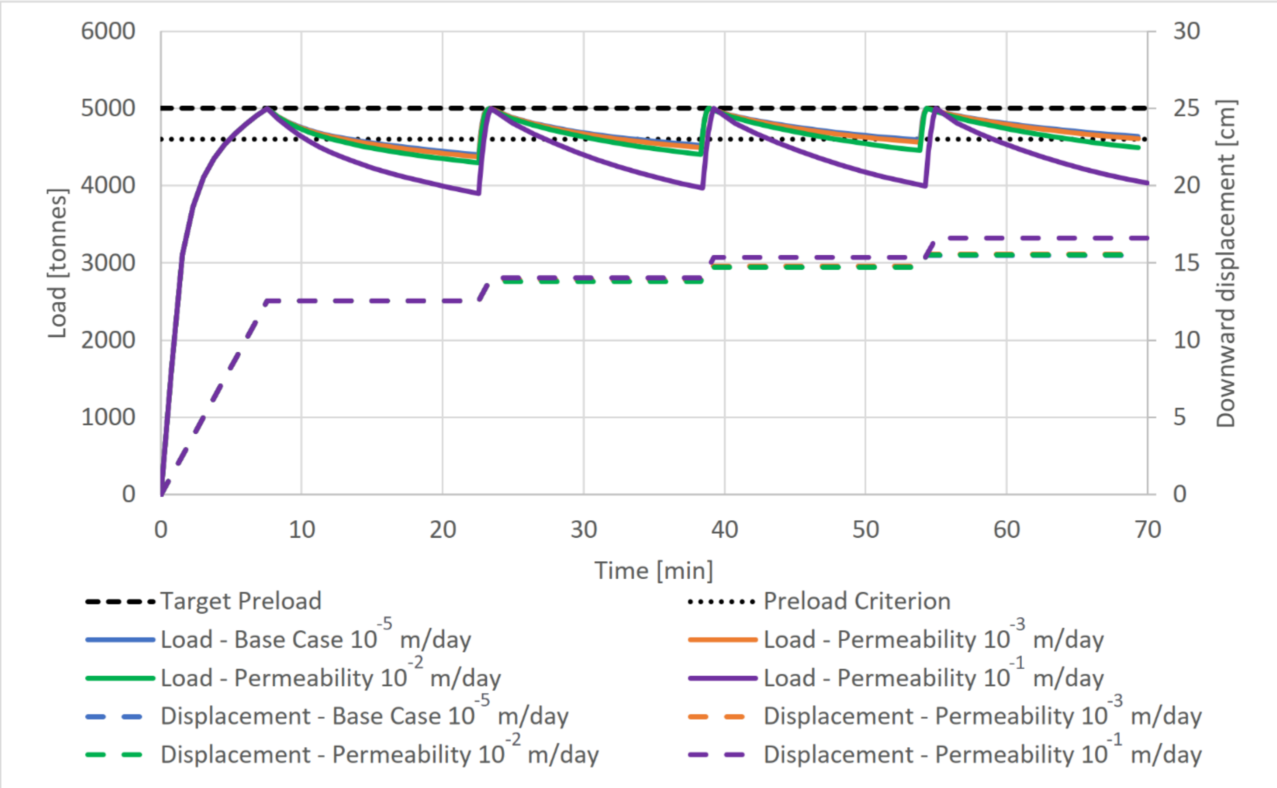

Figure 5: Results for Case 1 – influence of permeability

Case 2: influence of OCR

The effect of increasing the initial OCR from 1.3 to 2.0 over the soil domain is investigated in this case study. Higher OCR implies higher preconsolidation stress and consequently an expanded position of the yield surface cap. A larger part of the loading path (during one-directional loading) will occur within the elastic domain, therefore leading to a stiffer response with less visco-plastic deformations. As a consequence, spudcan foundations achieve sufficient bearing capacity at smaller embedment depths than soils with lower OCR. Nevertheless, the same whished-in-place depth of 15m is maintained in this assessment to facilitate direct comparison among results.

The results for the base case scenario (OCR=1.3) and for a soil with an overconsolidation ratio of 2.0 are presented in Figure 6. The increased OCR strongly affects the preloading cycles and spudcan resistance. The overconsolidated clay requires significantly smaller displacements to reach a resistance of 5000 tonnes. The preload criterion is reached after only one cycle, and limited deformation is observed in subsequent loading cycles.

This case study illustrates that for clays with an OCR in excess of approximately 2, viscous effects become insignificant according to SSC model predictions. However, time-dependent deformations are still observed in the field during preloading in (slightly) overconsolidated clays. Two main reasons contribute to such an outcome: (1) the SSC model is not suited to reproduce viscous effects in significantly overconsolidated clays;

(2) the wished-in-place approach followed herein does not enable the simulation of real remoulding (and decrease in OCR) occurring in the soil during spudcan penetration. Further studies including large deformation analysis coupled with enhanced viscoplastic clay modelling is required to better capture the state and properties of the clay prior to preloading.

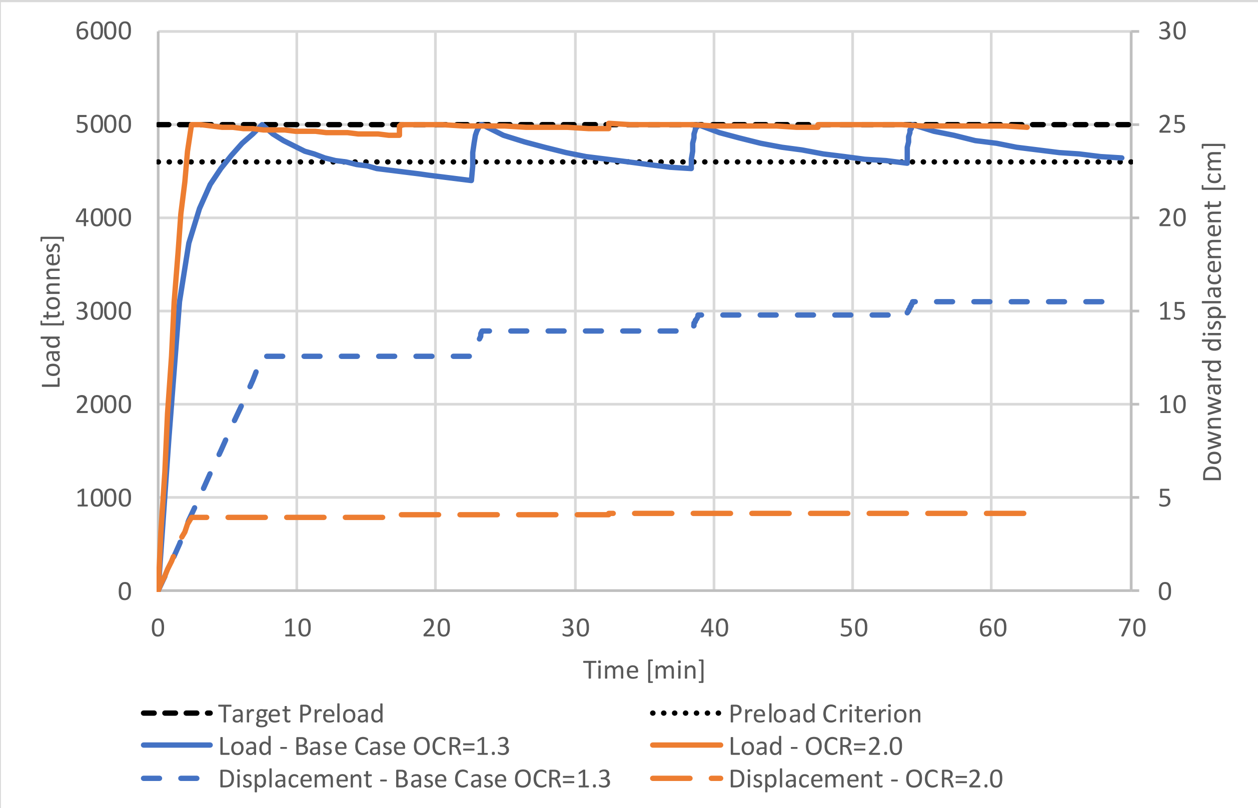

Figure 6: Results for Case 2 – influence of OCR

Case 3: Potential of overshooting preloading procedure

Alternative procedures may be considered in order to reduce the time required for preloading in soft clays. The overshooting method [5] represents an interesting example of such modified preloading procedure. The target preload is exceeded by 10 percent, after which the preload is actively reduced to the initial target preload. This is followed by the holding phase during which the response of the soil is evaluated against the preload criterion.

Numerical simulation results associated with standard and overshooting procedures for base case soil properties are presented in Figure 7. The overshooting procedure quickly meets the preload criterion after only one preload cycle, compared to four cycles for the standard procedure. The higher load required for the overshooting procedure is achieved by pushing the spudcan to greater depth. The first preloading cycle consequently requires more time to reach this depth and subsequent reduction of the leg load. However, the time savings associated with fewer preload cycles seem to substantially outweigh the larger time required for the first (overshot) cycle.

The potential reduction in preload duration using the overshooting method is illustrated for the considered case study. It is noted that the overshooting can only be successfully applied when loading capacity higher than the target preload is available. The increased preload can give rise to excessive penetrations under certain soil conditions, particularly when a weak soil layer is present below the final depth corresponding to the standard target preload.

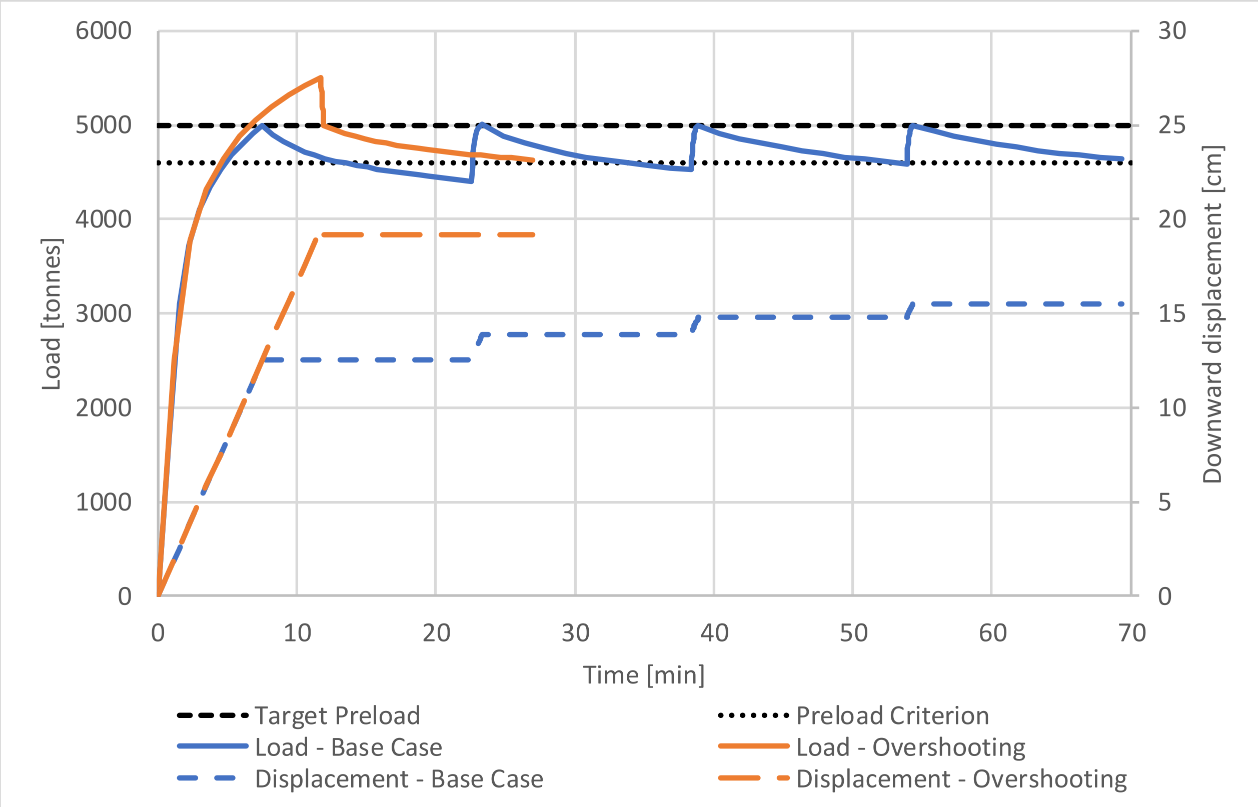

Figure 7: Results for Case 3 – potential of overshooting preloading procedure

CONCLUSIONS

Jacking in soft clays is often time consuming as multiple preload cycles are required to fulfill the preload criterion. The effects of soil viscosity were investigated through a 2D finite element (FE) soil-spudcan model, featuring elasto-viscoplastic soil modelling based on the Soft Soil Creep model available in the Plaxis FE software. The axisymmetric model with a wished-in-place spudcan proved able to reproduce the type of behaviour observed in the field, and enabled relevant parametric studies concerning the influence of certain soil properties and alternative preloading procedures. Based on the model outcome, it was concluded that consolidation effects do not play a significant role during preloading in soft clay. In contrast, the viscous effects were found to be important for time-dependent deformation during preloading. The model was used to demonstrate the potential time-savings of the overshooting preload procedure.

From a critical standpoint, FE results indicated only marginal viscous effects in overconsolidated clays, while in practice time-dependent deformations are often observed during preloading in this type of soils. Enhancing the (viscoplastic) constitutive modelling of overconsolidated clays will certainly add to the soundness of numerical predictions, especially if large deformations and remoulding effects are also taken into account. Better support to jack-up operation management is expected to be achievable through integrated simulations in which advanced description of non-linear soil behaviour is coupled with fully 3D modelling of the vessel and its footings. Current TU Delft-Van Oord joint work is already moving forward in such direction.

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