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A t-z approach for the design of axially loaded piles in consolidating soil

Une approche t-z pour la conception de pieux chargés axialement dans un sol consolidant

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ABSTRACT: This paper presents a t-z model for the analysis of vertically loaded single piles in consolidating soil, using a beam on hyperbolic vertical springs whose tangent stiffness is a function of the normalised mobilised stress in the soil (affected by the consolidation-induced increase in effective stresses) and load history (accounting for loading, unloading and reversed loading). The validation is carried out with published experimental and analytical results. Next, a parametric study illustrates, for floating and end-bearing piles, the temporal evolution of settlement and neutral plane, considering with a simplified approach both displacements and non-displacement piles. Contrarily to end-bearing foundations, the neutral plane location of floating piles is sensitive to the temporal evolution of excess pore water pressure; thus, for the analysis of floating piles, t-z springs with a constitutive law dependent on effective stress should be adopted.

RÉSUMÉ: Cet article présente un modèle t-z pour l'analyse de pieux simples chargés verticalement dans un sol consolidant, utilisant une poutre sur des ressorts verticaux hyperboliques dont la raideur tangente est une fonction de la contrainte mobilisée normalisée dans le sol (affectée par l'augmentation induite par la consolidation des contraintes effectives) et de l'historique de charge (tenant compte des phases de chargement, de déchargement et de chargement inversé). La validation est réalisée avec des résultats expérimentaux et analytiques publiés. Une étude paramétrique illustre, pour les pieux flottants et les pieux en butée, l'évolution temporelle du tassement et du plan neutre, en considérant, avec une approche simplifiée, à la fois les pieux à déplacement et les pieux sans déplacement. Contrairement aux fondations en butée, la localisation du plan neutre des pieux flottants est sensible à l'évolution temporelle de la pression interstitielle excessive; ainsi, pour l'analyse des pieux flottants, des ressorts t-z avec une loi constitutive dépendant de la contrainte effective devraient être adoptés.

Keywords: Consolidation; pile; settlement; t-z curve; neutral axis.

1 INTRODUCTION

When piles are affected by a combination of external loads and consolidation processes, performance-based design requires the estimate of settlements. Despite numerical modelling capabilities (Russo et al., 2020; Liang et al., 2023), practitioners mostly rely on simplified load capacity assessments (e.g. Danish National Annex to Eurocode 7; EN 1997-1 DK NA:2007) or neutral plane-based approaches to assess the effects of consolidating soil (Fellenius, 2023). However, these simplified methods have limitations. This paper presents an analytical model for the soil-pile interaction suitable for serviceability assessments.

2 INTERACTION MODEL

The proposed soil-pile interaction model is a beam on nonlinear t-z springs whose behaviour is affected by the consolidation. Namely, this model is based on a two-stage analysis method (i.e. consolidation-induced greenfield settlements used as input for the interaction analysis), Terzaghi's 1D consolidation theory for non-uniform initial excess pore water pressure distributions (Lovisa et al., 2010), the Euler-Bernoulli beam theory for the pile, nonlinear t-z springs (distributed along the shaft and base of the pile) as a ground model.

For the t-z springs, the approach of Chen et al. (2009) is adopted. The initial stiffness K_0 is estimated according to Randolph & Wroth (1978), if not stated otherwise, with base $K_{0,b} = \frac{d_p E_{s,0}}{1-\nu_s^2}$ and shaft per running meter $K_{0,s} = \frac{\pi E_{s,0}}{(1+\nu_s)\ln(2\, r_m/d_p)}$, where $E_{s,0}$= initial Young's modulus, ν_s = soil Poisson's ratio, r_m = magic radius, d_p = pile diameter. According to the Duncan hyperbolic stiffness degradation, the tangent stiffness for further loading or reverse loading is $K_{tan} = (1 - F_m/F_u)^2 K_0$, where F_m is the mobilised force at the spring, F_u is the ultimate spring force obtained by integrating the failure shaft friction τ_f or base pressure q_f, whereas $K_{tan} = K_0$ in the case of unloading (i.e. spring reaction F_m attains the largest, in magnitude, positive or negative force mobilised at the spring). If not stated otherwise, the beta-method model is used to estimate $\tau_f = \beta\sigma_v'$ and $q_f = N_q\sigma_v'$ from the vertical effective stress σ_v', obtained from the consolidation analysis. The model neglects effective stress variation at the soil-pile interface induced by local soil shearing in the near-pile soil region; therefore, the interaction and consolidation analyses are uncoupled (Kim et al., 2011). The self-weight of the pile is disregarded in this paper, although it can be included. The solution is solved using the Finite Element Method in incremental steps. For further details refer to Detlefsen (2023).

3 RESULTS

3.1 Validation

The model predictions are compared, with analytical and centrifuge results of a pile in consolidating soil for the two scenarios illustrated in Figure 1.

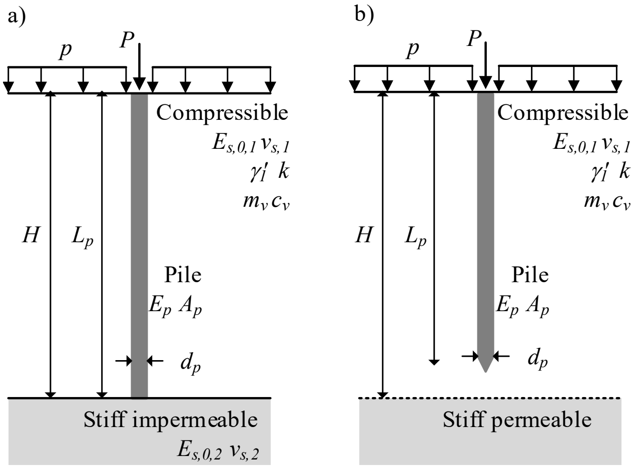

Figure 1. Modelled pile and ground conditions for a) end-bearing pile, and b) floating pile.

First, the model is validated against results obtained by Chen et al. (2009) using a similar analytical formulation for an end-bearing pile in consolidating soil and one-way drainage towards the surface (impermeable stiff bottom layer at the pile base). Figure 1a displays the problem geometry and parameters. The pile has length L_p = 10 m (equal to the consolidating layer thickness H), diameter d_p = 0.5 m, Young's modulus E_p = 20 GPa, and head load P. The compressible layer has γ' = 10 kN/m^3, $\beta = K \tan\phi'$ = 0.3. For the base layer, $E_{s,0,2}$ = 500 MPa, $\nu_{s,2}$ = 0.3, and ultimate base pressure q_f = 4.6 MPa. Surcharge pressure is set to p = 150 kPa. For direct comparison, along the shaft the initial tangent stiffness of the nonlinear springs $K_{0,s}$ is set to match the values adopted by Chen et al. (2009), associated with a displacement of 0.5 mm at $\tau_{f,0}$, which for r_m =17.5 m is associated with a gradient $E_{s,0,1}/z = 10.5$ MPa/m according to Randolph & Wroth's expression. Chen et al. (2009) adopted a 1D non-linear consolidation method, in which the coefficient of consolidation, c_v, and the coefficient of compressibility, m_v, are varying during consolidation. However, in this paper, Terzaghi's one-dimensional consolidation theory is adopted using m_v = 10^{-4} m^2/kN and c_v = 0.1644 m^2/day.

Figure 2 shows the response of the unloaded pile, in terms of mobilised shaft friction and axial force along the pile, for an average degree of consolidation $U_{v,avg}$ = 0.5 and 1. Also, Figure 2a reports ultimate shaft friction profiles τ_f during consolidation, as affected by excess pore water pressure dissipation and the impermeable bottom boundary. An excellent agreement with benchmark results is seen in Figure 2. Similarly, there is agreement with Chen et al. (2009) for the case of the loaded pile with P of 200 kN (Detlefsen 2023), which led to a downward shift in the neutral plane due to the external head load from a depth of 9 m to 8.5 m.

Second, the centrifuge test results from Lam et al. (2009) are simulated. As shown in Figure 1b, the experiment modelled a floating pile in consolidating clay under two-way drainage conditions (with the clay layer located between two coarse-grained layers); the base distance from the bottom coarse-grained layer is one diameter. The model pile was installed at 1 g; then, the model was spun up to 60 g for 16 hours, until an average degree of consolidation of 90% was reached. The tubular aluminium pile (E_p = 70 GPa, outer diameter d_p = 1.2 m, length L_p = 16.8 m) was embedded in fully saturated clay (height H = 18 m; pre-consolidation pressure of 80 kPa before centrifuge testing; effective unit weight γ' = 6.3 kN/m^3; water table at the clay surface) and having on both sides dense Leighton Buzzard 100/170 sand layers. The top sand layer had a unit weight γ_{dry} = 15 kN/m^3 and a thickness of 3 m, giving a surcharge load p = 45 kPa. In the analytical model, it is assumed for the clayed layer $E_{s,0,1}$ = 2.76 MPa, Poisson's ratio $\nu_{s,1}$ = 0.35, β = 0.3, N_q = 10.7, and r_m = 27.1 m. From back-analysis, using the method suggested by Lovisa et al. (2010), the coefficient of consolidation c_v = 0.0433 m^2/day and m_v = 3.64 10^{-4} m^2/kN were estimated from measured subsurface excess pore water pressures and greenfield surface settlements, respectively (Detlefsen, 2023).

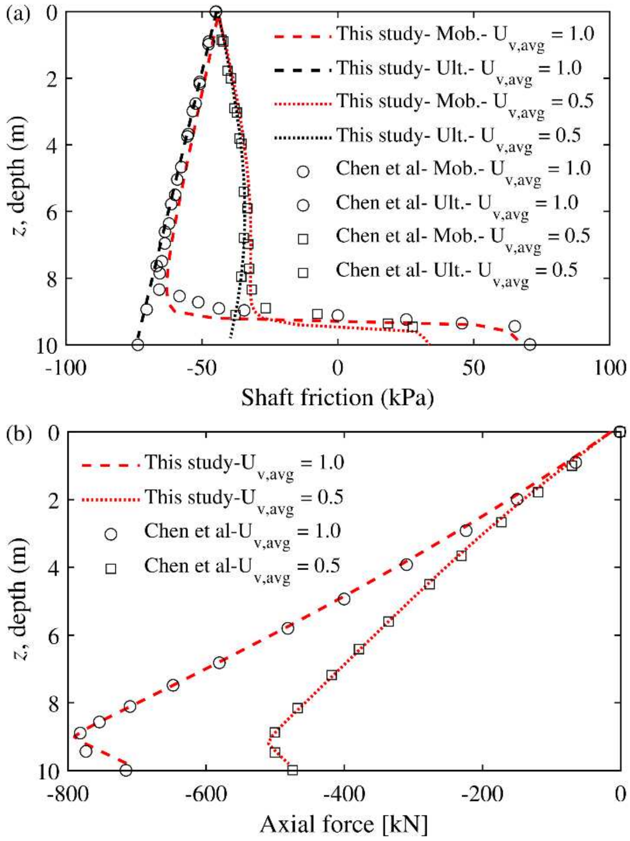

Figure 2. Comparison with analytical results for an unloaded pile: (a) shaft friction; (b) axial force.

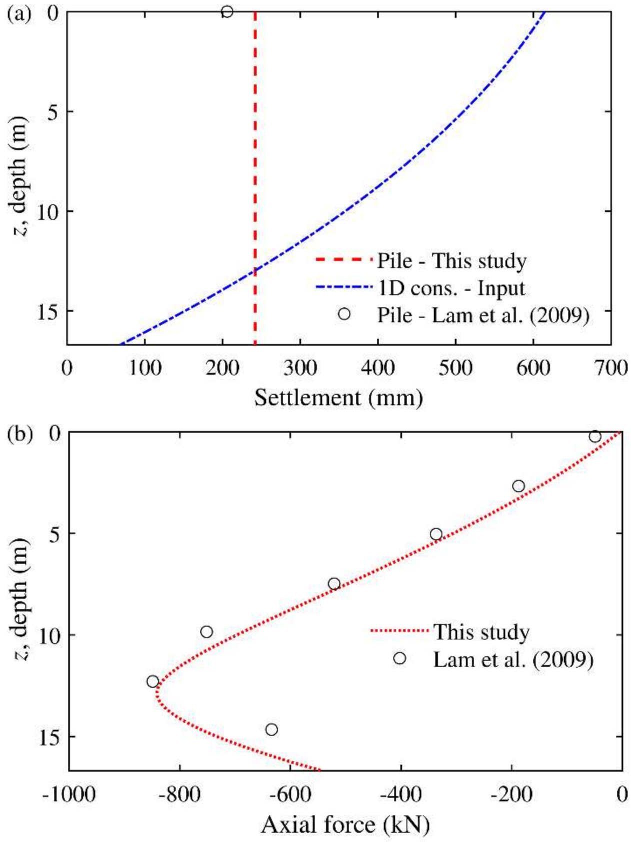

Figure 3. Comparison with centrifuge test results: (a) axial force; (b) greenfield and pile settlements.

Figure 3 compares prototype experimental and analytical results at 90% average degree of consolidation of. Despite a slight overestimation of the consolidation-induced settlement of the pile (predicted settlement of 242 mm instead of 206 mm, due to the stiffening effect of the base coarse-grained layer which was neglected), the predicted axial force profile is in satisfactory agreement with the experimental data. The axial force profiles show there is agreement between the experimental and analytical neutral planes, being at a depth of approximately 0.75 L_p.

3.2 Sensitivity study

A parametric study of the neutral plane depth and consolidation-induced settlements is carried out. The considered case study generalises the prototype experimental scenario in Figure 1b for head load P of 0 (for unloaded piles) or 1000 kN (for loaded piles).

Two different head load histories prior to consolidation and application of service loads are considered for displacement and non-displacement piles respectively. This is done to approximately take the effect of residual stresses and unloading stiffness along displacement piles into account, which will differ from ground stiffness and stress distributions of bored piles. Prior to the surcharge application p, (i) "non-displacement" piles have the head load P monotonically applied; (ii) "displacement piles" were subjected first to a head load of 99% the load capacity, then unloaded, and finally reloaded to the target P. During the consolidation, the head load P is kept constant. For both head loading and consolidation, the load transfer of the t-z springs is described by K_{tan}, as previously detailed. Results are normalised as for Kog (2016): the depth of the neutral plane is divided by the pile length giving $\psi = z_{np}/L_P$, while the normalised settlement of the pile head is $\Delta = \Delta_p E_p A_p/(p\ H^3)$.

Figure 4 displays the results for unloaded piles ($P = 0$) with a length $L_P = 0.4\ H$ to $1.4H$, where H is the thickness of the consolidating layer. The embedment L_P/H is found to impact the temporal evolution of the neutral plane depth ψ of floating piles ($L_P/H < 1.0$), whereas ψ is not affected by the time factor T_v for end-bearing piles ($L_P/H \geq 1.0$). This trend of ψ is also notable in Figure 5 which compares the neutral plane depth ψ of loaded piles when having an embedment for floating $L_P/H = 0.8$ and end-bearing $L_P/H = 1.2$. Thus, it is important to model the soil-pile interaction for floating piles in consolidating soil.

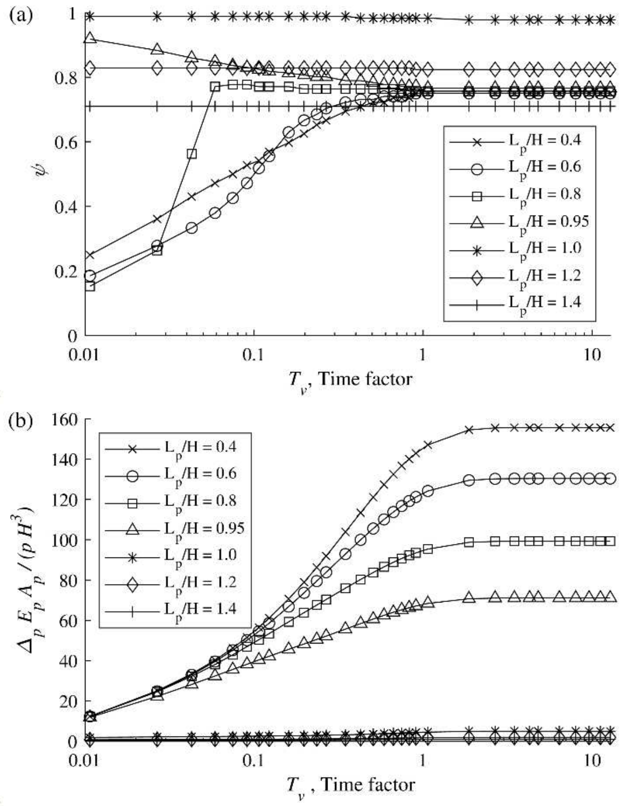

Figure 4. Settlement response of unloaded non-displacement piles against time factor with varying embedment depth: (a) neutral plane depth and (b) normalised settlements.

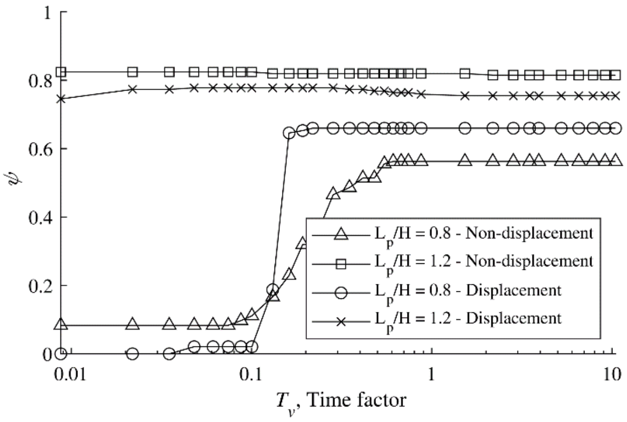

Figure 5. Normalised neutral plane depth of loaded (P = 1000 kN) displacement and non-displacement piles with varying embedment length.

4 CONCLUSIONS

This paper presents a beam on hyperbolic t-z springs model for the time-dependent stress analysis of unloaded and loaded piles in consolidating soil. A parametric study illustrated the importance of modelling the excess pore water pressure dissipation and installation in the case of floating piles.

Future work will address a consistent stiffness formation in terms of effective stresses.

REFERENCES

Chen, R., Zhou, W. and Chen, Y. (2009). Influences of soil consolidation and pile load on the development of negative skin friction of a pile. *Computers and Geotechnics*, 36(8): 1265–1271. DOI:10.1016/j.compgeo.2009.05.011.

Detlefsen, A. E. (2023). An effective stress nonlinear model for the analysis of axially loaded single piles in consolidating soil. *MSc thesis*, Aarhus University, Aarhus, Denmark.

Fellenius, B. H. (2023). Basics of foundation design–a textbook. Electronic Edition. https://www.fellenius.net/papers.

Kim, H.-J. and Mission, J.L.C. (2011). Development of negative skin friction on single piles: uncoupled analysis based on nonlinear consolidation theory with finite strain and the load-transfer method. Canadian Geotechnical Journal, 48(6): 905–914. DOI:10.1139/t11-004.

Kog, Y.C. (2016). Axially loaded piles in conso- lidating layered soil. *International Journal of Geomechanics*, 16 (1): 905–914. DOI:10.1061/(ASCE)GM.1943-5622.0000523.

Lam, S., Ng, C.W., Leung, C. F. and Chan, S. (2009). Centrifuge and numerical modeling of axial load effects on piles in consolidating ground. *Canadian Geotechnical Journal*, 46(1): 10–24. DOI:10.1139/T08-095.

Liang, R., Yin, Z.Y., Yin, J.H. and Wu, P. C. (2023). Numerical analysis of time-dependent negative skin friction on pile in soft soils. *Computers and Geotechnics*, 155, 105218. DOI:10.1016/j.compgeo.2022.105218.

Lovisa, J., Read, W. and Sivakugan, N. (2010). Consolidation behavior of soils subjected to asymmetric initial excess pore pressure distributions. *International Journal of Geomechanics*, 10(5): 181–189. DOI:10.1061/(ASCE)GM.1943-5622.0000143.

Randolph, M. F. and Wroth, C. P. (1978). Analysis of deformation of vertically loaded piles. *Journal of the geotechnical engineering division*, 104(12): 1465–1488. DOI:10.1061/AJGEB6.0000729.

Russo, G., Di Girolamo, L. and Marone, G. (2020). BEM and FEM Approaches to the Analysis of Negative Skin Friction on Piles. *Geotechnical Engineering Journal of the SEAGS & AGSSEA*: 51(2). http://seags.ait.asia/journals/2020/51-2.